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Control of Standalone Wind energy conversion system using Pitch control Technique

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Abstract
Present energy need heavily relies on the conventional sources. But the limited availability and steady increase in the price of conventional sources has shifted the focus toward renewable sources of energy. Of the available alternative sources of energy, wind energy is considered to be one of the proven technologies. With a competitive cost for electricity generation, wind energy conversion system (WECS) is nowadays deployed for meeting both grid-connected and stand-alone load demands. However, wind flow by nature is intermittent. In order to ensure continuous supply of power suitable storage technology is used as backup. In this paper, the sustainability of a 4-kW hybrid of wind and battery system is investigated for meeting the requirements of a 3-kW stand-alone dc load representing a base telecom station. A charge controller for battery bank based on turbine maximum power point tracking and battery state of charge is developed to ensure controlled charging and discharging of battery. The mechanical safety of the WECS is assured by means of pitch control technique. Both the control schemes are integrated, and the efficacy is validated by testing it with various load and wind profiles in MATLAB/SIMULNIK.
Keywords: *Wind energy, Maximum power point tracking, Wind turbine, Pitch control technique.*

1. Introduction

Energy is the considered to be the pivotal input for development. At present owing to the depletion of available conventional resources and concern regarding environmental degradation, the renewable sources are being utilized to meet the ever-increasing energy demand. Due to a relatively low cost of electricity production wind energy is considered to be one of the potential sources of clean energy for the future. But the nature of wind flow is stochastic [1]. So rigorous testing is to be carried out in laboratory to develop efficient control strategy for wind energy conversion system (WECS). Nowadays, many stand-alone loads are powered by renewable source of energy. With this renewed interest in wind technology for stand-alone applications, a great deal of research is being carried out for choosing a suitable generator for stand-alone WECS. The major advantage of asynchronous machine is that the variable speed operation allows extracting maximum power from WECS and reducing the torque fluctuations. Induction generator with a lower unit cost, inherent robustness, and operational simplicity is considered as the most viable option as wind turbine generator (WTG) for off grid applications. However, the induction generator requires capacitor banks for excitation at isolated locations.

The excitation phenomenon of self-excited induction generator (SEIG) is explained in [2]. The power output of the SEIG depends on the wind flow which by nature is erratic. Both amplitude and frequency of the SEIG voltage vary with wind speed. Such arbitrarily varying voltage when interfaced directly with the load can give rise to flicker and instability at the load end. So, the WECS are integrated with the load by power electronic converters in order to ensure a regulated load voltage. Again, due to the intermittent characteristics of the wind power, a WECS needs to have energy storage system. An analysis of the available storage technologies for wind power application is made in and. The advantage of battery energy storage for an isolated WECS is discussed in. With battery energy storage it is possible to capture maximum power from the available wind. A comparison of several maximum power point tracking (MPPT) algorithms [3] for small wind turbine (WT) is carried out in and. In order to extract maximum power form WECS the turbine needs to be operated at optimal angular speed.

However, do not take into account the limit on maximum allowable battery charging current nor do they protect against battery overcharging. In order to observe the charging limitation of a battery a charge controller is required. Such a charge control scheme for battery charging for a stand-alone WECS using MPPT is explained in. However, in this paper also the maximum battery charging current is not limited. The discontinuous battery charging current causes harmonic heating of the battery. Also, the MPPT implementation is highly parameter dependent and will be affected by variation of these parameters with operating conditions [4].

2. Maximum Power Point Tracking

Maximum Power Point Tracking, frequently referred to as MPPT, is an electronic system that operates the Photovoltaic (PV) modules in a manner that allows the modules to produce all the power they are capable of. MPPT is not a mechanical tracking system that physically moves the modules to make them point more directly at the sun. MPPT is a fully electronic system that varies the electrical operating point of the modules so that the modules are able to deliver maximum available power [5]. Additional power harvested from the modules is then made available as increased battery charge current. MPPT can be used in conjunction with a mechanical tracking system, but the two systems are completely different. The problem considered by MPPT methods is to automatically find the voltage VMPP or current IMPP at which a PV array delivers maximum power under a given temperature and irradiance. In this section, commonly used MPPT methods are introduced in an arbitrary.

2.1 Fractional open circuit voltage

The method is based on the observation that, the ratio between array voltage at maximum power VMPP to its open circuit voltage VOC is nearly constant.

$$V_{MPP} \approx k_1 V_{OC}$$

This factor k_1 has been reported to be between 0.71 and 0.78. Once the constant k1 is known, VMPP is computed by measuring VOC periodically. Although the implementation of this method is simple and cheap, its tracking efficiency is relatively low due to the utilization of inaccurate values of the constant k1 in the computation of VMMP.

