Analytical Models and Evaluation for A Wind Turbine Connected Multi-stage Flywheels

Shuguang Wei

A Thesis Submitted in Partial Fulfillment of Requirements for
degree of Master of Engineering in Electrical and Computer Engineering
December 2023

Analytical Models and Evaluation for A Wind Turbine Connected Multi-stage Flywheels

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เสนอต่อมหาวิทยาลัยมหาสารคาม เพื่อเป็นส่วนหนึ่งของการศึกษาตามหลักสูตร

ปริญญาวิศวกรรมศาสตรมหาบัณฑิต สาขาวิชาวิศวกรรมไฟฟ้าและคอมพิวเตอร์

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The examining committee has unanimously approved this Thesis, submitted by Mr. Shuguang Wei , as a partial fulfillment of the requirements for the Master of Engineering Electrical and Computer Engineering at Mahasarakham University

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ABSTRACT

This article advocated using flywheel energy storage to store wind electricity in a cost-effective manner.The depletion of oil reserves and fossil fuels has transformed the way people think about energy, resulting in a heavy emphasis on renewable energy sources. As the concept of micro grid and domestic power integration is in place, the wind energy sector is a possible topic of research. Wind turbines that can utilise low wind velocities for power generation are critical.However, energy storage has emerged as the most pressing issue today.The use of flywheel energy storage has tremendous potential in a variety of energy-related sectors. Because flywheels have a high energy density, they can store a lot of energy in a tiny, light package. As a result, they are suitable for use in compact energy storage systems.Flywheels can swiftly adjust to fluctuations in wind power generation or the amount of electricity required. Flywheels are well-known for having a long cycle life, which means they can be charged and discharged repeatedly without breaking down significantly.In this study, a flywheel energy storage modelling system was constructed and coupled with wind power generation utilising Matlab-Simulink as the platform.It offers concepts and fundamental facts for tiny wind power generating and flywheel energy storage.

Keyword : Wind turbine modeling Renewable energy Flywheel energy storage, Matlab-Simulink

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Chapter 1 Introduction

1.1 Background

Since wind is generated by the Earth's natural atmospheric processes, harnessing its energy requires the presence of both solar radiation and the Earth's rotation. Therefore, wind energy is a plentiful and renewable source of power. Wind energy is a clean and renewable way to generate electricity. It does not produce any greenhouse gases or other air pollutants. In comparison to fossil fuels like coal, oil, and natural gas, this makes it a greener option.

By reducing reliance on foreign fossil fuel imports, energy independence can be furthered through the use of wind power. As a result, a country's energy security improves and its vulnerability to geopolitical unrest decreases. Wind turbines have a low water footprint compared to conventional power facilities that use coal, nuclear, or natural gas. Wind turbines, in contrast to these more typical methods, may operate without any external source of water. This is especially important in places where water is scarce. Wind farms are scalable because they can meet energy needs from community projects to utility-scale deployments. This versatility lets wind farms meet several energy needs. After installation, wind turbines have low operation and maintenance costs, resulting in long-term cost savings. Wind energy can supplement solar, hydroelectric, and geothermal energy to diversify an energy portfolio. This integration can improve energy mix balance and reliability. Wind farms are built faster than other energy infrastructure, making them easier to meet electricity needs.

The generation of wind power is primarily characterized by its intermittent and variable nature. The wind velocity is subject to rapid changes, leading to fluctuations in the power output. The aforementioned conditions may pose challenges to the stability of the electrical grid, requiring the adoption of additional measures such as energy storage or backup generation to provide a reliable power supply. The utilization of various energy storage technologies, encompassing lithium-ion batteries, pumped hydro storage, and thermal storage, can provide a multitude of advantages, including but not limited to increased adaptability and higher cost-efficiency. Different storage technologies exhibit unique characteristics that make them suitable for specific applications within the power grid.

The utilization of flywheels as energy storage mechanisms for wind power distribution systems has been suggested as an advanced and intricate approach for various compelling justifications. Flywheels have a high energy density, which means they can store a lot of energy in a small, light package. Because of this, they can be used in small energy storage devices. Flywheels can quickly adapt to changes in wind power production or changes in the amount of power that is needed. They can quickly release energy that has been saved or take in extra energy to help keep the grid stable. This quick reaction can help keep the grid stable and reliable. Flywheels are famous for having a long cycle life, which means they can be charged and discharged many times without breaking down much. Because of this, they are a long-term, cost-effective way to store energy. Most people think of flywheels as being good for the earth because they don't use any harmful materials or produce any pollution when they work. This fits with the goals of developing wind power to be clean and last a long time. Compared to other ways of storing energy, like batteries, flywheels don't need as much upkeep. This could mean lower costs to run the machine over its entire life. Compared to other ways of storing energy, like batteries, flywheels don't need as much upkeep. This could mean lower costs to run the machine over its entire life. Flywheels are a good way for the grid to get frequency control services. They can quickly change how fast they spin to help keep the grid frequency stable, which is very important for grid stability. Flywheels work well with renewable energy sources like wind power. They can help make the grid's power supply more dependable and consistent by reducing the power that these sources lose when the wind blows.

Nevertheless, in order to achieve a greater capacity for energy storage, the flywheel necessitates a high velocity. Hence, in the event of wind instability, the wind turbine's energy production will experience variations. Hence, the primary objective of this research is to conduct a comparative analysis of the energy conversion efficiency between two flywheel systems based on the varying magnitudes of wind energy. This analysis aims to ascertain the viability of implementing the aforementioned flywheel system.

1.2 Objectives

(1) To design and develop the multi-stage flywheels for the grid-connected wind turbine with flywheel energy storage systems using MATLAB –Simulink program.

(2) To evaluate and compare the performance of the proposed multi-stage flywheels with the conventional flywheels.

1.3 Research Scope

(1) The simulation program and tools used for this research was developed via the MATLAB-Simulink.

(2) The specifications of the wind turbine used in this research were based on the commercial ones from Wetzel Engineering, Inc., model: WEI6K, a 6-kW 7-m small wind turbine [1].

(3) The specifications of the flywheels used in this research were based on the commercial ones from Innotec Power PMG Technology [2].

1.4 Research Significance

(1) Gain the knowledge on design and develop the models for wind turbines and flywheel energy storage devices using MATLAB-Simulink

(2) Get new types of flywheel energy storage and their performance evaluation.

Chapter 2 Literature Reviews

This chapter presents basic information, principles and literature reviews related to the wind turbines and flywheel energy storages; including also their structures, characteristics and applications. Details of each device are as follows:

2.1 Common Types of Wind Turbines

Wind turbines can be classified in terms of the arrangement of the axis into 3 types: Horizontal Axis Wind Turbines (HAWT), Vertical Axis Wind Turbines (VAWT) and Hybrid Wind Turbines. Details are as follows:

2.1.1 Horizontal Axis Wind Turbines (HAWTs)

HAWT upwind configuration is the prevailing form in which the rotor is oriented towards the direction of the wind. The turbines commonly observed in expansive wind farms are typically characterized by a three-bladed configuration. Downwind turbines are characterized by their rotor orientation, which faces away from the wind. Typically, these turbines are equipped with a pair of blades. The prevalence of these entities is diminished as a result of the inherent difficulties associated with their construction. Some example of VAWTs are shown in Figure 1 [3].

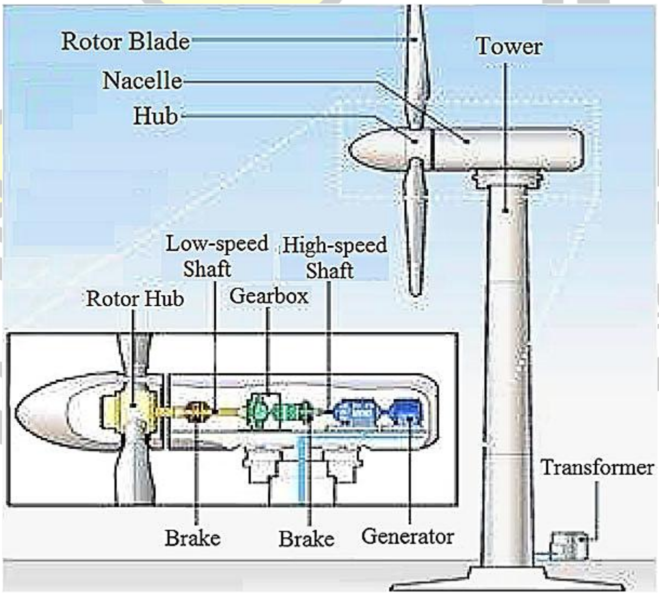
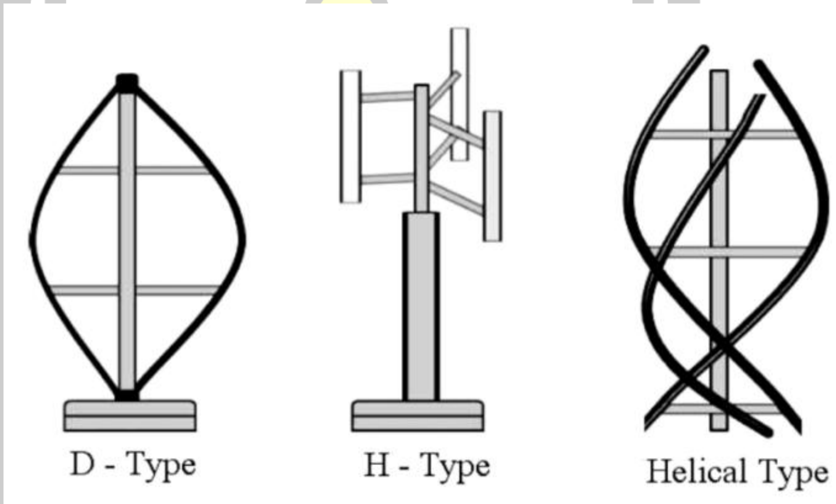


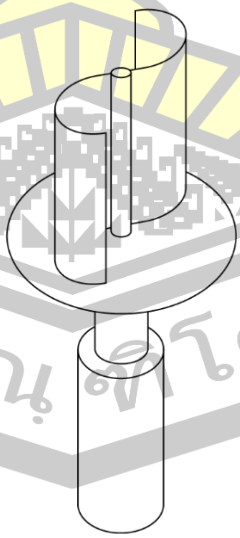
Figure 1 Example of Horizontal Axis Wind Turbine (HAWT)

2.1.2 Vertical Axis Wind Turbines (VAWTs)

VAWTs can be categorized into 2 types: Darrius and Savonius. The Darrius VAWTs can be identified by their square, eggbeater-like shape. They are typically employed in smaller-scale applications and have the ability to capture wind from any direction. On the other hand, the Savonius VAWTs are ideal for small-scale applications and low wind speeds because to their distinctive S-shaped design. Although they may begin producing power at lower wind speeds than HAWTs, they are less efficient than HAWTs. Some example of VAWTs are shown in Figure 2 [4], [5].



(a)



(b)

Figure 2 Vertical Axis Wind Turbines (VAWTs)

2.1.3 Hybrid Wind Turbines

It is alternatively referred to as combination or dual-axis wind turbines, integrate both horizontal and vertical rotor axes. The utilization of a dual-axis design enables the gathering of wind energy from several directions. In essence, wind energy can be harnessed irrespective of the wind's horizontal or vertical direction. The integration of horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT) characteristics allows hybrid turbines to effectively respond to dynamic wind conditions. In cases where the wind exhibits consistent and largely unidirectional patterns, the utilization of the horizontal axis component may yield greater efficiency. On the contrary, in situations when the wind is characterized by turbulence or originates from multiple directions, the vertical axis component can exhibit superior performance. Some examples of VAWTs are shown in Figure 3 [6].

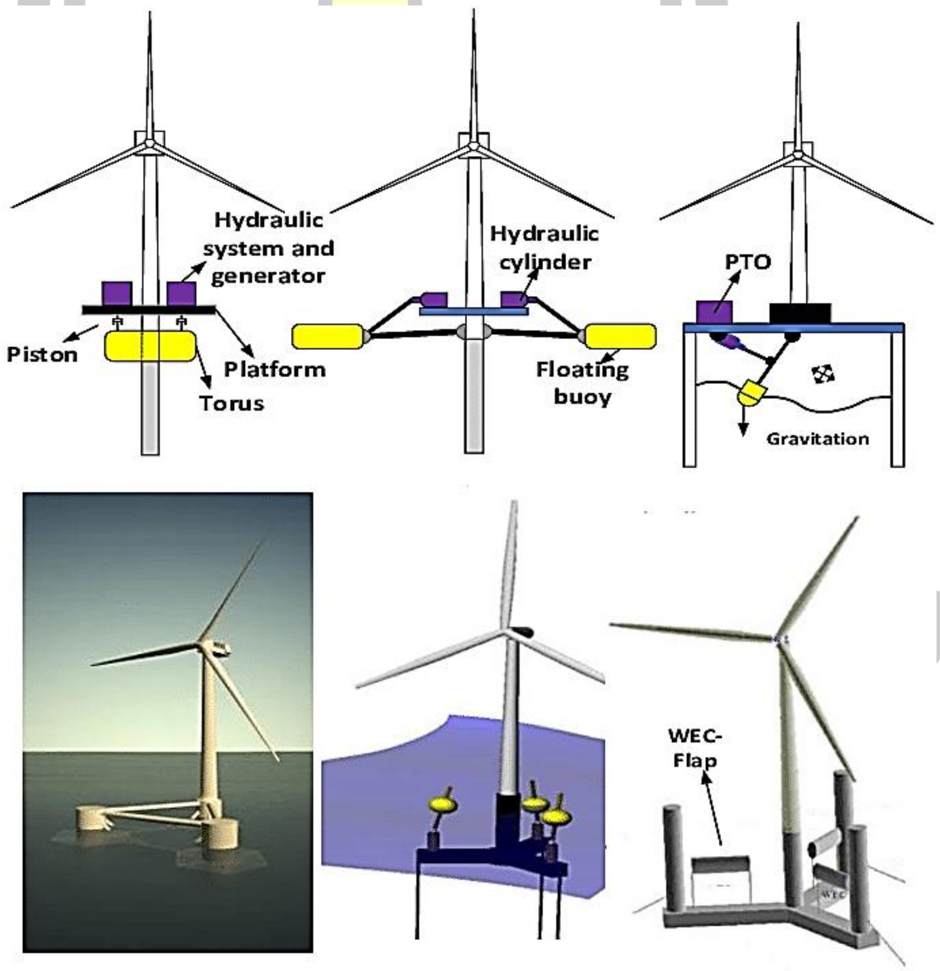


Figure 3 Hybrid Wind Turbines

2.2 Special Types of Wind Turbines

Since the purpose of this study was to consider the wind turbines that could be installed closely to the residential and thus the small-scale wind turbines were taken into consideration in order to achieve high efficiency for wind energy conversion at the very low-low wind speed levels as details below.

