Feasibility Study of a Novel 6V Supercapacitor based Energy Harvesting Circuit Integrated with Vertical Axis Wind Turbine for Low Wind Areas

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Received: 16.05.2016 Accepted:23.07.2016

Abstract- This paper provides a platform for a novel innovative approach towards an off-grid Supercapacitor based battery charging and hybrid energy harvesting system for low wind speed Vertical Axis Wind Turbine (VAWT). A 3-Phase Permanent Magnet Synchronous Generator (PMSG) was chosen for its low maintenance cost, light weight and less complicated design. Simulation studies was carried out to obtain an optimized design and a 200W 12V 16 Pole PMSG attached to a VAWT of 14.5m radius and 60cm of height was sent for fabrication with Maglev implementation (Magnetic Levitation). Upon arrival, the optimized system is implemented into the energy harvesting circuit and field testing is carried to observe the performance. Under wind speed range of 3-5m/s, the energy harvesting circuit showed better efficiency in charging battery in all aspects comparing to direct charging of battery regardless of with or without converter. Based on analysis and results carried out in this paper, all feasibility studies and information were successfully provided for future work.

Keywords: Energy Harvesting; Supercapacitor; Battery Charging; Low Wind; Vertical Axis Wind Turbine.

1. Introduction

A burning concern of the 21st century is that conventional energy sources are depleting. Thus, it has become a necessity to find alternative power generating sources. Having considered the speedy development of electronic devices, the need for power has never been greater. Each day, people spend more time on electronics but are often found to be in difficult situations with limited battery charge. Wind power can be an alternate renewable energy source to this problem. Wind energy research in Malaysia is still in the early stage and not many researches have been conducted on off-grid wind energy harvesting device for low wind speed [1] [2]. Although crude oil and natural gas are the leading energy sources in Malaysia, studies estimate that fossil fuels will only be supplying energy to mankind till 2088 [1][3]. As a main part of renewable energy, wind power is emerging as a strong alternative source to fossil fuels [4]. By utilizing the wind energy, countries like Malaysia demand to have a standalone system to charge up their small scale electronic devices in a greener way.

The averages wind speed of Malaysia is less than 5m/s and more commonly in the range of 2-3m/s, which is not favorable to Horizontal Axis Turbine [5-6]. Therefore, Vertical Axis Wind Turbine (VAWT), capable of working at multidirectional low wind speed [6], could be used. In addition, use of powerful neodymium magnets instead of DC field, light weight and smaller size make the Permanent Magnet Synchronous Generator (PMSG) a good match for VAWT [7]. Implementing wind power and connecting it to grid system is not possible for most of the rural areas in Malaysia. Therefore, these places require an off-grid energy harvesting turbine being able to work in low wind. But there has been a lack of research in the field of small scale low voltage wind turbine when it comes to low wind off-grid standalone system. Previous work in the field of 'PMSG adopted Maglev VAWT' and 'energy harvesting' was mostly carried out on separate field. For example, in 2008, Lei created a power electronic interface for a Battery Supercapacitor Hybrid Energy Storage System which was of MW power range and meant for grid connection [8]. Tankari and Camara, in 2011, integrated ultracapacitor and batteries with wind-PV hybrid system but the PMSG used was of 4.5KW [9]. Abbey and Joos proposed Supercapacitor Energy Storage for Wind Energy Applications. Again they used a 1MW doubly fed induction generator for simulation and the system was built for grid connection [10]. Similar work was also done by L. QU and W. Qiao [11].

This paper fills up the gap in research providing an off-grid standalone energy harvesting circuit (EHC) incorporated with 3-Phase PMSG adopted to Maglev VAWT that can perform in low wind speeds. This research works with an off-grid VAWT which makes the system easier to implement in rural places and areas where grid system has not yet been available. Having compared with previous models, in which Tankari used a 4.5KW PMSG [9], Abbey as well as L. QU used a 1MW induction generator [10-11]; this VAWT adopts a 200W small scale PMSG making it as a portable standalone system. Also areas with low wind does not require a system that includes a generator of Mega Watt range. Coming back to the energy harvesting circuit, this investigation discovers a novel hybrid circuit with a combination of a battery and supercapacitor bank. Hybrid energy harvesting technology is not new. In 2010, Worthington proposed a novel circuit that combines the Synchronous Switched Harvesting technique which was connected to a load capacitor directly to harvest energy [12]. This allowed the capacitor to act as a reservoir that would be disconnected when fully charged and then would discharge to a load. The circuit was connected with a charge pump tire circuit [12]. Experiment results showed that this idea was capable of harvesting three times more amount of energy compared to the usual bridge rectifier circuit. However, this idea has not yet been implemented into off-grid wind energy sector. Although Lee [8] implemented a hybrid energy harvesting storage in 2008 for wind power application, it was meant for grid connection and again was of high power range. Hence, it was impossible for the energy storage system to be implemented for off-grid system. Our study brings the supercapacitor based hybrid energy harvesting for first time into the off-grid low wind power application. A supercapacitor bank is used in our experiment that charges up from the turbine and discharges through the battery with the use of power electronics. As far as low wind speed is concerned, a 6V battery is used for energy harvesting. A full phase complete system analysis was made, starting from optimization of the design, followed by design fabrication, field testing and lastly efficiency analysis.

2. Methodology

At first, simulation was carried out for small scale low speed VAWT with the adaptation of 3-Phase PMSG into the system. The optimized system design configuration, supported by the Matlab Simulink modelling, was then was sent for fabrication. In the meantime, Energy Harvesting Circuit (EHC) was configured and upon arrival of the turbine, EHC was implemented into VAWT. The control strategies were made by the use of power MOSFET switching and system was brought into the field for testing. While the system was operational, data were collected from the Labview interface through DAQ and result was analyzed to find out the efficiency of the system. Figure 2.1 shows the data process flow of the system.

