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An Integrated Control Strategy for a Wind Energy Conversion System

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Abstract

This paper presents control scheme for a stand-alone wind energy conversion system. 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.

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 [1] is considered tube one of the potential sources of clean energy for the future. But the nature of wind flow is stochastic. So rigorous testing into be carried out in laboratory to develop efficient control strategy for wind energy conversion system (WECS) [2]. The study owes and the associated controllers are, thus, becoming more and more significant with each passing day. 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. A detailed comparison between asynchronous and synchronous generators for wind farm application is made. The major advantage of asynchronous machine is that the variable speed operation allows extracting maximum power from WECS and reducing the torque fluctuation. Induction generator with a lower unit cost, inherent robustness, and operational simplicity is considered as the most viable option as wind turbine generator (WTG) [3] 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) [4] is explained. The power output of the SEIGdepends 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.

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So the WECS are integrated with the load by power electronic converters in order to ensure a regulated load voltage. Again duet the intermittent characteristics of the wind power, a WECSneeds to have energy storage system. An analysis of the available storage technologies for wind power application is made in. The advantage of battery energy storage for an isolated WECS is discussed. With battery energy storageit is possible to capture maximum power from the available wind. A comparison of several maximum power point tracking (MPPT) algorithms [5] for small wind turbine (WT) is carried outing. In order to extract maximum power form Waste 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 WECSusing MPPT is explained. However, in this paper also the maximum battery charging current is not limited. The discontinuous battery charging current causes harmonic heating of the battery. The terminal voltage instead of state of charge (Sock) is used for changeover from current mode to voltage mode. Also the MPPT implementation is highly parameter dependant and will be affected by variation of these parameters with operating conditions. Moreover, as the wind speed exceeds its rated value, the WT power and speed needs to be regulated for ensuring mechanical and electrical safety. This is achieved by changing the pitch angle to the required value. Several pitch control techniques are explained.

The experimental result from a prototype 3-kW pitch controlled horizontal axis WT is presented. However, these references (except) have considered only grid-connected systems. Even in, a battery storage system has not been considered. From a study of the aforementioned literature, it is observed that MPPT schemes with and without battery charging mode control and pitch control technique have been implemented independently for stand-alone wind energy applications. However, none of the control strategy proposed so far has integrated all these three control objectives. In this paper, a hybrid wind-battery system is considered to meet the load demand of stand-alone base telecom station (BTS). The BTS load requirement is modeled as a dc load which requires a nominal regulated voltage of 50 V. The WECS is interfaced with the stand-alone load by means of ac–dc–dc power converter to regulate the load voltage at the desired level. The proposed control scheme utilizes the turbine maximum power tracking technique with the battery Sock limit logic to charge the battery in a controlled manner. Unlike [14], the MPPT logic used here actually forces the turbine to operate at optimum TSR and hence is parameter independent. The battery charging current is always continuous with very low ripple thus avoiding harmonic heating. The changeover between the modes for battery charging is affected based on the actual value of the Sock Further it also provides protection against turbine over speed, over loading, and overvoltage at the rectifier output by using pitch control [6].

FUNDAMENTALS OF WIND ENERGY

Wind power:

Wind is abundant almost in any part of the world. Its existence in nature caused by uneven heating on the surface of the earth as well as the earth’s rotation means that the wind resources will always be available. The conventional ways of generating electricity using non renewable resources such as coal, natural gas, oil and so on, have great impacts on the environment as it contributes vast quantities of carbon dioxide to the earth’s atmosphere which in turn will cause the temperature of the earth’s surface to increase, known as the green house effect. Hence, with the advances in science and technology, ways of generating electricity using renewable energy resources such as the wind are developed. Nowadays, the cost of wind power that is connected to the grid is as cheap as the cost of generating electricity using coal and oil. Thus, the increasing popularity of green electricity means the demand of electricity produced by using non renewable energy is also increased accordingly.

