Performance Analysis of Stand-Alone Wind Energy Power Conversion System

Mahendra Kumar Singar, M N Nachappa, Chandra Kant Gautam and Kuldeep Singh Kulhar

Mahendra Kumar Singar, Assistant Professor, Civil Engineering, Vivekananda Global University, Jaipur, India, Email Id-mahendra.kumar.singar@vgu.ac.in
M N Nachappa, Professor, Department of Computer Science and Information Technology, Jain (Deemed to be University), Bangalore, India, Email Id- mn.nachappa@jainuniversity.ac.in
Mr. Chandra Kant Gautam, Scholar, Department of Mechanical Engineering, Sanskriti University, Mathura, Uttar Pradesh, India, Email Id- chandrakant@sanskriti.edu.in
Kuldeep Singh Kulhar, Professor, Civil Engineering, Vivekananda Global University, Jaipur, India, Email Id-k.singh@vgu.ac.in

Abstract— **Earlier, the production of electricity was primarily reliant on non-renewable sources such as coal and diesel. However, these sources have limited availability and will eventually be depleted. Therefore, it is crucial to shift our focus towards renewable sources for electricity generation. Wind energy is considered one of the cleanest and most sustainable forms of renewable energy. The cost and maintenance associated with generating electricity from wind energy are significantly lower compared to other sources. However, the irregular flow of wind energy makes it challenging to directly convert it into electrical form. To address this issue, Wind Energy Conversion Systems (WECS) are required. WECS can be utilized in both grid-connected and stand-alone systems to meet their respective load demands. One of the main concerns with WECS is the mechanical safety and the output power of the system. The inconsistent supply of wind can lead to wear and tear of the turbine blades. To prevent this, a pitch control system is implemented to regulate the blades' angle. Additionally, the rotational speed of the rotor is affected by improper wind supply, which ultimately impacts the output power. To maximize the power output from the rotor, an MPPT (Maximum Power Point Tracking) control scheme is employed. In this study, a DC load system representing a telecom base station is used as the base system to analyze the control scheme under various wind profiles using MATLAB/SIMULINK.**

Index Terms— **MPPT, Wind power generation, SoC, Pitch Control System.**

Corresponding Author: mahendra.kumar.singar@vgu.ac.in

1. INTRODUCTION

Wind energy is a crucial renewable resource that plays a significant role in meeting the increasing demand for electricity. In the past, electricity generation heavily relied on non-renewable sources such as coal and diesel. However, these sources have limited storage and will eventually deplete. Therefore, it is imperative to shift our focus towards renewable sources for sustainable electricity generation.

Wind energy is distinguished among the numerous renewable energy sources due to its exceptional cleanliness. It offers several advantages, including low cost and maintenance compared to other energy sources. However, harnessing wind energy directly for electricity generation is challenging due to its irregular flow. To overcome this, Wind Energy Conversion Systems (WECS) are designed.

WECS are specifically engineered to convert the kinetic energy of wind flow into electrical energy. They can be utilized in both grid-connected and stand-alone systems to meet the increasing load demands. However, the erratic nature of wind energy poses challenges in terms of wear and tear on the equipment.

The turbine blades are essential for the operation of a WECS. The rotational speed of the rotor is directly influenced by the condition of these blades, which in turn affects the output power supply. To ensure the system remains undamaged, a suitable control system is implemented in the WECS. The mechanical well-being of the system is achieved through the application of the pitch control method, while the output power is regulated by a charge controller that follows the maximum power point approach. To effectively manage the charging and discharging of the battery, a State of Charge (SoC) algorithm is developed. In this proposed work, the MPPT method using TSR (Tip Speed Ratio) is utilized. By maintaining a continuous charging current with low ripples, the battery's harmonic heating can be minimized. The switching between charging and discharging is determined based on the real-time value of SoC, providing protection against over voltage, overloading, rectifier output, and turbine over speed.