2.2.1 Floating Wind Turbines

This wind energy is intended to harness wind power in deeper offshore areas where regular fixed-bottom wind turbines are impractical. These turbines are installed on floating platforms, allowing them to be deployed in deeper ocean areas where conventional fixed-bottom foundations would be too deep. One of the key advantages of floating wind turbines over fixed-bottom turbines is their ability to operate in much deeper water. This opens up enormous swaths of offshore land for wind energy development, where wind resources are frequently greater and more consistent. Floating wind turbines are often erected on a variety of floating platforms, including spar buoys, semi-submersibles, and tension leg platforms. These platforms are built to provide stability in rough seas and bad weather, ensuring the turbines' safety and functionality. Because floating wind turbines are not tethered to the seabed, they can be put in areas with favourable wind conditions and close proximity to energy demand centres. This adaptability may result in more efficient energy production and lower transmission losses. Some example of the floating HAWTs are shown in Figure 4 [7].

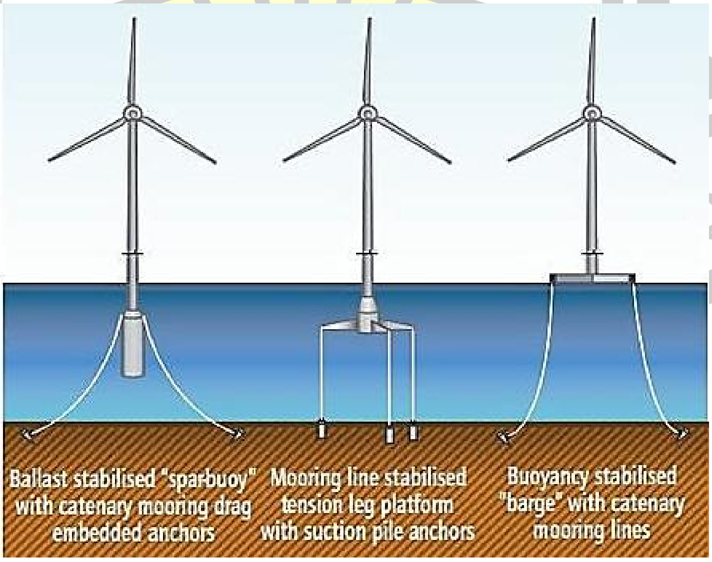


Figure 4 Examples of Floating HAWTs

2.2.2 Small-scale Wind Turbines

Small-scale wind turbines are often known as domestic or micro wind turbines, are renewable energy devices that generate power from the wind. These turbines are smaller in size than their bigger commercial counterparts and are often used to power homes, small enterprises, or distant off-grid places. The quantity of power a small-scale wind turbine can create is determined by various factors, including wind speed, turbine size, and the local wind resource. These turbines can greatly contribute to a household's energy demands in locations with continuous and strong winds. Small-scale wind turbines are typically smaller in size and have lesser power-generation capacity than utility-scale wind turbines. They typically have a few kilowatts to tens of kilowatts of capacity. These turbines are appropriate for installation in residential areas, farms, and other small-scale applications. They are frequently erected on long poles or towers to gather wind at higher altitudes, away from objects that could hinder airflow as shown in Figure 5 [8].

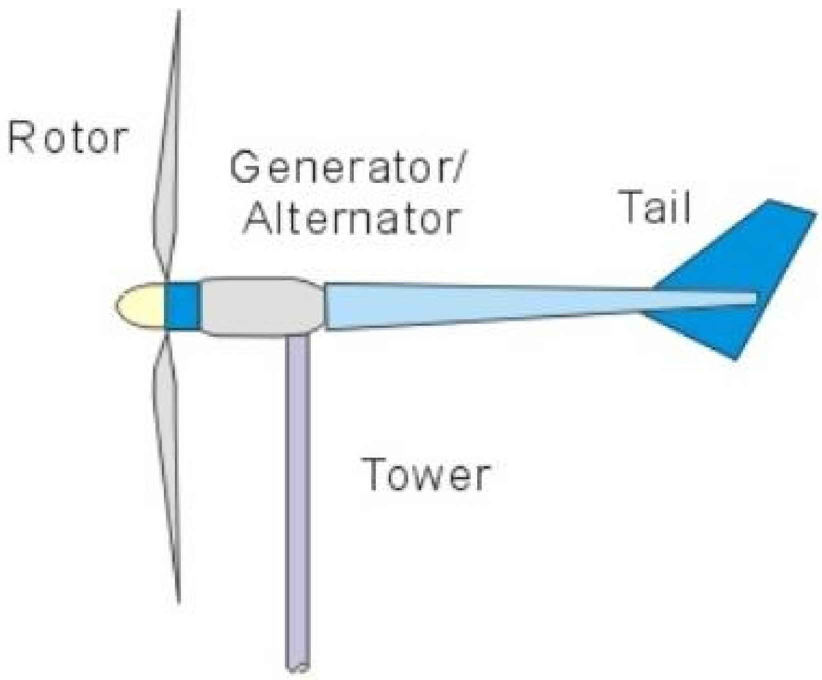


Figure 5 An Example of a Small-Scale HAWT

Alternatively, Vertical Axis Wind Turbines (VAWTs) are a type of wind turbine where the main rotor shaft is set vertically, and the main components are arranged around this axis. Unlike horizontal axis wind turbines (HAWTs), which have a horizontal rotor shaft and blades that rotate like an airplane propeller, VAWTs have blades that rotate around a vertical axis, similar to a spinning top. Each design has its own set of advantages and disadvantages in terms of efficiency, stability, and cost. Some VAWTs use sail-like blades that capture the wind's energy as it flows across the blades. These blades are often curved or shaped to create lift and generate rotational motion. The curved shape of the blades is reminiscent of sails on a boat, hence the term "sail wind turbines." One advantage of VAWTs is that they can operate effectively at lower wind speeds compared to HAWTs. This makes them suitable for locations with variable or low wind conditions. VAWTs are often considered omnidirectional, meaning they can capture wind from any direction without the need to face into the wind. This feature makes them potentially useful in turbulent or highly variable wind environments. VAWTs tend to be quieter and have a smaller visual footprint compared to HAWTs, which can make them more suitable for urban or residential areas. However, their efficiency may be lower, as shown in Figure 6 [9].

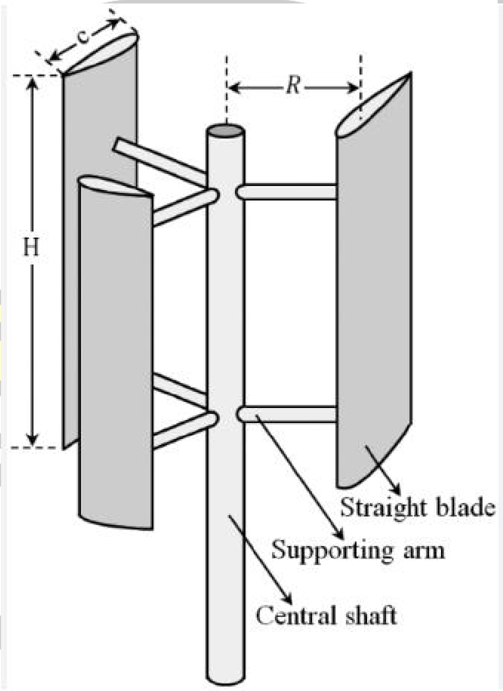


Figure 6 An example of a small-scale VAWTs

2.2.3 Wind Lens Turbines

Wind Lens Turbines (WLTs) represent a novel wind turbine configuration that endeavors to enhance the conversion efficacy of wind energy through the implementation of a specialized framework referred to as a "wind lens." By capturing and concentrating the incoming wind, the wind lens causes the wind to accelerate as it approaches the turbine rotor. The surge in wind velocity has the potential to substantially augment the kinetic energy accessible for the purpose of generating electricity. Wind Lens Turbines (WLTs) utilize the wind's increased speed and concentration to enhance the efficiency of converting wind energy. Wind-lens turbines often have a lower cut-in speed, which is the minimum wind velocity required for the turbine to start generating energy. This provides a benefit in areas characterized by comparatively modest mean wind velocities. This can lead to increased electricity production during periods of lesser wind velocity, rendering them more compatible with a broader spectrum of wind circumstances. Additionally, the wind lens can aid in the reduction of turbine-generated noise and vibration, potentially rendering the turbines more compatible with residential or urban settings. As depicted in Figure 7 [10].

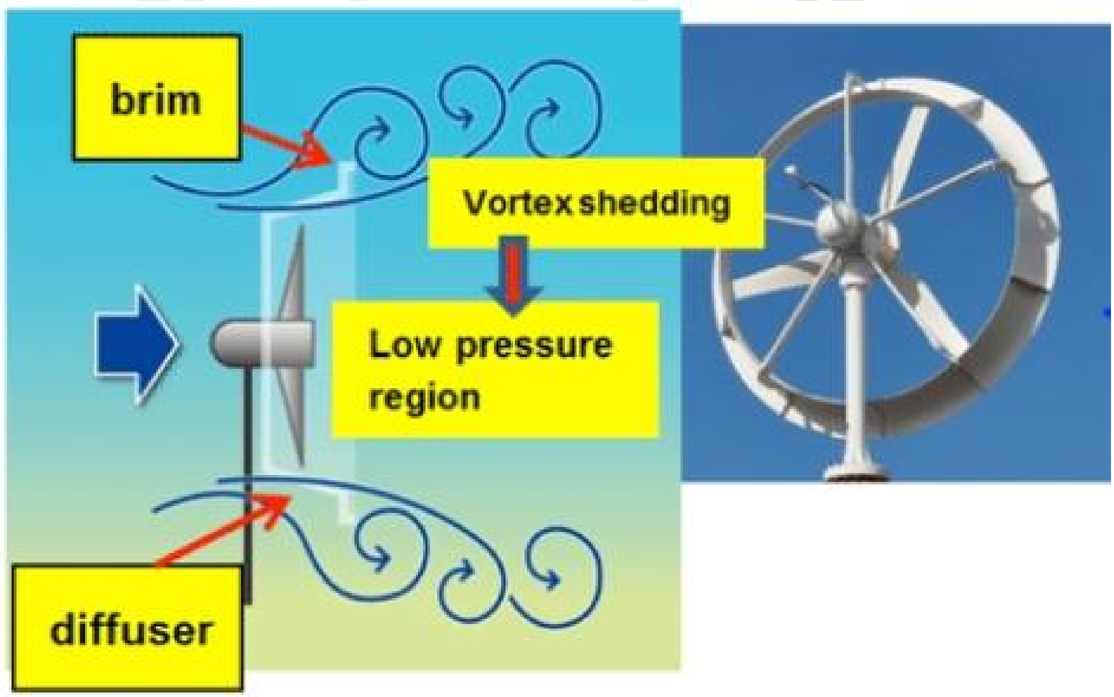


Figure 7 Wind Lens Turbines (WLTs)

2.2.4 Multi-rotor wind turbines

Multi-rotor wind turbines are a type of wind energy technology that features multiple rotors (blades) attached to a single support structure or tower. These turbines are designed to harness wind energy efficiently and overcome some limitations of traditional single-rotor wind turbines.

Multi-rotor wind turbines aim to capture more energy from the wind by utilizing multiple rotors. Each rotor contributes to electricity generation, resulting in higher overall energy capture compared to single-rotor turbines. It is can start generating electricity at lower wind speeds than single-rotor turbines. This makes them suitable for areas with lower average wind speeds, expanding their potential deployment locations. The redundancy provided by multiple rotors can improve the reliability of multi-rotor turbines. Even if one rotor experiences a malfunction, the others can continue to generate electricity, reducing downtime.

Multi-rotor wind turbine designs are often scalable, allowing for adjustments in the number of rotors and their size to match the wind conditions and power requirements of a specific location. It is can produce less turbulence and wake effects compared to large single-rotor turbines. This can make them suitable for installations in densely populated areas or areas with limited space. Smaller rotors in multi-rotor turbines may have simpler blade designs, which can lead to cost savings in manufacturing and maintenance. As shown in Figure 8 [11].

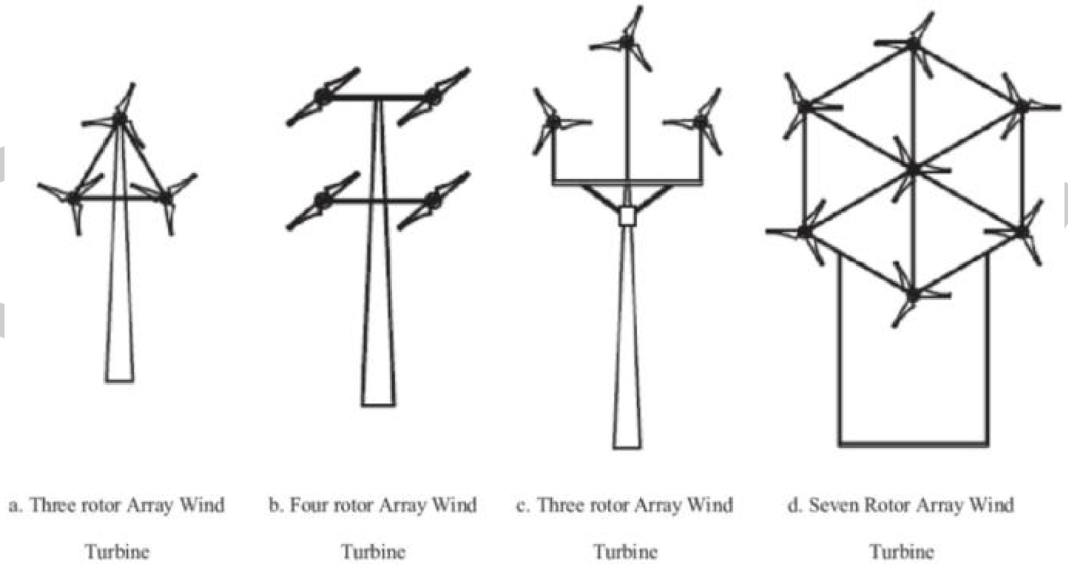


Figure 8 Multi-rotor wind turbines

2.3 Common Types of Flywheels

2.3.1 Classification according to structure

There are 2 common types of flywheels as below:

(1) Solid Disk Flywheels

A solid disk flywheel is, broadly speaking, a circular solid disk that is generally used in cast iron single flywheel thresher systems. Several key parameters are taken into account while designing these flywheels. Two different types of stresses are used in solid disk flywheels – radial stress and tangential stress. These high-utility tools typically have a disk and a hub section. In order to get a proper idea about the usability of a solid disk flywheel, its 'mass amount of inertia' has to be calculated (by using the disk mass and the outer radius). The density of the flywheel material also has to be considered. As shown in Figure 9 [12].