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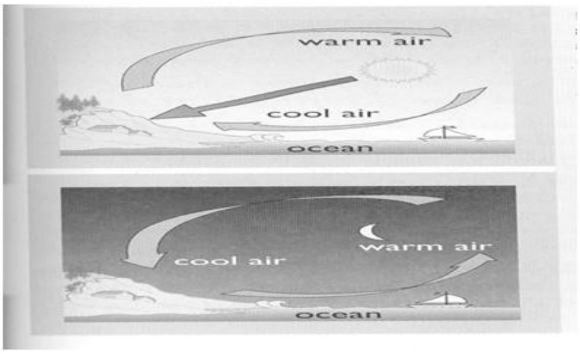


Fig: Formation of wind due to differential heating of land and sea

Features of wind power systems:

There are some distinctive energy end use features of wind power systems

I. Most wind power sites are in remote rural, island or marine areas. Energy requirements in such places are distinctive and do not require the high electrical power.

II. A power system with mixed quality supplies can be a good match with total energy end use i.e. the supply of cheap variable voltage power for heating and expensive fixed voltage electricity for lights and motors.

III. Rural grid systems are likely to be weak (low voltage 33 KV). Interfacing a Wind Energy Conversion System (WECS) in weak grids is difficult and detrimental to the workers' safety.

IV. There are always periods without wind. Thus, WECS must be linked energy storage or parallel generating system if supplies are to be maintained.

Power from the Wind:

Kinetic energy from the wind is used to turn the generator inside the wind turbine to produce electricity. There are several factors that contribute to the efficiency of the wind turbine in extracting the power from the wind [7]. Firstly, the wind speed is one of the important factors in determining how much power can be extracted from the wind. This is because the power produced from the wind turbine is a function of the cubed of the wind speed. Thus, the wind speed if doubled, the power produced will be increased by eight times the original power. Then, location of the wind farm plays an important role in order for the wind turbine to extract the most available power form the wind.

The next important factor of the wind turbine is the rotor blade. The rotor blades length of the wind turbine is one of the important aspects of the wind turbine since the power produced from the wind is also proportional to the swept area of the rotor blades i.e. the square of the diameter of the swept area.

Hence, by doubling the diameter of the swept area, the power produced will be fourfold increased. It is required for the rotor blades to be strong and light and durable. As the blade length increases, these qualities of the rotor blades become more elusive. But with the recent advances in fiberglass and carbon-fiber technology [8], the production of lightweight and strong rotor blades between 20 to 30 meters long is possible. Wind turbines with the size of these rotor blades are capable to produce up to 1 megawatt of power. The relationship between the powers produced by the wind source and the velocity of the wind and the rotor blades swept diameter is shown below.

$$P_{wind} = \frac{\pi}{8} dD^2 v_{wind}^3$$

The derivation to this formula can be looked up in [2]. It should be noted that some books derived the formula in terms of the swept area of the rotor blades (A) and the air density is denoted as δ□.

Thus, in selecting wind turbine available in the market, the best and efficient wind turbine is the one that can make the best use of the available kinetic energy of the wind.

Wind power has the following advantages over the traditional power plants.

- Improving price competitiveness,
- Modular installation,

- Rapid construction,
- Complementary generation,
- Improved system reliability, and
- Non-polluting.

Wind Turbines:

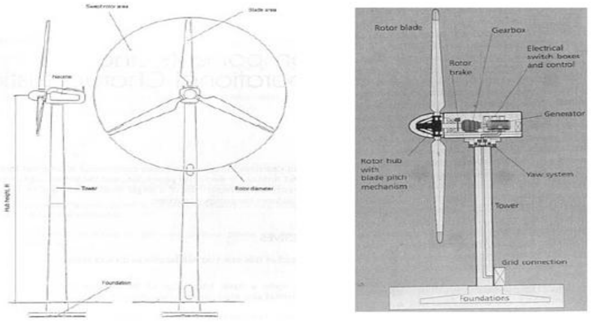
There are two types of wind turbine in relation to their rotor settings. They are:

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

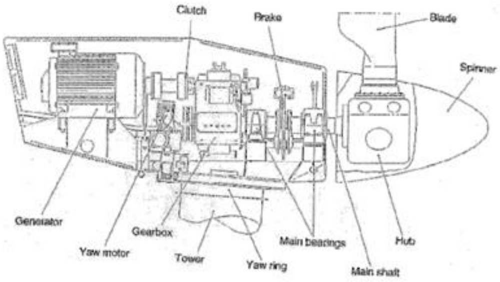
In this report, only the horizontal-axis wind turbine will be discussed since the modeling of the wind driven electric generator is assumed to have the horizontal-axis rotor.