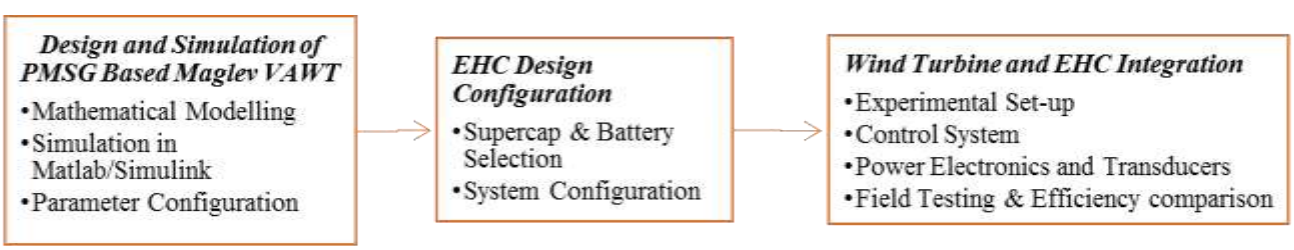


Fig. 2.1: Data Process Flow of the System

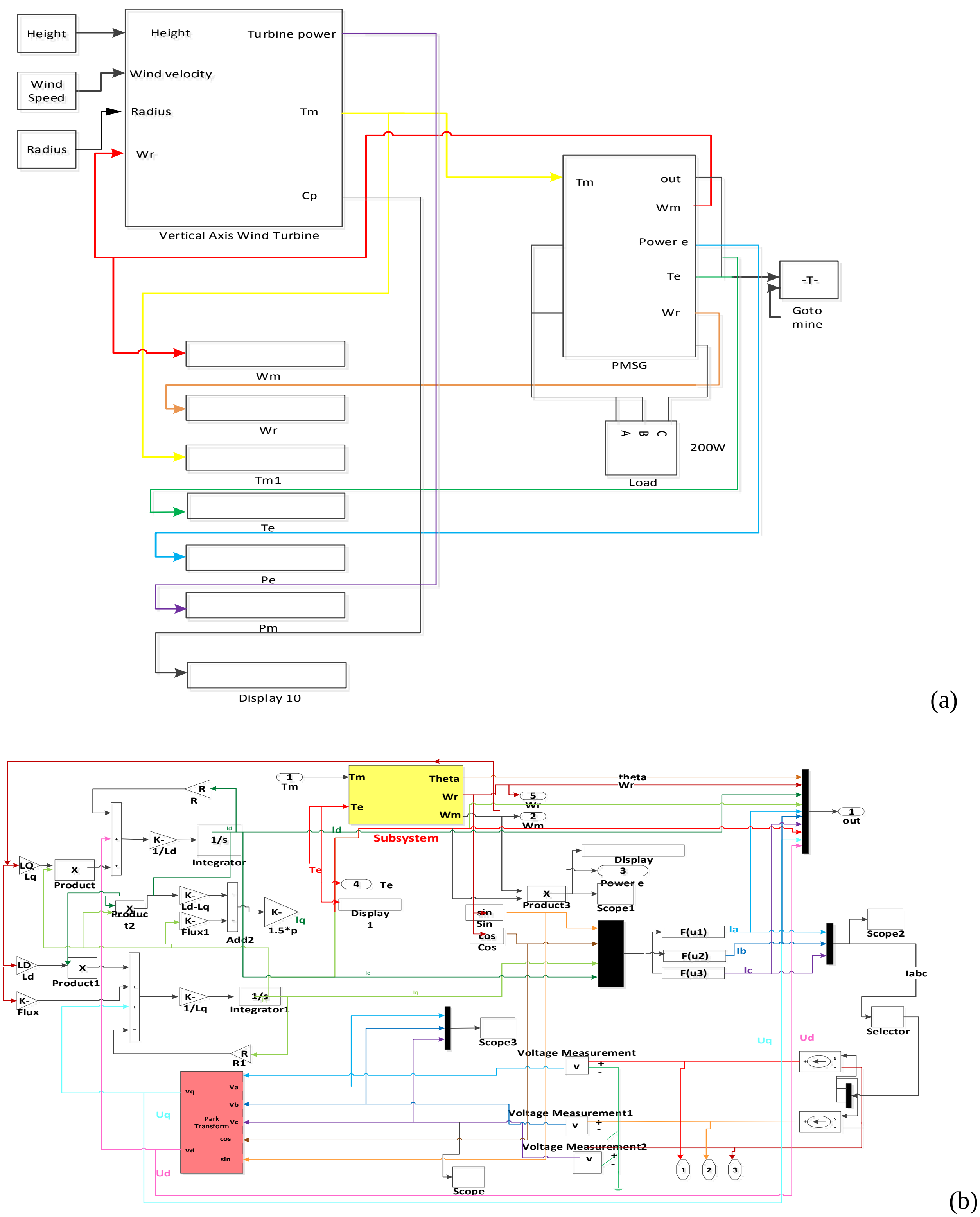


Fig. 3.1: (a) Simulink Modelling of PMSG adopted VAWT, (b) Simulink Modelling of PMSG subsystem

3. Design and Simulation of PMSG based Maglev VAWT

3.1. Modelling

The mathematical equations of VAWT was given as follows [13-16].

