Control of battery banks for wind energy conversion system

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Abstract. In this paper, the essential methodology to control the battery banks for a renewable power system is explained. The power converter used for the above is a step-down voltage regulator also known as Buck converter. It can be used to garner power from a small wind turbine. The paper also explains the charging process of the battery to track the point where maximum power output is obtained in a wide range of speed variations and proper circuit parameter design. Smart Management of battery charging and control is crucial since the lack thereof, would affect the battery’s performance. This method helps avoid the overcharging and overvoltage and also helps build systems that are economic and efficient. This process helps improve the charging efficiency of the battery, also its performance in terms of degradation rate and lifetime. Simple circuit and high reliability are the key factors in the usage of Buck DC/DC converter. A PMSG Stand-alone Wind Turbine System is also modelled and simulated using MATLAB.

1. Introduction
Renewable energy also known as sustainable form of energy, is derived from natural sources or continually renewed processes like sunshine, wind, water flow, combustion and geothermal heat flow. Examples include solar energy, tidal energy, wind energy etc. These alternative sources are being developed and researched on to reduce the environmental impact and carbon footprint that is caused by the exhaustible sources. While renewable energy is often thought of as a new technology, harnessed energy from sustainable sources is utilized for heating, transportation, lighting, and more. One of the most feasible forms of energy, both economically and technically is the wind energy.

For the countryside and remote regions, a small-size stand-alone wind energy conversion system with a battery bank as the energy stockpiling component is essential as it can be easily included in the grid. For these systems, DC micro alternators and permanent magnet (PM) generators are widely used to generate electrical energy. In this paper, a PMSG Stand-alone Wind Turbine System is modelled and the output power variations over a range of turbine speeds are observed. A permanent magnet synchronous generator is used for the energy conversion because of its compatibility with low speeds. It is directly-driven i.e. it can directly be connected to the gearbox which makes the entire architecture considerably less expensive. The electrical power output of the energy system is a function of the the speed of the wind and can be controlled by variations in the pitch angle of the blade ($\beta$). The graph characteristics of the output power vs rotor voltage is non-linear in nature. Thus, it is a difficult task to obtain maximum power output from the turbine for all values of the wind speed.

In this paper, the Maximum Power Point Tracking (MPPT) algorithm devised for the same is discussed. The energy sink in this system is a battery with almost steady voltage. The battery absorbs
power until the charging current exceeds its threshold value. The value of voltage across the battery remains almost consistent, but the current through it can be varied, therefore it can be considered as a load with a variable resistance. As a storage option, battery banks as load is the most popular choice due to an edge over other options. It proves to be a comparatively inexpensive choice with better efficiency, energy storage period and energy density. Another crucial issue of the stand-alone wind power system is the lifetime of the battery bank. Taking into account the monetary restraints, the lead–acid battery remains the widely used energy stockpiling device for the stand-alone wind energy conversion system. However, the degradation of the lead–acid battery in turn affects the system’s reliability.[1] The usage of pulsating currents to charge the battery can increase the lifetime of a battery as well as improve its charging efficiency.

2. Wind energy and wind turbine system

Wind energy, or wind power, is generated with the help of a wind turbine, a device that utilizes the power in the wind to generate electricity. A wind turbine connected to a generator via a shaft is responsible for the conversion of wind energy to electrical energy. Small, individual wind turbine systems can produce around 100 kilowatts of power. The energy produced is enough to sustain small domestic needs. They are also used in places like water pumping stations. In a wind energy conversion system, the difference in pressure of the air between the two sides of the blades of the wind mill cause their rotation. They are connected to the generator which takes in the rotating movements of the shaft and then converts the mechanical energy (kinetic energy of the wind) to electrical energy that helps charge the battery banks to supply power to the load. The output power of a wind turbine system is given by the expression:

\[ P_m = \frac{1}{2} \rho \pi C_p (\lambda, \beta) R^2 V_w^3 \]  

(1)

In the above equation, \( \rho \) is the air density, \( C_p (\lambda, \beta) \) is the power conversion coefficient, \( R \) is the radius of the blade of the wind turbine, \( V_w \) is the speed of the wind and \( P_m \) is the power output of the stand-alone wind energy system.