2. LITERATURE REVIEW

The reliable and proper control scheme is crucial for the efficient functioning of a WECS. Therefore, the study of controllers required for the system is becoming increasingly important. The fundamental components of a WECS include the structural elements of the system, the aerodynamics, and the electrical conversion system [1-2]. There are four types of generators used in WECS: synchronous with coiled field, induction with coiled rotor, squirrel cage induction generators, and synchronous with permanent magnet [1], [3]. A detailed comparison of these generators is provided in [3]. By using asynchronous machines, maximum power can be extracted while allowing for variable speed operation and minimizing fluctuation torque. The induction generator is considered the most suitable option for off-grid applications due to its lower cost, robustness, and simplicity [2]. A battery storage system is necessary for the WECS to provide uninterrupted power supply. Different storage technologies for the battery bank are analyzed in [10]. Battery storage ensures maximum power output even in irregular winds [5]. A comparison of different MPPT techniques is conducted in [4]. The charge control technique plays a vital role in the operation of the battery bank as it regulates the charging and discharging processes [7]. The terminal voltage is used to switch from current mode to voltage mode based on the state of charge. Regulating the wind speed is essential to prevent damage to the system. The pitch angle of the blades is adjusted to the required value for safe operation [16]. Various pitch control techniques are explained in [14]-[19]. It is important to note that the references mentioned above only consider grid-connected systems.

3. HYBRID WIND-BATTERY POWER SUPPLY SYSTEM

The outline of the whole system along with control method is shown in figure 1. The specification of the wind turbine, squirrel cage induction machine and the battery bank are systematized in the appendix. The proposed work is planned for a 3.0kW dc load, which comprises of 4.0kW Wind Energy Conversion System and 400Ah, C/10 batteries. The system consists of a 4.2kW horizontal axis wind turbine. The stator terminals are linked to the capacitor bank to enable self-excitation as the stand-alone DC load is connected to the system. Gearbox is connected between the blades and the rotating machine. The ac output comes from the machine is connected to the three phase ac-dc diode rectifier to rectify the harmonics. The purpose of the battery bank in the system is to provide continuous power supply to the system during insufficient or discontinuous winds. This hybrid system needs proper control system for meeting load. The output of the diode rectifier is connected to charge controller which is dc-dc buck converter. This charge controller tunes the discharging/charging rate of the battery bank. The battery bank can operate as either a source or a load, depending on whether it is being charged or discharged. The charging process of the battery bank is accomplished through the use of the MPPT method, while the pitch controller ensures mechanical protection. The hybrid system ensures the reliable operation of WECS.

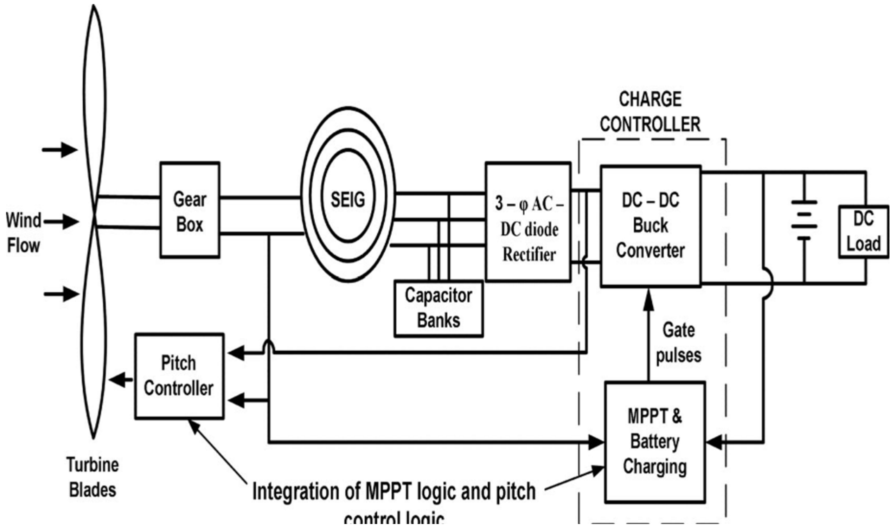

Fig. 1: Stand-alone wind power supply system.

4. STAND-ALONE WECS CONTROL STRATEGY

The control strategy of a WECS includes both the MPPT technique and pitch control technique. The MPPT technique is employed to maximize energy output from the wind turbine, while the pitch control technique is utilized to regulate the blade angle, ensuring mechanical safety of the WECS.