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 report, the term .horizontal-axis wind turbine refers to the upwind rotor arrangement [9].

The main components of a wind turbine for electricity generation are the rotor, the transmission system, and 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 [10]



(a) (b)



(c)

Figs: (a) Main Components of Horizontal-axis Wind Turbine (b) Cross-section of a Typical Grid-connected Wind Turbine (c) Cross-section of a Nacelle in A Grid-connected Wind Turbine

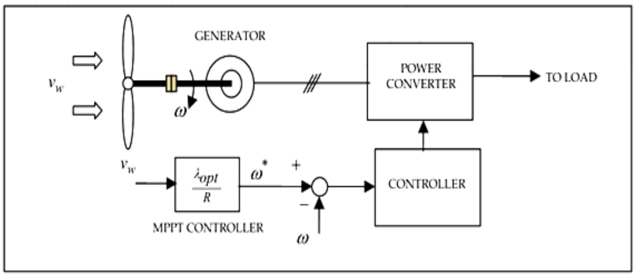
The main components of a wind turbine can be classified as I) Tower ii) Rotor system iii) Generator IV) Yaw v) Control system and VI) Braking and transmission system.

MAXIMUM POWER POINT TRACKING CONTROL (MPPT):

Wind generation system has been attracting wide attention as a renewable energy source due to depleting fossil fuel reserves and environmental concerns as a direct consequence of using fossil fuel and nuclear energy sources. Wind energy, even though abundant, varies continually as wind speed changes throughout the day. Amount of power output from a WECS depends upon the accuracy with which the peak power points are tracked by the MPPT controller of the WECS control system irrespective of the type of generator used.

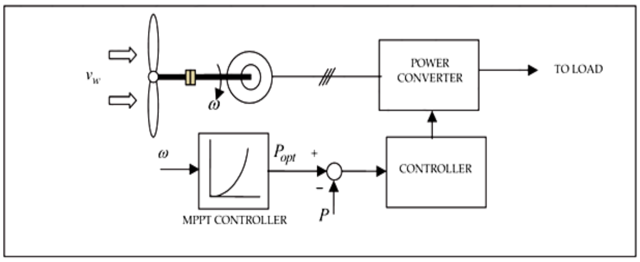
The maximum power extraction algorithms researched so far can be classified into three main control methods, namely tip speed ratio (TSR) control, power signal feedback (PSF) control and hill-climb search (HCS) control [11].

The TSR control method regulates the rotational speed of the generator in order to maintain the TSR to an optimum value at which power extracted is maximum. This method requires both the wind speed and the turbine speed to be measured or estimated in addition to requiring the knowledge of optimum TSR of the turbine in order for the system to be able extract maximum possible power. Fig. 2 shows the block diagram of a WECS with TSR control [12].



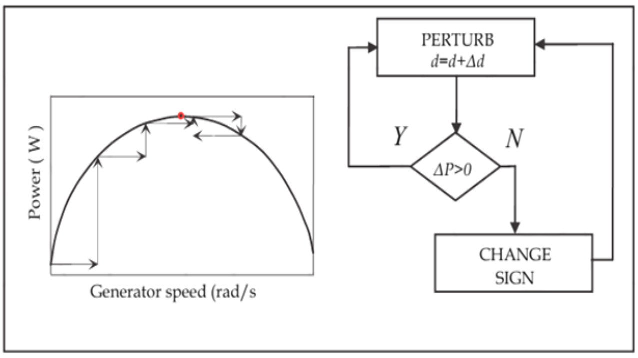
Tip speed ratio control of WECS.

