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Development and Optimization of an Urban-Scale Omnidirectional Wind Turbine with Integrated Solar Power System

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Abstract

Renewable energy sources are very important for the preparation for the shift from the fossil fuel. This study introduces the design and optimization of city wide hrbrid renewable energy system between wind turbine and solar system. The design aims at efficiently the turbulent and multidirectional urban wind, and supplementing energy generation with solar power on low wind conditions to ensure stable and continous output. Much emphasis has been given to design optimization, selection of materials, durability, cost-effectiveness, and easy installation in densely packed urban cities. Its compact hybrid design demonstrates strong potential for deployment in smart cities and sustainable urban energy infrastructure.

1. Introduction

Electrical energy is essential to modern urban life, and rising demand driven by population growth and urbanization has increased the need for sustainable and reliable power sources. Renewable energy, particularly when adapted to space-limited and densely built environments, offers a viable solution to reduce dependence on fossil fuels and environmental impact[1]. An effective approach is the integration of omnidirectional vertical axis wind turbines (VAWTs) [2] with solar photovoltaic (PV) panels, forming a compact hybrid system suitable for urban infrastructure such as rooftops and building facades. VAWTs are well suited to turbulent, low-speed urban wind conditions common in Malaysia, where average wind speeds are around 2 m/s [3], while solar panels complement energy generation during low wind periods. This hybrid configuration ensures more consistent power output, enhances energy security, and supports decentralized generation. The implementation of such wind–solar hybrid systems contributes to sustainable urban development, reduced carbon emissions, and the advancement of greener, smarter cities.

1.1 Problem Statement

The global shift towards sustainable energy sources underlines the importance of developing an efficient source that can be effectively used in complex urban environments. Cities are associated with issues like space confinement, shading, low-speed turbulent flow, and structural limitations that can hamper the efficient working of traditional solar PV technology and horizontal-axis wind turbine technology. The application of an urban-friendly hybrid system that combines the working of omni-directional vertical-axis wind turbines (VAWTs) and solar panels [4] may be an effective solution. The reason behind selecting these turbines is that they are ideally suitable for urban energy production because of their ability to produce energy for urban environments where wind approaches from any direction, reduced noise production, small size, negligible impact of turbulent low-speed flow on turbines, and efficient working. But existing gaps between research gaps include the application of techniques like CFD for enhancing turbine working, structural integrity, use of turbines for urban energy production in Malaysia, and a lack of dependable data on small urban turbines in Malaysia.

1.2 Objective

i. To design and develop a small scale hybrid wind-solar energy harvesting prototype for urban environment.

ii. To evaluate the electrical output character of the system under controlled operating condition.

iii. To investigate the contribution of wind and solar source in supporting battery charging behaviour.

1.3 Scope

i. Design an omnidirectional wind turbine suitable for urban applications considering factors such as size, orientation independence, noise reduction, safety, and aesthetics

ii. Integrated photovoltaic solar panels into the wind turbine structure to form a hybrid energy-generating system suitable for urban rooftops or compact urban spaces.

iii. Conduct simulations and experimental testing to analyze the aerodynamic efficiency, structural integrity, and power generation performance of the wind turbine.

2. Methodology

Methodology summarizes the systematic approach adopted to conduct research in order to achieve the objectives of the study through a structured and rigorous investigation. A sound, clearly defined methodology ensures that the results are credible and valid by providing guidelines on how data is to be collected, analyzed, and interpreted. This study is based on the positivist research paradigm. The research design follows from the aims and research questions of the study in adopting a mixed-methods approach so as to look in depth at the system under investigation. Further, this chapter addresses the hardware requirements and system components that were used in the implementation of the proposed design.

2.1 Literature

From past research, the viability and advantage of using hybrid renewable energy sources have been established in overcoming the issue of reliability and sustainability related to energy. In this regard, Afif et al. (2023) designed and developed a hybrid microgeneration system involving picohydro and photovoltaic solar energy sources, specifically targeting the requirement of rural areas in Malaysia. As discussed, the research specifically aimed to design and develop the microgeneration system, as well as to test and investigate the performance of the microgeneration system, specifically in terms of the voltage stability of the microgeneration system's energy output.

On broader aspects, Nijhawan et al. (2021) [5] and Suripto et al. (2023) [6] examined advanced hybrid energy systems that combine different renewable sources to further improve efficiency and continuity of supply. Accordingly, Nijhawan et al. presented a holistic hybrid system with solar, biomass, hydrogen storage, and fuel cell technologies, interfaced by power electronic converters and IoT-based monitoring for efficient energy management. This acts to enhance energy utilization, system control, and flexibilities for varied demands. Similarly, Suripto et al. have investigated in the year 2023 the hybrid solar–hydro energy model coupled with a backflow water system and discussed the reliability issues achieved by complementarities between two renewable sources. Thus, all these studies confirm that hybrid energy systems emerge as a feasible and sustainable solution to meet the ever-growing demand for energy with reduced dependence on any single energy source.