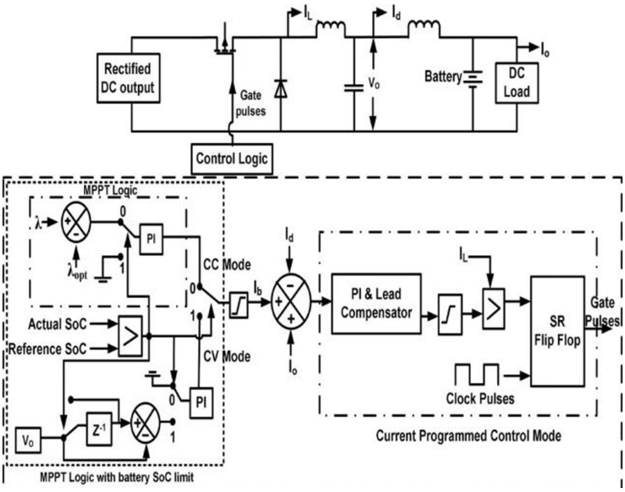

Fig. 2. (a) Diagram of control logic for battery [6]; Fig. 2.(b) Algorithm for Charge Controller [6].

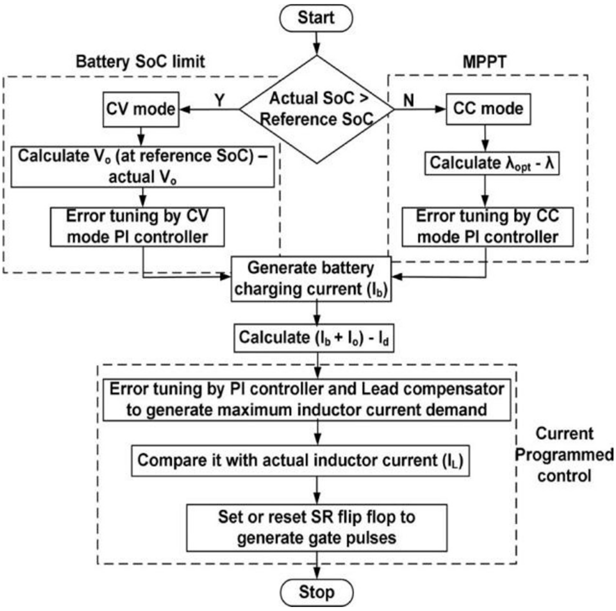

Fig. 3. Pitch Control Logic for WECS [6].

A. MPPT technique by TSR method*:*

Rotor generator characteristics play a crucial role in achieving the optimal power point, which can vary from one system to another. Therefore, it is imperative to implement an efficient MPPT controller in WECS. Extracting the maximum energy from wind can be challenging due to its unpredictable nature. However, this challenge can be overcome by employing a suitable MPPT mechanism. There are various techniques based on MPPT algorithms, including Tip Speed Ratio (TSR), Power Signal Feedback (PSF) control, Optimal Torque Control, and Perturb and Observation method, which can help us attain the desired output. In this proposed study, the TSR method is utilized to determine the optimum power point. The Tip Speed Ratio can be calculated using the following formula:

$$TSR = \frac{Rotor\ tip\ speed}{wind\ speed} = \frac{rpm\ \times\ \pi D}{60v}$$

The rotor speed of the turbine is denoted as rpm, while the rotor diameter is represented by D (in meters). The wind speed of the turbine is indicated as v (in meters per second)..

B. Pitch control technique*:*

The wind turbine's output power is directly proportional to the cube of the wind velocity [14-15]. If the turbine is allowed to operate at any speed of the wind without any control scheme, the angular speed of the shaft will increase, leading to wear and tear of the turbine blades. Therefore, an appropriate mechanism is required to control the speed and power above the rated wind speed. Adjusting the pitch angle of the blades is how the wind turbine's pitch control scheme can be modified to achieve this. To study the effects of different pitch angles, the Cp versus TSR characteristics are determined and shown in figure 6. The power coefficient reaches its maximum value when the pitch angle is set to zero degrees, as evident from the diagram. In the pitch control scheme, the power output is controlled by minimizing the Cp at intense wind speeds, while maintaining the pitch angle at zero degrees below the rated wind speeds to maximize power output. The blade pitch increases as the wind turbine parameters reach their rated values. It also regulates the power output of the converter to prevent the system from experiencing overvoltage conditions. Figure 7 illustrates the pitch control mechanism of the WECS. In this mechanism, each input is equated to one to determine the error. The MAX block extracts the maximum power from each PI controller and forwards it to the limiter. The limiter generates the pitch request for the wind turbine, with the actual pitch request equated to the rated value. The lower limit of the pitch request is set to zero. If the pitch command exceeds or falls below the specified limit, an error occurs in the system. The pitch controller adjusts the pitch angle according to the wind speed to ensure the smooth operation of the WECS.

