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VERIFICATION TESTING OF A WELL-MATCHED WIND TURBINE POWER GENERATION SYSTEM

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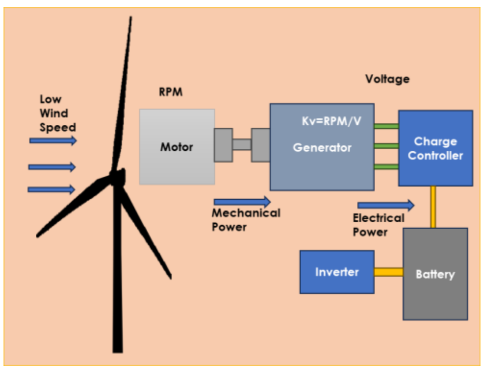
Graphical abstract



Abstract

Due to Malaysia's typically low and fluctuating wind speeds, it is crucial to carefully select and match appropriate wind turbine generators to ensure efficient power production. However, the data provided by manufacturers for wind turbine generators often differs from actual operational performance. This study aims to develop a test rig and setup to characterize the generator constant. The verification testing involved validating a 1kW generator with a rated voltage of 48V and a rated RPM of 380 under both unloaded and loaded power systems. The results showed that the calculated generator constant (Kv) for the 1kW 48V generator was 4.56 rpm/V when the system was unloaded. When the system starts charging, using an Energy Storage Capacity (ESC) of 4.8kWh, the Kv value increased to 63.13 rpm/V. The maximum charging power (Pc) that could be generated under these conditions was 944W at 533 rpm. According to the results, at the generator's rated RPM of 380, the maximum charging power attainable is 608W. This test result contradicts the manufacturer's claim that at a rated RPM of 350, the power output is 1kW.

Keywords: Wind turbine, generator, low wind Speed, rated power, verification testing

Abstrak

Oleh kerana kelajuan angin di Malaysia yang rendah dan berubah-ubah, adalah penting untuk memilih dan memadankan penjana turbin angin yang sesuai untuk memastikan pengeluaran kuasa yang cekap. Walau bagaimanapun, data yang disediakan oleh pengeluar untuk penjana turbin angin sering berbeza daripada prestasi operasi sebenar. Kajian ini bertujuan untuk membangunkan rig ujian dan penyediaan untuk mencirikan pemalar penjana. Pengujian pengesahan melibatkan pengesahan penjana 1kW dengan voltan terukur 48V dan RPM terukur 380 dalam kedua-dua sistem kuasa tanpa beban dan berbeban. Hasilnya menunjukkan pemalar penjana yang dikira (Kv) untuk penjana 1kW 48V ialah 4.56 rpm/V apabila sistem tidak berbeban. Apabila sistem mula mengecas, dengan menggunakan Kapasiti Penyimpanan Tenaga (ESC) sebanyak 4.8kWh, nilai Kv meningkat kepada 63.13 rpm/V. Kuasa pengecasan maksimum (Pc) yang boleh dijana dalam keadaan ini ialah 944W pada 533 rpm. Menurut hasilnya, pada RPM terukur penjana iaitu 380, kuasa pengecasan maksimum yang boleh dicapai ialah 608W. Hasil ujian ini bercanggah dengan dakwaan pengeluar bahawa pada RPM terukur 350, kuasa terhasil adalah 1kW.

Kata kunci: Turbine angin, penjana, kelajuan angin rendah, kuasa diukur, ujian pengesahan

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1.0 INTRODUCTION

Wind power is still under investigation and being studied in certain countries, especially in Malaysia. It is because Malaysia's annual average wind speed is about 2 m/s which is categorized as a low wind speed region. The average wind speed in Malaysia is lower than 3m/s which is not enough to generate electricity [1, 2].

There was a study and installation of a vertical axis wind turbine in Dungun, Terengganu, although the efficiency of this wind turbine was found to be low [3]. It is possible that the wind turbine is not well-matched to the generator. Efforts to address this issue include aerodynamic solutions, such as optimal blade design [4], and improvements in the electrical power generation system focused on the generator [5]. However, these studies typically focus on high wind-speed turbines. There is a notable lack of research on well-matched systems for low wind-speed turbines.