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2.2 System Flowcharts

The system flowchart illustrates the overview of the integrated omnidirectional wind turbine and solar system. The output for each sources must be in same voltages to charge 12V battery.

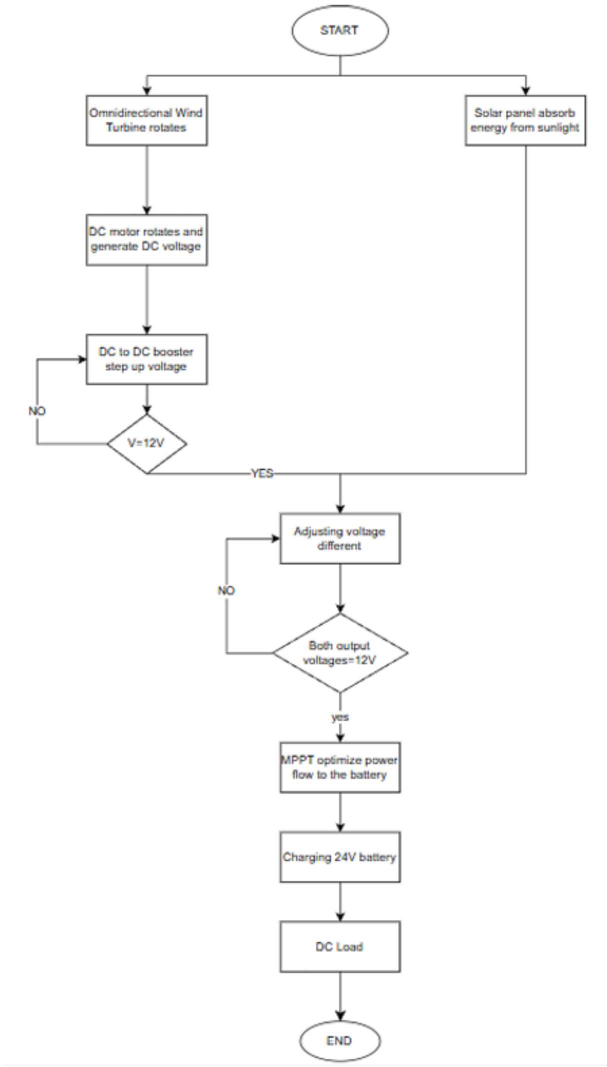

Fig.1 The flowchart of the system

2.3 Components

The components used for this project include 3D print omnidirectional wind turbine and small solar panel 18V that can easily be mount. Besides, the brushless DC motor that can support the output 12V to give the constant voltage. Also MPPT Charge Controller needed to manage the DC input to output.

Fig.2 Actual prototype of Omnidirectional Wind Turbine

2.3.1 System Analysis

This will be a hybrid renewable energy generation unit that will integrate an omnidirectional wind turbine with a solar PV system for supplying electrical power in urban environments. The design is intended to cope with low and highly variable wind while ensuring maximum energy capture by complementary solar generation. Wind energy is converted into electrical energy with the help of a brushless generator coupled to the VAWT, while solar energy is captured via PV panel mounted within the system structure. Both sources, after processing with appropriate power electronics, are combined and stored in a 24 V battery system. A charge controller regulates voltage and current, offers protection against overcharging, and ensures safely working batteries. In this respect, the architecture of the system is optimized for compactness, low noise, ease of installation, and minimum maintenance; therefore, it is especially suitable for rooftops or generally dense urban settings. Generally, the hybrid configuration increases the reliability of energy, reduces intermittency, and accordingly enhances total efficiency compared to stand-alone renewable systems.

3. Result and Discussion

Overall, it can be stated that the hybrid system that integrates wind and solar energy has shown its possibility to be used on a smaller scale for powering urban areas. Though it has been found that the solar system is highly efficient, yet the design of the turbine used has proved to be inefficient for lower speed winds and needs further improvements.

