



Control Scheme for A Stand-Alone 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 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). 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) 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. 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 need 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 storage it is possible to capture maximum power from the available wind. A comparison of several maximum power point tracking (MPPT) algorithms for small wind turbine (WT) is carried out. In order to extract maximum power from wind 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. 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. The paper is organized as follows.

A brief description of the hybrid wind-battery system powering an off-grid dc load along with the power converter topology is presented in Section. The control strategy comprising of the pitch controller for the turbine and the charge controller for the battery is discussed in section. The results obtained by simulating the hybrid system with different wind profiles and load variations validating the efficacy of the proposed control logic are presented in Section and concludes the paper

MODELLING OF CASE STUDY

HYBRID WIND-BATTERY SYSTEM FOR AN ISOLATED DC LOAD:

The proposed hybrid system comprises of a 4-kW WECS and 400 Ah, C/10 lead acid battery bank. The system is designed for a 3-kW stand-alone dc load. The layout of the entire system along with the control strategy

is shown in Fig. 1. The specifications of the WT, SEIG, and battery bank are tabulated in the Appendix. The WECS consists of a 4.2-kW horizontal axis WT, gear box with a gear ratio of 1:8 and a 5.4 hp SEIG as the WTG. Since the load is a stand-alone dc load the stator terminals of the SEIG are connected to a capacitor bank for self-excitation.

The ac output is rectified by three-phase uncontrolled diode rectifier. However; there is a need for a battery backup to meet the load demand during the period of unavailability of sufficient wind power. This hybrid wind-battery system requires suitable control logic for interfacing with the load. The uncontrolled dc output of the rectifier is applied to the charge controller circuit of the battery. The charge controller is a dc-dc buck converter which determines the charging and discharging rate of the battery.

The battery bank connected to the system can either act as a source or load depending on whether it is charging or discharging. However; regardless of this the battery ensures that the load terminal voltage is regulated. Further, as shown in Fig.1, the charging of the battery bank is achieved by MPPT logic, while the pitch controller limits

the mechanical and electrical parameters within the rated value. The integrated action of the battery charge and pitch controller ensures reliable operation of the stand-alone WECS.

CONTROL STRATEGY FOR STAND-ALONE HYBRID WIND-BATTERY SYSTEM

The wind flow is erratic in nature. Therefore, a WECS is integrated with the load by means of an ac–dc–dc converter to avoid voltage flicker and harmonic generation. The control scheme for a stand-alone hybrid wind-battery system includes the charge controller circuit for battery banks and pitch control logic to ensure WT operation within the rated value. The control logic ensures effective control of the WECS against all possible disturbances.

A. Charge Controller for the Battery Bank:

This section discusses in detail the development of charge controller circuit for a 400 Ah, C/10 battery bank using a dc–dcbuck converter in MATLAB/SIMULINK platform. Generally, the batteries are charged at C/20, C/10, or C/5 rates depending on the manufacturer's

specification where C specifies the Ah rating of battery banks. So, the battery bank system considered in the design can be charged at 20, 40, or 80 A. But, in this paper, C/10 rate (i.e., 40 A) for battery charging is chosen. However, the current required for charging the battery bank depends on the battery SoC. A typical battery generally charges at a constant current (CC), i.e., C/10 rate mode till battery SoC reaches a certain level (90%–98%). This is referred to as CC mode of battery charging. The CC mode charges the battery as fast as possible. Beyond this SoC, the battery is charged at a constant voltage (CV) which is denoted as CV mode of battery charging in order to maintain the battery terminal voltage.

B. Control Strategy:

The implementation of the charge control logic as shown in Fig. 2 is carried out by three nested control loops. The outermost control loop operates the turbine following MPPT logic with battery SoC limit. To implement the MPPT logic, the actual tip speed ratio (TSR) of turbine is compared with the optimum value. The error is tuned by a PI controller to generate the battery current demand as long as the battery SoC is below the CC ode limit. Beyond this

point, the SoC control logic tries to maintain constant battery charging voltage. This in turn reduces the battery current demand and thus prevents the battery bank from overcharging. The buck converter inductor current command is generated in the intermediate control loop. To design the controller, it is essential to model the response of the battery current (I) with respect to the inductor current (IL).