The generator plays a crucial role in converting mechanical energy into electrical energy, and its selection must consider cost-effectiveness [6]. The importance of proper generator selection is highlighted by the hybrid wind turbine installation at Small Perhentian Island, where a generator malfunction led to the wind turbine's inability to operate effectively, causing both energy and cost losse. Similarly, the failure of a wind turbine generator during its installation by TNB Malaysia at Trumbu Layang-layang underscores the significant impact of generator issues on overall system efficiency [7].

DC generators are not commonly used in wind turbines because of their higher costs and maintenance requirements [8]. Instead, permanent magnet generators are widely used in small wind turbine applications due to their high power density and low mass [9]. Synchronous wind turbine generators, however, often have limited damping capabilities, making them less effective at absorbing transient forces from the drivetrain [10]. In contrast, doubly-fed induction generators (DFIGs) are prevalent in variable speed wind turbine applications due to their efficiency and versatility [11]. Direct drive permanent magnet generators (PMGs) are highly advantageous for low-speed wind turbines because they eliminate the losses associated with gear systems. Furthermore, at low loads, direct drive PMGs experience minimal copper losses. The inherent stability of permanent magnets makes these generators ideal for power generation in low wind speed conditions[12]. Wind speeds range from approximately 5.71 m/s to 8.76 m/s, the power output of permanent magnet generators (PMGs) ranges from 37.70V to 40.90V. This power can be efficiently stored in a 48V battery, ensuring stable power generation[13].

Labuschagne and Kamper (2021) [5], developed an impedance matching method for wind generator compatibility by investigated the impact of impedance in the wind turbine system. Additionally, a motor-generator setup has been used for testing the matching of wind turbine generators [6,15]. While Potgieter *et al*. (2015) [14] used a motor-to-generator setup with a 15kW capacity to examine the time-dependent behavior of the power generation system, focusing on voltage, current, and power characteristics. Research on matching wind turbines has also been conducted by Kao (2016) [4], who created a procedure specifically focused on matching turbine blades with generators.

The importance of precisely matching turbines with generators lies in the potential to improve overall energy production, efficiency, and the return on investment in wind power applications [15]. To maximize power extraction from wind, it is recommended to operate the turbine using a maximum power point tracking (MPPT) method[17, 18, 19]. Accurate turbine modeling allows for MPPT without the need for wind measurements, reducing costs and increasing the wind system's competitiveness. However, the overall wind system's performance is affected by the relationship between the parameters of the permanent magnet (PM) generator and the wind turbine[19].

2.0 METHODOLOGY

Figure 1 illustrates the research flowchart detailing the overall methods of verification testing for 1kW generators.

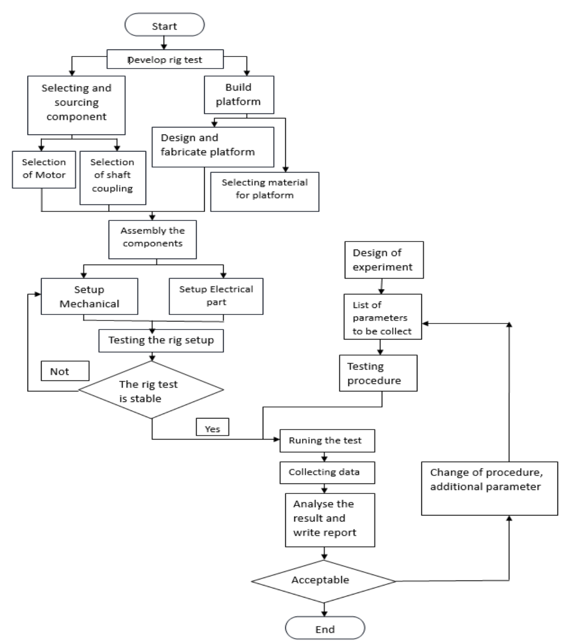

Figure 1 Research flowchart

To verify the loaded generation system of wind turbine, the 1kW generator setup at wind turbine lab is used for the verification testing. Figure below shown block diagram of the power generation setup at Wind Turbine Lab UTM

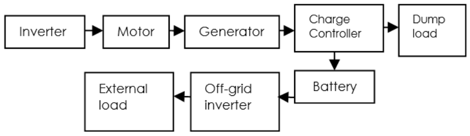

Figure 2 Block diagram of motor-generator setup

Figure 3 shows the three-phase motor are used that will be connected with the inverter and three-phase power supply. The motor used in the testing are 37kW motor, 1475 rated RPM and 239Nm rated torque.