2.2 Fractional short circuit current

The method results from the fact that, the current at maximum power point IMPP is approximately linearly related to the short circuit current ISC of the PV array.

$$I_{MPP} \approx k_2 I_{SC}$$

Like in the fractional voltage method, k2 is not constant. It is found to be between 0.78 and 0.92. The accuracy of the method and tracking efficiency depends on the accuracy of K2 and periodic measurement of short circuit current.

2.3 Perturb and observe

In P&O method, the MPPT algorithm is based on the calculation of the PV output power and the power change by sampling both the PV current and voltage. The tracker operates by periodically incrementing or decrementing the solar array voltage. If a given perturbation leads to an increase (decrease) in the output power of the PV, then the subsequent perturbation is generated in the same (opposite) direction. So, the duty cycle of the dc chopper is changed, and the process is repeated until the maximum power point has been reached. Actually, the system oscillates about the MPP. Reducing the perturbation step size can minimize the oscillation. However, small step size slows down the MPPT. To solve this problem, a variable perturbation size that gets smaller towards the MPP.

However, the P&O method can fail under rapidly changing atmospheric conditions. Several research activities have been carried out to improve the traditional Hill-climbing and P&O methods. A three-point weight comparison P&O method that compares the actual power point to the two preceding points before a decision is made about the perturbation sign. Reference proposes a two-stage algorithm that offers faster tracking in the first stage and finer tracking in the second stage.

3. Wind Turbine

Today's energy situation requires the introduction of new generation methods [6]-[7]. A potential new source is distributed generation of electricity from many relatively small and variable sources, harnessing local renewable forms of energy. Whilst centralized electricity generation systems tend to suggest favorable economics due to their scale, distributed generation systems can demonstrate higher efficiency through direct use of heat, lower transmission Such distributed systems will comprise of plant at many sites utilizing multiple sources of renewable energy. These pose a number of challenges to planners, designers and users alike, in particular if the plant is to operate for significant periods of time without an operational grid connection. In this case, performance will be a function of varying sources, load demands, and the ability to store energy. In addition, it is difficult to determine, in advance, the optimum relative proportions of, for example, photovoltaic generation capacity, wind generation capacity and battery capacity, for a given site (weather pattern) and required power availability. Much literature exists recognizing the importance of the optimization of remote renewable energy sites; generally, split into three areas, sizing, control and both. Significant work includes [8]-[10], offering a comprehensive analysis of system components.

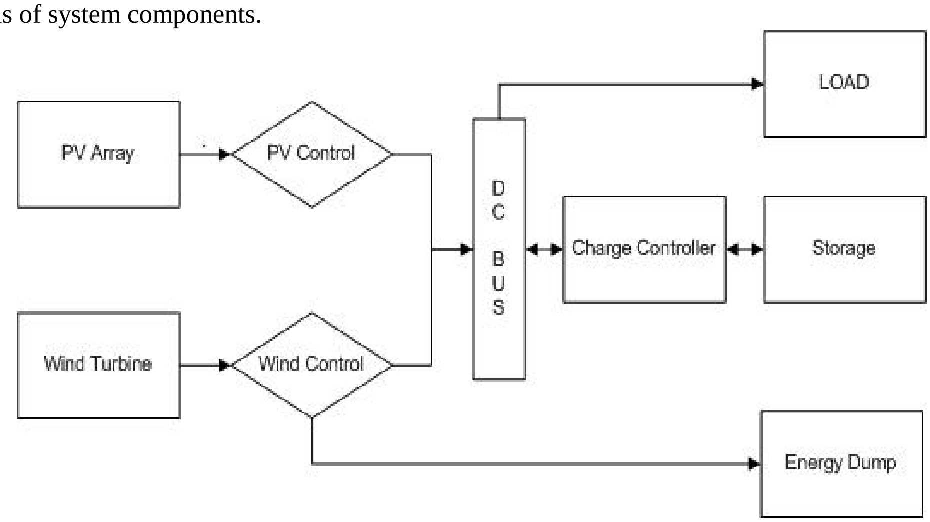

Fig. 1 Multi source renewable energy system

This paper presents a modelling method to aid in the design and evaluation of multi-source power systems. For site specific weather data and load requirements, it visualizes the (the relative proportions of wind and solar, for example). In this manner, given the particular needs, a designer can arrive at the most suitable balance for preferred system architecture. As an example, to illustrate the method developed, an autonomous site powered from several renewable sources has been analyzed.

3.1 Types of Wind Turbines

There are two types of wind turbine in relation to their rotor settings. They are:

- Horizontal-axis rotors, and
- Vertical-axis rotors.

In this paper, only the horizontal-axis wind turbine will be discussed since the modeling of the wind driven electric generator is assumed to have the horizontal-axis rotor [11].

