Modeling and Control of Solar PV with Battery Energy Storage for Rural Electrification

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ABSTRACT

In rural areas where electric power grid network is rarely available, power generation from renewable energy resource such as solar photovoltaic (PV) is mostly accomplished in standalone mode. The standalone solar PV system requires energy storage device to achieve reliable power supply to the end users. This paper presents modelling and coordination control of solar PV with battery energy storage system (BESS) for rural-electrification applications. The proposed control is accomplished via a bidirectional buck-boost converter with the objective of maintaining voltage at the DC bus constant. Simulation results based-on MATLAB/Simulink platform confirms good performance of the proposed system.

Keywords: Photovoltaic (PV), Energy Storage System (ESS), Maximum Power Point Tracking (MPPT)

INTRODUCTION

Electricity generation worldwide is mainly attained from non-renewable sources such as fossil fuel and renewable energy sources (RESs) such as solar PV. However, the rapid depletion of non-renewable sources and release of greenhouse gases to the atmosphere have escalated the global warming calamity. This has made the choice of the renewable energy sources inevitable as they are inexhaustible and have less adverse impacts on the environment (Kainkwa, 2008). Nevertheless, the RESs have disadvantages, which are their incapability to ensure reliability and their nature that depends on weather conditions (Muralikrishna and Lakshminarayana, 2008).

There is excessive demand of energy in rural Tanzania in which the main energy consumption (about 60-80%) is biomass in the form of firewood and charcoal (Rosillo-Calle, 2016). The Tanzania’s Rural Electrification Program of 2013-2022 has the goal of increasing electricity access to at least 75% by 2033 (Teske et al., 2017). To enhance this goal in Tanzanian rural areas, the effective extraction of energy from the RESs such as solar PV and wind, which are vastly available, is inevitable.

The use of RESs for power generation can be either in standalone or grid connected modes. Currently, the promotion of RESs in standalone operation has been largely achieved all over the world (Deshmukh and Singh, 2019). However, since these sources
cannot deliver continuous energy, the use of energy storage system (ESS) is unavoidable so as to satisfy the power demands (Nehrir et al., 2011).

Recently, solar PV has been one of the used RES mainly for power generation due to decrease in its installation cost and mature technology (Wu et al., 2014; Dizqah et al., 2014; Quintana et al., 2013; Daniel and AmmasaiGounden, 2004; Mellit et al., 2007). Nevertheless, the nature of sun irradiation that is intermittent, has been a challenge in operation of the solar PV generator leading to an oscillatory output power. To mitigate this problem, an energy storage system (ESS) is integrated with the solar PV system (Nehrir et al., 2011; Vazquez et al., 2010). However, ESS is imperative for the efficient operation of standalone solar PV systems. The commonly employed ESS with renewable energy system is the battery ESS (BESS) (Riffonneau et al., 2011; Teleke et al., 2010). The BESS needs a proper charging control for effective operation with the varying solar insolation.

The approach that has been widely used for battery charging in solar PV system is that of direct connection of battery bank to the solar array (Yamazaki and Muramoto, 1998). The setback of this method is that the battery 100% state of charge (SOC) does not always correspond to the overcharge limit and voltage regulation set point. Another approach is that of on/off control in which there is either a full application of solar array current or no current to the battery bank (Woodworth et al., 1994). The drawback of this approach is the prolonged time to complete the charging process since during off time no charge is transferred to the battery. Charge equalization algorithms is another approach, but there is limitation in feasibility of this approach since there is a requirement to access individual cells or blocks of cells (Mishra et al., 1996). Duryea et al. (1999) proposed an algorithm based on ampere-hour measurements, but this method is affected by error in current measurement that affects determination of SOC and battery lifetime. Furthermore, to achieve longer battery life time and high SOC, Koutroulis and Kalaitzakis (2004) suggested a control strategy for battery charging.