In PSF control, it is required to have the knowledge of the wind turbines maximum power curve, and track this curve through its control mechanisms. The maximum power curves need to be obtained via simulations or off-line experiment on individual wind turbines. In this method, reference power is generated either using a recorded maximum power curve or using the mechanical power equation of the wind turbine where wind speed or the rotor speed is used as the input. Fig. 3 shows the block diagram of a WECS with PSF controller for maximum power extraction [13].

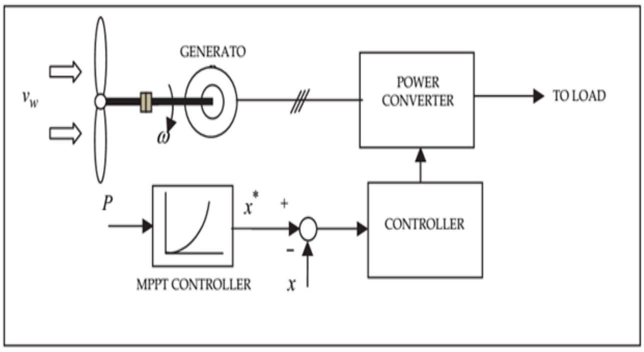


Power signal feedback control.

The HCS control algorithm continuously searches for the peak power of the wind turbine. It can overcome some of the common problems normally associated with the other two methods. The tracking algorithm, depending upon the location of the operating point and relation between the changes in power and speed, computes the desired optimum signal in order to drive the system to the point of maximum power. Fig shows the principle of HCS control and shows a WECS with HCS controller for tracking maximum power points.



HCS Control Principle.

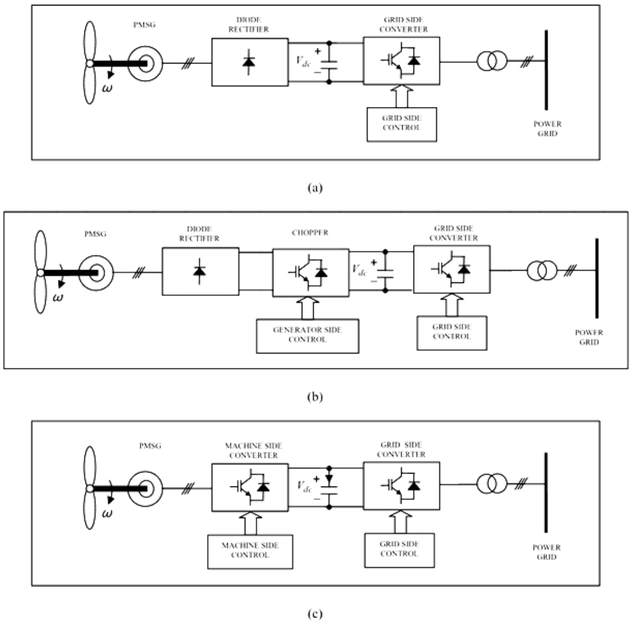


WECS with hill climb search control.

MPPT control methods for PMSG based WECS

Permanent Magnet Synchronous Generator is favored more and more in developing new designs because of higher efficiency, high power density, availability of high-energy permanent magnet material at reasonable price, and possibility of smaller turbine diameter in direct drive applications. Presently, a lot of research efforts are directed towards designing of WECS which is reliable, having low wear and tear, compact, efficient, having low noise and maintenance cost; such a WECS is realizable in the form of a direct drive PMSG [7] wind energy conversion system.

There are three commonly used configurations for WECS with these machines for converting variable voltage and variable frequency power to a fixed frequency and fixed voltage power. The power electronics converter configurations most commonly used for PMSG WECS are shown.



PMSG wind energy conversion systems

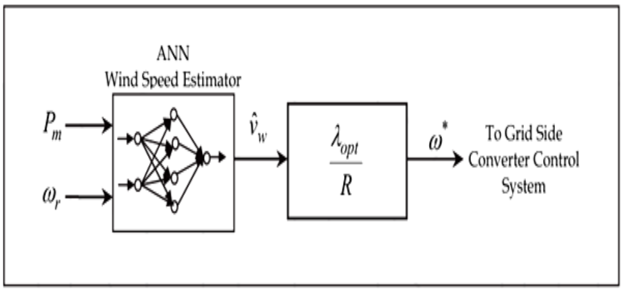
Depending upon the power electronics converter configuration used with a particular PMSG WECS a suitable MPPT controller is developed for its control. All the three methods of MPPT control algorithm are found to been use for the control of PMSG WECS.