The horizontal-axis wind turbine is designed so that the blades rotate in front of the tower with respect to the wind direction i.e., the axis of rotation are parallel to the wind direction. These are generally referred to as upwind rotors. Another type of horizontal axis wind turbine is called downwind rotors which has blades rotating in back of the tower. Nowadays, only the upwind rotors are used in large-scale power generation and in this project, the term. horizontal-axis wind turbine refers to the upwind rotor arrangement.

The main components of a wind turbine for electricity generation are the rotor, the transmission system, the generator, and the yaw and control system. The following figures show the general layout of a typical horizontal-axis wind turbine, different parts of the typical grid-connected wind turbine, and cross-section view of a nacelle of a wind turbine.

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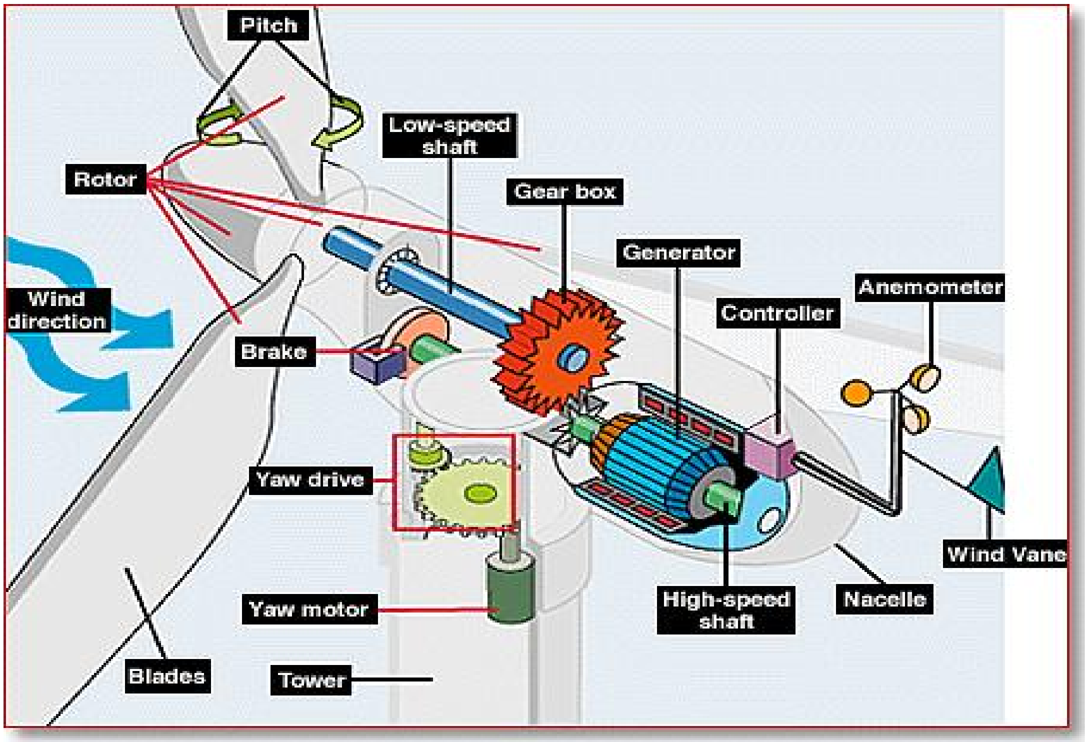

Fig. 2 Components of a wind turbine

3.2 Rotor speed

Low speed and high-speed propeller are the two types of rotors. A large design tip speed ratio would require a long, slender blade having high aspect ratio. A low design tip speed would require a short, flat blade. The low speed rotor runs with high torque and the high-speed rotor runs with low torque. The wind energy converters of the same size have essentially the same power output, as the power output depends on rotor area. The low-speed rotor has curved metal plates. The number of blades, weight, and difficulty of balancing the blades makes the rotors to be typically small. They get self-started because of their aerodynamic characteristics. The propeller type rotor comprises of a few narrow blades with more sophisticated airfoil section. When not working, the blades are completely stalled, and the rotor cannot be self-started. Therefore, propeller type rotors should be started either by changing the blade pitch or by turning the rotor with the aid of an external power source (such as generator used as a motor to turn the rotor). Rotor is allowed to run at variable speed or constrained to operate at a constant speed [12]. When operated at variable speed, the tip speed ratio remains constant and aerodynamic efficiency is increased.