In this paper, modeling of solar PV together with the coordination control between the solar PV and BESS is proposed. This control strategy is attained through a bidirectional buck-boost converter that links between the BESS and the DC bus. The control strategy is proposed in order to maintain the voltage at the DC bus by charging and discharging the battery through a bidirectional DC-DC converter. Moreover, the use of proper Maximum Power Point Tracking (MPPT) algorithm is inevitable in order to obtain maximum possible power at any instant from the solar PV generator. Various MPPT algorithms such as perturb and observe (P&O) and incremental conductance have been proposed in previous literature (Liu et al., 2008) (Tafticht et al., 2008). The P&O MPPT algorithm is adopted in this work due to its simplicity. The maximum power point (MPP) is attained by using a boost converter that links the solar PV with the DC bus. The system setup is simulated in MATLAB/Simulink software in order to validate the system’s performance. The software is used due to its accuracy and simplicity.
METHODS AND MATERIALS

Proposed System Configuration

The system layout investigated in this paper is shown in Figure 1. It consists of a solar PV connected through a DC/DC boost converter where the MPPT algorithm measures the current ($I_{PV}$) and voltage ($V_{PV}$) values of the solar PV and outputs the duty cycle that switches the boost converter in order to extract maximum power from the solar PV. On the other hand, the charging and discharging of the battery is performed by the battery charge controller through the bidirectional buck-boost converter, whereby the parameters considered are battery current ($I_b$) and voltage at the DC bus ($V_{DC}$) to ensure that the voltage at the DC bus is kept constant.

Figure 1: The proposed system layout

PV System Modelling and MPPT Control

The system is designed to operate at a DC bus voltage of 750 V as will be described later in this work. Moreover, considering the needs of loads in rural areas, the solar PV generates up to 200 kW Solar PV as the main source of power operates at Maximum Power Point (MPP) while the battery ESS complements the entire system by charging or discharging in order to balance power supplied to the DC loads.

Solar PV modelling

In the literature, various equivalent circuits of PV cell have been proposed, but the most commonly used model is the single-diode circuit due to its simplicity and accuracy (Yazdani et al., 2010; Ye et al., 2012). The single diode equivalent circuit of the PV cell is shown in Figure 2. The circuit is comprised of a diode in parallel with a current source, a series and parallel resistance. The basic equation is as shown in equation (1).

$$I = I_{PV} - I_0 \left[ \exp \left( \frac{V + IR_s}{V_t} \right) - 1 \right]$$

where $I_{PV}$ and $I_0$ are the PV and saturation currents of the array, respectively. $R_s$ is the equivalent series resistance of the array and $R_p$ is the equivalent parallel resistance; $a$ is the diode ideality constant, $V_t$ is the thermal array voltage which is obtained by using equation (2).

$$V_t = \frac{N_s k T}{q}$$

where $N_s$ is the number of series connected cells, $k$ is the Boltzmann constant ($1.3806503 \times 10^{-23}$ J/K), $T$ is
the \( p-n \) junction temperature (in Kelvin), \( q \) is the charge of the electron \( (1.60217646 \times 10^{-19} \text{ C}) \).

The module of solar PV array is designed using MATLAB software based on the system requirements. The considered solar PV generator is capable of generating up to 200 kW. The voltage required for maximum power is 54.7 V for a single module. Then by connecting 10 solar PV modules in series \( (N_s) \) the voltage \( (V_{mpv}) \), is obtained as depicted in equation \( (3) \).

\[
V_{mpv} = V_{mp} \times N_s \quad (3)
\]

Then, the system current value is determined by equation \( (4) \).

\[
I_{mpv} = \frac{P}{V} \quad (4)
\]

Table 1 shows the parameters of the PV array module.

The current required for the available maximum power is 5.58 A for a single module as shown in Table 1. Then, the number of parallel connected strings of the solar PV modules \( (N_p) \) is obtained as shown in equation \( (5) \).

\[
N_p = \frac{I}{I_{mp}} \quad (5)
\]

The light-produced current of the PV cell is influenced by the solar irradiance and temperature (Sera et al., 2007; Driesse et al., 2007; De Soto et al., 2006; Kou et al., 1998). The simulation of one module was carried out for different irradiance and temperature levels to demonstrate this variation. The variation of irradiance level was from 250 W/m\(^2\) to 1000 W/m\(^2\) and the resultant \( P-V \) curve is as shown in Figure 3. It is observed that as the irradiance increases, the power from the solar PV also increases. On the other hand, the variations of temperature is set from 2°C to 7°C and the resulting \( P-V \) curve is as shown in Figure 4. It was observed that the solar PV power decreases with the increase in temperature. This concludes the necessity of tracking the maximum power point (MPP) at any instant on the solar PV for effective generation of power as this MPP varies with irradiance and temperature.