Figure 3 Motor

The generator was purchased from overseas (China), where the company offers the option to customize the generator based on specifications such as rated voltage, rated torque, and power. The generator used in the testing are permanent magnet generator (PMG) with 1kW power rated, 380 rated RPM and 48V rated voltage as shown in

Figure 4. The motor is to be linked with the generator. The experimental setup involves the utilization of weighing scale to measure generator torque. The generators are AC generators because, with variable wind speeds, PMG generators can efficiently convert mechanical energy into electrical energy over a wide range of speeds.

Figure 4 1kW generator

The inverter is utilized to regulate the motor's torque and speed, which subsequently drives the system. Figure 5 illustrates the inverter's connection to the motor, while the variable factors include torque and speed.

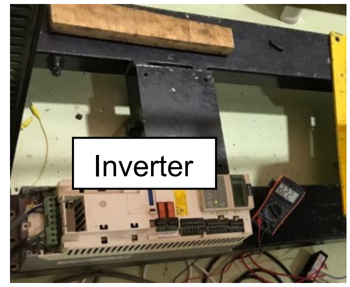

Figure 5 Inverter

In the process of setting up a 1kW, 48V wind turbine system, a charge controller (Figure 6) is employed to regulate battery voltage, while a dump load is utilized to prevent overcharging. These components are critical for maintaining the system's safety and efficiency.

Figure 6 Charge controller

In this experiment, lead-acid batteries are employed with specific configurations: the 1.2 kWh setup utilizes a 12V battery with a capacity of 25Ah, while the 4.8 kWh setup also uses a 12V battery but with a larger capacity of 100Ah. These configurations illustrate the varying energy storage capacities implemented in the study, crucial for understanding performance and efficiency in renewable energy systems.

The motor and generator shafts are linked via shaft couplings equipped with shock and vibration absorbers as shown in Figure 7 effectively mitigating operational disturbances within the system.

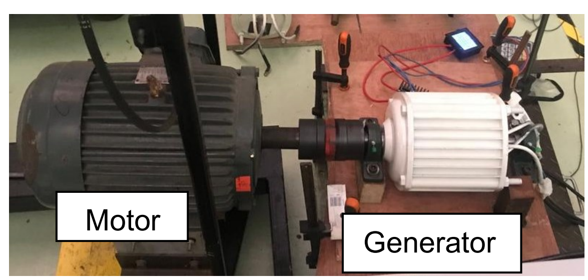

Figure 7 Motor to generator setup

The 3-phase generator cable will connect to the charge controller designed for a 1kW, 48V wind turbine system. This controller regulates the voltage sent to the battery and is equipped with a dump load to prevent overcharging. Additionally, an off-grid inverter is used to integrate the storage system with an external load, as depicted in Figure 8.

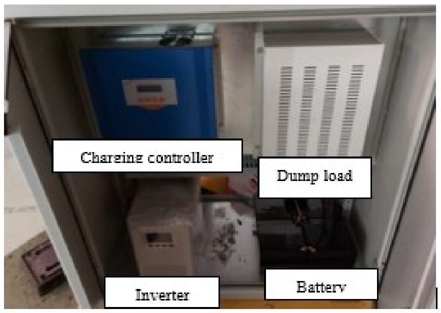

Figure 8 Electrical setup

Once the mechanical and electrical setup is completed, testing will commence to collect the following parameters as per the designed experiment. Specifically, for the generator testing, the parameters to be measured include:

Ω_{motor} = Motor speed (RPM).
$Q_{generator}$ = Generator torque (N.m).
V_{dc} = DC voltage from the generator (V).
$I_{generator}$ = Output current generator (A)
P_c = Charging power (W)
SoC = State of Charge (%).
V_b = Voltage battery (V).

The generator constant, KV can be defined as the ratio of the motor speed (Ω_{motor}) to the DC voltage output (V_{dc}). It is calculated by dividing the motor speed by the DC voltage, providing a measure of how efficiently the generator converts mechanical speed into electrical voltage.

