BATTERY ENERGY STORAGE SYSTEM FOR A STAND ALONE WINDMILL - BASED ON STATE-OF-CHARGE (SOC) BALANCING CONTROL

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Abstract-- Renewable energy sources such as wind turbine generators produce fluctuating electric power. The fluctuating power can be compensated by installing an energy storage system in the vicinity of these sources. This paper proposes the integration of a Battery energy storage system with a typical stand-alone wind energy system during wind speed variation as well as transient performance under variable load. The investigated system consists of a 200 W variable speed wind turbine with permanent magnet DC generator, buck-boost converter, charge controller, loads and battery unit with focus on a control method for state-of-charge (SOC) balancing of the battery units. The State of Charge (SOC) method control is used for controlling the battery units in order to ensure the difference of energy, if the wind turbine can’t supply the total energy for the loads. Laboratory system combining a State of Charge (SOC) balancing control with four sealed lead acid battery units is designed, constructed, and tested to verify the validity and effectiveness of the proposed balancing control. Simulation of the system using Matlab/Simulink software was performed in order to validate the SOC balancing control.

Index: Terms--wind energy, SOC, energy storage, stand-alone system.

I. INTRODUCTION

Environmental concern and continuous depletion of fossil fuel reserves have spurred significant interest in renewable energy sources [1-4]. However, renewable energy sources such as wind turbine generators are intermittent in nature, and produce fluctuating active power. Interconnecting these intermittent sources to the utility load at a large scale may affect the voltage/frequency control of the load, and may lead to severe power quality issues [5-8]. An energy storage system is indispensable for compensation of the active-power fluctuation, which is often referred to as “power levelling.” If a wind turbine generator produces a larger power than an average power over a period of time, say several seconds to 30 min, the energy storage system stores the excess power available to the load. On the other hand, if the generator produces a smaller power, it releases the shortage of power back to the load. The energy storage system brings a significant enhancement in power quality, stability, and reliability to the load [9-13]. There is a growing interest in using storage devices for power smoothing and power quality in stand-alone wind energy systems. The small wind turbines in conjunction with battery storage, is best suit for the electrical energy produced for stand-alone applications. For wind applications, the following characteristics are desirable in a storage system: long term storage, operation over a wide range of power outputs, high efficiency, low maintenance, long life and fast response to rapid changes.

Wind energy systems have a fluctuating power output due to the variability of the wind speed with power output varying by the cube of the speed. Integrating an appropriate energy storage system in conjunction with a wind generator removes the fluctuations and can maximize the reliability of power to the loads. It is therefore necessary to have methods capable of accurately estimating battery SOC to avoid overcharge for battery protection. In [14-18] are presented different methods for estimating SOC such as, electrolyte specific gravity, stabilized float current, coulomb metric measurement, open circuit battery voltage, and loaded battery voltage. The battery SOC balanced control is achieved by permanent update from one time step to the next, with a discrete integrator.

The paper is organized as follows: in Section II the system configuration Section III presents the SOC control method; Section IV describes the developed model and simulation results while experiments are in section V and conclusions are provided in Section VI.
SYSTEM CONFIGURATION

Stand-alone wind energy conversion system

The proposed wind stand-alone system for a residential location is a 200W wind turbine system with a permanent magnet DC generator, buck-boost converter, charge controller[19-24], sealed lead acid battery storage device, inverter, load splitter and loads. It supplies 24 V DC load and single-phase consumers, at 230V and 50Hz.

A block representation of the stand-alone wind energy system with battery energy storage is provided in Fig. 1.

![Block diagram of the stand-alone wind energy system with battery energy storage](image)

The wind turbine (Parameters are listed in Table I and Table II) generates a variable dc. While the input voltage to the buck-boost converter varies with the wind speed, the output voltage is kept constant to the battery storage by the charge controller. The Battery Bank is connected to a load splitter through the charge controller, connected to a dc-ac inverter and DC load. The Battery energy storage is able to supplement the power provided to the load by the wind turbine when the wind speed is below a threshold value. Current flow into and out of the Battery energy storage system is controlled by the bidirectional charge controller [30-37].