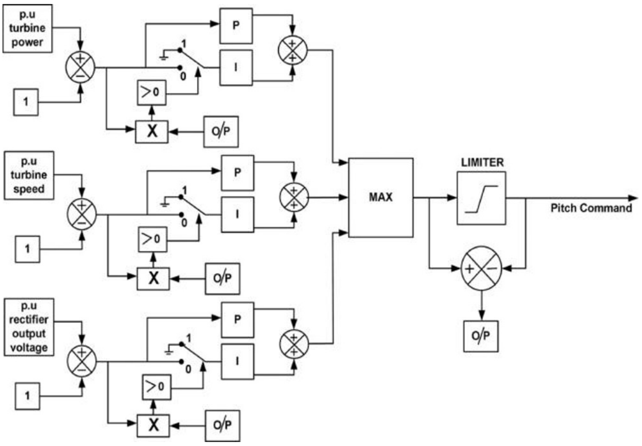

Fig. 4. Charging operation of Battery at Continuous Wind Speed of 10m/s [6].

5. MODES OF BATTERY CHARGING

The charge controller is tasked with overseeing the charging and discharging operations of a battery bank, featuring a dc-dc buck circuit. The charging rates of batteries vary based on the specifications set by the manufacturer. For the charging operation, a 400Ah battery bank with a C/10 rating is selected, where C represents the Ah rating of the battery bank. There are two methods for charging batteries: constant current mode and constant voltage mode. Responses of battery are depicted in Fig. 5.

A. . In the constant current mode, a typical battery charges at a steady rate until its state of charge (SoC) reaches a specific level (95%-99%). This mode, known as constant current (CC) operation, allows the battery to charge as quickly as possible. The charging demand in this mode is determined by the MPPT logic, with the PI controller adjusting the error for battery charging current based on wind speed. The MPPT implementation relies on comparing the actual and optimum Tip Speed ratio to ensure power supply even in low wind conditions. In this mode, both the SoC and battery voltage increase rapidly over time. Additionally, the power from the primary source is transferred to the battery during the mode of constant current.

B. In the Constant Voltage Mode, the battery charging process enters a state where the terminal voltage is balanced. This mode, known as CV mode, is implemented to prevent the electrolyte from gasifying due to overcharging. To transition from the Constant Current to the Constant Voltage Mode, the controller relies on the battery state of charge reaching the reference state of charge. During this operation, the buck converter output determines the battery charging voltage (V0). The converter output remains fixed, causing the battery voltage and state of charge to gradually increase over time. The output voltage is regulated in constant voltage mode as the circuit current diminishes.

6. RESULTS AND DISCUSSION

A. In order to maintain a consistent power supply to the load, a WECS requires an appropriate and efficient control system. The control strategy implemented in this system is designed for a hybrid wind-battery setup. This control scheme consists of a charge controller for the battery bank and a pitch controller for the turbine blades. The MPPT technique, using the Tip Speed Ratio (TSR) method, is utilized to achieve the optimal power output from the system. Various parameters of the system are adopted from [21-23].

B. The charge control strategy focuses on regulating the discharging and charging of the battery bank to prevent overload, overvoltage, and over current. On the other hand, the pitch control logic is applied to the turbine blades to ensure the mechanical safety of the wind turbine.

To ensure the effectiveness of these control systems, they have been tested under various wind profiles:

C. Gradual deviation of wind speed

D. Step deviation of wind speed

E. Arbitrary deviation of wind speed

The power supply in the system ranges from 0 to 4 kW, and the wind turbine specifications including pitch angle, shaft speed, TSR, and turbine power are examined for different wind profiles as depicted in figures 5.(a), 6.(a), and 7.(a). The battery parameters corresponding to these wind profiles can be found in the respective figures, namely 8.b, 9.b, and 10.b..