$$\mathrm{Pm} = \mathrm{Cp}\frac{1}{2}\,\rho\, A\, V_w^3 \quad (3.1), \qquad \lambda = \frac{\omega_m R}{\mathrm{Vw}}\mathrm{Cp} \quad (3.2),$$

$$T_m = \frac{P_m}{\omega_m} \qquad (3.3)\ , \qquad A = 2RH \quad (3.4)$$

Introducing the equation parameter where A indicates the rotor cover area of VAWT in (m^2), ρ is the air density in (Kg/m^3), V_w is the wind speed in (m/s), Cp stands for Power Coefficient of VAWT, λ is the tip-speed ratio, ω_m is the rotor angular speed in ($rads^{-1}$), R is the radius of VAWT in (m) and H is the height of VAWT in (m). Tip speed ratio, λ, is the ratio of the rotor speed of the turbine to the wind stream velocity. The basic design parameters of the turbine were the radius, height and wind speed. The maximum value of Cp (0.48) is achieved for Pitch Angle, β = 0 degree, therefore the blade pitch angle was set to 0 [6]. The modelling of the 3-Phase PMSG was done with dq equivalent circuit reference frame. Voltage, current and electromagnetic torque for a PMSG in the d-q axis frame had then been expressed as following (equation 3.5-3.8) [17-19]:

$$V_q = -(r + pL_q)i_q - w_e L_d i_d + w_y \lambda_m \quad , \qquad (3.5)$$

$$V_d = -(r + pL_d)i_q - w_e L_q i_q$$

$$L_d = L_{ds} + L_{ls} \ , \quad L_q = L_{qs} + L_{ls} \qquad (3.6)$$

$$\frac{di_d}{dt} = \frac{-R_s i_d}{L_d} + \frac{w_e L_q i_q}{L_d} + \frac{U_d}{L_d} \quad , \qquad (3.7)$$

$$\frac{di_q}{dt} = \frac{-R_s i_q}{L_q} + \frac{w_e L_d i_d}{L_q} + \frac{w_e}{\lambda_0} + \frac{U_d}{L_d}$$

$$w_e = p w_m \qquad (3.8)$$

$$T_e = 1.5p((L_d - L_q)i_d i_q + i_q \lambda_0) \qquad (3.9)$$

Here, L_d, L_q and L_{ld}, L_{lq} are the inductances and leakage inductances of d and q axis respectively; i_q, i_d and U_q, U_d are the stator currents and voltages; R_s is the stator resistance in ohms (Ω); λ_o is the magnetic flux in Weber (Wb); W_e is the electrical rotating speed (rad/s); *p* is the number of poles and T_e indicates the electromagnetic torque. Having implemented the equations in the Matlab/Simulink, the Fig. 3.1 and 3.2 represent the block diagram of Simulink modelling. The stator resistance of the PMSG was taken as 15 Ω; the inductance as 0.8mH; the flux linkage of magnet was 0.175 Wb and mass inertia was considered to be 0.089 kg/m^2. Research had been made on previous works conducted in this field and for the sake of simulation these values were taken as a standard basis [6] [14] [17].

3.2. Simulation Analysis

Figure 3.3 and 3.4 display the mechanical torque generated for different height and radius respectively under various wind speeds. While running the simulation for turbine torque under different heights, radius was fixed at 0.2m. In such way, the swept area will vary with only the change of the turbine height. As it can be seen, the low torque generated in the low wind (2m/s-5m/s) was improved with the gradual increase of the height from 0.4m onwards. Similarly, from figure 3.4, it can be spotted the low torque generated in the low wind (2m/s-5m/s) was getting better with the increase of the radius from 0.2m onwards. Therefore, for an optimized design, turbine height was fixed at 60cm whereas the radius was set as 15cm.

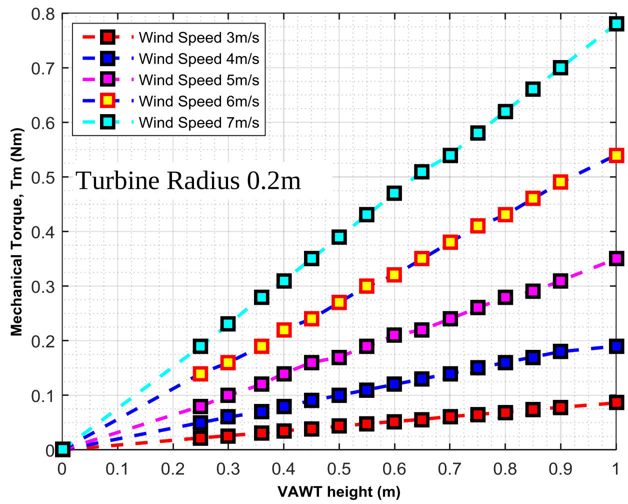


Fig. 3.3: Mechanical Torque generated for different heights under different wind speeds

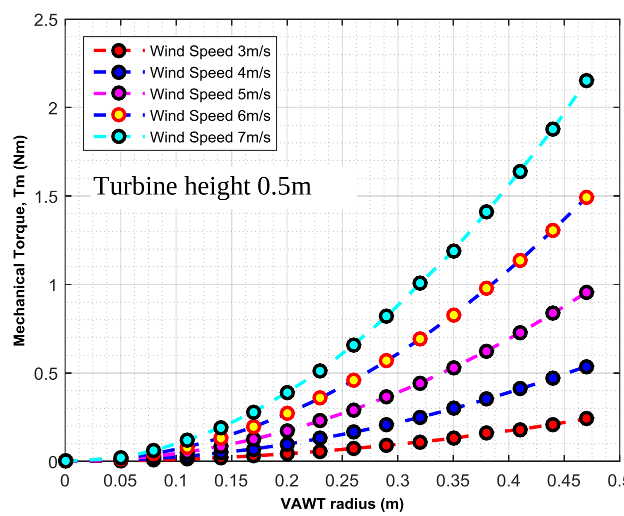


Fig. 3.4: Mechanical Torque generated for different heights under different wind speeds

Figure 3.5 illustrates the effect of turbine torque on generator output power on various pole pairs. Here, the generator power jumped from 548W to 3.6KW with changing pole pair (8 to 18). At low torque range such as at 5Nm, generator power increased from 6.6W to 24W for the same change in Pole Pair. Thus, number of pole plays a vital role in generator performance regardless wind speed. Result shows for low torque, the rated power from the generator could maximum be 500W. Therefore, a rated power of 200W was fixed as the generator output. The pole pair was decided to be 8 for a realistic system. Coming to the friction factor, it basically represents the friction in the bearing while being rotated with relative to the shaft. Since Maglev reduces the friction to in the bearing by levitating the system with the repulsive force of the magnets, a minimal of friction factor hence may represent the Maglev implementation in the system.