3.3 Rotor Alignment

The alignment of turbine blades with the direction of wind is made by upwind or downwind rotors. Upwind rotors face the wind in front of the vertical tower and have the advantage of somewhat avoiding the wind shade effect from the presence of the tower. Upwind rotors need a yaw mechanism to keep the rotor axis aligned with the direction of the wind. Downwind rotors are placed on the lee side of the tower. A great disadvantage in this design is the fluctuations in the wind power due to the rotor passing through the wind shade of the tower which gives rise to more fatigue loads. Downwind rotors can be built without a yaw mechanism, if the rotor and nacelle can be designed in such a way that the nacelle will follow the wind passively. This may however include gyroscopic loads and hamper the possibility of unwinding the cables when the rotor has been yawing passively in the same direction for a long time, thereby causing the power cables to twist. Upwind rotors need to be rather inflexible to keep the rotor blades clear of the tower, downwind rotors can be made more flexible. The latter implies possible savings with respect to weight and may contribute to reducing the loads on the tower. The vast majority of wind turbines in operation today have upwind rotors.

4. Pitch Control of Wind Turbine Generators

The pitch function gives full control over the mechanical power and if the most common method is used for the variable speed wind turbines. At wind speeds below the rated power of the generator, the pitch angle is at its maximum though it can be lower to help the turbine accelerate faster. Above the rated wind speed, the pitch angle is controlled to keep the generator power at rated power by reducing the angle of blades. The pitch control system is one of the most widely used control techniques to regulate the output power of a wind turbine generator. The method relies on the variation in the power captured by the turbine as the pitch angle of the blades is changed. Hydraulic actuators are used to vary the pitch angle. The wind turbine generator describes the design of the pitch controller and discusses the performance of the system in the presence of disturbances [13].

The control system consists of two controllers are inverter controller that keeps the load voltage constant and the pitch controller acting on the blades angle by using simulation. The variable speed induction generator using Volts/Hertz control enables efficient wind energy capture and is shown in Fig 3. The output of the generator-side converter can be varied to control the speed of the induction generator. The grid-side converter can be controlled to inject the desired power and reactive power into the grid. Thus, the wind system is capable of providing reactive power support, if required. The disadvantage of this configuration is the large cost associated with the power converter, since the converter has to be rated for the maximum power output of the generator.

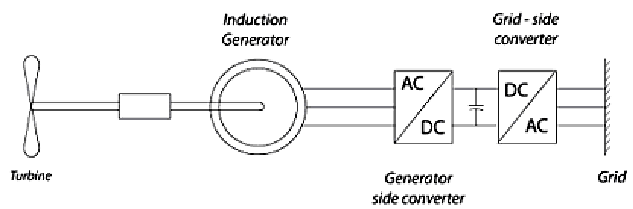

Fig. 3 Voltage-controlled induction generator

4.1 Aerodynamic Power Control for Wind Turbines

When a generator reaches rated power, the turbines must limit the mechanical power delivered to the generator. This is valid because the generator reaches the rated power at for instance 15 m/s while the maximum speed is typically 25 m/s for a wind turbine. Control is done by three different methods called stall, pitch and a combination called active stall. There are no moving parts in the stall-controlled blades and the challenge is in the construction of the blades to avoid vibration and make them stall gradually. The pitch angle is controlled to keep the generator power at rated power by reducing the angle of the blades. By regulating, the angle to be on the of stalling, fast torque changes from the wind will be reutilized. The power captured by the turbine is given by $Pm = Pw \times Cp$

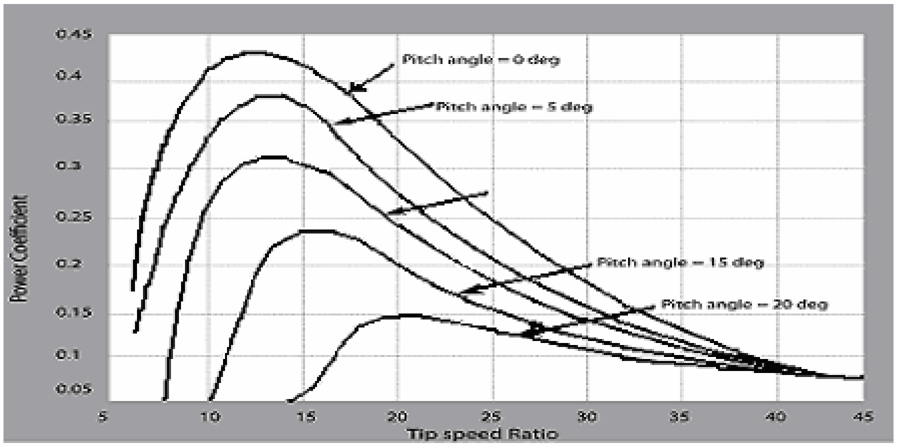

Fig. 4 Power Coefficient vs Tip speed ratio for various values of pitch angle

4.2 Turbine Control with OptiTip

When the turbine is stopped (PAUSE, STOP or EMERGENCY STOP), the blades will be present in a pitch angle of 90 (out of the wind), as shown in Figure 4.5. When the turbine is in RUN-mode, it is able to produce electrical energy, but the momentary wind conditions are determining for how much. This is controlled by the OptiTip control system of the multi-processor controller. The momentary wind conditions can be divided into four categories, shown by the power curve in Figure 5.