TABLE I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator type</td>
<td>PM DC</td>
</tr>
<tr>
<td>Voltage (V)</td>
<td>110 V DC</td>
</tr>
<tr>
<td>Watts @ Rated wind speed</td>
<td>200 watts</td>
</tr>
<tr>
<td>Type of hub</td>
<td>Fixed pitch</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>1.85 m</td>
</tr>
<tr>
<td>Swept area</td>
<td>2.4m²</td>
</tr>
<tr>
<td>Number of blades</td>
<td>3</td>
</tr>
<tr>
<td>Rotor speed @ rated</td>
<td>500 RPM</td>
</tr>
</tbody>
</table>

TABLE II

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated electrical power</td>
<td>200 W @8m/s</td>
</tr>
<tr>
<td>Rated wind speed</td>
<td>8 m/s</td>
</tr>
<tr>
<td>Cut-in</td>
<td>3.5 m/s</td>
</tr>
<tr>
<td>Shut-down (high wind)</td>
<td>23 m/s</td>
</tr>
<tr>
<td>Peak (survival)</td>
<td>60 m/s</td>
</tr>
<tr>
<td>Calculated annual output</td>
<td>1100 kwh @ 4.5 m/s</td>
</tr>
</tbody>
</table>

Energy Storage Systems

Energy storage systems based on different storage devices have been investigated [25-28]. Recently, batteries have emerged as promising storage devices for power system applications. Batteries have the highest energy density. Batteries have the potential of being used for power levelling of renewable energy sources.

A typical Sealed Lead-Acid battery bank (Parameters listed in Table III) consists of four cells in series, this combination gives both the voltage and power necessary for load. While common, these configurations are not as efficient as they could be, because any capacity mismatch between series-connected batteries reduces the overall battery bank capacity. Battery balancing techniques increase the capacity, and system operating time.

TABLE III

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Sealed Lead-Acid</td>
</tr>
<tr>
<td>Voltage (V)</td>
<td>12 DC</td>
</tr>
<tr>
<td>Capacity</td>
<td>26 AH</td>
</tr>
<tr>
<td>Standby use</td>
<td>13.6 V – 13.8 V</td>
</tr>
<tr>
<td>Cycle use</td>
<td>14.1 V – 14.4 V</td>
</tr>
<tr>
<td>Max initial current</td>
<td>5.2 A</td>
</tr>
<tr>
<td>Temperature</td>
<td>27°C</td>
</tr>
<tr>
<td>No. of Battery</td>
<td>4 Nos.</td>
</tr>
</tbody>
</table>

Loss of bank capacity in a series connected pack results from two main factors. First, battery must maintain a voltage within strict limits. If the voltage on any battery goes too high, charging must stop. If the voltage on any battery goes too low, discharge must stop. Second, series-connected batteries in a battery bank usually have capacity mismatches.

Lead-Acid battery experience two primary kinds of mismatch. State-of-charge (SoC) mismatch occurs when initially-equal-capacity batteries gradually...
dive to contain different amounts of charge. Capacity/energy (C/E) mismatch occurs when cells with different initial capacities are used together. Because batteries are typically matched fairly well in the assembly, SoC mismatch is the more common. The combination of cell voltage limits and SoC mismatch ties the battery bank capacity (Ah) to the capacity of the weakest battery. In a battery pack where the batteries all have roughly the same capacity[38-41], the open-circuit voltage (OCV) of the bank is a good measure of the SoC. So, charging an unbalanced battery bank results in one or more battery reaching the maximum charge level before the rest of the cells in the series string. During discharge the batteries that are not fully charged will be depleted before the other cells in the string, causing an early under-voltage shutdown of the bank. These early charge and discharge limits reduce the usable charge in the battery.

Manufactured battery capacities are usually matched within 3% self-discharge, or if cells with differing self-discharge characteristics are allowed to remain on the shelf for long periods prior to pack manufacture, battery voltage differences of 150 mV at full charge are possible. These differences could result in an initial 13 - 18% reduction in battery capacity. Even if they are matched by capacity in the assembly[42-45], the varying battery-to-battery self discharge rates could reduce the capacity of a battery bank over time, simply by sitting on the shelf.

A battery management system (BMS) plays an important part in estimating the SOC, which is often called the “fuel gauge” function. The SOC estimation may be based on measuring some convenient parameters such as voltage, current, and internal impedance, which vary with the SOC [9]. For stable operation of the battery bank, state-of-charge (SOC)-balancing control would be indispensable.

This paper focuses on SOC-balancing control for a battery energy storage system based on a cascade PWM converter. The experimental system includes acid battery units that have no voltage PWM converter. The experimental system includes battery energy storage system based on a cascade battery unit that have no voltage PWM converter. This control algorithm uses two variable parameters called the “fuel gauge” function. The SOC estimation may be based on measuring some convenient parameters such as voltage, current, and internal impedance, which vary with the SOC [9]. For stable operation of the battery bank, state-of-charge (SOC)-balancing control would be indispensable.