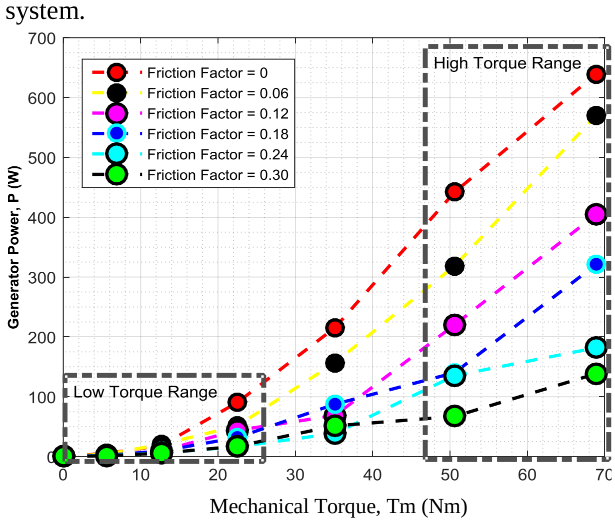
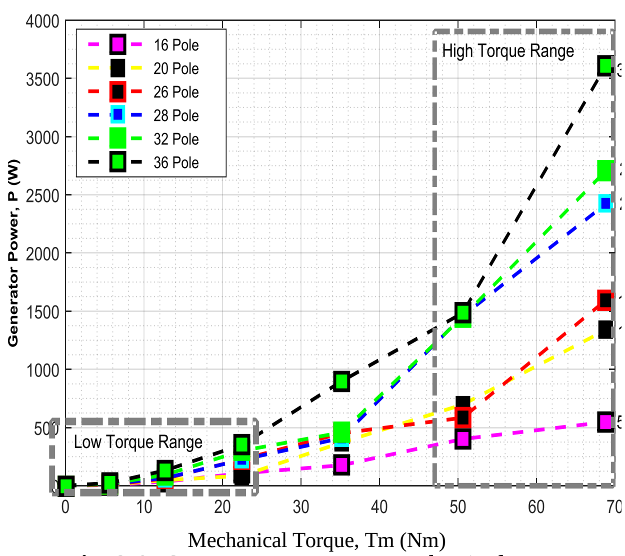


Fig. 3.5: Generator Power vs Mechanical Torque for different Friction Factor



Fig, 3.6: Generator Power vs Mechanical Torque under Various Pole Number

Figure 3.6 demonstrates that a 0.3 reduction in the friction factor increases the output power from 1.32W to 5.45W at a mechanical torque of 5Nm. As Maglev makes noteworthy improvement in efficiency, it was decided to be implemented in the system.

After analyzing the results from simulation, a 200W 12V 16 Pole PMSG adopted to a VAWT of 14.5m radius and 60cm of height was sent for fabrication with Maglev.

4. EHC Design Configuration

At this stage, Battery and Supercap were combined to create a hybrid system. Voltage coming from PMSG is not constant, wind dependent and may fluctuate. Therefore a combination of Supercapacitor and battery is needed to be employed as battery needs a constant charging voltage.

Upon arrival, the turbine was tested and PMSG open circuit voltage ranged from 3.5V to 8V for low wind speed configuration. It was decided to use a 6V (3.2AH/20HR) lead-acid battery for charging. Considering all the facts, lead-acid battery remained as the best choice [20]. A Supercapacitor bank were to be placed before the battery which would be charged up by the turbine and subsequently would be discharged through the battery. To form a Supercapacitor bank, four Supercapacitors of 35F each with voltage rating of 2.7 V, were placed in a series connection. Thus a 10.8V Supercapacitor bank with 8.75F was assembled.

5. Wind Turbine and EHC Integration

Figure 5.1 shows the architecture of the overall system.

5.1. Control Strategy

In this system, two N-channel MOSFETs namely, P36NF06L, with the aid of Arduino UNO microprocessor, were used to create the switching. Even though MOSFET 3 does not have any role in the control system, it was put in the circuit if battery needed to discharge to the load manually. Figure 5.2 shows the flowchart of the control architecture of the system. Until the battery was charged up to its desired voltage, the charging and discharging process would be continued. Here, current and voltage transducer were used to measure the Supercapacitor and battery rating. A rotary encoder was used for turbine rotational speed whereas anemometer for wind speed. All the signals were passed through the DAQ to the Labview interface.