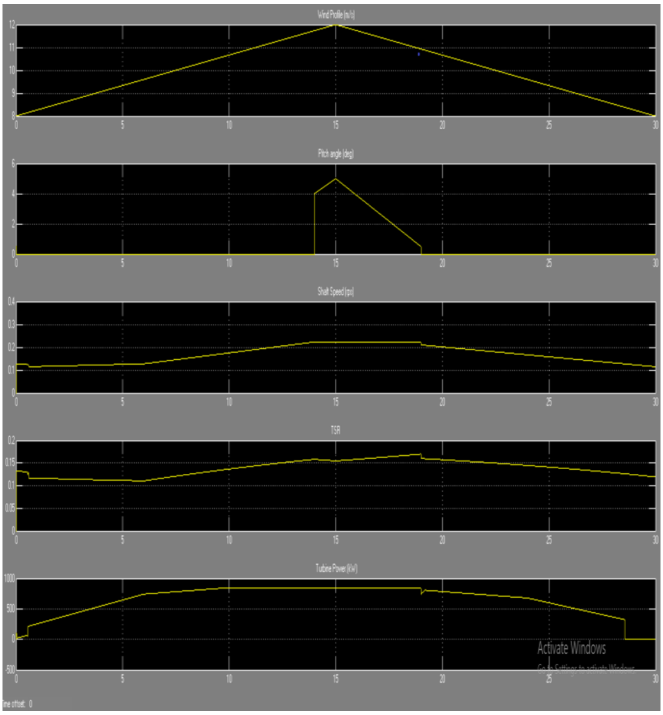

Fig. 5. (a) Wind Turbine Framework under the Impact of Gradual Deviation of Speed.

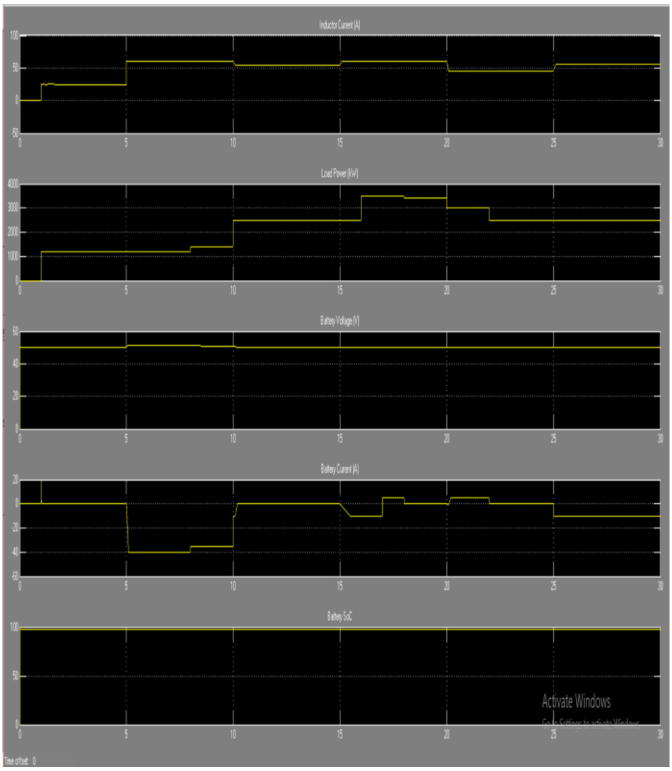

Fig. 5. (b) Battery's Framework under the Impact of Gradual Deviation of speed.

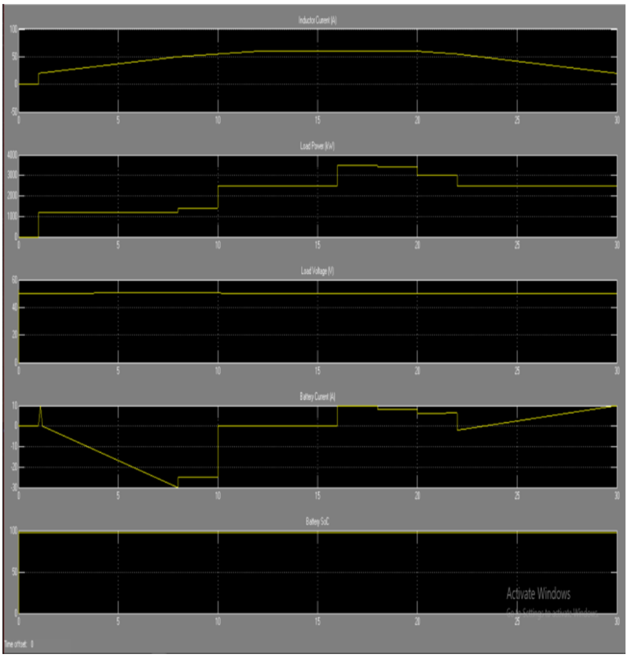

Fig. 6. (a) Wind Turbine Framework under the Impact of Step Deviation in Speed.