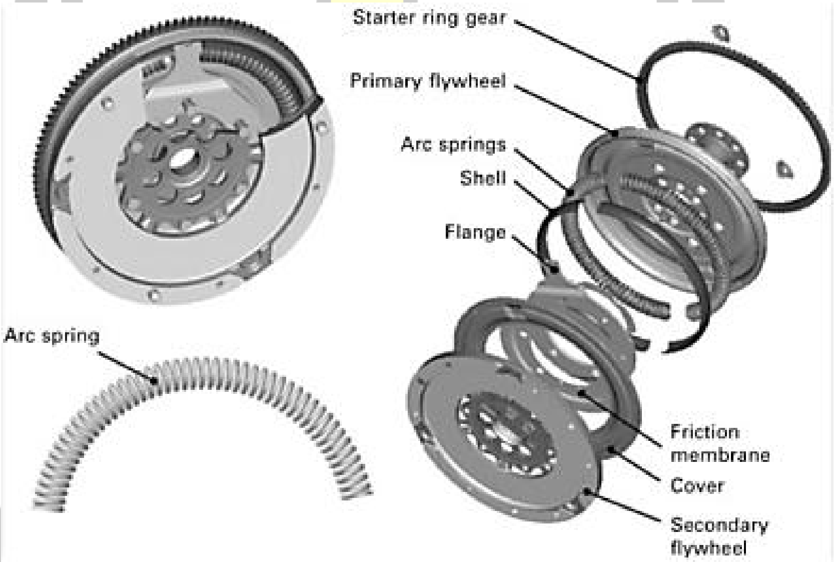


Figure 9 Solid Disk Flywheels

(2) Rimmed Flywheels

The main parts of a rimmed flywheel are its inner hub, outer ring (also known as the 'rim'), and arms. Generally, rimmed flywheels have 4-6 arms. A definite centrifugal force is exerted on the rims of the flywheel – and that generates tensile stress on it. The moment of inertia of the rim, along with the factor for the mass moment of inertia, are important parameters of rimmed flywheels. The detonation of rimmed flywheels happens at a significantly lesser rotary speed than that of solid disk flywheels (other things remaining the same, like diameter, weight, etc.). The thickness at the center can be higher, to provide greater mechanical strength to the flywheel. As shown in Figure 10 [12].

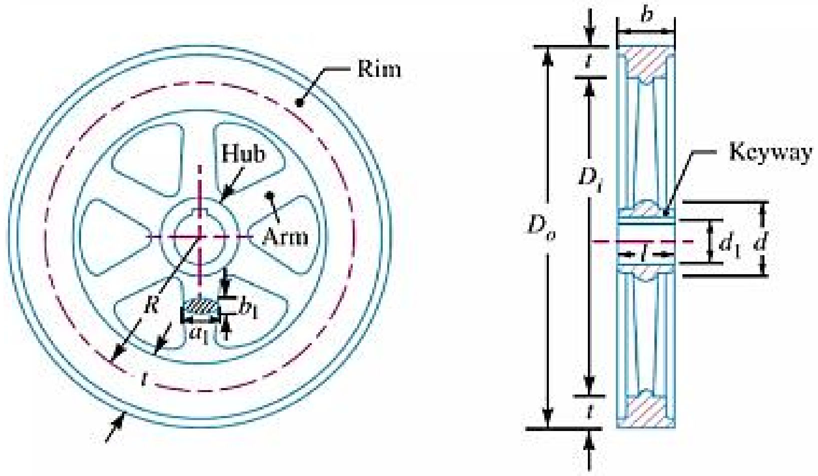


Figure 10 Rimmed Flywheel

2.3.2 Classification according to quality

There are 2 common types of flywheels as below:

(1) Single Mass Flywheels

It is manufactured with a single piece of casting material, and they do not have any movable pieces. They facilitate fast-revving of engines and help to maintain a stable connection between the engine and the clutch assembly system. The enhanced warp resistance and thermal resistance of single mass flywheels are big advantages – and these flywheels can withstand sudden changes in gear and engine speed. Durability is one of the most important features of any flywheel variety. Single mass flywheels are resurfaced as and when required, in order to boost their overall reliability and service life. Their cost is relatively lower as well. However, excessive vibration and noise can be a problem associated with using these flywheels. As shown in Figure 11 [12].

Figure 11 Single Mass Flywheels

(2) Dual Mass Flywheels

There are two separate flywheels in a dual-mass flywheel – the first fitted to the clutch, and the other to the crankshaft. These flywheels have very good weight capacities (up to 50 kg) and monthly capacities. Diesel vehicles that are rather large in size and have manual transmissions generally use dual-mass flywheels (select petrol vehicles use them too). The strong springs in the flywheels minimize torsional spikes and keep the gearbox protected. As shown in Figure 12 [12].

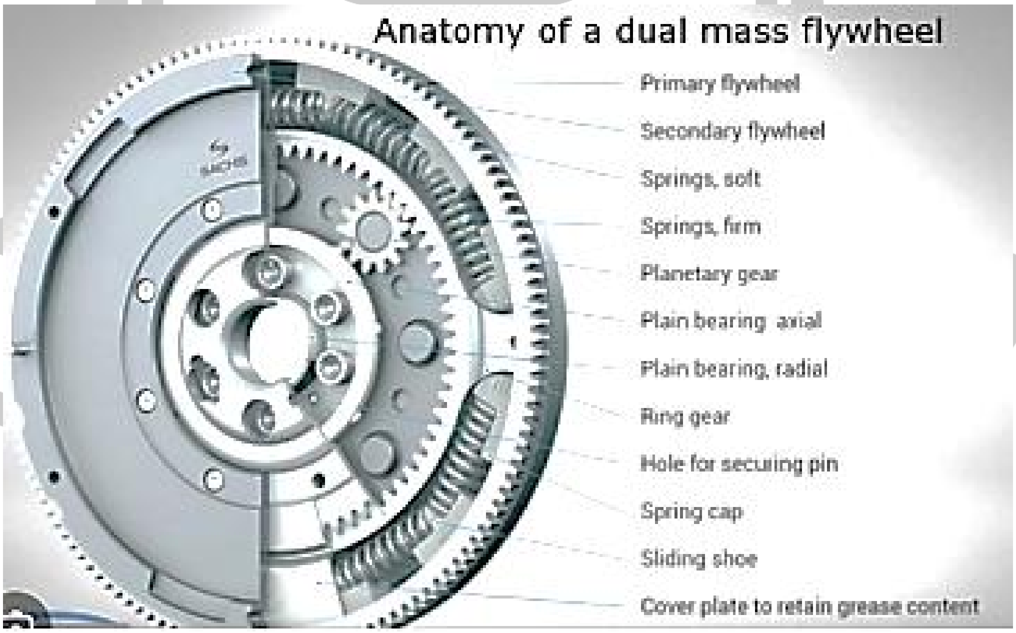


Figure 12 Dual Mass Flywheels

2.3.3 Classification based on angular velocity

There are 2 common types of flywheels as below:

(1) High-velocity Flywheels

The rakish speed of high-velocity flywheels generally varies in the 30K rpm and 60K rpm range. If required, this velocity can be increased to a certain extent. The user-friendly and lightweight nature of these flywheels is one of the biggest reasons behind their popularity. The cost of high-velocity flywheels is usually higher than that of low-velocity flywheels. These tools have excellent durability and require minimal maintenance. The capacity, size, and other attributes of these flywheels can be customized by the manufacturers as per buyer needs [12].

(2) Low- velocity Flywheels

As their name suggests, the angular velocity of low-velocity flywheels is significantly lower than their high-velocity counterparts (generally, the maximum speed of these flywheels is 10K rpm). While they are relatively cheaper in terms of cost, the huge size of low-velocity flywheels can prove to be a challenge. Unlike high-velocity flywheels, a low-velocity flywheel does not have handy levitation directional features. In addition, the latter also requires support on an intermittent basis. When installed correctly (generally, with additional construction support), low-velocity flywheels deliver efficient and economical performance [12].

Chapter 3 Research Methodology

This chapter establishes basic data based on the annual average wind speed, temperature record data in Beihai City, Guangxi, China, to simulate the wind speed experienced by wind turbines.

3.1 Device and System Configurations

3.1.1 Configuration of Wind Profile

Average annual wind speed in Beihai City, Guangxi Province, China [13]:

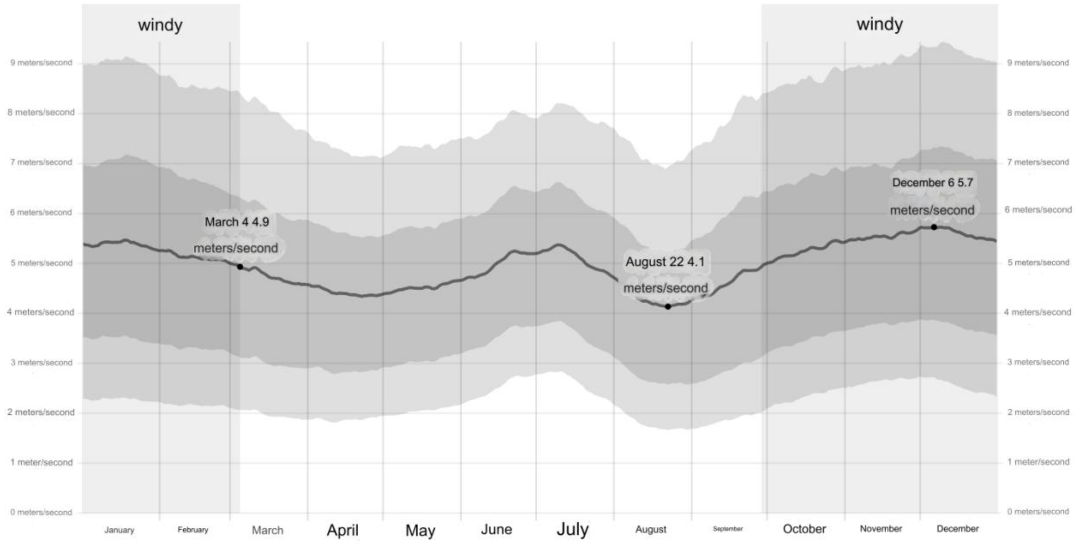


Figure 13 Average annual wind speed in Beihai City, Guangxi Province, China

Wind speed classification [14]:

0 --- Calm	less than 1 mph (0 m/s)	Smoke rises vertically
1 --- Light air	1 - 3 mph 0.5-1.5 m/s	Smoke drifts with air, weather vanes inactive
2 --- Light breeze	4 - 7 mph 2-3 m/s	Weather vanes active, wind felt on face, leaves rustle
3 --- Gentle breeze	8 - 12 mph 3.5-5 m/s	Leaves & small twigs move, light flags extend
4 --- Moderate breeze	13 - 18 mph 5.5-8 m/s	Small branches sway, dust & loose paper blows about
5 --- Fresh breeze	19 - 24 mph 8.5-10.5 m/s	Small trees sway, waves break on inland waters
6 --- Strong breeze	25 - 31 mph 11-13.5 m/s	Large branches sway, umbrellas difficult to use
7 --- Moderate gale	32 - 38 mph 14-16.5 m/s	Whole trees sway, difficult to walk against wind
8 --- Fresh gale	39 - 46 mph 17-20 m/s	Twigs broken off trees, walking against wind very difficult
9 --- Strong gale	47 - 54 mph 20.5-23.5 m/s	Slight damage to buildings, shingles blown off roof
10 -- Whole gale	55 - 63 mph 24-27.5 m/s	Trees uprooted, considerable damage to buildings
11 -- Storm	64 - 73 mph 28-31.5 m/s	Widespread damage, very rare occurrence
12 -- Hurricane	over 73 mph over 32 m/s	Violent destruction

Figure 14 Wind speed

Average annual air temperature in Beihai City, Guangxi Province, China [13]:

