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Design Optimization and Performance Enhancement of Small-Scale Vortex-Induced Turbines for Sustainable Energy Generation

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Abstract

This study presents the development and evaluation of a vortex bladeless wind turbine prototype designed to harness wind energy in low wind speed conditions, making it suitable for regions such as Malaysia. The prototype consists of a 2-meter-tall, 0.2-meter-diameter cylindrical structure mounted on a flexible shaft, which utilizes vortex-induced vibrations to generate mechanical energy. Testing was conducted in a wind tunnel with airflow ranging from 1 m/s to 10 m/s, as well as in outdoor field locations around UTHM. Results demonstrated the turbine's effectiveness at low to moderate wind speeds. Vibrations were converted into electrical energy using an electromagnetic induction system. Analysis of oscillation frequency, voltage output, and efficiency indicated promising performance under conditions where traditional turbines are less effective. Design enhancements further improved the turbine's performance.

1. Introduction

Electricity is a vital component of modern society, influencing nearly all aspects of life, from education and communication to home life and business operations. It powers our daily routines, enabling conveniences such as lighting, refrigeration, and entertainment while supporting critical functions like healthcare systems, public safety, and industrial production. Through its role in technologies like radio, television, email, and the Internet, electricity enhances communication and fosters global connectivity, driving innovation and economic growth [1]. Furthermore, electricity is indispensable in modern transportation systems, powering trains, electric vehicles, and urban infrastructure, which collectively underpin the functioning of contemporary urban and rural settings.

Given its importance, the pursuit of sustainable electricity generation is crucial in addressing global challenges such as climate change, environmental degradation, and energy security. Currently, coal remains the dominant source of electricity worldwide due to its affordability and availability [2]. However, coal combustion releases significant quantities of harmful pollutants, including lead, mercury, sulfur dioxide, nitrogen oxides, particulates, and heavy metals, which are detrimental to both human health and the environment [3]. The contribution of coal-fired power plants to greenhouse gas emissions exacerbates global warming, making the transition to cleaner energy sources imperative.

To reduce dependence on coal and other fossil fuels, countries worldwide are investing in renewable energy. Malaysia, endowed with favorable geographical and climatic conditions, has made strides in developing its renewable energy capacity, particularly through hydroelectric power. As the largest contributor to Malaysia's renewable energy mix, hydroelectricity harnesses the country's abundant rainfall and river systems, providing a reliable and relatively low-emission energy source [4]. However, the development of large-scale hydropower projects is often accompanied by challenges, such as environmental concerns and the displacement of communities.

Wind energy represents another promising avenue for diversifying Malaysia's energy portfolio. Traditional wind turbines, towering between 40 and 90 meters, capture the kinetic energy of the wind and convert it into electricity using aerodynamic principles. While these large structures are efficient in areas with consistent wind patterns, their size and land requirements can limit their deployment in densely populated or ecologically sensitive areas [5]. Research and development are addressing these limitations by exploring smaller, more adaptable turbine designs and offshore wind farms, which offer significant potential for Malaysia's coastal regions. As technology evolves, wind energy could rival hydroelectricity as a key renewable energy source in Malaysia, contributing to the nation's transition to a sustainable energy future [6].

This shift toward renewable energy aligns with global commitments to sustainable development, reducing environmental impacts, and ensuring energy security for future generations. By investing in technologies like wind and hydroelectric power, Malaysia can not only meet its growing energy demands but also position itself as a leader in the renewable energy sector [7].

2. Methodology

The VIT prototype, designed using SolidWorks 2019, consists of a thin, flexible cylindrical structure mounted on a solid base. The prototype includes 14 key parts made from various materials such as plywood, PVC pipes, and 3D-printed plastics. The VIT prototype includes the following parts: (i) Base plate and body made from plywood and concrete, (ii) Fixed and flexible rods made from PVC, and (iii) Various connectors and covers made from ABS and PLA plastics. Each component is carefully designed and fabricated to ensure the smooth functioning of the prototype. The electrical system includes proper wiring, an inverter to convert DC to AC power, and components for energy storage and conversion. Proper wiring ensures efficient operation and accurate data collection.