Fig. 5. (a) The wind turbine's gradual variation in wind speed is depicted in the graph. The wind speed increases gradually from 8 m/s to 12 m/s over a duration of 15 seconds. Subsequently, it gradually decreases over the next 15 seconds. The wind turbine parameters can be observed from figure 5(a), while the battery parameters can be observed from figure 5(b), based on the speed variation.

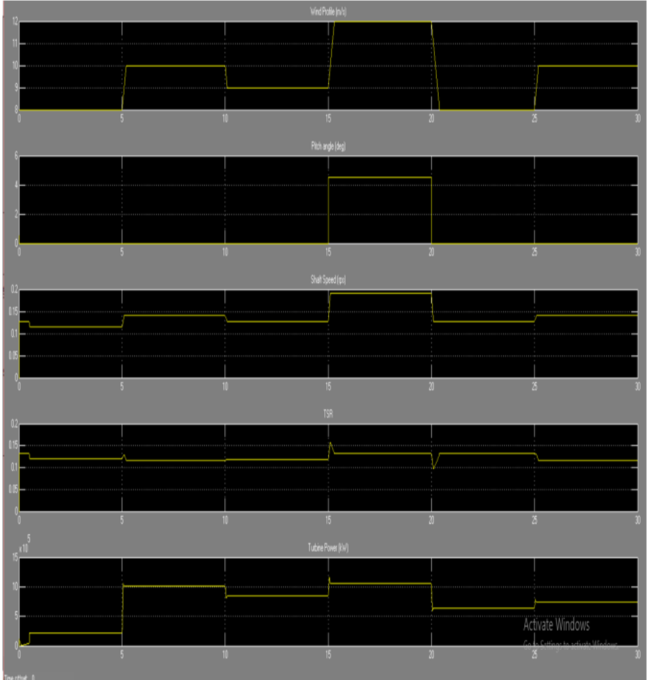

Fig. 6. (b) Battery Framework under the Impact of Step Deviation of speed.

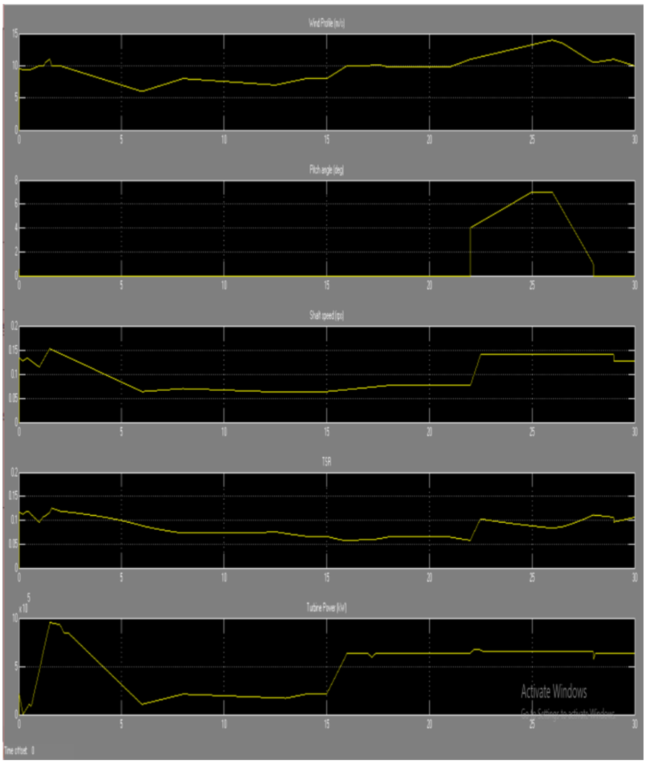

Fig. 7. (a). Wind Turbine Framework under the Impact of Arbitrary Deviation in Speed.