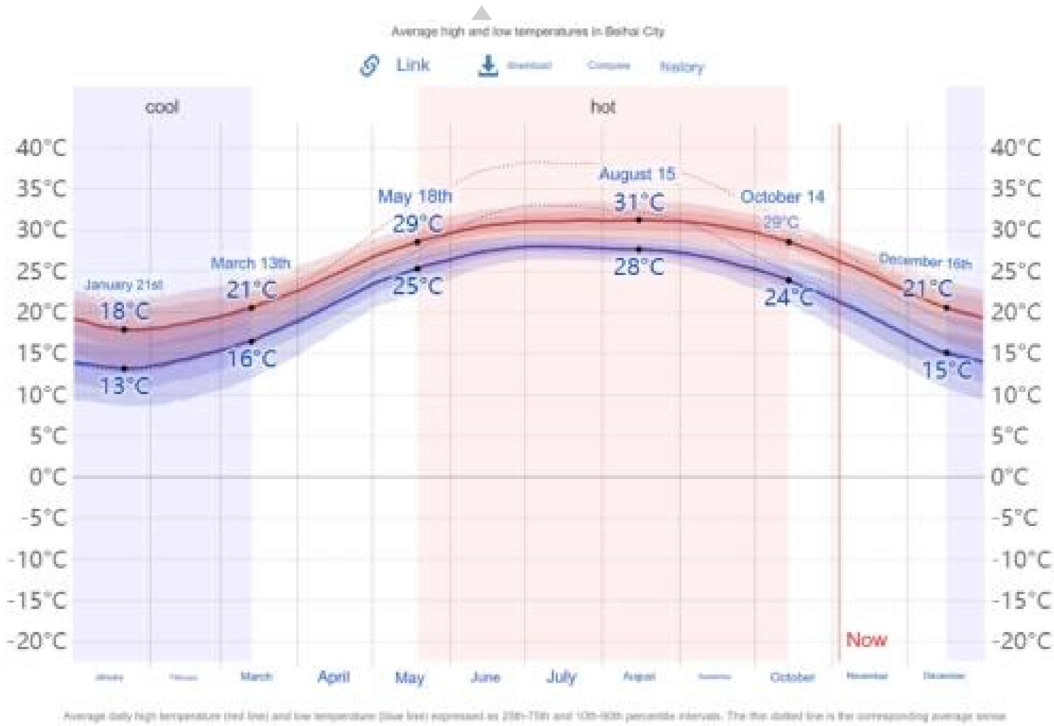


Figure 15 Average annual air temperature in Beihai City, Guangxi Province, China

Temperature		Density		Specific heat	Thermal Conductivity	Kinematic Viscousity	Density Ratio	
T		ρ		C_p	η	υ		
°C	°F	kg/m³	lb/ft³	kJ/kg.K	W/m.K	$m^2/s \times 10^{-6}$	Up	Down
-150	-238	2.787	0.1740	1.026	0.0116	3.08	0.43	2.31
-100	-148	1.980	0.1236	1.009	0.0160	5.95	0.61	1.64
-50	-58	1.535	0.0958	1.005	0.0204	9.55	0.78	1.27
0	32	1.293	0.0807	1.005	0.0243	13.3	0.93	1.07
20	68	1.205	0.0752	1.005	0.0257	15.11	1.00	1.00
40	104	1.128	0.0704	1.005	0.0271	16.97	1.07	0.94
60	140	1.067	0.0666	1.009	0.0285	18.90	1.13	0.89
80	176	1.000	0.0624	1.009	0.0299	20.94	1.21	0.83
100	212	0.945	0.0590	1.009	0.0314	23.06	1.27	0.78
120	248	0.897	0.0560	1.013	0.0328	25.23	1.34	0.74
140	284	0.854	0.0533	1.013	0.0343	27.55	1.41	0.71
160	320	0.815	0.0509	1.017	0.0358	29.85	1.48	0.68
180	356	0.778	0.0486	1.022	0.0372	32.29	1.55	0.65
200	392	0.746	0.0466	1.026	0.0386	34.63	1.61	0.62
250	482	0.674	0.0421	1.034	0.0421	41.17	1.79	0.56
300	572	0.615	0.0384	1.047	0.0454	47.85	1.96	0.51

Figure 16 Several key indicators that affect wind speed

3.1.2 Configuration of Wind Turbine

Wind turbine' specifications under this research study， take WEI6K， a 6-kW 7-m Small Wind Turbine as an example, As shown in Figure 17,18 [15]：

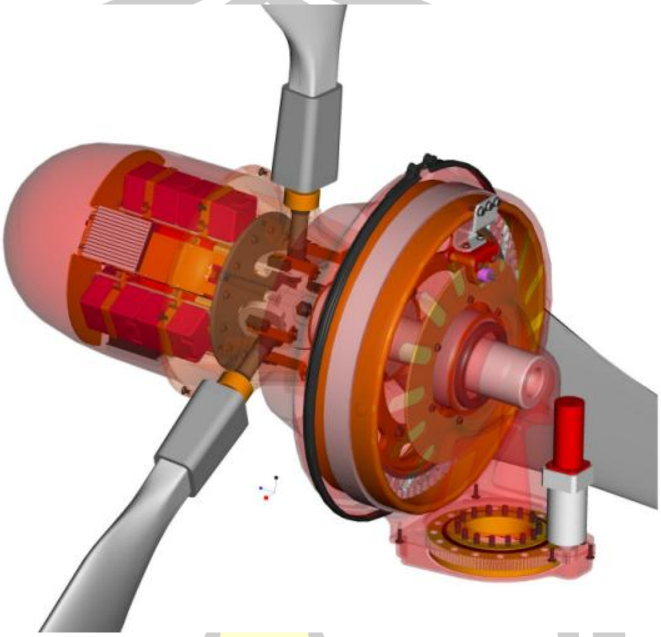


Figure 17 Outside and Cut-Away Views of the WEI6K Turbine

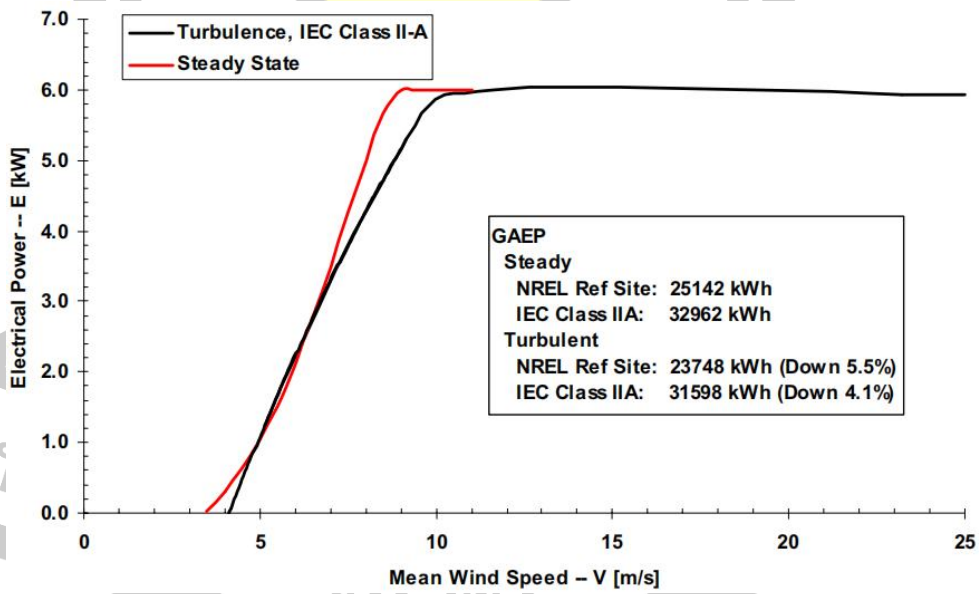


Figure 18 Power Curve for the WEI6K Wind Turbine

3.1.3 Configuration of Flywheels

(1) Conventional 6 kW-Flywheel (1x6kW-FW):

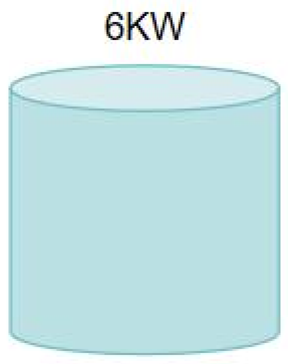


Figure 19 Conventional 6 kW-Flywheel (1x6kW-FW)

(2) Proposed Multi-stage Flywheels

Step 1: Multi-stage 6x1kW-Flywheel (6x1kW-FW):

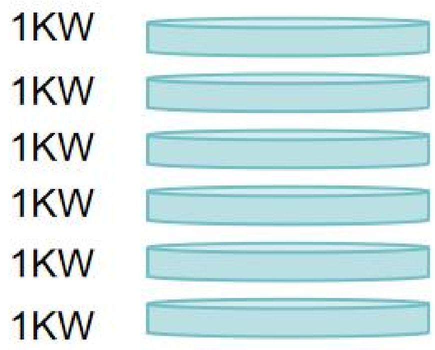


Figure 20 Multi-stage 6x1kW-Flywheel (6x1kW-FW)

Step 2: Multi-stage 1-2-3kW-Flywheel (1-2-3kW-FW):

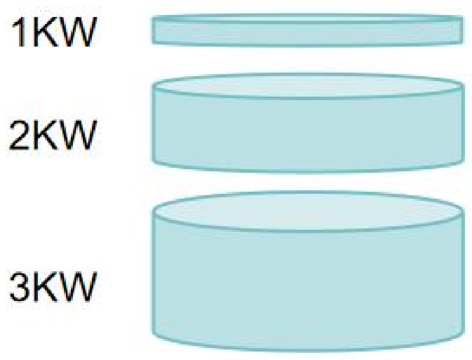


Figure 21 Multi-stage 1-2-3kW-Flywheel (1-2-3kW-FW)

3.2 Operation Principles

When the wind speed continues to increase, the energy of the wind turbine will continue to increase, and the energy transferred to the flywheel will also increase. Therefore, the flywheel will increase the number of flywheels used for energy storage based on the electronic energy sensing system.

3.2.1 1x6kW-FW Illustration of the influence of wind turbine conversion wind speed

Wind speed: $V_1 < V_2 < V_3 < V_4 < V_5 < V_6$.

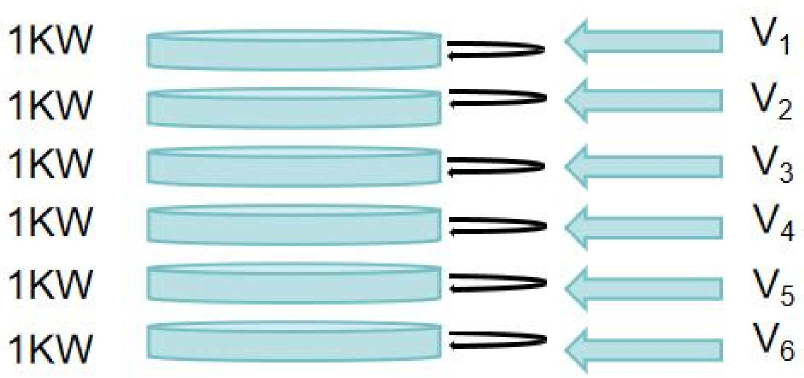


Figure 22 1x6kW-FW at different wind speeds

3.2.2 1-2-3kW-FW Illustration of the influence of wind turbine conversion wind speed

Wind speed: $V_1 < V_2 < V_3 < V_4 < V_5 < V_6$.

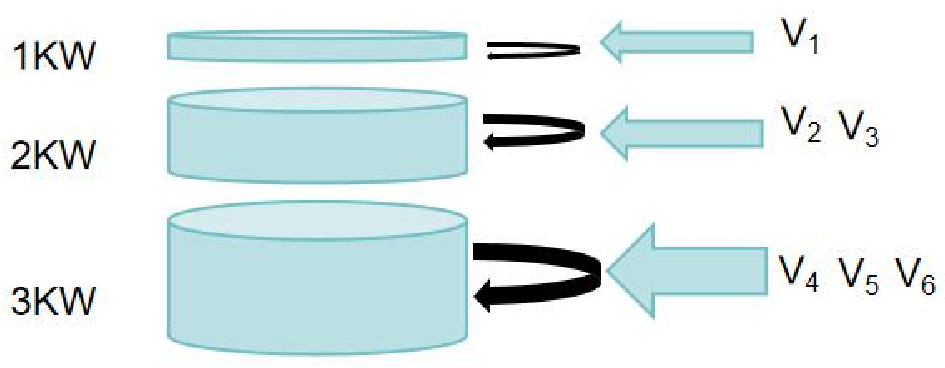


Figure 23 1-2-3kW-FW at different wind speeds

3.3 Experimental Tests

3.3.1 Experimental Procedures

(1) Wind turbine using MATLAB-Simulink

Development of model:

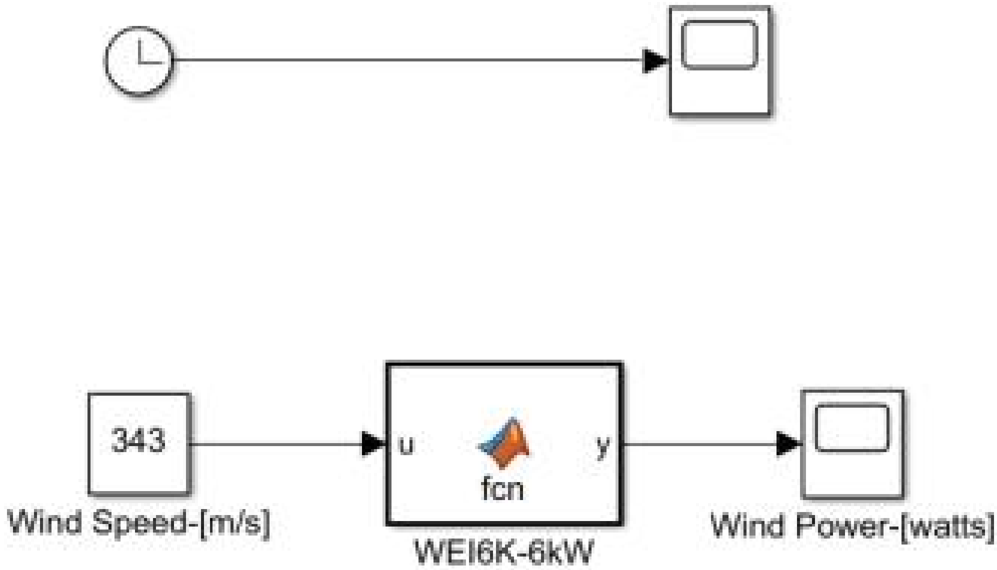


Figure 24 WEI6K Wind Turbine Simulink

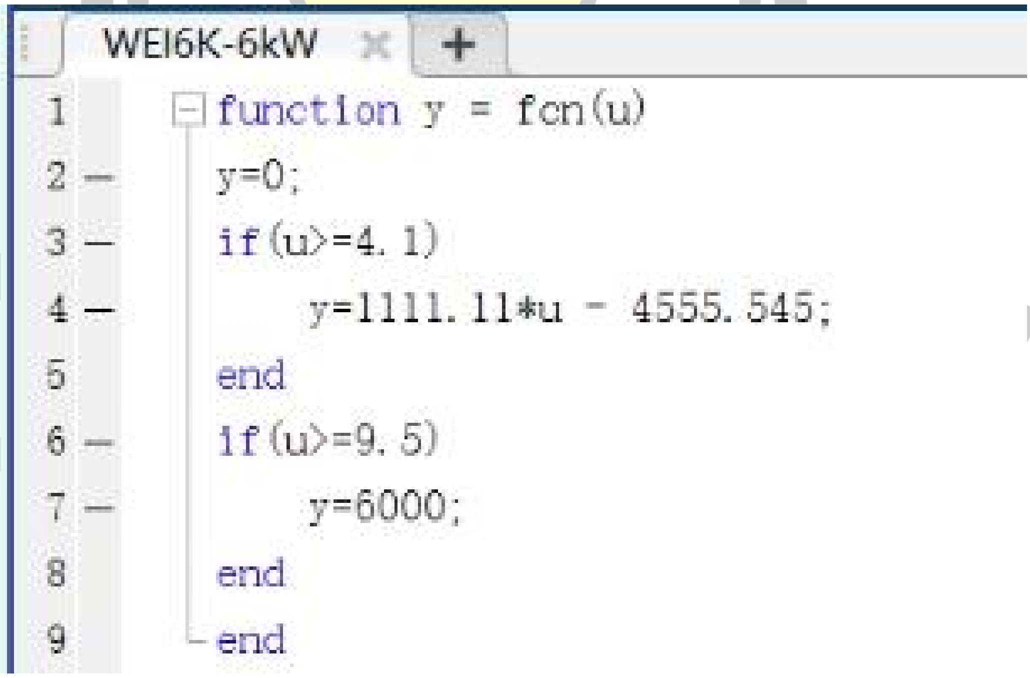


Figure 25 WEI6K Function Programming

Test at rated power of wind turbine:

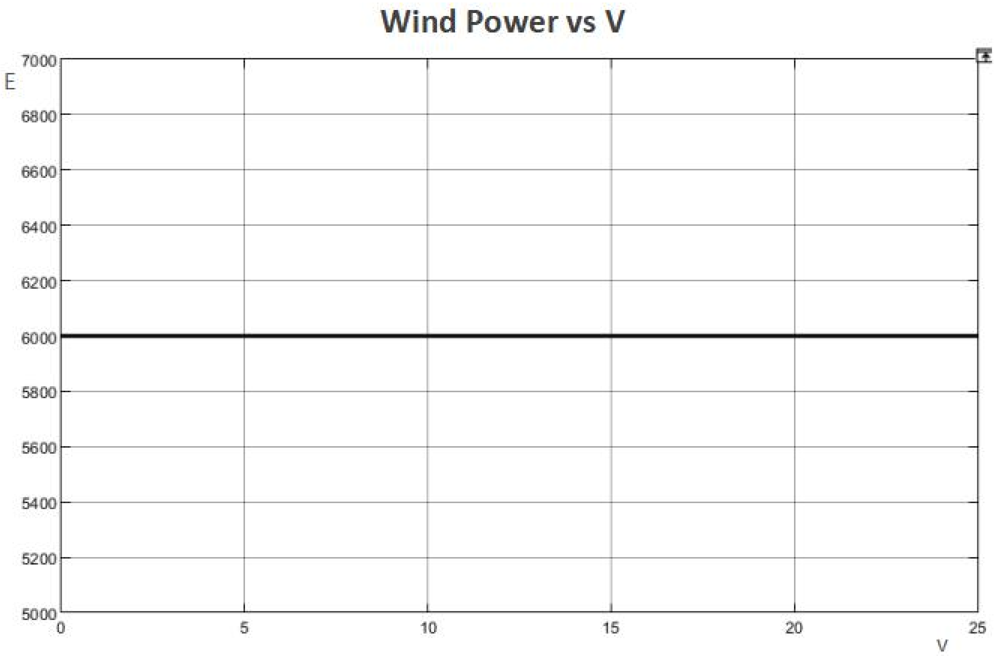


Figure 26 Wind Power

Analysis of Test results:

Calm	Wind Speed	Wind Power
1	0-4.0	0
2	4.1-9.4	1111.11-4555.545
3	9.5	6000

Table 1 The relationship between wind speed and energy in WEI6K

When V (Wind speed) ＞ =9.5m/s; ρ (air density)=1.205kg/m^3; A(rotor area)=30m^2;

According to the wind energy formula:

$$E = \frac{1}{2} A \rho V^3 C_P \tag{1}$$

So E (wind) =6000kWh.

“E” is the energy produced by the wind turbine (J/kWh). “A” is the area covered by the fan rotor (m2). “ρ” is the air density (kg/m3). “V” is the wind speed (m/s). “Cp” is the wind energy utilization coefficient, which is a value between 0 and 1, indicating the efficiency of the fan in extracting energy from the wind.

(2) Flywheels using MATLAB-Simulink

1. Conventional 6 kW-Flywheel (1x6kW-FW)

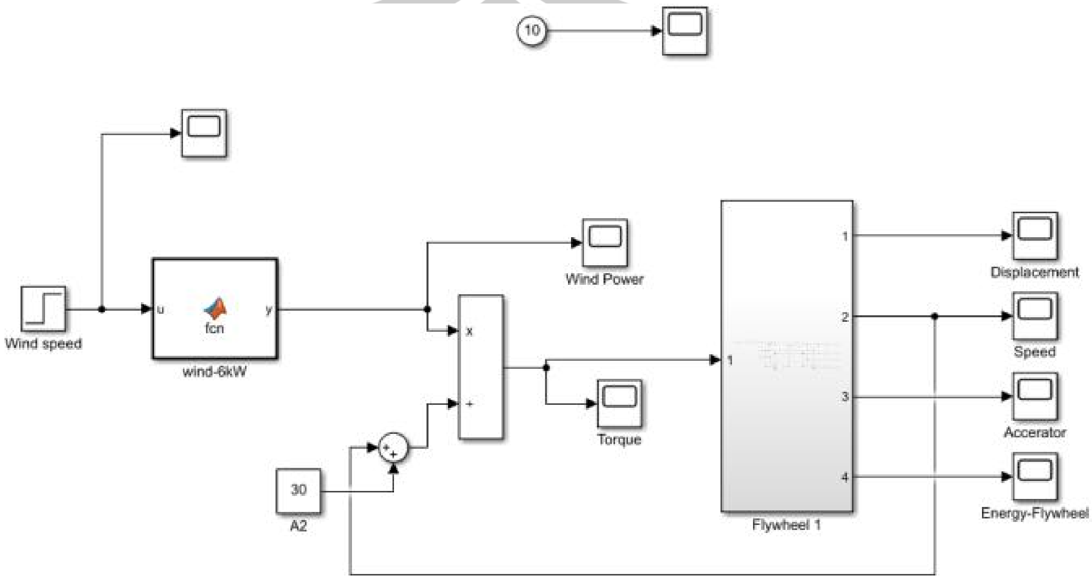


Figure 27 1x6kW- Flywheels using MATLAB-Simulink (a)

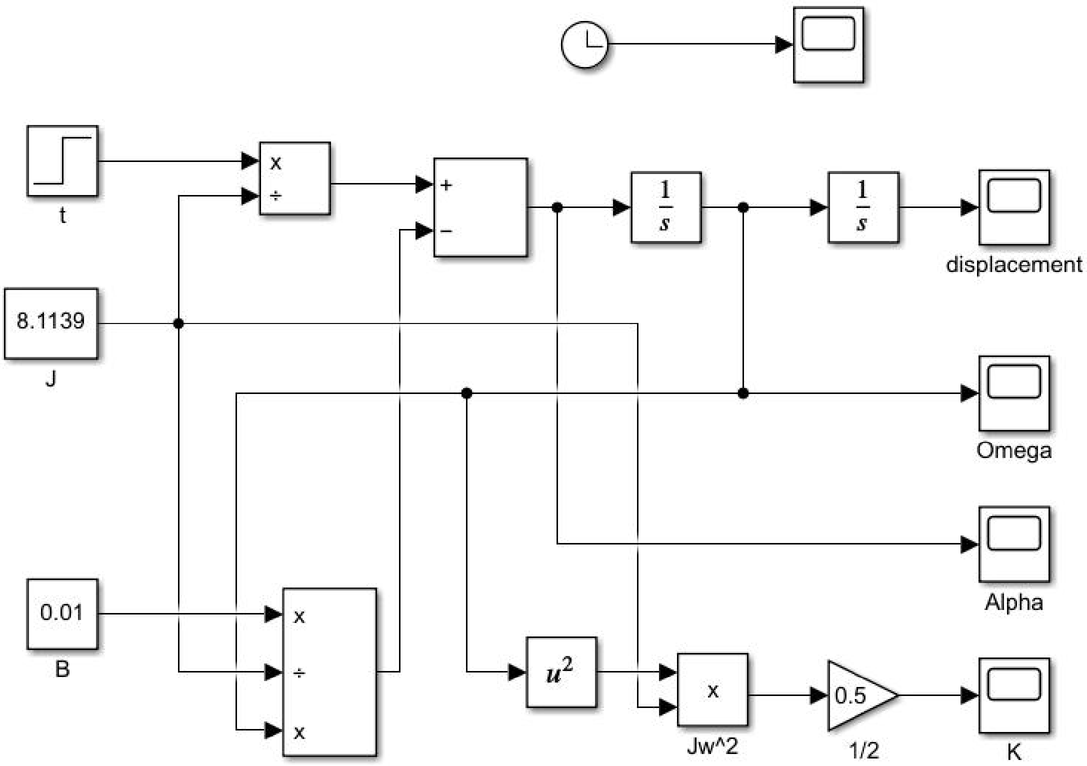


Figure 28 1x6kW- Flywheels using MATLAB-Simulink (b)

2. Multi-stage 6x1kW-Flywheel (6x1kW-FW)

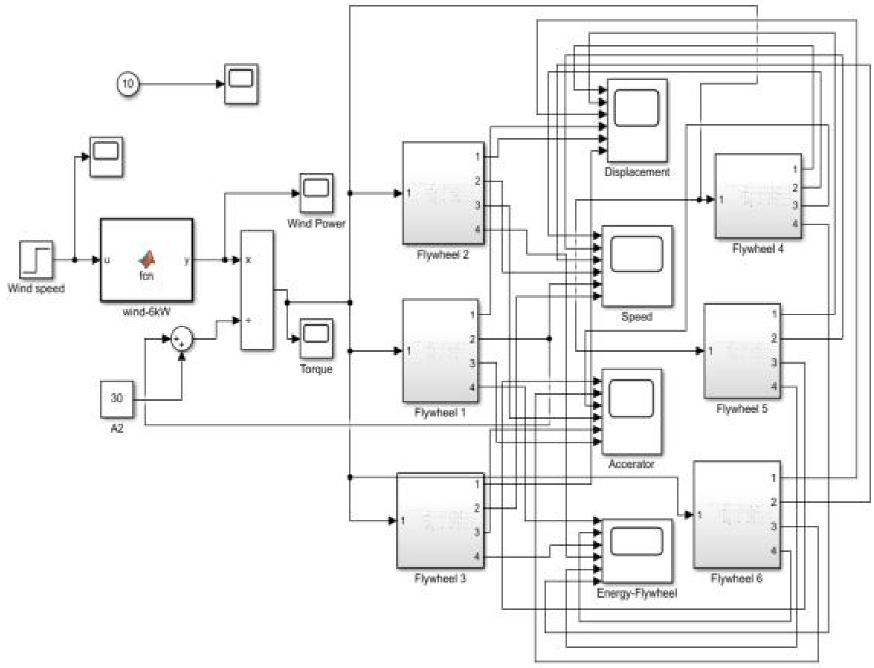


Figure 29 6x1kW-Flywheel using MATLAB-Simulink

3. Multi-stage 1-2-3kW-Flywheel (1-2-3kW-FW)

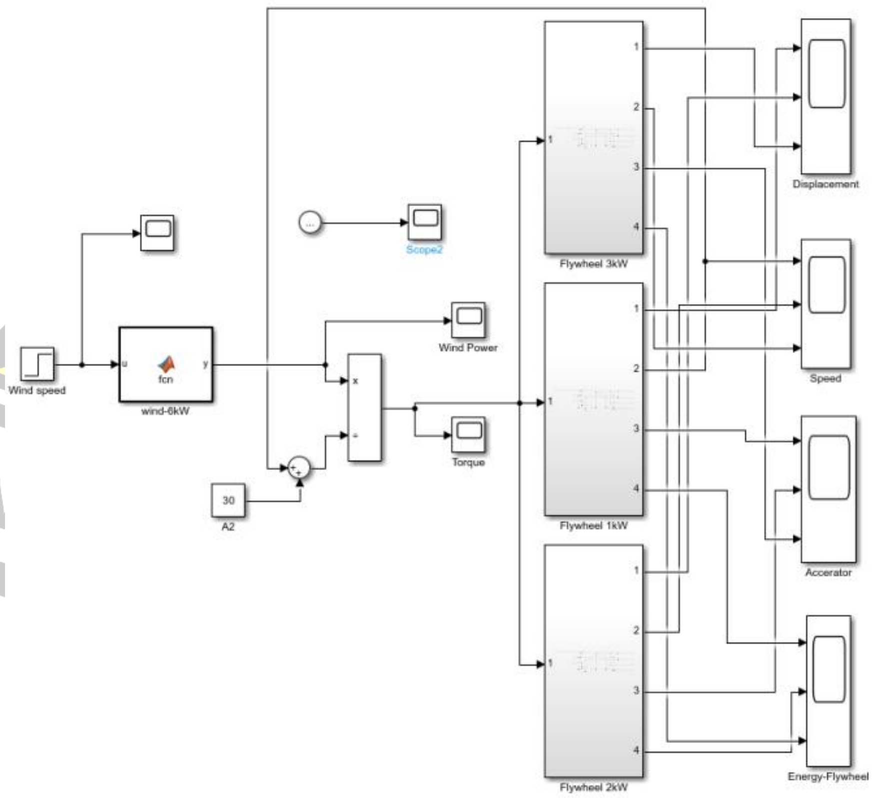


Figure 30 1-2-3kW-Flywheel using MATLAB-Simulink

3.3.2 Equipment and Tools

Using MATLAB-Simulink version: Simulink is a block diagram environment for multi-domain simulation and model-based design. It supports system-level design, simulation, automatic code generation, and continuous testing and verification of embedded systems. Simulink provides a graphical editor, customizable block libraries, and solvers to model and simulate dynamic systems. Simulink integrates with MATLAB®, so you can incorporate MATLAB algorithms into your models in Simulink and export simulation results to MATLAB for further analysis.

Chapter 4 Results and Discussions

This chapter presents the results obtained from the tests that were designed and presented in Chapter 3. The MATLAB simulation program has been used for the tests. Details of the results and discussions are as follows.