The generator torque, Q are calculated by multiply F_g with r_g. Where F_g is the force generated by the generator when it begins to operate, and the r_g is the radius of the generator, measured from the center to the outer diameter where the force are measured.

3.0 RESULTS AND DISCUSSION

This section will discuss the results obtained from the experiment, focusing on four main analyses: the effect of SoC, the effect of external load, the influence of ESC, and the generator constant KV. The discussion will encompass the behavior of the system in both 48V setups, considering both loaded and unloaded conditions.

A 1kW generator was tested with a 1.2kWh battery, with initial battery percentages of 19%, 25%, and 40%. The experiment involved varying motor speeds. Results were recorded in three separate tables corresponding to each battery percentage: Table 1 for 19%, Table 2 for 25%, and Table 3 for 40%. The testing was repeated with an increased energy storage system (ESC) of 4.8kWh, starting with a battery percentage of 47.5%. The results of this testing are presented in Table 4.

According to the presented results, the system experienced an unloaded phase where no charging power was produced until reaching a specific point, at which the charging power began to generate once a certain cut-in speed was reached.

Table 1 Testing result of 1kW generator ,1.2kWh ESC with 19% SoC

RPM	I(A)	Vdc	Q(N.m)	Pc(W)	Kv
100	3.20	23.00	1.2	0	4.35
148	3.70	33.00	1.2	0	4.48
200	3.60	46.00	2.2	0	4.35
250	6.30	49.00	11.8	185	5.10
275	7.00	50.00	14.0	240	5.50
294	7.40	51.00	15.5	290	5.76
344	11.00	56.00	24.2	500	6.14
355	11.80	57.00	25.6	550	6.23

Table 2 Testing result of 1kW generator ,1.2kWh battery capacity with 25% battery percentage

RPM	I(A)	Vdc	Q(N.m)	Pc(W)	Kv
100	3.20	23	1.20	0	4.35
148	3.80	33	1.20	0	4.48
204	3.90	45.5	1.40	0	4.48
227	3.90	49	2.80	10	4.63
233	4.00	50	3.60	25	4.66
254	4.70	51	7.40	100	4.98
333	9.80	56	21.60	458	5.95
347	10.60	57	23.40	500	6.09

Table 3 Testing result of 1kW generator ,1.2kWh battery capacity with 40% battery percentage

RPM	I(A)	Vdc	Q(N.m)	Pc(W)	Kv
100	3.20	23	1	0	4.35
209	3.80	46	1.2	0	4.54
227	3.80	49	2.5	7	4.63
233	3.90	50	3	20	4.66
244	4.20	51	4.8	56	4.78
297	7.20	55	14	275	5.40
316	8.30	56	17	350	5.64
326	8.30	57	18.8	400	5.72
345	9.03	58	25	460	5.95

Table 4 Testing result of 1kW generator ,4.8kWh ESC with 47.5% SoC

RPM	I(A)	Vdc	Q(N.m)	Pc(W)	Kv
206	1.20	44.95	1.0	0	4.58
227	1.30	49.30	1.4	0	4.60
247	1.90	51.75	3.8	38	4.77
261	2.60	52.10	6.8	100	5.01
352	6.30	54.00	24.0	510	6.52
426	8.90	55.00	32.0	757	7.75
466	12.23	55.50	34.0	851	8.40
501	11.30	55.80	34.6	900	8.98
533	12.10	56.20	35.0	944	9.48

Illustrated in Figure 9 is the graph depicting the relationship between speed (RPM) and direct current voltage (Vdc) for various combinations of battery SoC and battery capacities: 47.5% for a 4.8kWh battery, and 19% ,25%, and 40% for a 1.2kWh battery. When the ESC is 4.8kWh, the slope of the graph, representing the generator constant, is measured at 62.104, which is higher compared to the system with an ESC of 1.2kWh, where the slope is 12.954 at SoC around 40% to 47.5% as shown in Table 5.