The VIT prototype was tested around the UTHM aerodynamics laboratory (Fig. 1). Due to low natural wind speeds, a wind tunnel was used to obtain electric current data. Initial tests faced wiring issues, impacting results. Proper operation of the wind tunnel required safety equipment and experienced operators. The prototype was tested at the UTHM football field and road site, where wind speeds ranged from 0.8 m/s to 3.0 m/s. The open space allowed wind to cause vibrations in the prototype, generating small amounts of energy. Both modified and unmodified prototypes were tested to gather data on vibrations and voltage. Safety measures included using safety glasses, earmuffs, and proper tools. Accurate measurement tools like wind speed meters and stopwatches ensured reliable data collection.

The installation of a system involves careful arrangement of the base, flexible and permanent rods, mast-rod connector, copper coil holder, wiring, battery connection, magnet holder, cap, inner magnet ring, lower mast part, outer magnet ring, and screws. The base is arranged straight, and the copper coil holder is placed on fixed rods. The wiring process begins with wires connected to copper coils and directed through the holes in the fixed rod to the base of the mast (Fig. 2). The battery connection is disconnected, and the charger controller is connected to the battery. The assembly then includes the magnet holder, cap, and inner magnet ring above the copper coil holder. The lower mast part is trimmed to make room for the outer magnet ring, and the outer magnet ring is carefully placed. Four screws are used to secure the lower mast part through the mast-rod connector. The inverter is connected to the battery wire, and the assembly is completed with a functional and integrated system.

(a) **(b)** **(c)**

Fig. 1 *Testing location. (a) Wind tunnel; (b) Field; (c) Roadside*

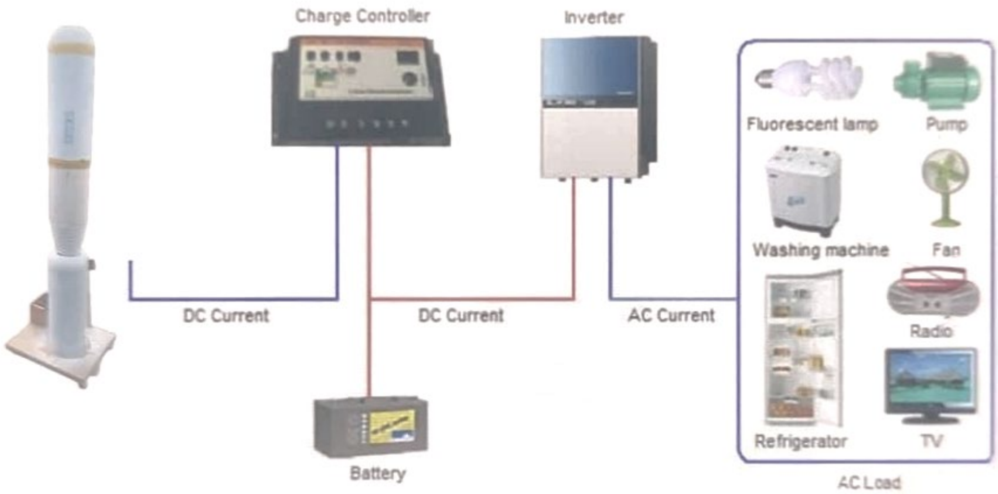

Fig. 2 *Complete electrical connection setup of the prototype*

3. Result & Discussion

Tables 1 and 2 present the oscillation data for the original and enhanced prototypes. The original prototype showed a maximum oscillation frequency of 1.32 Hz, with performance limited by heavier structural materials. The enhanced prototype demonstrated higher oscillation frequencies due to structural modifications, such as replacing PVC with lightweight plastic materials. These changes reduced the body's weight and improved vibration response. Fig. 3 shows a comparison of the number of oscillations against wind speed for the original and enhanced prototypes. The enhanced prototype achieved up to 30 oscillations compared to the original 26, representing a 15% increase. Modifying the center structure to use plastic instead of PVC pipes reveals the difference, leading to increased oscillation and vibration.