4.1 Simulation Model and Test Results of Wind Turbine

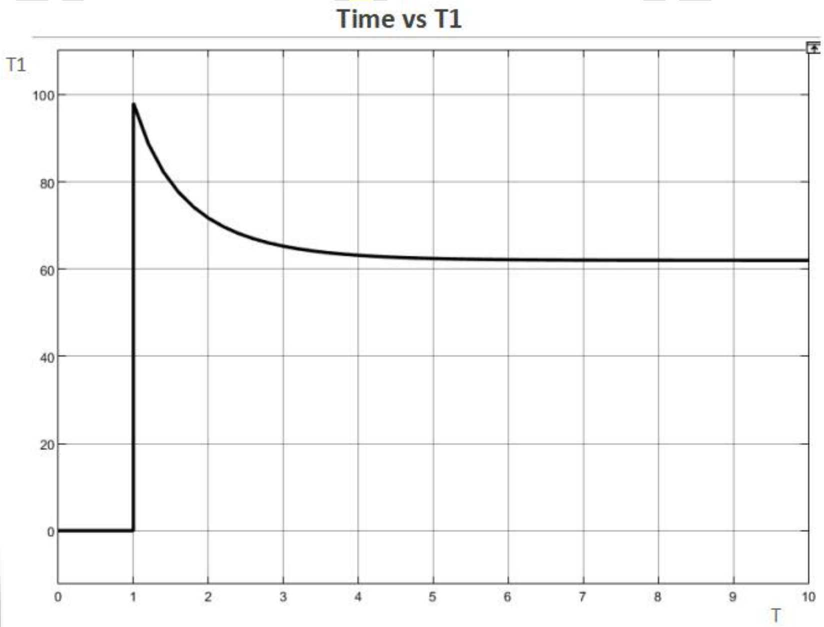


Figure 31 wind turbine MATLAB-Simulation results Time vs T1

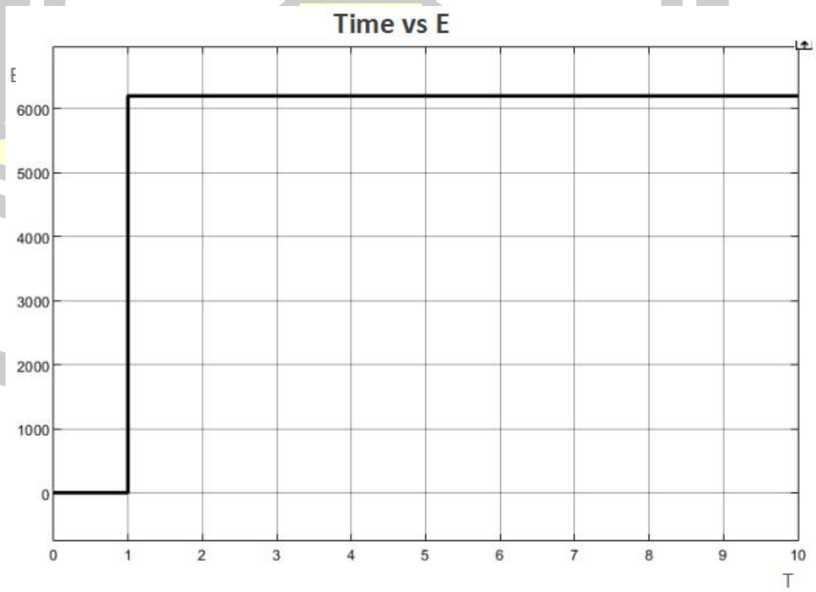


Figure 32 wind turbine MATLAB-Simulation results E (wind power) vs T

4.2 Simulation Model and Test Results of Flywheels

4.2.1 Conventional 6 kW-Flywheel (1x6kW-FW)

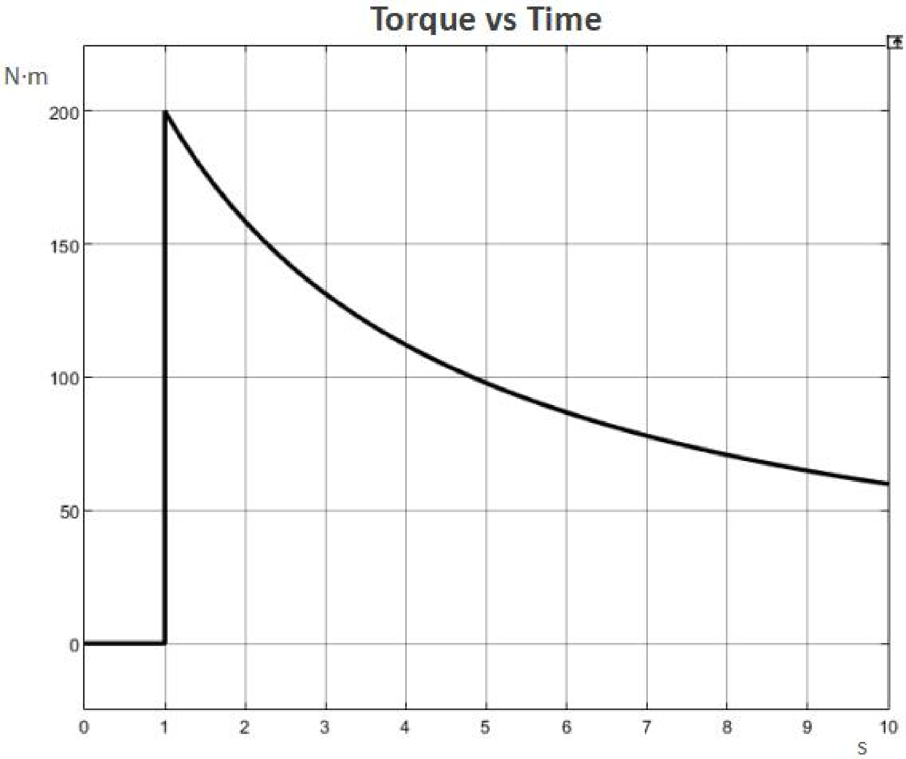


Figure 33 1x6kW-FW MATLAB-Simulation Torque vs Time

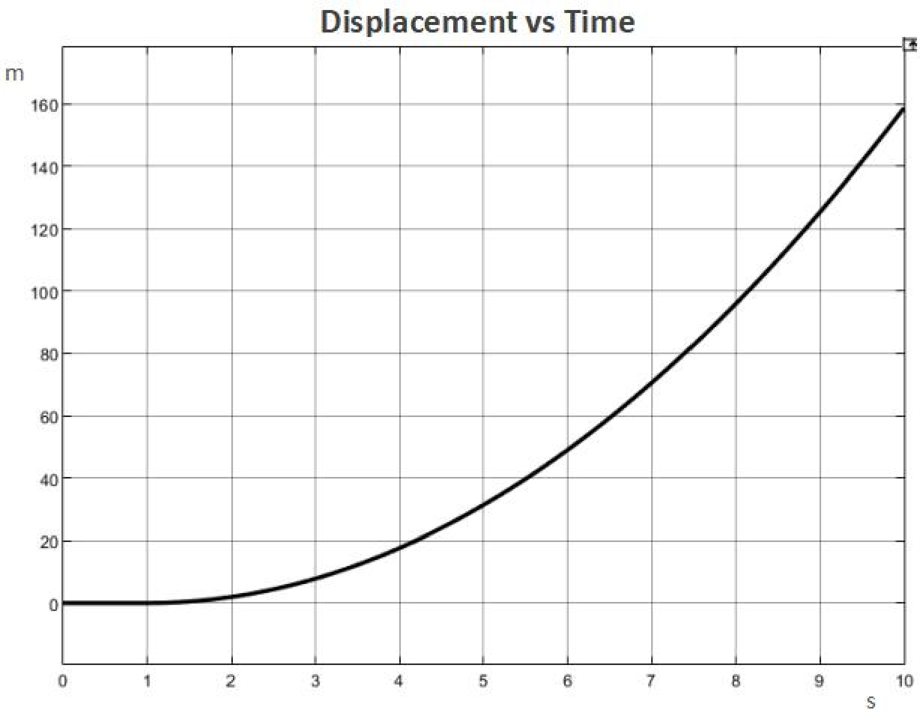


Figure 34 1x6kW-FW MATLAB-Simulation Displacement vs Time

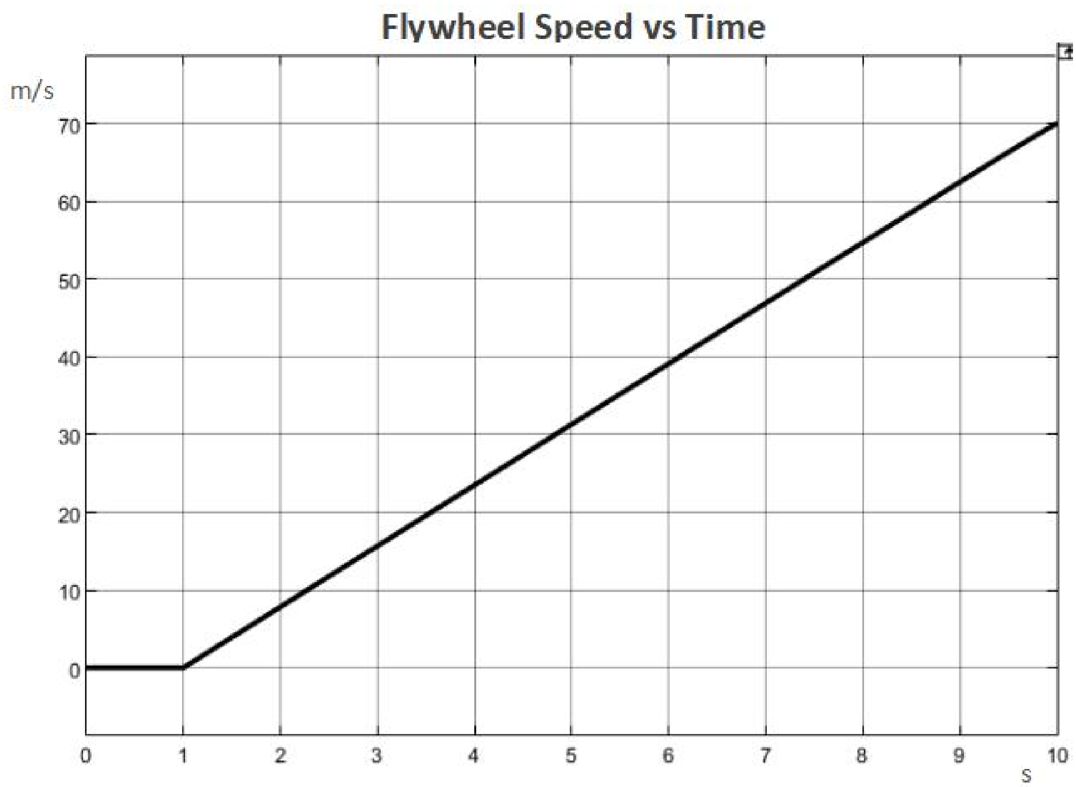


Figure 35 1x6kW-FW MATLAB-Simulation Flywheel Speed vs Time

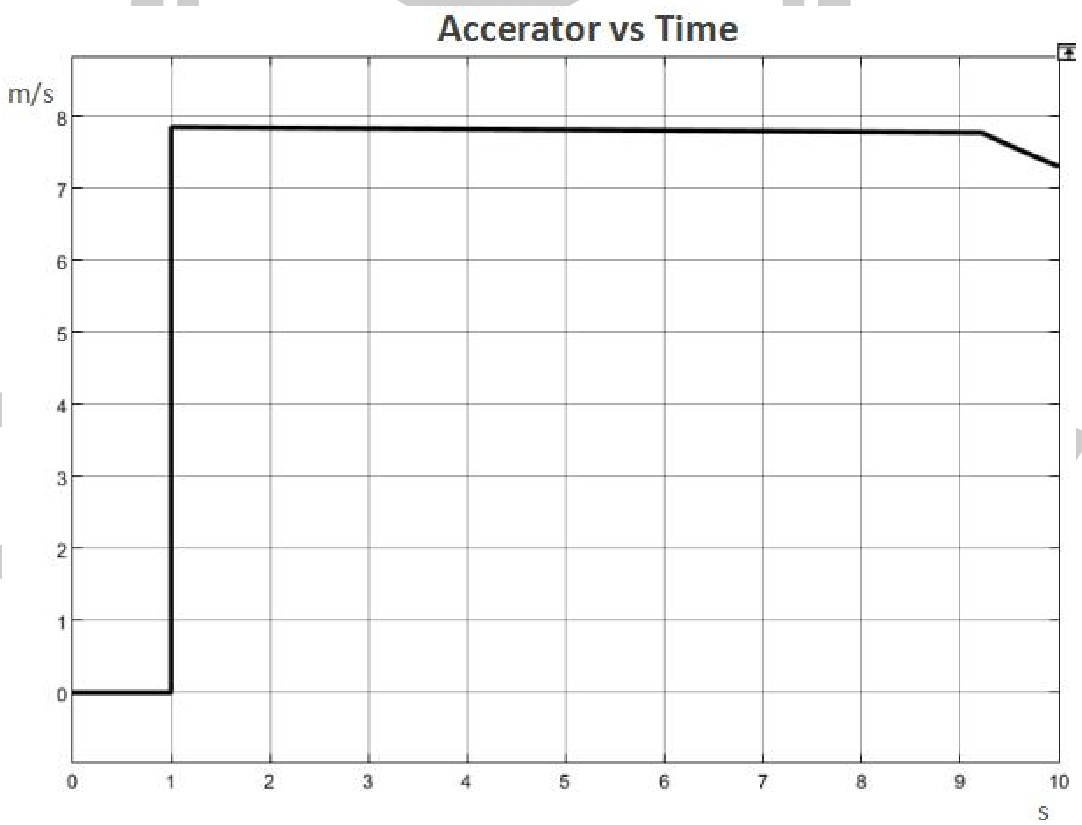


Figure 36 1x6kW-FW MATLAB-Simulation Accerator vs Time

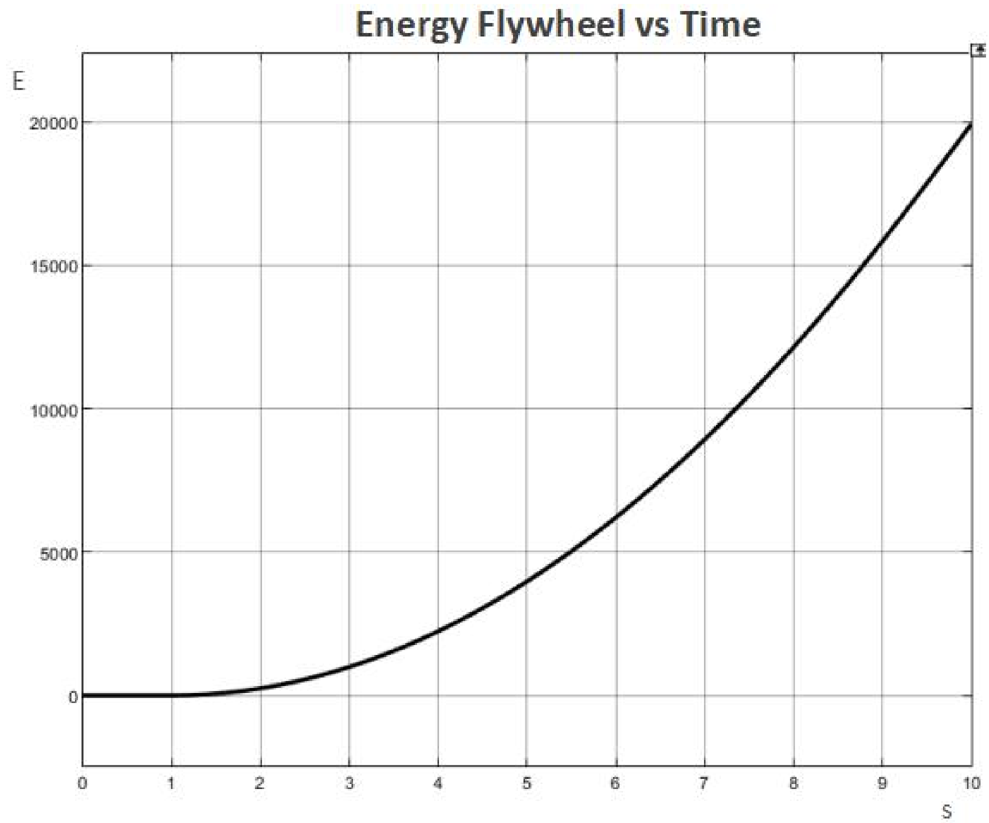


Figure 37 1x6kW-FW MATLAB-Simulation Energy Flywheel vs Time

4.2.2 Multi-stage 6x1kW-Flywheel (6x1kW-FW)

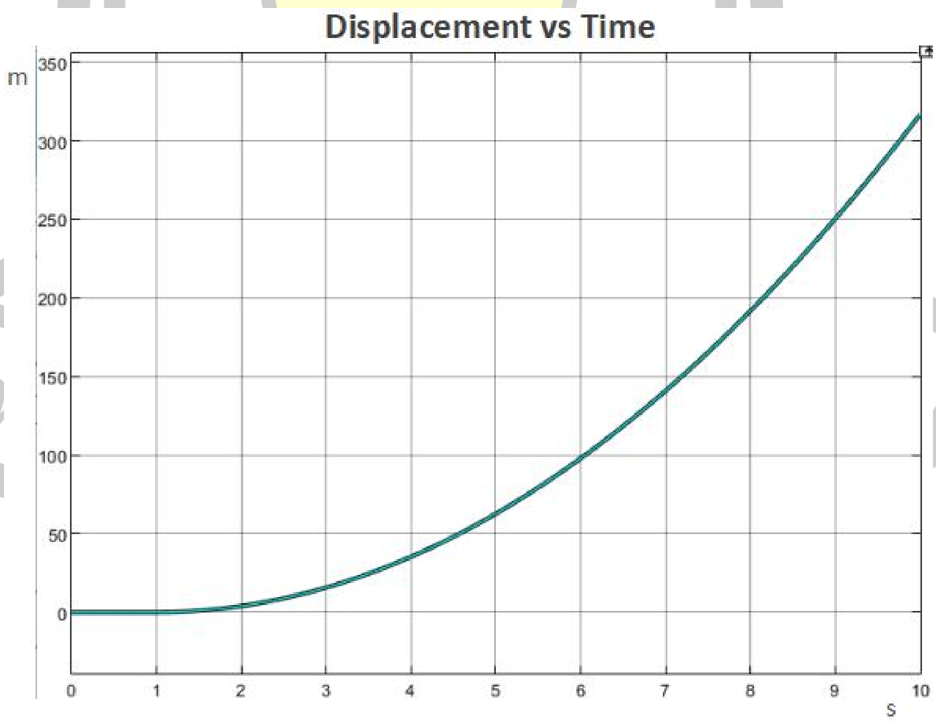


Figure 38 6x1kW-FW MATLAB-Simulation Displacemen vs Time

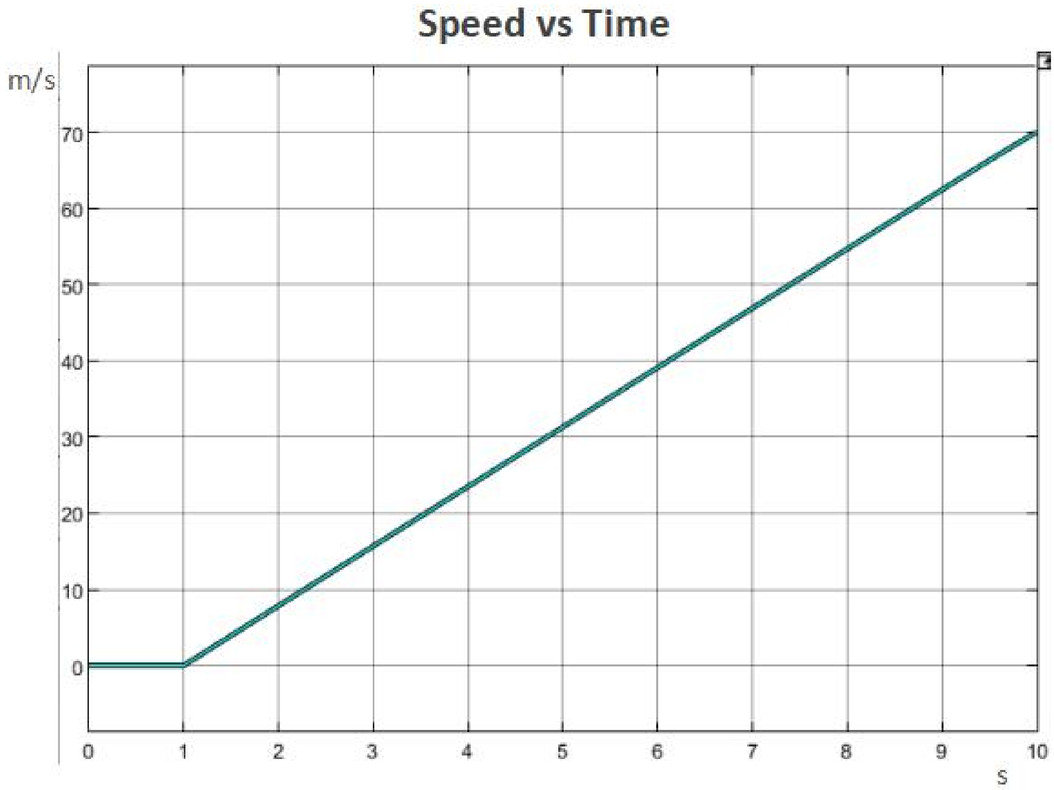


Figure 39 6x1kW-FW MATLAB-Simulation Speed vs Time