From equation (1), it can be concluded that the power output of the wind turbine depends on the power conversion coefficient \( C_p \) for a particular wind speed. \( C_p \) is a function of the tip speed ratio (\( \lambda \)) which is defined as the speed of rotation at the tip of the blade by the speed of the wind for a pitch angle (\( \beta \)). Therefore, to obtain maximum power from the wind energy conversion system, the wind turbine should be rotated at different speeds.

![Maximum Power Point Curve of a wind turbine system](image)
The Permanent Magnet Synchronous Generator attached to the blades is responsible for the energy conversion. The output voltage responsible for charging the battery is proportional to the rotor speed. Initially, the PMSG of the wind energy conversion system starts at no-load with the maximum output voltage. With the increase in the output current there is a subsequent increase in the output power but the output voltage drops. Once the output power attains a specific value, the increase in output current will cause a significant output voltage drop leading to a steep output power drop and the PM wind turbine will stall eventually. The dotted line in the above figure represents the MPP curve. It can mathematically be represented as a polynomial equation of order 2 and is a function of the turbine speed for constant $C_p$.

3. MPPT battery charging process

![Proposed circuit diagram for MPPT Battery Charger](image)

The battery can be charged in two modes: Pulsating Current Mode (PCM) and Constant Voltage Mode (CVM). The battery operates in the Pulsating Current mode (PCM) when the voltage across the battery ($V_b$) is below the threshold voltage ($V_{bth}$), and the Switch 2 (SW2) is open. Whereas, if the battery voltage crosses its threshold value ($V_b > V_{bth}$), the battery charger switches over to the Constant Voltage mode (CVM) with SW2 closed. For the generation of the pulsating current required by the battery bank during the PCM, the charger operates with constant on-time control in the discontinuous conduction mode (DCM). [2] Further, the increase in wind speed in turn increases the output voltage of the wind turbine causing the charger to enter into continuous conduction mode (CCM). The increased current will result in decreased rotor speed as well as the input voltage.

Once the battery is charged and the charger has entered CVM, the output capacitor provides constant voltage across the battery. Further, to prevent the overcharging of the battery, the constant on-time control of the charger is replaced by the voltage-mode control. It helps to regulate the output voltage. During charging period $d_1$, switch SW1 is closed and there is a linear increase in the inductor current. Whereas, during discharging period $d_2$, switch SW1 is open, $I_L$ decreases and drops to zero. Period $d_3$, the rest duty is meant for stabilization of the chemical actions of the battery allowing it to be ready for the next charging current. This improves the battery charging efficiency. The equations for the charge and discharge cycles when the switches SW1 and SW2 are closed in Figure 2 are given by Equation (2) and Equation (3) respectively.

$$V_{in} - \frac{L \Delta i}{d1} - V_b = 0$$  \hspace{1cm} (2)
From Equation (2) and Equation (3) we can get the amplitude of the charging current. It is given by Equation (4) from which we in turn obtain Equation (5).

\[ V_b - \frac{L \Delta i f}{d_2} = 0 \]  
\[ \Delta i = \frac{(V_{in} - V_b)d_1}{fL} = \frac{V_b d_2}{fL} \]  
\[ d_2 = \frac{(V_{in} - V_b)d_1}{V_b}. \]  

Average current flowing through the output inductor is given by Equation (6).

\[ I_{avg} = \frac{1}{2} \Delta i (d_1 + d_2) = \frac{d_1^2}{2fLV_b} (V_{in}^2 - V_b V_{in}) \]  

Average power charges into the battery during one charge/discharge cycle is given by Equation (7).

\[ P_o = I_{avg} V_b = \frac{d_1^2}{2fL} (V_{in}^2 - V_b V_{in}). \]  

The rest duty d3 is zero for operation of the battery between continuous conduction mode and discontinuous conduction mode. Therefore, d1+d2=1 (charging period + discharging period =1). On substituting Equation (7) in Equation (5), \( V_{in} \) can be derived as,
Hence, the previous claim that the average power into the wind turbine’s battery is a polynomial equation of order 2 and is a function of $V_{in}$, is substantiated. The equation is in accordance with the MPP curve of the Wind Turbine System.