Table 1: Solar Module Properties

<table>
<thead>
<tr>
<th>Module data (Sun Power SPR-305E-WHT-D)</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum power, ( P_m )</td>
<td>305.226 W</td>
</tr>
<tr>
<td>Voltage at maximum power point, ( V_{mp} )</td>
<td>54.7 V</td>
</tr>
<tr>
<td>Current at maximum power point, ( I_{mp} )</td>
<td>5.58 A</td>
</tr>
<tr>
<td>Cells per module, ( N_{cell} )</td>
<td>96</td>
</tr>
<tr>
<td>Open circuit voltage, ( V_{OC} )</td>
<td>64.2 V</td>
</tr>
<tr>
<td>Short circuit current, ( I_{SC} )</td>
<td>5.96 A</td>
</tr>
<tr>
<td>Voltage/temp. coefficient, ( K_v )</td>
<td>-0.27269%/°C</td>
</tr>
<tr>
<td>Current/temp. coefficient, ( K_i )</td>
<td>0.061745%/°C</td>
</tr>
</tbody>
</table>

A DC/DC boost converter which connects the solar PV to the DC bus is controlled via an MPPT algorithm. The dynamics of irradiance and temperature necessitates the need of an MPPT algorithm that continuously updates the duty cycle to enhance the tracking speed and accuracy (Abdulkadir et al., 2012). Figure 5 shows the solar PV connected through the boost converter to the DC bus.
For the extraction of maximum power, the solar PV current ($I_p$) and voltage ($V_p$) are sensed and the MPPT controller adjusts the duty cycle so that the MPP is precisely tracked. Tracking of the MPP can be carried out using various techniques. The Perturb and Observe (P&O), which involves injection of small perturbation to the system resulting to driving of the operating point towards the MPP is adopted due to its simplicity (Ayang et al., 2018).

In the MPPT algorithm, the instantaneous values of voltage, $V(t)$ and current, $I(t)$ are measured, then power, $P(t)$ is calculated. The deviation in voltage ($\Delta V$) and power ($\Delta P$) are obtained, compared and appropriate action is taken on the reference voltage value ($V_{ref}$) in order to track the MPP accordingly. Figure 6 shows the flow chart of the MPPT algorithm implemented.

The input voltage of a boost converter is the voltage of the PV array ($V_{PC}$) at MPP, which is calculated using equation (3). For the power transfer, the minimum DC bus voltage ($V_{dc}$) is to be at least equal to 1.1 times the peak of line voltage ($V_l$) as shown in equation (6) (Kewat et al., 2017).

$$V_{dc} = 1.1 \times \sqrt{2} \times V_l$$
Figure 6: The flowchart of P&O algorithm

The designed value of the boost inductor \( L_B \) is given by equation (7) (Philip et al., 2016).

\[
L_B = \frac{V_{mp} \times D}{\Delta i_{rp} \times f_s} \ldots \ldots \ldots \ldots \ldots \ldots (7)
\]

where \( V_{mp} \) is the voltage at MPP, \( D \) is the duty cycle, \( \Delta i_{rp} \) is the ripple current, considered as 10% of the MPP solar PV current and \( f_s \) is the switching frequency.

The input capacitor is calculated using equation (8) (Rashid, 2009).

\[
C_t \geq \frac{D}{8 \times f_s \times L_B \times \Delta V} \ldots \ldots \ldots \ldots \ldots \ldots (8)
\]

where \( \Delta V \) is input voltage ripple of 1%. Also, the DC bus capacitor considering a voltage ripple \( (\Delta V_{dc}) \) of 1.5% is calculated as shown in equation (9).

\[
C_{DC} = \frac{P_{dc}}{2 \times \omega \times V_{dc} \times \Delta V_{dc}} \ldots \ldots \ldots \ldots \ldots \ldots (9)
\]

Where \( P_{dc} \) is DC bus power, \( V_{dc} \) is DC bus voltage and \( \omega \) is the angular frequency.

**Battery ESS sizing**

The proposed solar-PV system is designed to provide load requirement \( (P_{req}) \) of 200 kW for time \( (t_{hrs}) \) up to 24 hrs. In sizing the battery an additional 20% of the load requirement is considered to account for the energy that is lost in the course of energy exchange. Considering the battery voltage \( (V_b) \) of 240 V that corresponds to the desired DC bus voltage, the Ampere-Hour rating of the battery \( (Q_r) \) is obtained as shown in equation (10) (Tiwari et al., 2018).

\[
Battery \ Rating \ (Q_r) = \frac{P_{req} \times t_{hrs} + 0.2(P_{req} \times t_{hrs})}{V_b}
\]

**Bidirectional Buck-Boost converter design**

The bidirectional buck-boost converter connects the battery ESS to the DC bus. This converter is designed to function as the buck converter while charging the battery and as boost converter on discharging mode. The proposed circuit showing solar PV and battery connected via bidirectional buck-boost converter is as shown in Figure 7.