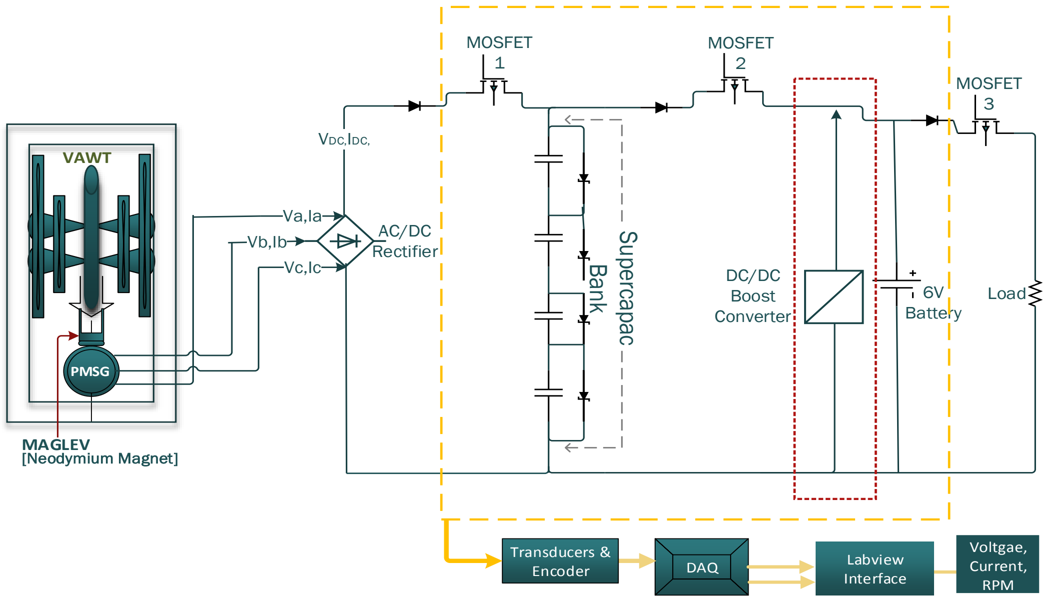


Fig. 5.1: Schematic Diagram of System Architecture of Energy Harvesting system

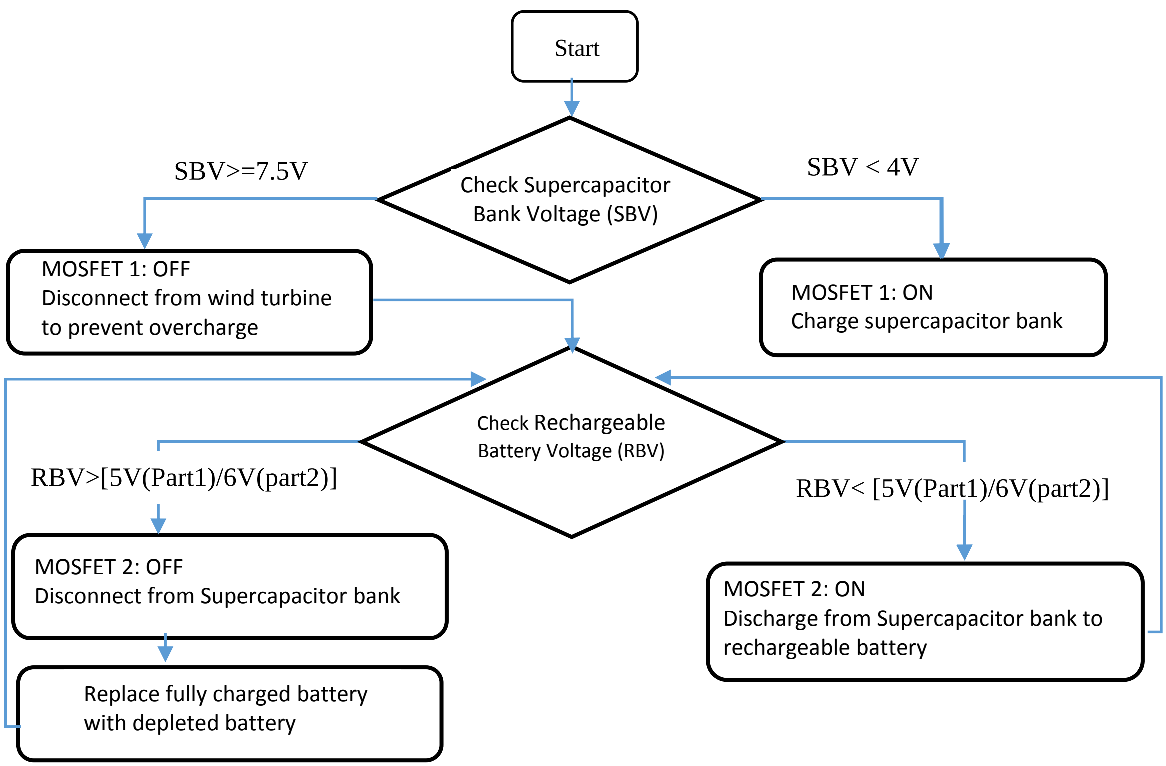


Fig. 5.2: Flow Chart of Energy Harvesting Control Architecture

5.2. Experimental Set-up

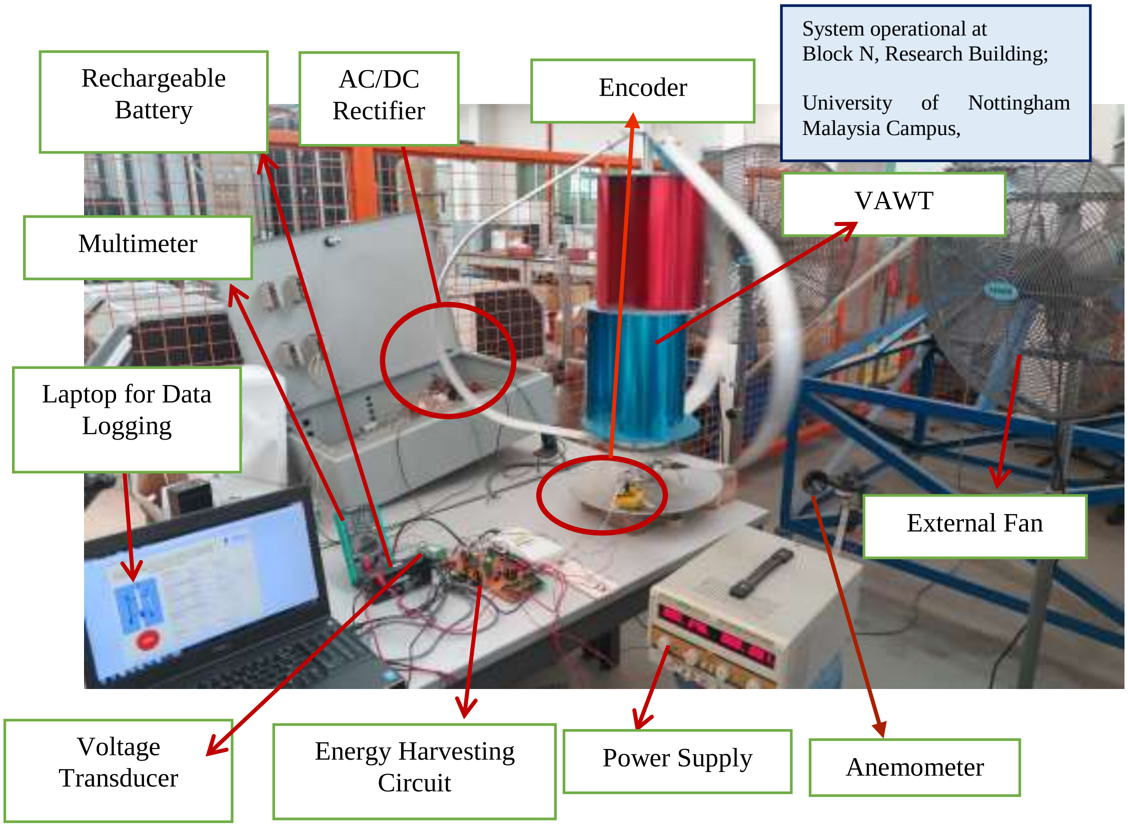


Fig. 5.3: Experimental Setup for the Integrated System

Figure 5.3 and 5.4 illustrate the experimental set-up and the EHC of the integrated system respectively.

Fig. 5.4: Energy Harvesting Circuit Built on Stripboard

5.3. Experimental Result

For better understanding, results have been divided into two parts. First part includes 3 cases of battery charging performance in which battery was charged up to 5V from 4.2V. 1st case shows battery charging by EHC, 2nd case describes battery charging with converter whereas last one shows direct battery charging without converter. Second part of this section deals with the complete charging analysis which is given in the later part of the result.

5.3.1. <u>Battery Charging: From 4.2V to 5V</u>

<u>For wind Speed = 5m/s</u>

In the 1st case, battery was charged through Supercapacitor. Supercap, being charged by the generator, discharged to battery. One entire charging and discharging process was considered as one cycle. For a wind speed of 5 m/s, 18 cycle was needed to charge the battery from 4.2V to 5V. Each cycle was for 27 minutes in which charging of Supercap took 25 minutes on average whereas discharging took 2minutes. 