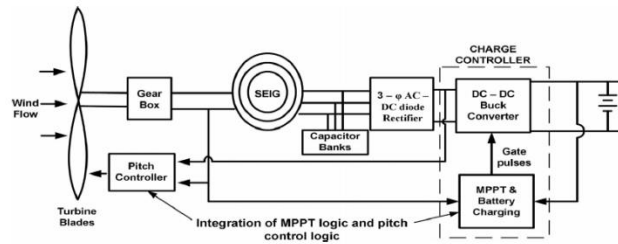


Fig.1. Layout of hybrid wind-battery system for a stand-alone dc load.

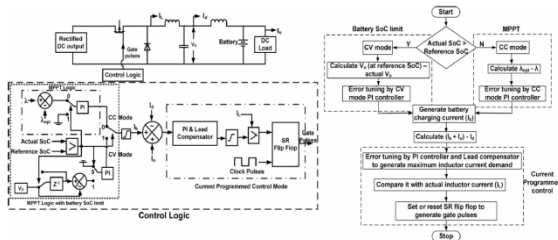


Fig.2. Block schematic and flowchart of the charge controller circuit for battery.

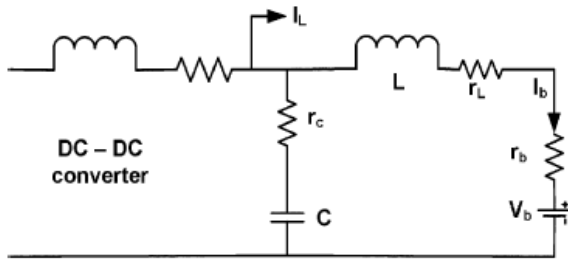


Fig.3. Circuit representation of buck converter output.

The transfer function can be computed from Fig. 3 and is given by

$$\frac{I_b(s)}{I_L(s)} = \frac{r_c C s + 1}{L C s^2 + (r_L + r_c + r_b) C s + 1} \quad (1)$$

As shown in Fig. 3, the battery is assumed to be a CV source with a small internal resistance (r_b). The effective series resistances (ESR) of the capacitor (r_c) and the inductor (r_L) are also considered. The ESR of the capacitor and the inductor is taken to be $1\text{m}\Omega$ each. The battery internal resistance is $10\text{ m}\Omega$. For regulating the peak-to-peak (p-p) ripple of battery current and converter output voltage within 2% of the rated value the L and C are calculated to be 10 mH and 5 mF , respectively.

For controlling the battery current the actual converter output current (I_d) is compared with the reference ($I+ I_{an}$) and the error is processed by a cascade of a PI and a lead compensator. The PI controller is modeled as an inverted zero. To maintain the phase margin of the open-loop system the frequency of this zero is 50 times lower than the crossover frequency. To improve the phase margin of the battery charging

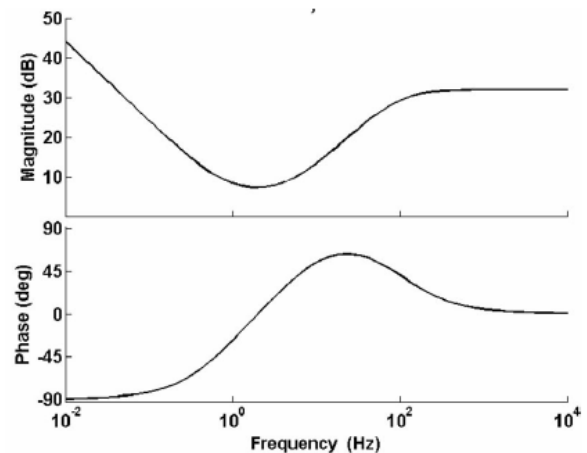
current control loop (i.e., (1) along with the PI controller) a lead compensator is connected in cascade with the PI controller as shown in Fig. 2.