On charging the battery, the filter inductor \( (L_{BB}) \) of the battery is designed as presented in equation (11) (Kewat et al., 2017).

\[
D = \frac{V_b}{V_{dc}}, \quad L_{BB} = \frac{D(V_{dc} - V_b)}{f_s \Delta I_L} \ldots \ldots \ldots \ldots \ldots \ldots (11)
\]

where \( V_{dc} \) is DC bus voltage, \( V_b \) is battery voltage, \( D \) is the duty cycle, \( f_s \) is the switching frequency, \( \Delta I_L \) is the
current ripple and is taken as 20% of the charging current.

Figure 7: Solar PV with battery via bidirectional buck-boost converter

On discharging the battery, the filter inductor of the battery is designed as depicted in expression (12).

\[
D = \frac{(V_{dc} - V_b)}{V_{dc}}, \\
L_{BB} = \frac{DV_b}{f_s \Delta I_L} \ldots \ldots \ldots \ldots \ldots (12)
\]

Here, \(V_{dc}\) is DC bus voltage, \(V_b\) is battery voltage, \(D\) is the duty cycle, \(f_s\) is the switching frequency, \(\Delta I_L\) is the current ripple and is considered to be 20% of the discharging current.

Battery control through a bidirectional Buck-Boost converter

The main objective of this control is to maintain DC bus voltage constant. The bidirectional buck boost converter maintains the DC bus voltage so as to ensure that there is continuous flow of power between the DC bus and the battery ESS (Jayalakshmi et al., 2014). Hence, the converter is controlled in a manner that the DC bus voltage remains constant during the changes in solar variables and load variations. Figure 8 shows the control strategy for the bidirectional buck-boost converter.

The voltage \(V_{dc}\) is compared with reference voltage \(V_{ref}\) to get the error signal that is passed through the first PI controller to produce the reference battery current, \(I_{bref}\). Then, this reference current is compared with the sensed battery current, \(I_b\) to obtain an error signal that is passed through the second PI controller to obtain the control signal. The control signal is then compared with a carrier signal to obtain switching pulses. When the DC bus voltage \(V_{dc}\) is greater than the reference voltage \(V_{ref}\) and the state of charge (SOC) is within the accepted range (20% to 80%), switch \(S_{BB2}\) is activated to run the circuit as a buck converter and when \(V_{dc}\) is less than \(V_{ref}\) and SOC is between 20% and 80% switch \(S_{BB1}\) is activated to run the circuit as a boost converter. The PI controllers are tuned based on the tuning method described in Visioli (2006). The control parameters that results to a constant DC bus voltage are listed in Table 2.

Table 2: Controller Parameters

<table>
<thead>
<tr>
<th>Gain</th>
<th>(K_p)</th>
<th>(K_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage loop</td>
<td>0.001</td>
<td>45</td>
</tr>
<tr>
<td>Current loop</td>
<td>0.001</td>
<td>0.00035</td>
</tr>
</tbody>
</table>
RESULTS AND DISCUSSION

In this section, simulation results of the solar PV system are presented to verify the effectiveness and feasibility of the proposed strategies. The simulations are carried out in MATLAB/Simulink platform since it is accurate and simple to use. The parameters used in this simulation studies are shown in Table 3.

Case 1: The solar PV is first tested without connection of the battery ESS. Variation of irradiance and temperature is made as shown in Figure 9 whereby initially temperature is maintained constant at 25°C for 6 s. Then, during this time, irradiance is varied whereby from 0 s to 1 s irradiance is at 1000 W/m² and the DC bus voltage is observed to increase as shown in Figure 10 to the desired voltage of 750 V. The irradiance is then decreased to 750 W/m² from 1 s to 4 s that led to the decrease of the DC bus voltage to 620 V. Irradiance is then increased to 1000 W/m² from 4 s to 6 s and it is observed that the DC bus voltage increased simultaneously and then maintained at 750 V. Afterwards, irradiance is maintained at 1000 W/m² up to 12 s and the temperature is decreased from 25°C to 10°C from 6 s to 7.5 s. It was observed that the DC bus voltage increased to 780 V. After that the temperature is increased to 30°C from 7.5 s to 12 s, and the DC bus voltage decreased from 780 V to 745 V. Hence, it can be observed that the DC bus voltage varies depending on the irradiance and temperature values.