Tip speed ratio control

A wind speed estimation based TSR control is proposed in [3] in order to track the peak power points. The wind speed is estimated using neural networks, and further, using the estimated wind speed and knowledge of optimal TSR, the optimal rotor speed command is computed. The generated optimal speed command is applied to the speed control loop of the WECS control system [9].

The PI controller controls the actual rotor speed to the desired value by varying the switching ratio of the PWM inverter. The control target of the inverter is the output power delivered to the load. This WECS uses the power converter configuration shown in Fig. 6 (a). The block diagram of the ANN-based MPPT controller module is shown in Fig. 7. The inputs to the ANN are the rotor speed brand mechanical power Pm. The Pmis obtained using the relation.

$$P_m = \omega_r\left(J\frac{d\omega_r}{dt}\right) + P_e$$



ANN-based MPPT control module of turbine rotor speed.

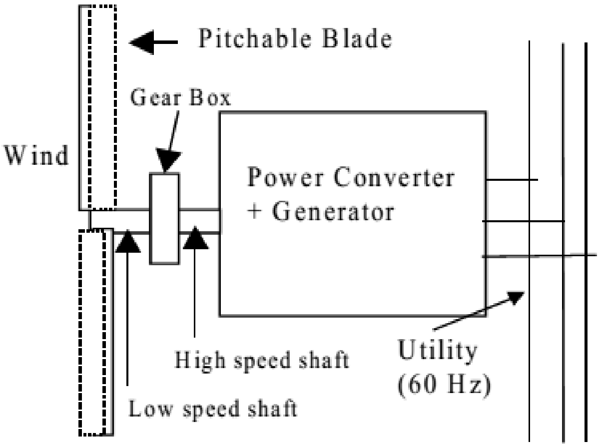
PITCH CONTROL :

Wind turbine pitch control system can change incidence of rotor blades in a wind power generation system based on real-time wind speed for the purpose of adjusting output power, achieving higher utilization efficiency of wind power and providing protection for rotor blades. When wind speed is not higher than the rated speed, the blade incidence stay near the angle 0° (highest power point), which is similar to that of a generator with constant pitch, generating an output power that changes along with wind speed. When wind speed is higher than the rated speed, the pitch control mechanism changes blade incidence so that the output power of generator is within the allowed range.

The development of wind turbine power generation has been expanding during the past 10 years. The global market for the electrical power produced by the wind turbine generator (WTG) has been increasing steadily, which directly pushes the wind technology into more competitive arena. Recently, there have been positive trends shown by the utilities to offer renewable energy to customers. Many customers who are environmentally conscious now have the option of subscribing to clean energy such as wind energy from the power provider.

The European market has showman ever-increasing demand for wind turbines. Variable-speed wind turbine generation has been gaining momentum, as shown by the number of companies joining the variable-speed WTG market. Variable-speed generation is claimed to have a better energy capture and lower loading. The effect of turbulence on energy captures and power fluctuations invariable-speed wind turbines is affected by the overall control algorithm used. The method of controlling the generator strongly affects the electrical power generated by the generator. Different types of generators are used for variable-speed generation for direct drives; however, control algorithms for wind turbine operation are not discussed in these papers.

The goal of this project is to study the behavior of the wind turbine generator operated under variable speed with pitch-control capability under turbulent winds. The basic comparison between a constant-speed wind turbine and a variable-speed wind turbine will also be explained. The constant-speed wind turbine.



Physical diagram of the system

Operation is a very simple case that can be used as a base line. The variable-speed algorithm was chosen based on the maximum energy and steady-state limit of the wind turbine. The steady-state limit is based on theCP-TSR curve provided. Thus in the steady statecalculation, wind gust and wind shear are notconsidered. It turns out that using the steady state limitis a good approximation in the lower wind speeds, asshown by the performance ratio and energy captured bythe wind turbine.