The zero and pole of the lead compensator are designed to have a positive phase margin and to restrict the crossover frequency to about 14% of the switching frequency. The bode plot of the PI controller along with the lead compensator and the loop gain of the battery current control loop are shown in Fig. 4(a) and (b). As shown in Fig. 4, the phase margin is 34.2° at 130 Hz. The output of the lead compensator determines inductor current reference for the dc–dc converter.

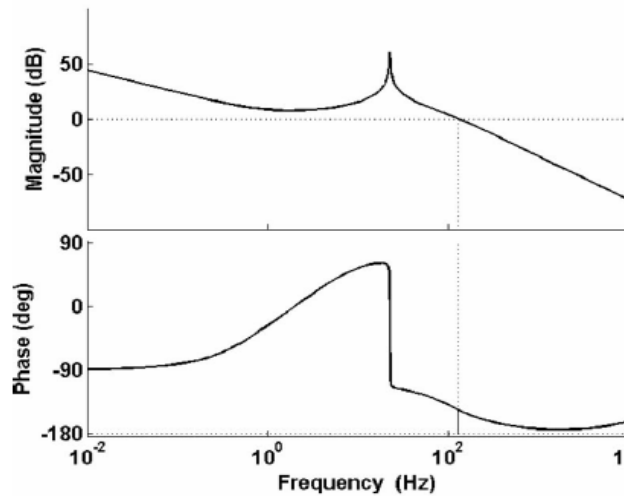
In order to prevent over loading the turbine (and its consequent stalling) the lead compensator output is first passed through an adjustable current limiter. The lower limit is set to zero and the upper limit is varied according to the maximum power available at a given wind speed. The output of this limiter is used as the reference for the current controller in the dc–dc converter.

Finally, in the inner most loop the actual inductor current is made to track the reference using peak current mode control [21]. The compensated output of the

intermediate loop is compared with the instantaneous inductor current of the buck converter. The output of the comparator is applied to an SR flip flop to produce the gate pulses for the dc–dc buck converter. The frequency of the clock pulses is 2 kHz. The frequency of the gate pulse is equal to the clock pulse frequency. This method of generating gate pulses for the converter is known as the current programmed control technique. The advantage of this method is that it does not allow the inductor current to go beyond the rated limit. This in turn protects the buck converter switch and Inductor from over current situation.



(a)



(b)

Fig. 4. Bode plot of (a) PI controller in cascade with lead compensator. (b) Loop gain of the battery current control loop.

MODES OF BATTERY CHARGING:

A. CC Mode of Battery Charging:

In CC mode, the battery charging current demand is determined from the MPPT logic. MPPT is implemented by comparing the actual and optimum TSR (opt). The error is tuned by a PI controller to generate the battery charging current as per the wind speed. In this mode, the converter output voltage rises with time while the MPPT logic tries to transfer as much power as possible to charge the batteries. The actual battery charging current that can be achieved does not remain constant but varies with available wind speed subject to a maximum of $C/10$ rating of the battery. The

battery charging current command has a minimum limit of zero. In case the wind speed is insufficient to supply the load even with zero battery charging current the inductor current reference is frozen at that particular value and the balance load current is supplied by the battery.

B. CV Mode of Battery Charging:

In the CC mode, the battery voltage and SoC rise fast with time. However, the charge controller should not overcharge the batteries to avoid gasification of electrolyte [14]. As a result, once the battery SoC becomes equal to the reference SoC the controller must switch over from CC mode to CV mode. In CV mode, the battery charging voltage is determined from the buck converter output voltage (VO). The value of the converter voltage when the battery SoC reaches 98% is set as the reference value and is compared with the actual converter output voltage. The error in the voltage is then controlled by a cascaded arrangement of PI controller and lead compensator to generate the inductor current reference. It is then compared with the actual inductor current by a logical

comparator to generate gate pulses in a similar way as described in Section A. In this mode, the converter output voltage is maintained at a constant value by the controller action. So, in CV mode the battery voltage and SoC rise very slowly with time as compared to CC mode. The battery charging current slowly decreases with time, since the potential difference between the buck converter output and battery terminals gradually reduces.