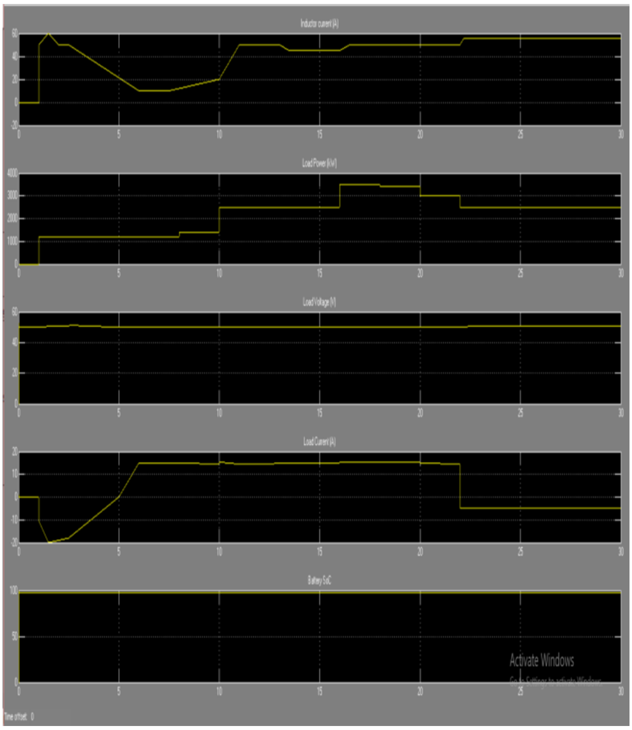

Fig. 7. (b) Battery Framework under the Impact of Arbitrary Deviation in Speed.

Additionally, the system undergoes analysis when subjected to step changes in wind speed. The impact of these step changes on the parameters of the wind turbine and battery can be evaluated, as illustrated in figure 6(a) and 6(b) respectively. The speed variation occurs in discrete increments within the range of 8 to 12 m/s.
In a similar manner, the parameters of the wind turbine and battery are examined when subjected to arbitrary fluctuations in wind speed, ranging from 8 to 12 m/s. This analysis is depicted in figure 7(a) for the wind turbine parameters and figure 7(b) for the battery parameters.

It can be observed from figures 5-7 that when the wind speed is lower than the estimated value, the MPPT strategy adjusts the TSR to its optimal value regardless of any changes in wind variation. This allows for the extraction of maximum power from the WECS at all wind speeds, ensuring the fulfillment of load demands and the charging and discharging of the battery bank. In cases where the wind power is insufficient to meet the load demand, the battery power is utilized to fulfill the load requirements. Additionally, the pitch angle of the wind turbine remains at zero degrees below rated wind speeds. The charge controller is responsible for preventing the battery current from surpassing 40 A while charging or discharging. Conversely, if the wind speed surpasses its predicted value, the pitch angle will be adjusted to restrict the rotor speed and output power of the wind turbine, ensuring a secure and consistent operation.

7. CONCLUSION

In order to ensure a continuous supply of power and safe operation, a suitable control strategy is implemented in WECS. The primary objective of this proposed study is to analyze the MPPT technique by employing the TSR method and the pitch control technique. In order to ensure the proper charging and discharging of the battery bank, a charge controller is essential. The TSR method is investigated to identify the most efficient power output of the system, while the pitch control technique is utilized to regulate the pitch angle of the turbine blades. By adjusting the pitch angle, the system is protected from damage caused by turbulent winds and ensures a regulated wind flow to the turbine. The charge controller's function is to track the optimal power and charge the battery bank in a controlled manner. Up to the rated wind speed (10 m/s), the pitch angle is set to zero and the optimal power is extracted. Beyond the rated wind speed (up to 12m/s), the pitch angle varies from 0 to 5 degrees without affecting the output power. The proposed study is simulated and analyzed using MATLAB/SIMULINK with different wind profiles..

8. APPENDIX: PARAMETERS OF VARIOUS UNITS.

TABLE1: WIND TURBINE.

Parameters	Values
Operating Power.	4.0kW
Radius.	2.25m
Operating Wind Speed.	10.0 m/s
Cut-in Wind Speed.	4.0 m/s
Inertia Co-efficient.	7Kgm^2
Optimum Power Co-efficient.	0.42
Optimum Tip Speed Ratio.	7.0

TABLE 2: Squirrel cage induction generator.

Parameters	Values
Operating Power.	5.5hp
Resistance of stator.	2.59Ω
Stator Leakage Inductance.	4.1mH
Mutual Inductance.	239mH
Resistance of rotor.	2.01Ω
Rotor Leakage Inductance.	4.12mH
Excitation Capacitance.	15.01µF

TABLE 3: Batteries.

Parameters	Value (Units)
Ampere Hour Rating.	400Ah
Nominal Voltage.	48.0V
Voltage when fully charged.	55.2V
Charging Rate.	C/10

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