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\[ \text{SOC} = \frac{\text{Current Energy in Battery}}{\text{Total Energy Capacity}} \]  

(1)

If the battery is fully charged, SOC = 1 and if the battery is discharged at the maximum value, SOC = SOC\text{min}. For instance the maximum recommended discharge for battery is 80%, thus SOC\text{min}=0.2.

The control method used to keep track of the state of charge is to update the SOC variable from one time step to the next, based on the power that goes through the battery bank. The change in SOC is implemented as follows:

\[ \text{SOC}_{t+1} = \text{SOC}_t + \Delta \text{SOC} \]  

(2)

In this method, the data of the Energy Storage SoC is fed back to the battery bank itself via micro controller. This is a conventional method to control SoC. The Energy Storage system has the fastest response in the Standalone wind mill, this bias caused by the SoC control would not be compensated. This would result in deterioration of the tie line’s power quality.

\[ \Delta \text{SOC} = \frac{\Delta \text{E}}{\text{E}_\text{capacity}} = \frac{\text{P}_{\text{stack}} \times \text{Time}_\text{step}}{\text{E}_\text{capacity}} \]  

(3)

\[ \Delta \text{SOC} = \frac{\text{I}_{\text{stack}} \times \text{V}_{\text{stack}} \times \text{Time}_\text{step}}{\text{P}_\text{rating} \times \text{Time}_\text{rating}} \]  

(4)

This control algorithm uses two variable parameters \((I_{\text{stack}}, V_{\text{stack}})\). With a discrete time-integrator block by accumulation the SOC is thus computed each cycle based on the previous SOC, depending on the input values. The simplified control methods block is shown in Fig. 3.

\[ I_{\text{Stac}} \rightarrow \Delta \text{SOC} \rightarrow \frac{1}{Z - 1} \rightarrow \text{SOC} \]  

Fig. 3. Control method for battery energy storage

Fig. 2. Control method for battery energy storage

Fig. 1. Control method for battery energy storage

STATE OF CHARGE (SOC) CONTROL METHOD

The system state of charge can be defined as

\[ \text{SOC} = \frac{\text{Current Energy in Battery}}{\text{Total Energy Capacity}} \]  

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The calculations Battery parameters are based on estimating losses of 21% (15% internal losses + 6% parasitic losses) in the worse case operating point, for a maximum voltage of 12V, and a current of 26 A, therefore the value of the power rating is greater than 300W. The discharging process of a charged battery (SOC = 80%) at a constant output power of 300W.

**B. Results**

The results of the simulation are shown in Fig.6. In the simulation, the discharge Characteristics are shown in fig 5. The value of K has been set at K=0.1875. The parameters of the PI controller in autonomous SoC control have been set at KP=0, KI=0.003 respectively.

**SIMULATION**

Using the control system proposed in section III, a control simulation by use of the model Standalone wind mill has been carried out (Fig 4). Load data acquired from previous experiments was used in the simulation.

**Conditions of the Simulation**

In the simulation, the controller is represented by first-order delay elements whose delays are decided by the output response characteristics. Samplers in the system hold signals averaged over a second for a second. The control system sends its signals every second and the autonomous control system for the battery bank sends its signals every millisecond. The reference value of the tie line power flow was set at 200W and nominal value of the battery bank DC voltage was set at 24V.

The simulation was done in two following cases.
1. without any SoC control
2. with SoC control
Since the effectiveness of proposed SoC balancing control system has been confirmed by the simulation, a verification test using real machines has been carried out using the Standalone wind mill.

**Experiment Conditions**

The control system of the Standalone wind mill is same as the system used in the simulation (Shown in Fig.2). The experiment has been carried out for the following two cases.

1. Without SoC control

   ![SIMULINK model output for standalone windmill with battery energy storage SOC balanced](image1)

   In case, the DC voltage constantly decreased for the first 100 seconds of the experiment. Since the parameter of the PI controller in autonomous SoC balance control is set at a very low level, this period is the time when autonomous SoC control is relatively ineffective. It can be assumed that the DC voltage would continue to drop in the case autonomous control was cancelled completely. In the actual measurement, the DC voltage swings in the range of 0-110V DC.

2. With SoC balancing control

   ![Experimental output for standalone windmill with battery energy storage with SOC balanced](image2)

   The effect of SoC balance control to the power quality can be increased by setting its parameter at lower level, but this will cause larger swing in DC voltage (fig 7) and require larger energy capacity.

**CONCLUSION**

In this paper, a SoC balancing control system has been proposed and its effectiveness has been verified by simulation and experiment using real machine (standalone 200W Windmill). The proposed SoC balancing control system enables to control battery bank’s SoC with little effect to the power quality of the tie line with less energy capacity.

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