18 cycles, therefore, indicate 7.5 hours of total charging process of the battery. Figure 5.5 (A) indicates the Supercap readings while charging and discharging whereas Fig. 5.5 (B) provides the EHC efficiency comparison.

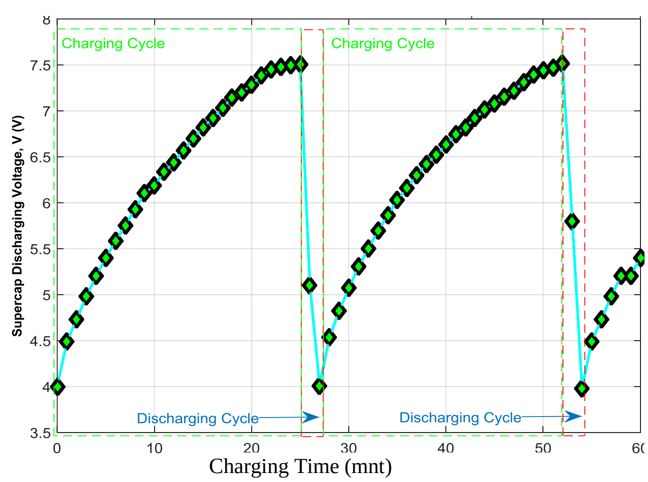


Fig. 5.5 [A]: For wind speed 5m/s- Supercap Charging & Discharging Complete Cycle

Without the use of Supercap, turbine was fed to charge the battery through the converter which was Case B. According to fig. 5.5 [B], it took almost 17.5 hours to reach its maximum value of 4.8V. After that the increase of the voltage was so less with respect to time, the value was not taken in consideration. Case C connects the turbine directly with the battery. This approach took less time (10 hours) than case B (direct charging via converter). However, the generator output voltage fluctuates and battery needs a steady constant voltage for charging up. Therefore this method is not recommended and applying this method for a longer period will result damaging of the battery. Still results were gathered for the sake of comparison and data was graphically displayed.