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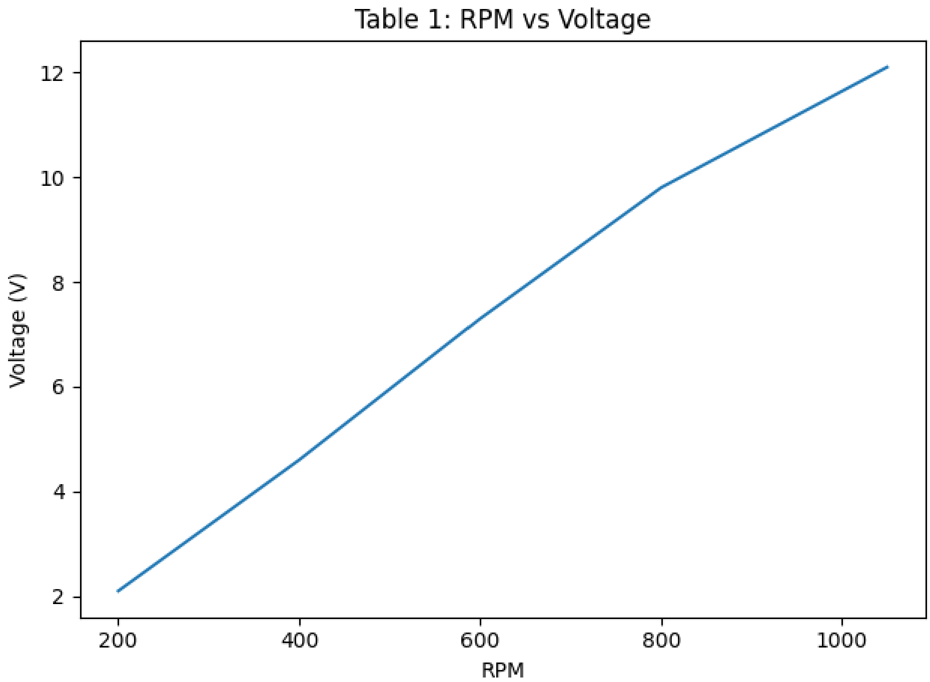
Table 1: Average Measurement for Certain RPM for Brushless DC Generator

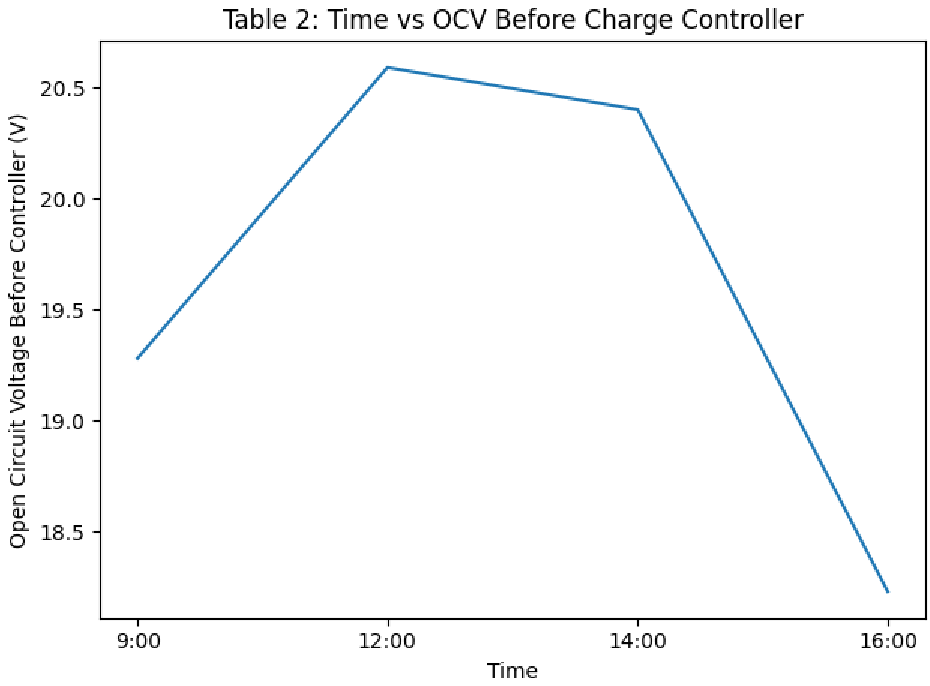
RPM	Voltage (V)	Current (A)	Power (W)
200	2.1	0.05	2.10
400	4.6	0.12	1.20
600	7.3	0.20	1.60
800	9.8	0.35	3.43
1050	12.1	0.51	6.17
Average	35.921	1.23	14.5



At rpm 1050, the voltage measured 12.1V, followed by the 800 rpm 9.8V, while at 600 rpm, 400 rpm and 200 rpm exhibited much lower voltage of7.3V, 4.6V and 2.1V respectively.