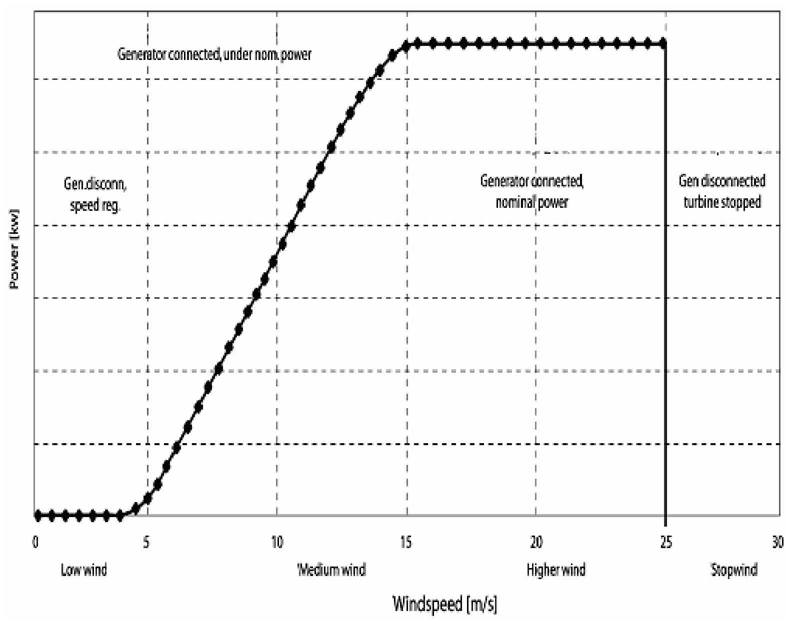

Fig. 5 Power Curve

4.3 Pitch Control System Design

Pitch control means that the blades can pivot upon their own longitudinal axis. The pitch control used for speed control, optimization of power production and to start and step the turbine. The control system structure used to generate the pitch angle reference is given in Fig. 6. The pitch controller consists of two paths a nonlinear feed forward path, which generates β_0 and a linear feedback path, which generates $\Delta\beta$.

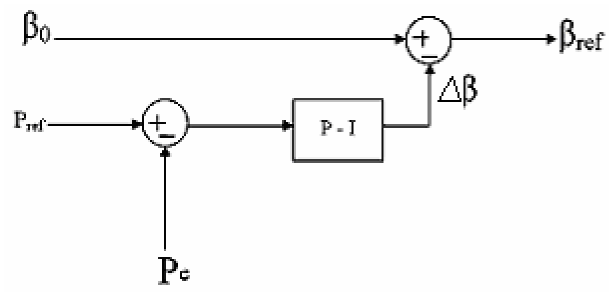

Fig. 6 Pitch angle reference generator

The feed forward path uses the information about the desired power output, wind velocity and the turbine speed to determine the pitch angle required. Below equation represents the pitch angle as a function of the measured variables.

$$\beta_0 = \sqrt{\frac{1}{0.022}\left[\gamma - 5.6 - \frac{2P_{ref}e^{0.17\gamma}}{P_w}\right]}$$

However, the feed forward term assumes that all the components are ideal and does not account for the losses in the system. The feedback path compensates for the losses by decreasing the pitch angle, if the output power is less than the desired power, to increase the power captured. The P-I controller (Proportional integration) for the system is designed using the Zeigler-Nicholas rules for tuning PID (Proportional integration and Differentiation) controllers.

4.4 Pitch Control Mechanism

The WT power output is proportional to the cube of wind velocity. Generally, the cut-off wind speed of a modern WT is much higher compared to the rated wind speed. If the WT is allowed to operate over the entire range of wind speed without implementation of any control mechanism, the angular speed of the shaft exceeds its rated value which may lead to damage of the blades. So, it is very much essential to control the speed and power at wind speeds above the rated wind speed. This is achieved by changing the pitch angle of the blade. Such a mechanism is referred to as the pitch control of WT. The power coefficient (*Cp)* versus TSR (λ) characteristics of the WT considered in this study for different pitch angles are shown in Fig. 6.6. As examined from the characteristics, at a pitch angle of zero degree the value of *Cp* is maxima. But the optimum value of power coefficient reduces with increase in pitch angle. This happens because with increase in blade pitch the lift coefficient reduces which results in decreasing the value of *Cp*. So, the pitch control mechanism controls the power output by reducing the power coefficient at higher wind speeds. Below the rated wind speed the blade pitch is maintained at zero degree to obtain maximum power. The pitch controller increases the blade pitch as the WT parameters exceeds the rated value. The reduction in the value of *Cp* by pitching compensates for the increase in WT power output under the influence of higher wind speeds. Apart from regulating the WT parameters, it is also essential to control the output voltage of the ac–dc rectifier to avoid overvoltage condition in the WECS. Hence, the pitch controller ensures that with desirable pitch command, the WT parameters and the rectifier output dc voltage are regulated within their respective maximum allowable limits to ensure safe operation of the WECS [14].