Thus, in CC mode the buck converter output current is regulated while the output voltage keeps on increasing with time. On the contrary in CV mode the output voltage is regulated, while the current in the circuit reduces gradually. To study the CC and CV mode of battery charging, rated value of wind speed I_s is applied to the system. The battery parameters and the converter Output parameters are observed with time. The results are shown in Fig. 5.

As shown in Fig. 5, the battery is charged both in CC mode and CV mode. The transition from CC to CV mode takes place when the battery SoC reaches 98%. This is because in the present design, the threshold SoC for switch over in the control logic is set at 98%. As discussed in the

earlier section, in the CC mode the battery charges at a CC of 40 A which is the C/10 value for a 400-Ah battery bank. During this mode, both converter output voltage and battery voltage rise. The battery SoC rises from an initial SoC level of 97.95% to 98% within 17 s. As the battery reaches the threshold SoC level, the buck converter voltage is regulated by the controller action at a constant value of 53 V while the converter current gradually reduces from 40 A at 17 s to 10 A at 40 s. The battery SoC slowly rises from 98% to 98.03%. The results indicate that the battery charges at a faster rate in CC mode as compared to CV mode. Thus, in CC mode much of the available power from primary source is injected into the battery whereas in CV mode the battery is charged slowly to avoid gasification and heating issue.

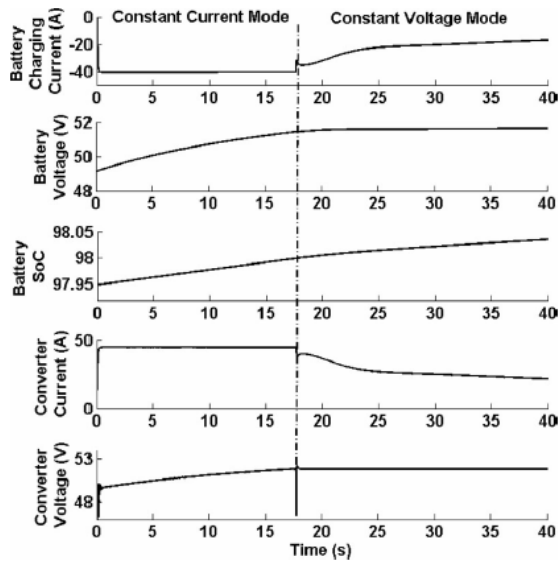


Fig. 5. Battery charging modes at a constant wind speed of 10 m/s.

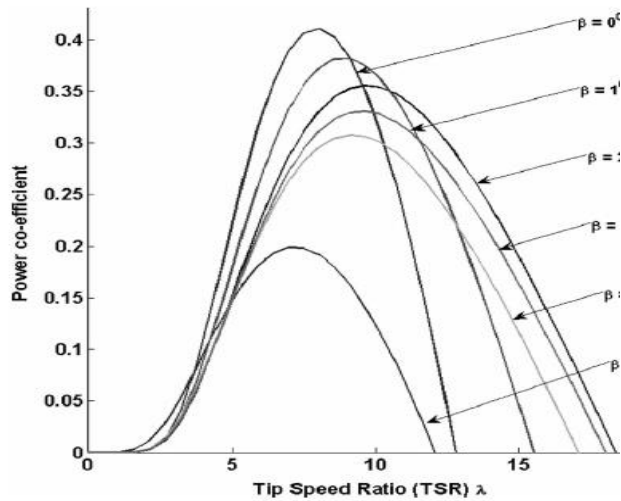


Fig. 6. $C_p - \lambda$ characteristics of the WT for different pitch angles.

C. Pitch Control Mechanism:

The WT power output is proportional to the cube of wind velocity

[15]. Generally the cut-off wind speed of a modern WT is much higher compared to the rated wind speed [9]. 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 (C_p) versus TSR (λ) characteristics of the WT considered in this study for different pitch angles are shown in Fig. 6. As examined from the characteristics, at a pitch angle of zero degree the value of C_p 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 C_p [15]. 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 exceed the rated value. The reduction in the value of C_p 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.

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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