Table 2: Open Circuit Voltage Collected Data for Solar System

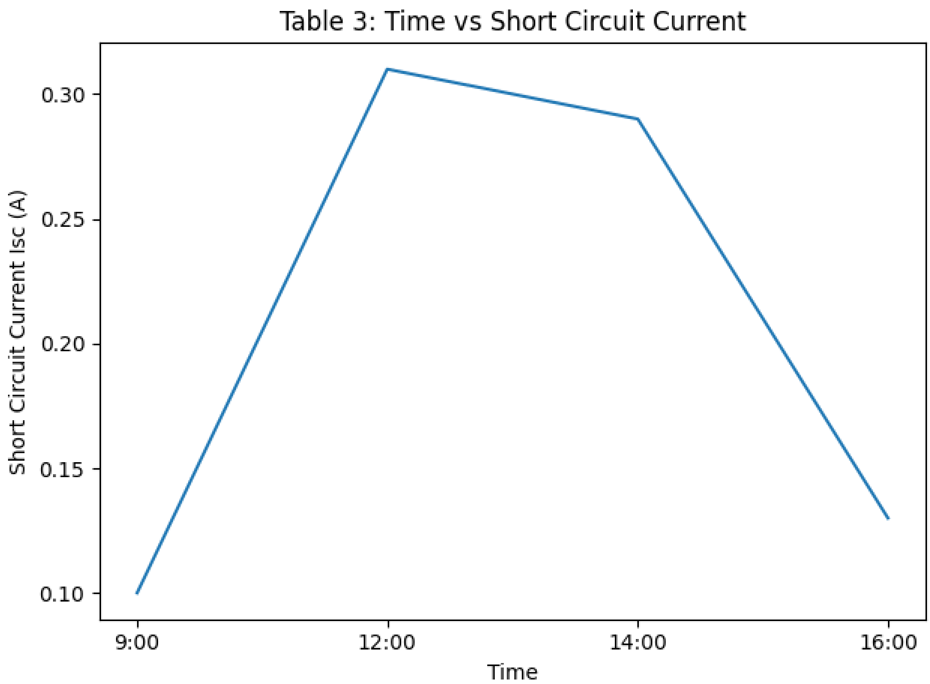
Time	Open Circuit Voltage Before Charge Controller (V)	Open Circuit Voltage After Charge Controller (V)
09.00 a.m.	19.28	12.00
12.00 p.m.	20.59	12.00
02:00 p.m.	20.40	12.00
04:00 p.m.	18.23	12.00



In the afternoon, the open circuit voltage was 20.59V, followed by the evening at 02:00 p.m. at 20.40V, while at 09.00 a.m. and 04:00 p.m. exhibited much lower open circuit voltage of 19.28V and 18.23V, respectively.

Table 3: Short Circuit Current Collected Data

Time	Short Circuit Current, Isc (A)
09.00 a.m.	0.10
12.00 p.m.	0.31
02:00 p.m.	0.29
04:00 p.m.	0.13
Average	0.2075



In the afternoon, the short circuit current was 0.31 A, followed by the evening at 02:00 p.m. at 0.29 A, while at 09.00 a.m. and 04:00 p.m. exhibited much lower open circuit voltage of 0.10 A and 0.13 A, respectively.

3.1 Data Analysis

The findings and discussion of the above study were anchored on experimental analysis carried out through controlled and practical simulations of the urban setting, taking certain assumptions and limitations into perspective. The performance of the wind turbine was analyzed using a rotational simulation driven by a tachometer because of the unreliable natural wind flow, ensuring that the output reading was mainly indicative of the generator performance rather than the actual efficiency of the turbine blades. The wind turbulence experienced within the urban setting predominantly impacted the self-start capability as well as the stability of the rotational movements of the turbine at low wind speeds. The solar panel measurements were considered through varying radiation intensity, taking into perspective the intensity of the Sun's radiation, shading, and variations in temperatures, which impacted the values of the voltages and currents, but the charge controller was able to ensure a steady output of 12V. The calculation of the hybrid system charge was considered through taking into perspective the ideal peak operating standards with the correction factors of efficiency, estimating a total charge time of 5.8 hours to charge the 24V battery. Although the real-time processing performance could be subject to environmental changes, it can be stated from the result that hybridization increases energy availability and reliability compared to other systems, stressing at the same time the need for optimization of wind turbine blades in low-speed urban wind energy extraction.

Charging Time (hours) = {Battery Capacity (mAh) / Average Current (mA)} x Efficiency Factor
= {2400/453.5}x 1.1
=5.8 hours

3.2 Conclusion

In conclusion, this final year project does not succeed in optimizing to capture wind for low speed because of the material as well as its design. Furthermore, the company which designs said wind turbine will display the outer blade only but not the material details and the inner one of the wind turbine. But for the solar power system, success is because of the simplicity wiring. Using the acquired output, in the situation where the wind turbine rotates with the brushless motor, it will produce an output generator operating at 1050rpm, a voltage of 12.1V, a current of 0.51A, and a 12.00 p.m. produced 20.59V before the charge controller and 12.0V after controller and 0.31A. whereas in the case of the hybrid, both can be measured at each peak value will provide sufficient to charge 24V battery for 5.8 hours.

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