The pitch control scheme is shown in Fig. 6.7. As seen the p.u. value of each input is compared with 1 to calculate the error. The errors are tuned by PI controller. The "MAX" block chooses the maximum output from each PI controller which is then passed on to a limiter to generate the pitch command for the WT. The actual pitch command is compared with the limited value. The lower limit of the pitch command is set at zero. There arises an error when the actual pitch command goes above or below the specified limit. This is multiplied with the error obtained from each of the comparator. The product is compared with zero to determine the switching logic for integrator. This technique is carried out to avoid integrator saturation. The pitch controller changes the pitch command owing to variation in turbine rotation speed, power, and output voltage of rectifier, which ensures safe operation of the WECS.

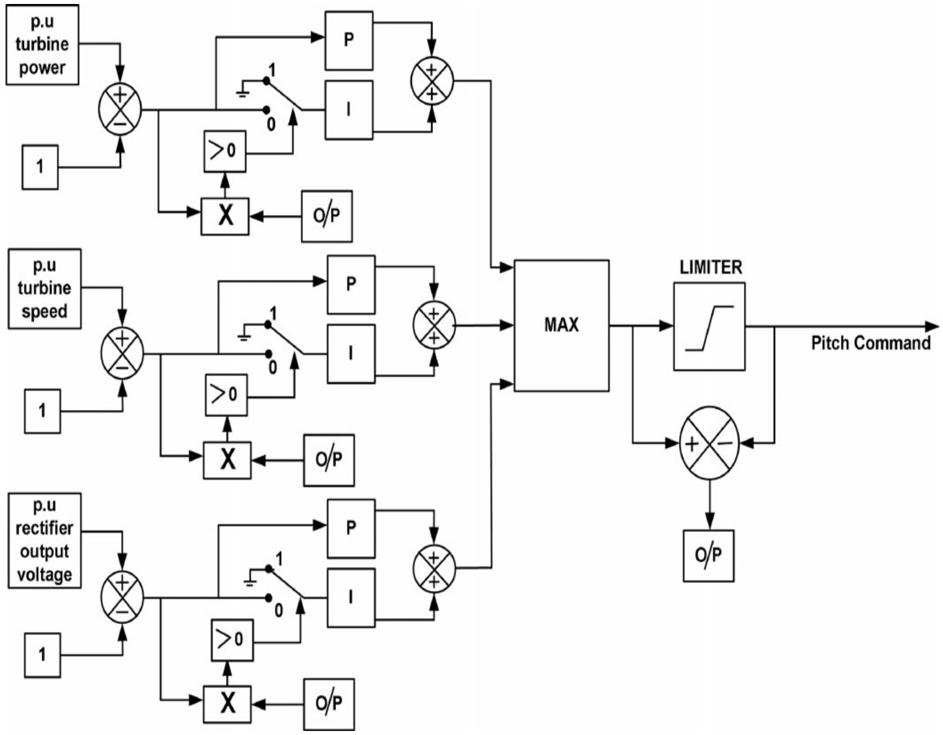

Fig. 7 Pitch control scheme for a stand-alone WECS

5. Simulation Results

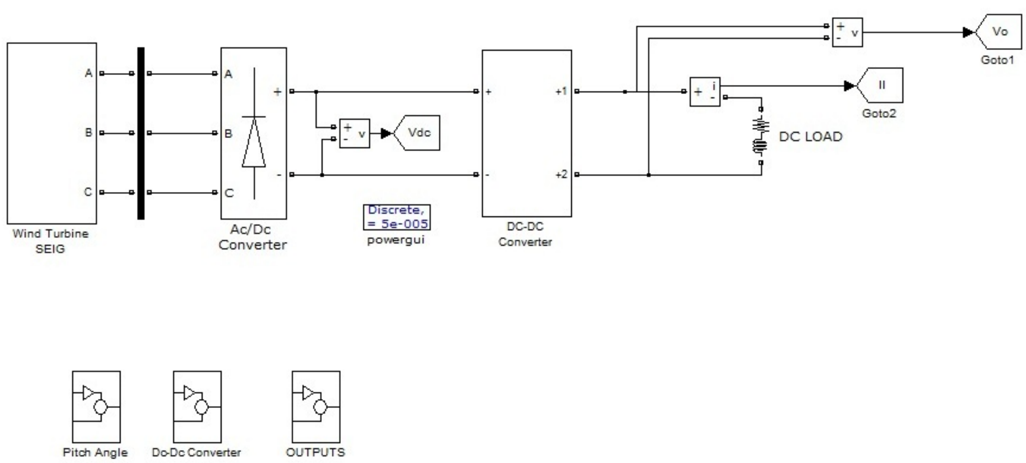

Fig. 8 Simulation model diagram

A WECS needs to be efficient to ensure continuous power flow to the load. The effectiveness can be achieved by integrating the hybrid wind-battery system with suitable control logic. This includes the charge control logic and the pitch control logic. The charge controller regulates the charging and discharging rate of the battery bank while the pitch controller controls the WT action during high wind speed conditions