One concept that is fundamental to the control dynamics is that the speed change is relatively slow because of the large inertia involved. This makes it difficult to use the power converter to control the speeding highly variable wind applications. Pitch control is relatively fast, however, and can be better used to regulate power flow especially when near the high-speed limit. The system under consideration.

The system under consideration the wind turbine is connected to a variable-speed wind turbine. The generator output can be controlled to follow the commanded power. The wind turbine has a Patchable blade to control the aerodynamic power. The dashed line indicates that the pitch angle can be controlled. It is shown that there is a mechanical component (such as a gearbox) between the high-speed shaft and the low-speed shaft. The low-speed shaft is driven by the turbine blades, which generates aerodynamic power. The high-speed shaft is loaded by the electric generator in the form of electrical load. The paper is organized as follows: The next section is devoted to the condition of the wind data.The third section is devoted to the method of control. In the fourth section, the discussion and analysis is presented, and in the fifth section, the conclusion is presented.

CHARGE ESTIMATION ALGORITHMS

Several different techniques such as Fuzzy Logic, Kaman Filtering, Neural Networks and recursive, self-learning methods have been employed to improve the accuracy of the SOC estimation as well as the estimation of state of health (SOH) [4].

A) Fuzzy Logic

Fuzzy Logic is simple way to draw definite conclusions from vague, ambiguous or imprecise information. It resembles human decision making with its ability to work from approximate data to find precise solutions.
Unlike classical logic which requires a deep understanding of a system, exact equations, and precise numeric values, Fuzzy logic allows complex systems to be modeled using a higher level of abstraction

originating from our knowledge and experience. It allows expressing this knowledge with subjective concepts such as big, small, very hot, bright red, a long time, fast or slow. This qualitative, linguistic representation of the expert knowledge presents a natural rather than a numerical description of a system and allows relatively easy algorithm development compared to numerical systems. The outputs can then be mapped into exact numeric ranges to provide a characterisation of the system. Fuzzy logic is used extensively in automatic control systems [8].

Using this technique we can use all the information available to us about the performance of a battery to derive a more accurate estimation of its state of charge or the state of health. Software packages are available which simplify this process.

B) Kaman Filter

Kalman filtering addresses an age-old question: How do you get accurate information out of inaccurate data? More pressingly, How do you update a "best" estimate for the state of a system as new, but still inaccurate, data pour in? An HEV automotive application is an example of this situation. The battery SOC is affected by many simultaneous factors and is continually changing due to the user driving pattern. The Kalman filter is designed to strip unwanted noise out of a stream of data. It operates by predicting the new state and its uncertainty, then correcting this with a new measurement. It is suitable for systems subject to multiple inputs and is used extensively in predictive control loops in navigation and targeting systems. With the Kalman Filter the accuracy of the battery SOC prediction model can be improved and accuracies of better than 1% are claimed for such systems.

As with Fuzzy Logic, standard software packages are available to facilitate its implementation.

C) Neural Networks

A Neural Network is a computer architecture modeled upon the human brain's interconnected system of neurons which mimics its information processing, memory and learning processes. It imitates the brain's ability to sort out patterns and learn from trial and error, discerning and extracting the relationships that underlie the data with which it is presented.

Each neuron in the network has one or more inputs and produces an output; each input has a weighting factor, which modifies the value entering the neuron. The neuron mathematically manipulates the inputs, and outputs the result. The neural network is simply neurons joined together, with the output from one neuron becoming input to others until the final output is reached. The network learns when examples (with known results) are presented to it; the weighting factors are adjusted on the basis of data - either through human intervention or by a programmed algorithm-to bring the final output closer to the known result. In other words, neural networks "learn" from examples (as children learn to recognize dogs from examples of dogs) and exhibit some capability for generalization beyond the training data.