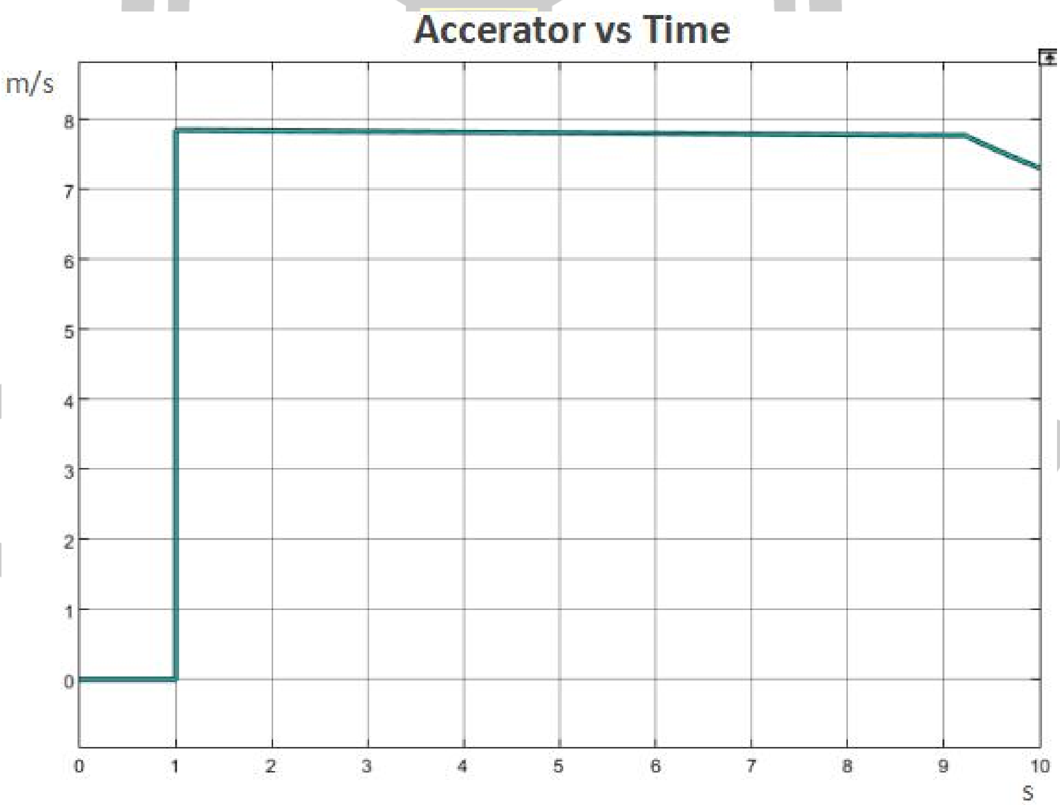


Figure 40 6x1kW-FW MATLAB-Simulation Accerator vs Time

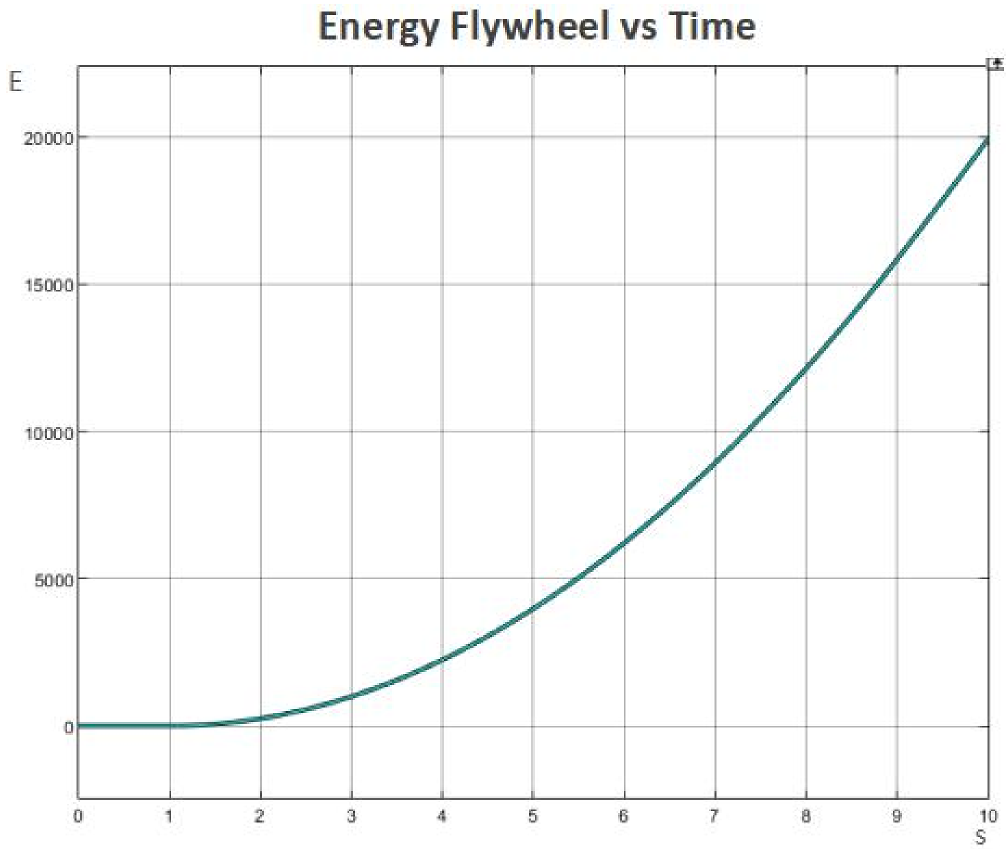


Figure 41 6x1kW-FW MATLAB-Simulation Energy Flywheel vs Time

4.2.3 Multi-stage 1-2-3kW-Flywheel (1-2-3kW-FW)

Figure 42 1-2-3kW-FW MATLAB-Simulation Displacement vs Time

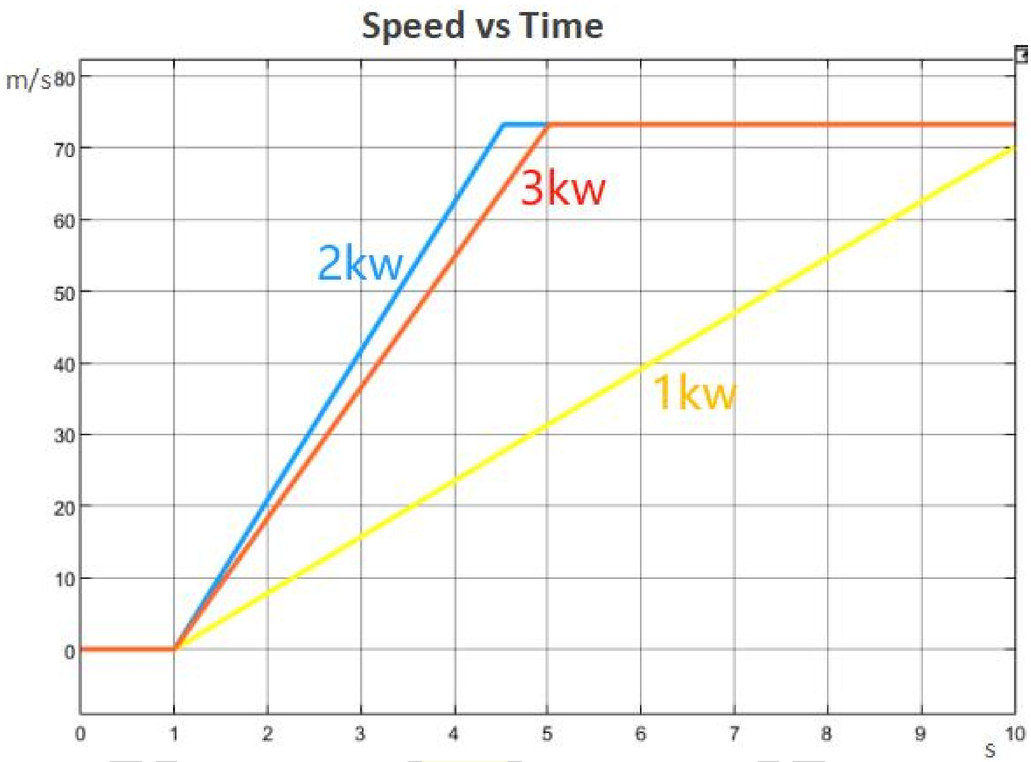


Figure 43 1-2-3kW-FW MATLAB-Simulation Speed VS Time

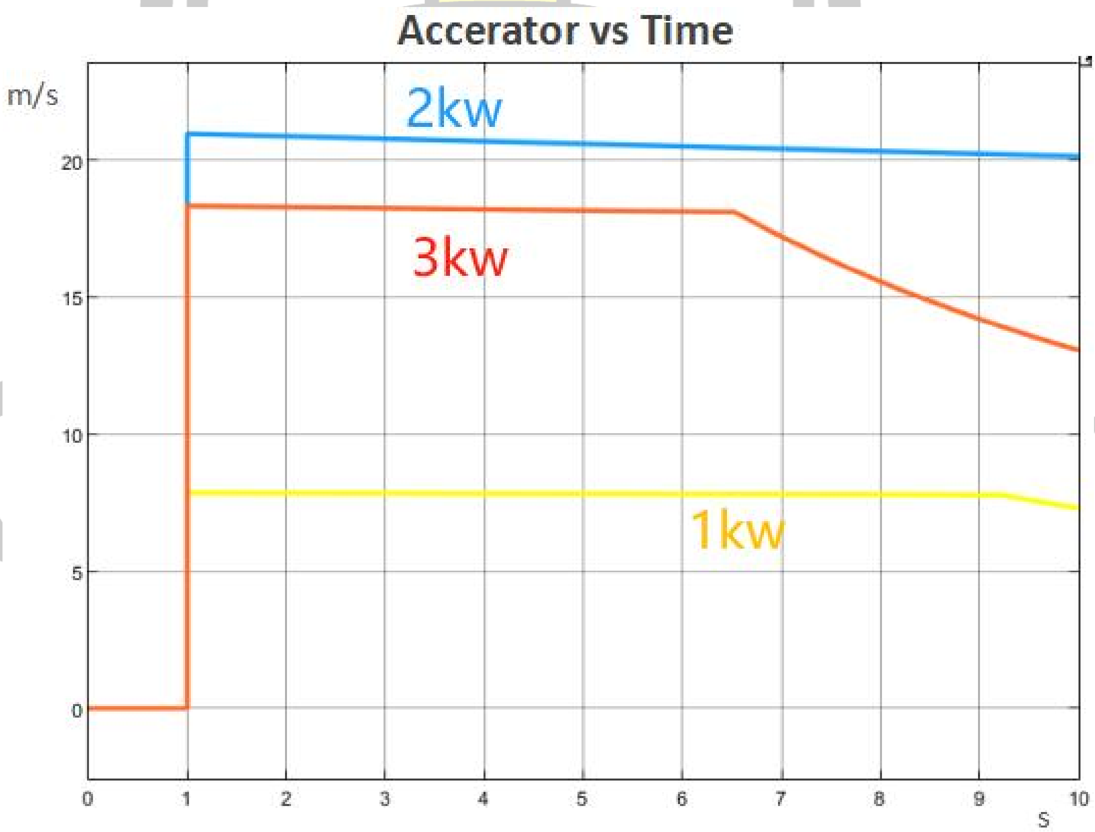


Figure 44 1-2-3kW-FW MATLAB-Simulation Accerator VS Time

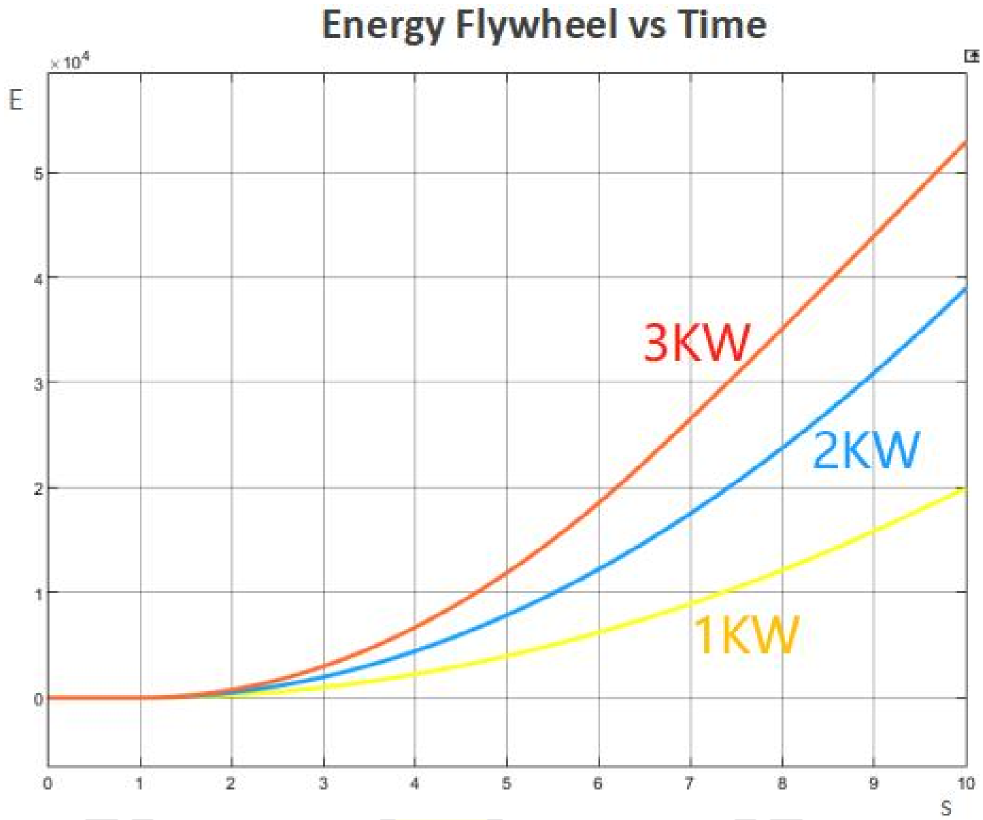


Figure 45 1-2-3kW-FW MATLAB-Simulation Energy Flywheel vs Time

4.3 Comparing energy and time simulation diagrams of three flywheel systems at the same wind speed

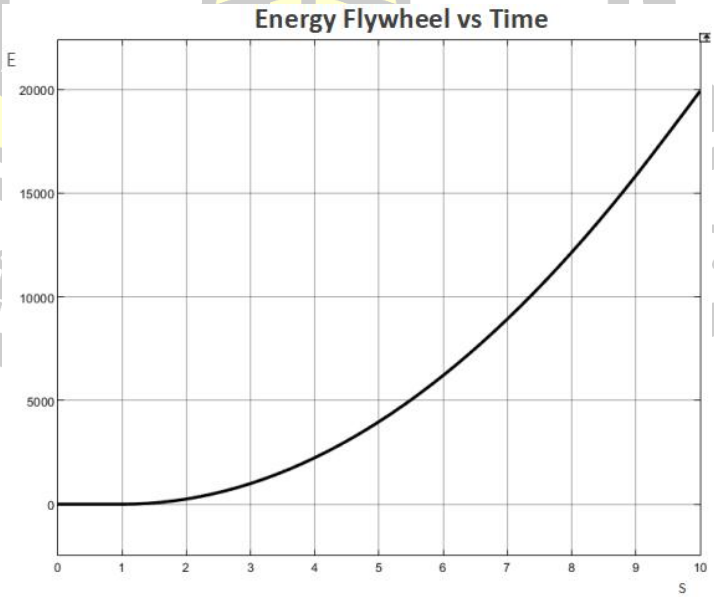


Figure 46 1x6kW-FW MATLAB-Simulation Energy Flywheel vs Time

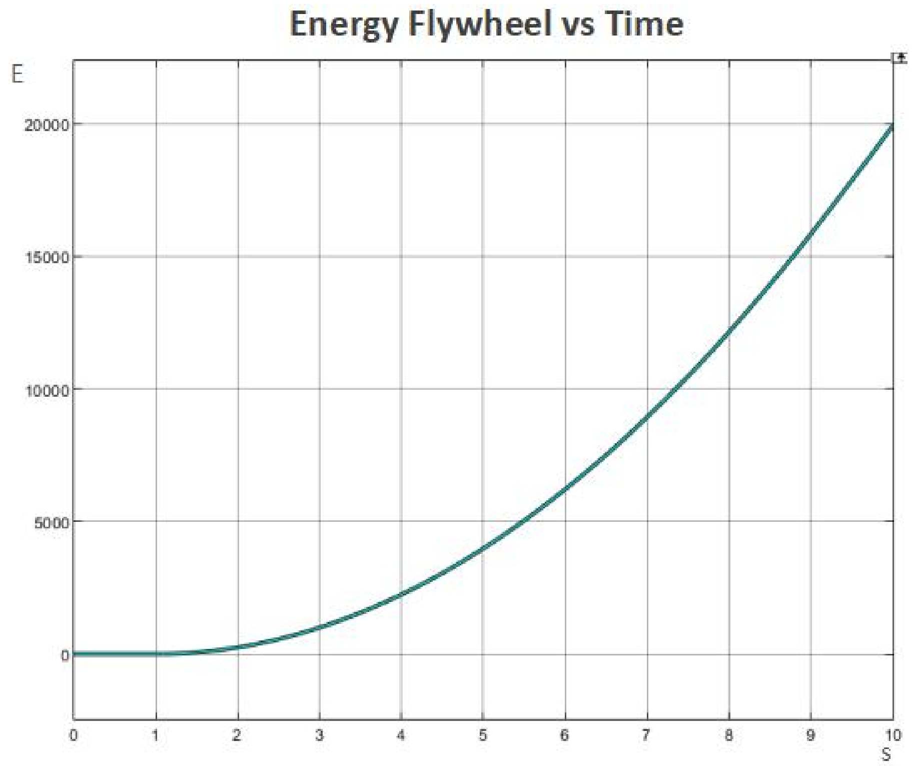


Figure 47 6x1kW-FW MATLAB-Simulation Energy Flywheel vs Time

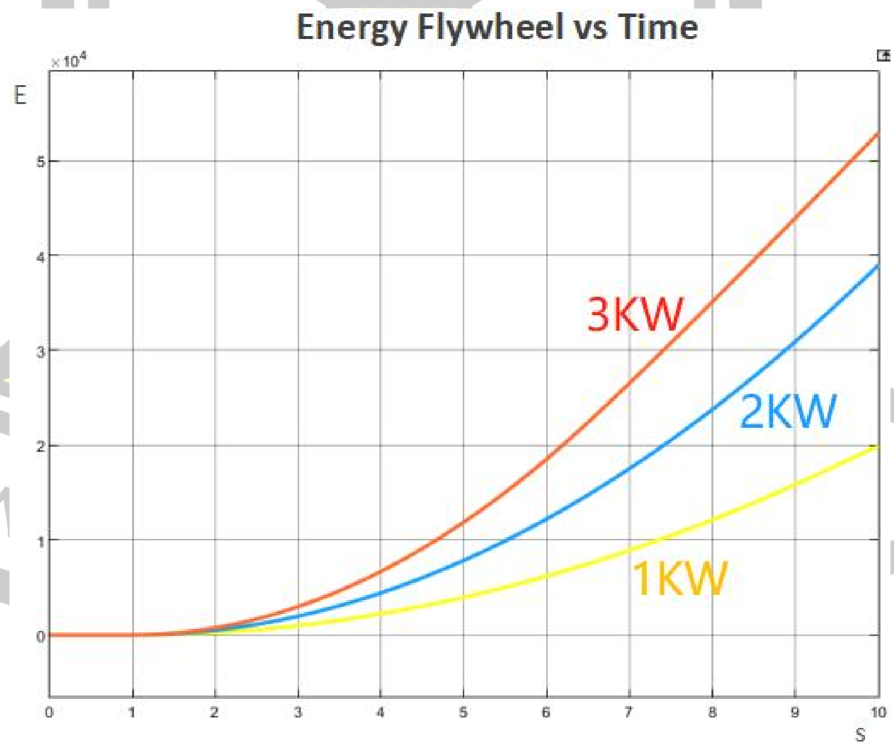


Figure 48 1-2-3kW-FW MATLAB-Simulation Energy Flywheel vs Time

Chapter 5 Conclusions

5.1 Conclusions

The conclusions of this research are as follows:

This research proposed a wind turbine system with a flywheel energy storage system. The conventional wind turbine generators were used for the analysis and evaluation of the proposed system.

The MATLAB simulation program were used for the test and the analysis of the proposed system.

Comparing the storage capacity of the two flywheel energy storage systems to the energy generated by the wind turbines, the results show that the Multi-stage 1-2-3kW-Flywheel (1-2-3kW-FW) unit is more efficient.

5.2 Future Works and Suggestions

The experimental test-rigs with the proposed system configurations should be developed to validate the practical implications of the proposed system.

Different types of the control strategies for the energy management should be considered for further enhancing the performances and efficiency of the proposed system.

The application of electronic devices in automatically switching flywheel energy storage can be further studied.

Future studies should fully consider multiple types of flywheel performance and efficiency.

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