or in case of a power mismatch. Both the control strategy is integrated with the hybrid system and simulated with various wind profiles to validate the efficacy of the system. The system is connected to a load profile varying in steps from 0 to 4 kW. The WT parameters like shaft speed, TSR, blade pitch and output power are analyzed with variation in wind speed conditions. The current profile of the converter, load, and the battery are also monitored with the wind profile. To ensure uninterrupted power flow, load demand is given more priority over battery charging. The WT and battery parameters are observed for the following wind profiles.

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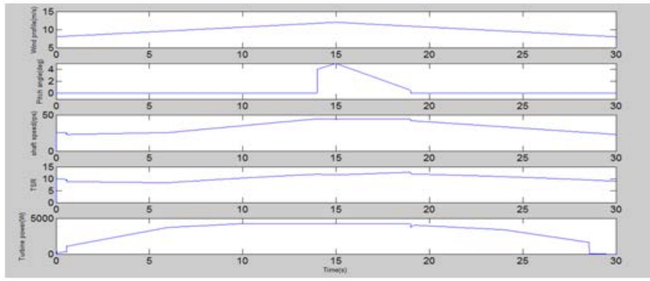
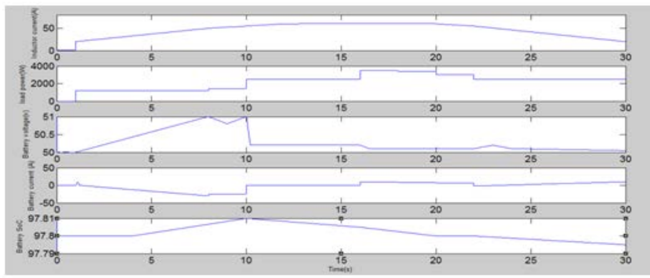
1) Gradual rise and fall in wind speed
2) Step variation in wind speed
3) Arbitrary variation in wind speed



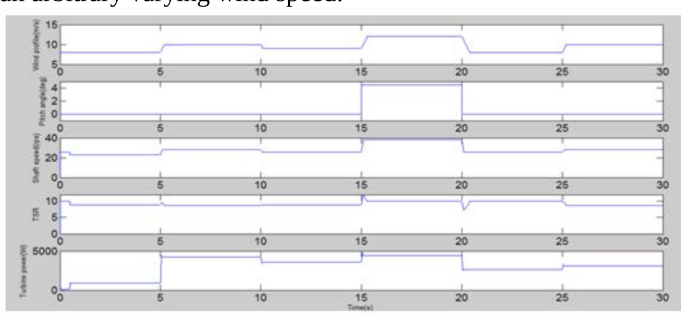
(a)



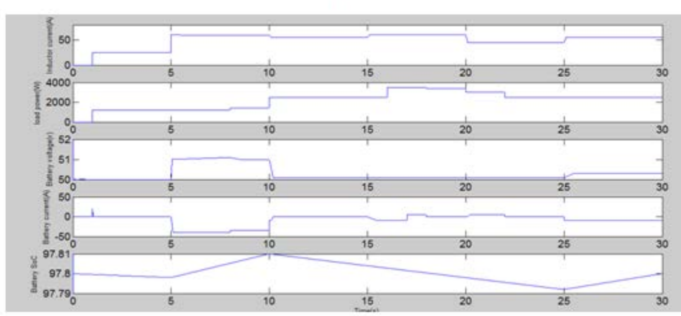
(b)

Fig. 9 (a) WT and (b) battery parameters under the influence of gradual variation of wind

A gradual rise and fall in wind speed as shown in Fig. 9 is applied to the WT. The wind speed gradually rises from 8 to 12 m/s in 15 s and then falls to 8 m/s in the next 15 s. The WT parameters and the current profile of the converter, load and the battery are observed in Fig. 9(a) and (b). Further the efficiency of the complete control scheme is validated with a step variation in wind profile and an arbitrary varying wind speed.