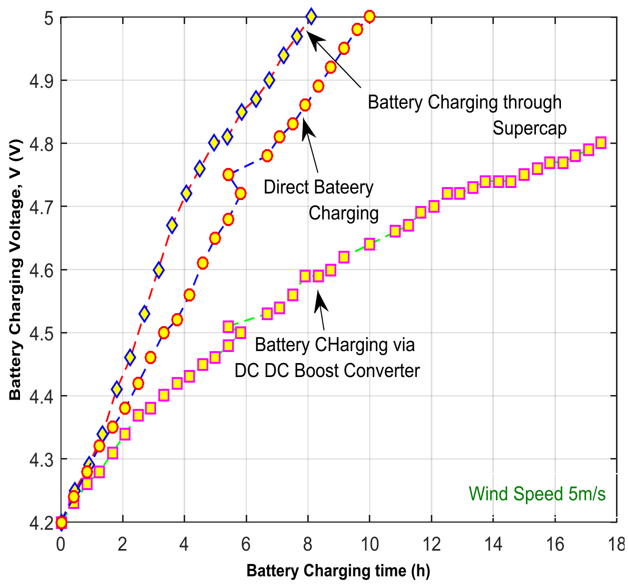


Fig. 5.5 [B]: For wind speed 5m/s- EHC Efficiency

Comparing all the 3 cases in 5m/s wind speed, 'Case C' was taken as a reference point. It was found out that charging through Supercap was 21% more efficient than direct charging without converter. Charging through converter was not successful as it failed to go beyond 4.8V. Therefore Case 2, technically, was considered as incompetent to work in 5m/s wind speed.

For wind Speed = 4m/s

At this stage, in Case A, one cycle was consisted of 37 minutes. Hence, it took 10.4 hours of charging time for 18 cycles (Fig. 5.6[A]). According to Fig. 5.6[B], Case B was incapable to charge the device at 4m/s. 'Case C' took 15 hours to finish the task. It was found out charging through Supercap was 31% more efficient that direct charging without the boost converter.

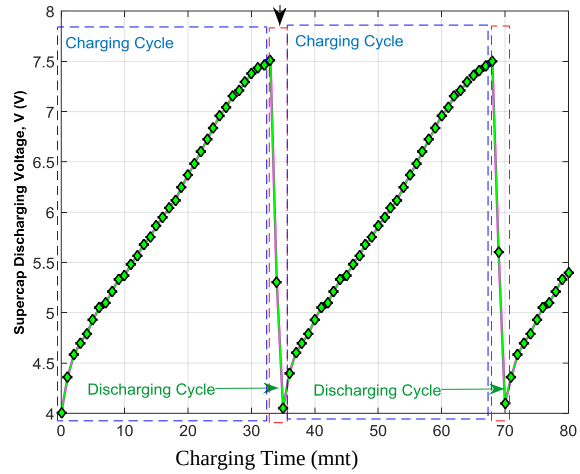


Figure 5.6 [A]: For wind speed 4m/s- Supercap Charging & Discharging Complete Cycle

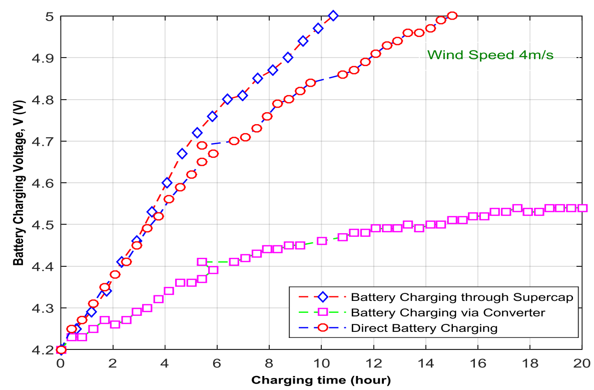


Fig. 5.6 [B]: For wind speed 4m/s- EHC Efficiency

For wind Speed = 3m/s

Unlike the previous experiments, Supercapacitor bank could not be charged up to 7.5V. This was due to the lack of the mechanical torque, as the system was put in a very low speed of 3m/s. In order to come up with a solution, Supercapacitor Bank charging voltage limit was reconfigured and lowered down to 6.8V. It took 95 minutes to finish the charging cycle. Also it ended up taking higher number of cycle (24 cycles) to finish charging.

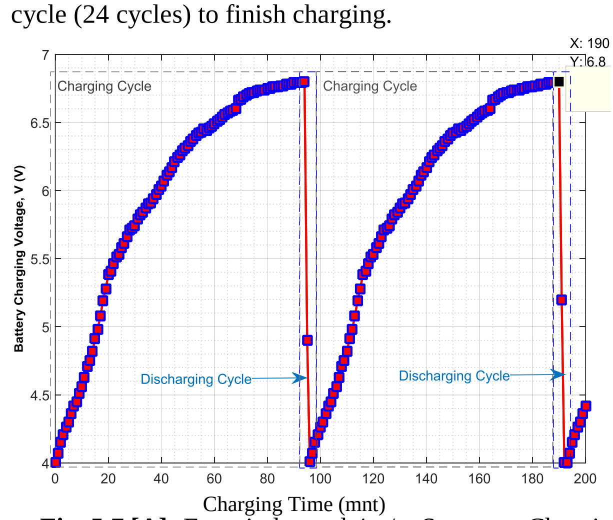


Fig. 5.7 [A]: For wind speed 4m/s- Supercap Charging & Discharging Complete Cycle