Neural networks thus resemble the human brain in the following two ways:

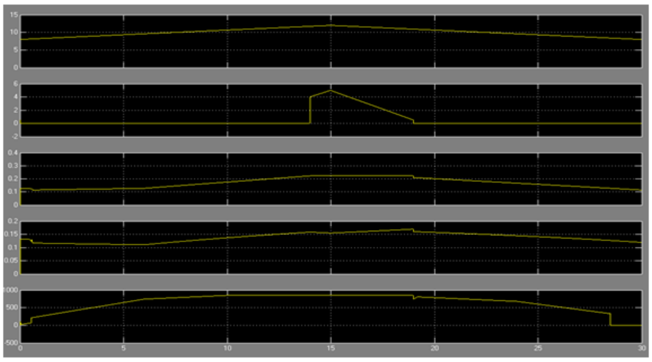
1.A neural network acquires knowledge through learning.

2.A neural network's knowledge is stored within inter-neuron connection strengths known as synaptic weights.

The true power and advantage of neural networks lies in their ability to represent both linear and non-linear relationships and in their ability to learn these relationships directly from the data being modelled. Among the many applications are predictive modelling and control systems.

Neural Network techniques are useful in estimating battery performance which depends on quantifying the effect of numerous parameters most of which cannot be defined with mathematical precision. Algorithms are refined with the aid of experience gained from the performance of similar batteries.

RESULTS AND DISCUSSIONS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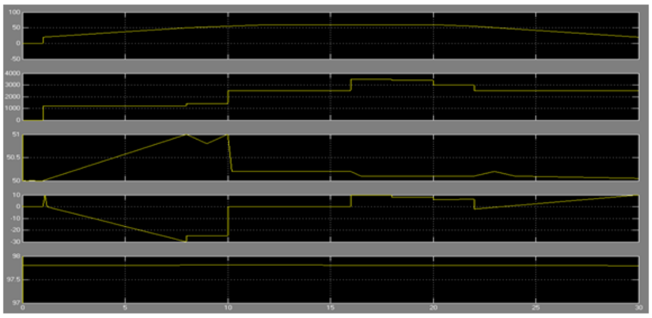
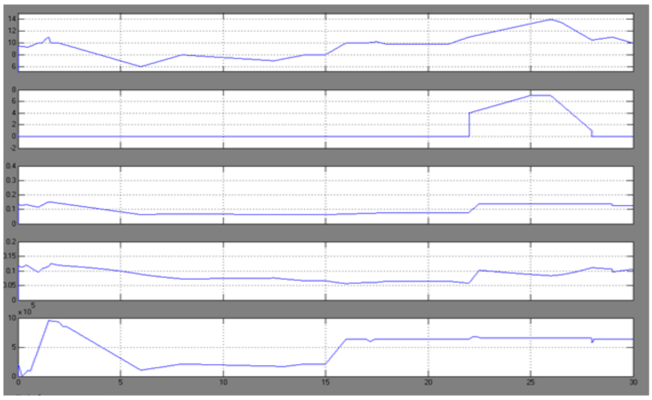

(b)

Fig. 8. (a) WT and (b) battery parameters under the influence of gradual variation of wind speed.

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 are 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.