4. **Maximum power point tracking algorithm**

The Maximum Power Point Tracking Algorithm for the stand-alone wind turbine system in this paper is constructed on the basis of speed of the wind. Here, the wind speed and the speed of the rotor of the wind turbine are measured to get the optimal value of $\lambda$ (tip speed ratio) which in turn helps us achieve the maximum power output of the wind turbine as given in Equation (1).

The MPPT Algorithm proposed in this paper divides one charging, discharging cycle into several intervals. The algorithm helps iterate through the intervals using loop control variable ‘k’, calculating the output power by multiplying the battery voltage with the current flowing through it. This helps find the maximum output power of a stand-alone wind turbine system for a particular wind speed.

![Flowchart for the MPPT Algorithm](image)

**Figure 4.** Flowchart for the MPPT Algorithm
5. Experimental Results
The following steps are supposed to be followed to design a buck-type MPPT battery charger for a stand-alone wind turbine system:

- Analyse the wind turbine specifications like the rated voltage, rated power, rotor speed, MPP curve etc.
- Select the appropriate value of the rated battery voltage based on the wind turbine specifications.
- Using equation (8), the rated battery and wind turbine voltage, obtain duty cycle d1.
- Further design the circuit parameters f and L listed in equation (7).

Consider a stand-alone wind turbine system with rated power of 480-W, a PM generator with a rotor speed of 300r/min and 34 poles. A diode rectifier is used to rectify the voltage. A buck-converter is also used, that is a step-down DC/DC converter. It helps reduce the rectified voltage to charge the battery. The circuit diagram for the above is given in Figure 5.

![Figure 5. MATLAB Simulation diagram for a PMSG Stand-alone Wind Energy Conversion System](image)

The above graph is of the PMSG stand-alone wind turbine system for the pitch angle ($\beta$) of the blades being 0 degrees. For a particular wind speed, the maximum power output is obtained from the
Generator for a certain turbine speed or rotor voltage. But after the power attains its maximum value represented by the peak in the graph, its decline is quite appreciable. The output voltage further reduces causing the power to subsequently tend to zero and the PM wind turbine will stall eventually.

The battery in the circuit diagram is considered to be a lead-acid battery with a nominal voltage of 48V. The variations in battery parameters are observed after simulation of the circuit for changes in the wind speed from 16 m/s to 12 m/s.

![Graphs for Battery Parameters](image)

**Figure 7.** Graphs for Battery Parameters

The graphs above show the changes in the battery parameters like the % SOC (State of Charge), battery current and battery voltage. It is observed that initially the wind turbine voltage helps charge the battery. Once the battery is charged (Vin> Vth) the battery starts supplying current to the load.

6. Conclusion

In this paper, the process of charging a battery for a stand-alone wind turbine system is discussed in detail and the formulae to obtain the various parameters of a Buck DC/DC converter used to charge the battery are derived. The output power equation is also obtained and it is a polynomial of order 2. This is in accordance to the MPP Curve of the system. The control strategy for charging the battery is also discussed. The battery is charged using pulsating current by operating the buck-type charger in the discontinuous mode with constant on-time control to achieve better efficiency. The MPPT Algorithm is also discussed and represented using a flowchart for its better understanding. It is essential to achieve maximum output power at different wind speeds. Furthermore, a PMSG Stand-alone Wind Turbine System is simulated using SIMULINK of the MATLAB Software. The output power of the generator is observed for a variation of wind and turbine speeds and the changes in battery parameters are also analyzed.

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