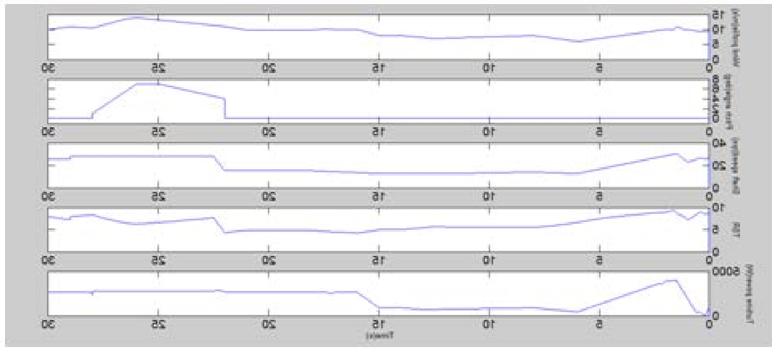
(a)



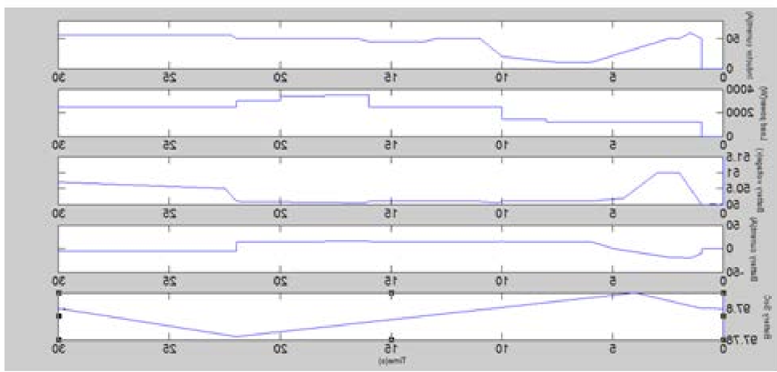
(b)

Fig. 10 (a) WT and (b) battery parameters under the influence of step variation of wind speed

The variation of the wind profile in step from 8 to 12 m/s is shown in Fig. 10(a) while the arbitrary variation in wind speed from 6 to 14 m/s is highlighted. The response of WT parameter and the current profiles with respect to step variations and arbitrary variations are shown in Figs. 10 and 11, respectively. The results also demonstrate the change in battery SoC for all possible wind profiles. From Figs 9-11, it is observed, that when the wind speed is below the rated value (10 m/s) the MPPT scheme regulates the TSR of WT at its optimum value irrespective of the variation in wind profile.



(a)



(b)

Fig. 11 (a) WT and (b) battery parameters under the influence of arbitrary variation of wind speed

Thus, maximum power is extracted from WECS at all wind speeds to meet the load requirement and charge the battery bank. But the wind power is not always sufficient to meet the load demand and charge the battery in CC mode. In such situations the system first meets the load requirement and charges the battery bank at a reduced rate. Moreover, when the wind power is not adequate as per the load demand, the battery discharges to meet the deficit. The battery SoC increases during charging but decreases while discharging. However, the charge controller ensures that the battery current during charging or discharging never exceeds 40 A. The pitch angle of WT is maintained at zero deg at wind speed below 10 m/s. But the pitch controller is activated as the wind speeds exceeds its rated limit. The increase in the pitch angle limits the power and speed output within the safe limits of WT operation. The response of WT and currents for all possible variations in wind profile indeed prove the efficacy of the proposed control logic for the hybrid wind–battery system.

6. Conclusions

The power available from a WECS is very unreliable in nature. So, a WECS cannot ensure uninterrupted power flow to the load. In order to meet the load requirement at all instances, suitable storage device is needed. Therefore, in this paper, a hybrid wind-battery system is chosen to supply the desired load power. To mitigate the random characteristics of wind, flow the WECS is interfaced with the load by suitable controllers. The control logic implemented in the hybrid set up includes the charge control of battery bank using MPPT and pitch control of the WT for assuring electrical and mechanical safety. The charge controller tracks the maximum power available to charge the battery bank in a controlled manner. Further it also makes sure that the batteries discharge current is also within the C/10 limit. The current programmed control technique inherently protects the buck converter from over current situation.

However, at times due to MPPT control the source power may be more as compared to the battery and load demand. During the power mismatch conditions, the pitch action can regulate the pitch angle to reduce the WT output power in accordance with the total demand. Besides controlling the WT characteristics, the pitch control logic guarantees that the rectifier voltage does not lead to an overvoltage situation. The hybrid wind-battery system along with its control logic is developed in MATLAB/SIMULINK and is tested with various wind profiles. The outcome of the simulation experiments validates the improved performance of the system.

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