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

A gradual rise and fall in wind speed as shown in Fig. 8(a)is applied to the WT. The wind speed gradually rises from 8 to12 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. 8(a) and (b). Further the efficacy of the complete control scheme is validated with a step variation in wind profile and an arbitrary varying wind speed. The variation of the wind profile in step from 8 to 12 m/s is shown in Fig. 9(a)while the arbitrary variation in wind speed from 6 to 14 m/s is highlighted in Fig 10(a). The response of WT parameter and the current profiles with respect to step variations and arbitrary variations are shown in Figs. 9 and 10, respectively. The results also demonstrate the change in battery SoC for all possible wind profiles.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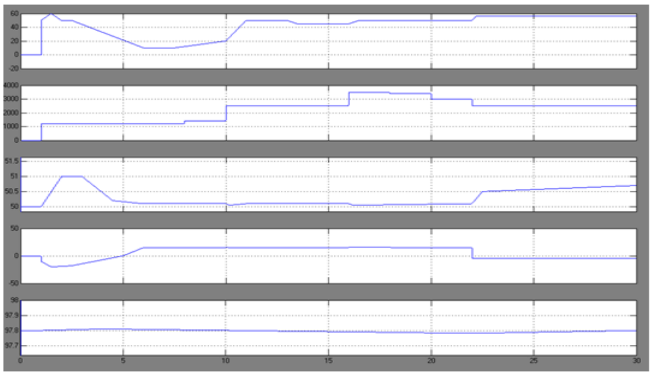
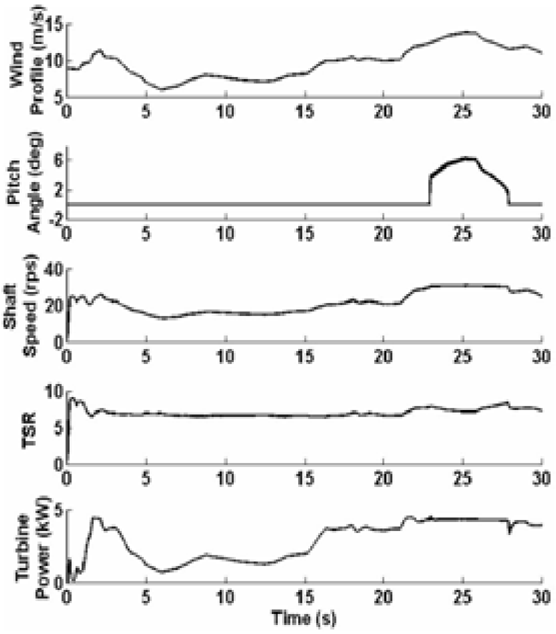

(b)

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

From Figs 8–10, it is observed, that when the wind speed isbelow the rated value (10 m/s) the MPPT scheme regulates theTSR of WT at its optimum value irrespective of the variationin wind profile. Thus maximum power is extracted from WECSat all wind speeds to meet the load requirement and charge thebattery bank. But, the wind power is not always sufficient tomeet the load demand and charge the battery in CC mode. Insuch situations the system first meets the load requirement andcharges the battery bank at a reduced rate.

Moreover, when thewind power is not adequate as per the load demand, the batterydischarges to meet the deficit. The battery Sock increases during charging but decreases while discharging. However, the chargecontroller ensures that the battery current during charging ordischarging never exceeds 40 A. The pitch angle of WT is maintained at zero deg at wind speed below 10 m/s. But thepitch controller is activated as the wind speeds exceeds its ratedlimit. The increase in the pitch angle limits the power and speedoutput within the safe limits of WT operation. The responseof WT and currents for all possible variations in wind profileindeed prove the efficacy of the proposed control logic for the hybrid wind–battery system.



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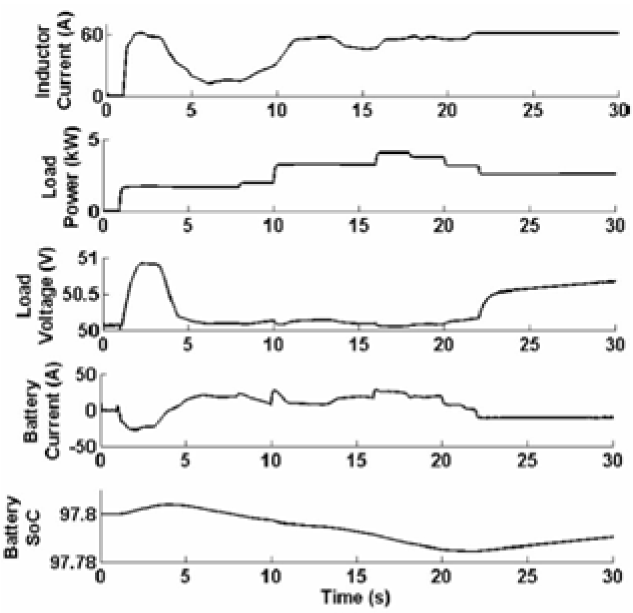

(b)

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

CONCLUSION

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 over voltage 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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