Table 1 *Oscillation frequency of the original prototype at varying wind speeds [8]*

Wind Speed (m/s)	No. of Oscillation				Time Taken (s)	Frequency of Oscillation (Hz)
	1	2	3	Average		
1	23	20	24	22.33	20	1.12
2	24	26	25	25.00		1.25
3	26	25	25	25.33		1.27
4	24	23	26	24.33		1.22
5	25	26	24	25.00		1.25
6	26	25	26	25.67		1.28
7	26	27	26	26.33		1.32
8	23	24	27	24.00		1.23
9	24	24	24	24.00		1.20
10	25	24	23	24.00		1.20

Table 2 *Oscillation frequency of the enhanced prototype at varying wind speeds*

Wind Speed (m/s)	No. of Oscillation				Time Taken (s)	Frequency of Oscillation (Hz)
	1	2	3	Average		
1	25	25	24	24.67	20	1.23
2	25	26	26	25.67		1.28
3	26	27	27	26.67		1.33
4	27	28	27	27.33		1.36
5	27	28	27	27.33		1.36
6	27	29	28	28.00		1.40
7	29	27	28	28.00		1.40
8	29	29	30	29.33		1.46
9	30	28	29	29.00		1.45
10	29	30	29	29.33		1.46

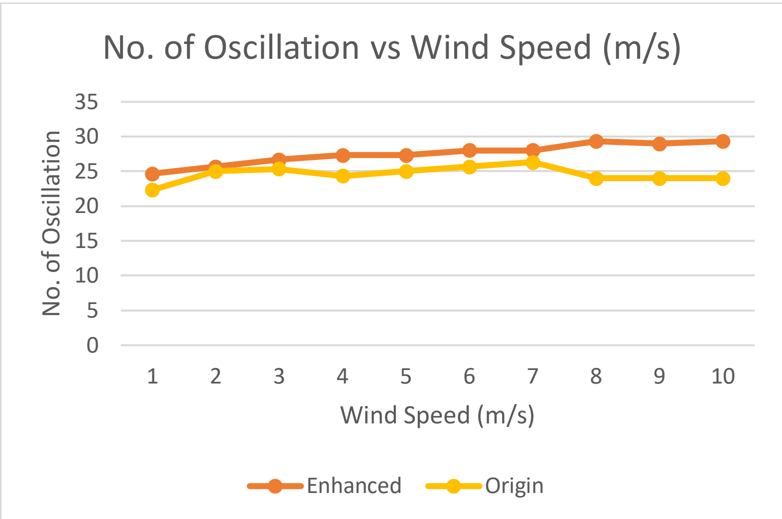

Fig. 3 *Comparison of oscillations versus wind speed for the original and enhanced prototypes*

3.1 Site Comparisons

Experiments have been conducted in several places around UTHM and found that voltage, current, and wind speed change according to the area and environment that affect the vortex as presented in Table 3 and Table 4. The wind tunnel lab demonstrated the highest voltage measurement and highest rate of volts, generating a power output of 2.74 W at a wind speed of 2.5 m/s. This indicates the wind tunnel lab's ability to maintain steady air flow, which is crucial for optimal wind turbine power generation. The football field had the lowest voltage value and current, with a power output of 1.287 W, due to irregular wind patterns. The roadside location had moderate values, with a voltage of 0.080 V and a current of 25.80 A at a wind speed of 2.6 m/s, generating a power output of 2.064 watts. This suggests that while roadside wind conditions were less reliable than those in a wind tunnel, they were more stable compared to a football field. The significant difference in power output and voltage measurements among different locations underscores the importance of wind constancy in wind energy installations. Areas with more consistent wind patterns, such as wind tunnels, generally yield higher power output and voltage production. However, changes in wind conditions, like those at the football field, could significantly affect wind energy production. These findings demonstrate the value of selecting suitable locations with reliable wind resources for wind energy projects to optimize efficiency and production.