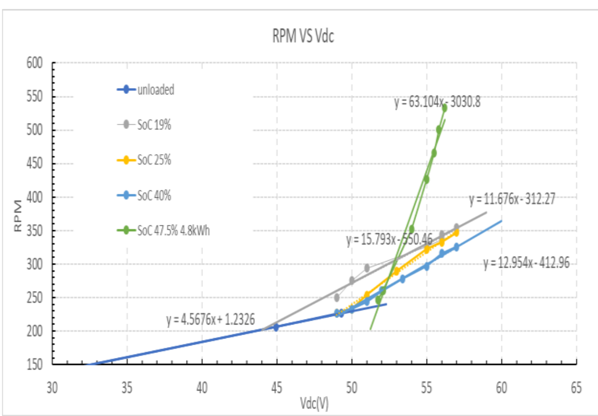

Figure 9 Graph rotational speed (RPM) versus Voltage (Vdc)

Table 5 Generator constant Kv and charging power at different experimental setup

SoC (%)	ESC (kWh)	Kv	Pc(W)
not significant	unloaded	4.57	0
19	1.2	15.79	519.24
25	1.2	11.68	355.77
40	1.2	12.95	123.5
47.5	4.8	63.1	944

Based on Table 5, when the system is tested with a 4.8 kWh setup, the generator can produce a maximum charging power of 944W, which is higher than the 519.24W produced by the 1.2 kWh setup. The manufacturer claims that at 380 RPM, the generator can generate 1kW. However, experimental results reveal that when the system runs at 380 RPM, the generated charging power is 608W, corresponding to an efficiency of 60.8% as shown in Figure 10.

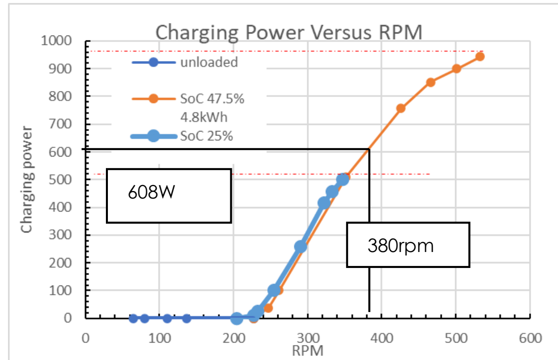

Figure 10 Charging power versus RPM

Based on Table 6, the initial charging torque when the battery is at a state of charge (SoC) of 18% is 11.8 N.m, which is higher than at SoC levels of 25% and 40%, where the torques are 7 N.m and 2.8 N.m, respectively. It can be concluded that a lower state of charge (SoC) requires a higher initial charging torque due to the increased load on the system.

Table 6 Initial charging torque at different SoC

SoC (%)	Initial charging torque, Qo (N.m)
18	11.8
25	7
40	2.8

The charging power generated by the wind turbine system depends significantly on the energy storage capacity (ESC) connected to the power generation system. Based on the data from Table 5 and the graph presented in Figure 10, it is evident that a higher ESC increases the range of charging power that the system can generate. Tests show that increasing the ESC from 1.2kWh to 4.8kWh results in a 62.3% increase in charging power, though this requires a higher RPM.

Additionally, Figure 9 illustrates that the generator constant Kv increases when the system starts charging or is under load. The load experienced by the system depends on the state of charge (SoC) and ESC during operation. A lower SoC results in a higher load, which necessitates a higher initial charging torque, as shown in Table 6. The effect of SoC to the system are crucial to be observe since the charging of lead acid are strongly dependent on the SoC and resistance [20].

These testing results characterize the generator within an actual wind turbine system, verifying its specifications. This is crucial to ensure that the generator matches the wind turbine power generation system, especially since the manufacturer's specifications differ from the actual requirements for operating the wind turbine at low wind speeds. The tests reveal that only 60.8% of the rated power can be produced by the 1kW generator at its rated speed.

4.0 CONCLUSION

The experimental results indicate a discrepancy between the manufacturer's claims and the actual performance of the generator. While the manufacturer asserts that the generator can produce 1kW at 380 RPM, the experiment shows that only 608W is generated at this speed, resulting in an efficiency of 60.8%. Additionally, the system's performance varies with different energy storage capacities: the 4.8 kWh setup achieves a higher maximum charging power (944W) compared to the 1.2 kWh setup (519.24W). These findings highlight the importance of empirical testing and procedure to validate manufacturer specifications and suggest that system efficiency can be influenced by the capacity of the energy storage system. Further investigation into the factors affecting generator efficiency and performance under different conditions is recommended.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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