Case 2: On connection of the battery via a bidirectional buck-boost converter, variation of irradiance and temperature is made as shown in Figure 9. It is observed that the DC bus voltage just started to decrease and the controller at the battery ESS is being discharged as observed in Figures 11 and 12, respectively, to maintain the desired DC bus voltage. From 4.5 s to 12 s in Figure 9 the irradiance is maintained at 1000 W/m² and temperature is decreased from 25°C to 10°C at 6 s to 7.5 s, the controller also responded accordingly, whereby the battery is charged as shown in Figure 12 to maintain the DC bus voltage. Also, when the temperature was increased from 10°C to 30°C at 7.5 s to 12 s the controller maintained the desired DC bus voltage by discharging the battery as depicted in Figure 12.
Table 4: Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC bus voltage: $V_{dc}$</td>
<td>750 V</td>
</tr>
<tr>
<td>Number of parallel PV modules: $N_p$</td>
<td>66</td>
</tr>
<tr>
<td>Number of series PV modules: $N_s$</td>
<td>10</td>
</tr>
<tr>
<td>PV voltage at maximum power point: $V_{mpV}$</td>
<td>547 V</td>
</tr>
<tr>
<td>PV current at maximum power point: $I_{mpV}$</td>
<td>365.63 A</td>
</tr>
</tbody>
</table>

**Boost Converter Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductor: $L_B$</td>
<td>200.5 $\mu$H</td>
</tr>
<tr>
<td>Capacitor: $C_i$</td>
<td>1538.66 $\mu$F</td>
</tr>
<tr>
<td>Capacitor: $C_{DC}$</td>
<td>37725.6 $\mu$F</td>
</tr>
</tbody>
</table>

**Bidirectional Buck-Boost Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductor: $L_{BB}$</td>
<td>14.87 $\mu$H</td>
</tr>
</tbody>
</table>

**Lead-acid Battery Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Voltage</td>
<td>240 V</td>
</tr>
<tr>
<td>Rated Capacity</td>
<td>24000 Ah</td>
</tr>
<tr>
<td>Nominal Discharge Current</td>
<td>4800 A</td>
</tr>
<tr>
<td>Internal Resistance</td>
<td>0.0001 $\Omega$</td>
</tr>
<tr>
<td>Cut-off Voltage</td>
<td>180 V</td>
</tr>
<tr>
<td>Exponential zone [Voltage, Capacity]</td>
<td>[244.3421V, 80Ah]</td>
</tr>
</tbody>
</table>

![Figure 10: Voltages on varying irradiance and temperature](image)

Figure 10: Voltages on varying irradiance and temperature

![Figure 11: Voltages on varying irradiance and temperature](image)

Figure 11: Voltages on varying irradiance and temperature

![Figure 12: Battery SOC on varying irradiance and temperature](image)

Figure 12: Battery SOC on varying irradiance and temperature

**Case 3:** The controller is also tested with varying load under standard temperature of 25°C and irradiance of 750 W/m². At starting, the first load is connected at time 0 s and the DC bus voltage increased up to the desired DC bus voltage and is maintained as illustrated in Figure 13 whereby the battery is being charged as seen in Figure 15. At 2 s the second load is added whereby the DC bus current increased from 110 A to 270 A. Also, the DC bus voltage dropped to 715 V at 2.03 s as shown in Figure 14 and Figure 13, respectively, the controller operated by discharging the battery as shown in Figure 15 and the desired DC bus voltage was obtained at 2.4 s as observed in Figure 13. At 4 s the third load is added that led to the drop in DC bus voltage to 683.6 V and rise in DC bus...
current from 270 A to 400 A as shown in Figure 14, respectively. The controller operated by discharging the battery as shown in Figure 15 in order to obtain the DC bus voltage at 750 V as depicted in Figure 13. Observing the three cases, the proposed system demonstrates a good performance in maintaining the voltage at the DC bus constant at 750 V.

**CONCLUSIONS**

In this paper, modelling and coordination control of solar PV with battery energy storage system for rural electrification applications has been presented. The proposed control scheme has been accomplished through a bidirectional buck-boost converter maintaining the DC bus voltage constant at 750 V. This voltage at the DC bus was maintained constant regardless of the change in solar PV input parameters and load variations. Performance of the system has been validated through simulations carried out in MATLAB/Simulink platform where different scenarios were successfully tested and demonstrated excellent results. However, incorporating this system with other renewable energy sources would improve the system’s reliability and reduce the entire system’s cost for rural electrification.

**REFERENCES**


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