Table 3 *Voltage, current, and wind speed measurements at various testing sites*

Location	Voltage (V)	Current (A)	Wind Speed (m/s)
Football Field	0.055	23.40	2.4
Roadside	0.080	25.80	2.6
Wind tunnel	0.105	26.10	2.5

Table 4 *Power output of the enhanced prototype at different sites*

Location	Voltage (V)	Current (A)	Power Output (W)	Wind Speed (m/s)	Power Input (W)
Football Field	0.055	23.40	1.287	2.4	8.459
Roadside	0.080	25.80	2.064	2.6	10.759
Wind Tunnel	0.105	26.10	2.7405	2.5	9.57

The data in Table 5 was gathered from the experiment done with the original VIT prototype prior to its enhancement. The data was gathered from three distinct locations next to the UTHM campus: the football field, the roadside, and the wind tunnel laboratory. Figure 4 illustrates the comparison between the original voltage and the voltage of the enhanced prototype. The illustration demonstrates a substantial increase in voltage on the football field, approximately 50%, from 0.023 V to 0.055 V. This indicates that the enhanced prototype yields favorable outcomes. The voltage at the roadside has risen by almost 30%, from 0.05 V to 0.08 V. The wind tunnel demonstrates an increase of up to 25%, with the voltage rising from 0.08 V to 0.105 V. The alteration of various components within the mast and flexible rod may have contributed to those alterations. The alteration in weight within the mast significantly influences the acceleration of vibrations and oscillations.

Table 5 *Power output of the original prototype at different sites*

Location	Voltage (V)	Current (A)	Power Output (W)	Wind Speed (m/s)	Power Input (W)
Football Field	0.023	13.40	0.308	2.4	8.475
Roadside	0.050	15.80	0.790	2.6	10.759
Wind Tunnel	0.080	16.10	1.288	2.5	9.570

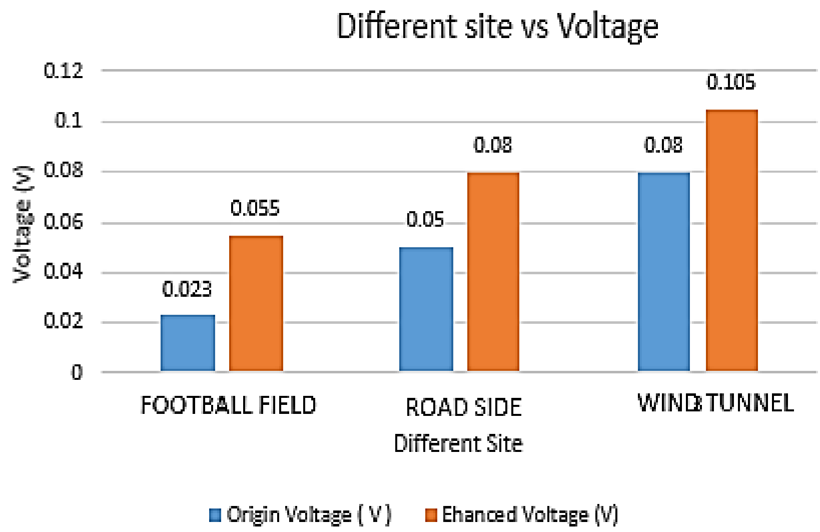

Fig. 4 *Voltage comparison of the original and enhanced prototypes at different testing locations*

4. Conclusion

The experiment aimed to determine the most effective way to operate a turbine system induced by vortices using various sensors. The results indicated that wind tunnel sites had the highest voltage rate, producing an output of 0.105 V and a power output of 2.74 W. Football field locations had the lowest voltage rate, producing an output of 0.055 V and a power output of 1.28 W. The enhanced prototype demonstrated greater effectiveness than the original VIT, indicating better performance. The improvement depends on wind speed and weather conditions at each location. The project received commendation for its positive environmental impact, despite the significant investment in time and work. The innovation resulted in efficient conservation of electrical energy and power harvesting from wind-induced vibrations, reducing carbon emissions and improving public health and safety. This demonstrates its potential as an economical and environmentally friendly alternative for conventional energy sources.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Sheikh Alif Habibullah Sheikh Hassan, Sofian Mohd;* ***data collection:*** *Sheikh Alif Habibullah Sheikh Hassan;* ***analysis and interpretation of results:*** *Sheikh Alif Habibullah Sheikh Hassan, Sofian Mohd;* ***draft manuscript preparation:*** *Sheikh Alif Habibullah Sheikh Hassan, Sofian Mohd. All authors reviewed the results and approved the final version of the manuscript.*

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