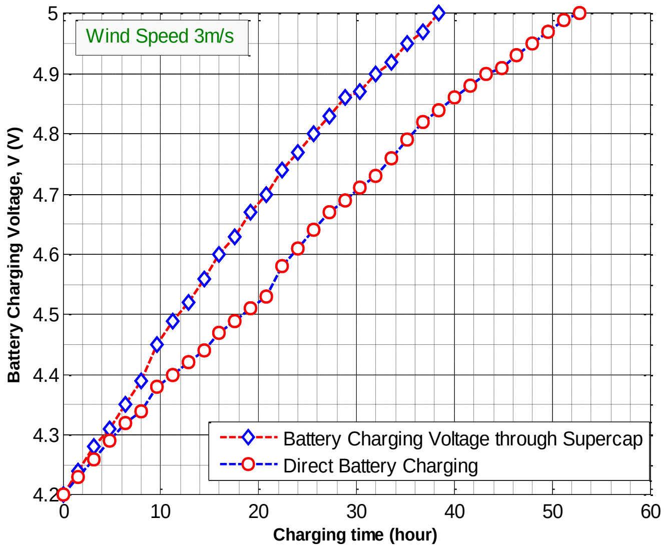


Fig. 5.7 [B]: For wind speed 4m/s- EHC Efficiency

Figure 5.7[A] displays the complete cycle of Supercapacitor bank and the charging and discharging period of it. For a number of 24 cycles, in which each cycle was made of 95 minutes, a total duration of 38.4 hours was required to complete the entire battery charging process. It is important to note that 'Case B' was not experimented in this section because of its poor performance in the earlier stage. For case C, it took nearly 53 hours to charge the battery up to 5V which surely was considerably longer than the previous charging. It was calculated and concluded that charging through Supercapacitor was 28% more efficient that direct charging without converter (Fig. 5.7 [B]).

Overall Summary and Efficiency comparison

The Energy harvesting circuit (ECH) shows excellent values for each of the different wind speed case with good performance overall. Change in the wind speed from 5m/s to 4m/s produces better efficiency as it goes to 31% from 19%. For a low speed of 3 m/s, EHC, even though took a long time of 38.4 hours to charge up the battery, still maintains its productivity by producing an efficiency 28%. Table 5.1 shows the summary of the result in this section.

Table 5.1. Summary of efficiency comparison for battery charging from 4.2V to 5V

Wind Speed (m/s)	Battery Charging via Supercap (hr)	Direct Battery Charging Time (hr)	Efficiency (%)
5	8.1	10	19
4	10.4	15	31
3	38.4	53	28

5.3.2. <u>Battery Charging- 5.5V to 6V</u>

After charging the battery from 4.2V to 5V, another experiment was conducted to charge battery from 5V to 6V at 5m/s. Figure 5.8 shows that with EHC, battery took almost 18.8 hours to finish charging whereas direct charging needed 24.2 hours. Hence, EHC was 22% more efficient than direct charging.

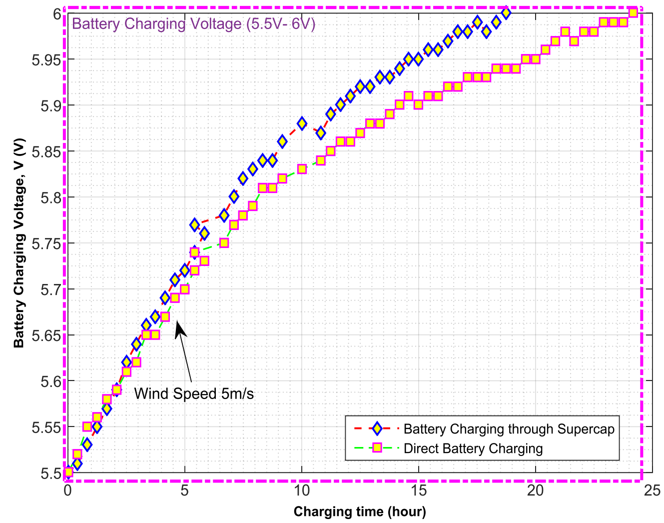


Fig. 5.8: Battery Charging Voltage [5.5V to 6V] comparison with respect to time

6. Conclusion

To conclude, this paper provides a platform for a novel innovative approach towards an off-grid energy harvesting system for Maglev VAWT. A complete simulation analysis was done for 3-Phase PMSG adopted to VAWT. With the variation of design parameters under low wind speeds, an optimized system of a 200W 12V 16 Pole PMSG attached to Maglev VAWT of 14.5m radius and 60cm of height was fabricated. Upon arrival, the optimized system was integrated with a 6V EHC. A 10.8V Supercapacitor bank with 8.75F capacitance was used in the ECH. While operational, EHC showed better efficiency in charging battery in all aspects comparing to direct charging of battery regardless of with or without converter. The highest amount of efficiency was drawn from the system was 31%. Comparing to the Worthington's work of pulling off 300% more efficiency with hybrid energy harvesting, it is drastically low. However, his storage system was implemented to a pump tire circuit, whereas our circuit was designed for a low wind application. As an off-grid standalone low voltage energy harvesting system, the EHC was able to provide noteworthy better efficiency in all three low wind speeds.

There were some issues and limitations encountered during this research. Firstly, turbine blade design was not taken in consideration in the simulation. As there was no proper mathematical model for a hybrid VAWT which would relate turbine blade number to output torque or power, the simulation therefore did not account blade design. Moreover, DC DC boost converter used in this research did not perform well according to the data sheet in the minimum range. As it was stated in the data sheet, the converter should be able to step up voltage from as low as 2.5V; practically it could not step up any amount of voltage less than 4V. Therefore the Supercap charging range was made from 4V-7.5V which should have been 3V-7.5V. This had a direct effect on system efficiency. Future works which can be outcomes from the research are quite a few. Apart from improving the converter, an important task that can be taken in consideration in the near future is to apply CFD (Computational Fluid Dynamics) in the magnet positioning and try to come up with few optimized designs which will give nearly zero friction. In addition, Finite Element Analysis could be made possible to apply on turbine blades. These will surely help to increase the efficiency of the system. A real time wireless monitoring interface could be made available. Embedded solutions, providing wireless end-point connectivity to devices like XBEE Modules, can be of use.

To recapitulate, sufficient groundwork and results had been laid out in this paper to deliver the necessary development and framework for further improvements. For rural areas in countries like Malaysia where grid connection is not always available, this standalone system can make a difference for using small scale electronic devices.

Acknowledgements

Authors would like to thank Ministry of Education Malaysia to fund their research project.

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