Design of a battery voltage regulator based on maximum power point tracking and charge equalisation concepts

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Abstract

This paper deals with loss of photovoltaic energy due to mismatch between PV array and battery-bank, and difference in equalisation of charge between cells of battery-bank. These are the two major problems that affect the performance and life of PV system. From $I-V$ characteristics of PV modules and the charging–discharging characteristic of the battery-bank it is shown that in contrary to general assumptions and practices the maximum power point tracker is still relevant, even for a PV system integrated with battery-bank. From charging and discharging cycles of the battery-bank, it was observed that there is a need of charge equalisation among different battery-cells. For overcoming the above limitations a battery voltage regulator (BVR) has been designed to utilise the maximum available PV energy and also to provide charge equalisation to different battery cells. This BVR is based on multiple output switch mode design. The control function is based on analog positive feedback control for pulse width modulation. The BVR has been fabricated and tested. The increase in utilisation of available solar power lies between 5% to 10%.

Keywords: Battery voltage regulator; Photovoltaic array; Analog positive feedback; Pulse width modulation; Maximum power point tracker; Maximum power point; Battery cells; Multiple output switch mode; Charge equalisation; Electromotive force

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1. Introduction

Battery voltage regulator's are used to improve the performance and life of battery-bank in photovoltaic systems. In this connections various types of BVRs have been suggested [1–3].

Even an optimised BVR [3] is not able to utilise maximum available PV energy because PV array is not always operated at maximum power point (MPP). Also it is not able to provide charge equalisation among different cells of the battery-bank. Due to these reasons, there is loss of available PV energy and also loss of life-cycles of battery-bank.

To utilise maximum PV energy various control schemes have been suggested for maximum power point tracking [4,5]. The principle of tracking can be based on any of these, i.e., perturb and observed scheme, unity power feed/maximum output current scheme, and array power ripple scheme. These circuits need complex monitoring and control circuits and often require a micro-computer and a large number of components. The reliability of the system is inversely proportional to the number of components. Thus, to ensure the "probability of success" for more than 90% for a period of 10 years, various reliability improvement techniques have to be considered [6]. However, the reliability schemes will have substantial impact on the cost of the systems. The idle power consumption of the above circuits will be of the order of 20 to 30 watts per day. As a consequence, the circuit can only be used in systems of a kw order. In view of the above problems, there is a lot of scope for redesigning the system.

An alternative simple control scheme based on monitoring the pilot cell is suggested in literature [7]. In this scheme, a pilot cell has been incorporated in one of the solar panels. This makes the installation of this special panel difficult and tricky for accurate input data. The error may arise because of difference in variation of the PV array characteristics and pilot cell parameters. The change in characteristic parameters is due to environmental conditions and degradation.

This paper describes the problem associated with the PV systems such as mismatch between PV array and battery-bank of the cells characteristics and difference in charge equalisation between cells of a battery-bank. To overcome the mismatch and provide charge equalisation an integrated control scheme is designed which eliminates the need of two different control schemes.

The present scheme is based on analog positive feedback control (APFC) and multiple output switch mode design which automatically latches the PV array to MPP and provides equalisation of charge to battery cells simultaneously. Based on this, a control circuit is fabricated and tested.

2. Theory

2.1. Photovoltaic generator coupled to battery-bank

The charging current delivered by the PV array to the battery-bank at different insolutions, battery voltage and temperature is given as [3]:
\[
I = (1 + R_s/R_{sh})I_{sc} - AT^3e^{(-qV_{go}/KT)}e^{q(V_{bb} + IR_s + IR_w + V_g)/NTK}\times
\left[\frac{1}{R_{sh}} + \frac{AT^3e^{(-qV_{go}/KT)}e^{q(V_{bb} + IR_s)/NTK}}{(NKTN_s)}\times(1 + R_sR_{sh} + \frac{V_{bb} + qV_{bb}}{NKTN_s})\right],
\]
where \( R_s \) and \( R_{sh} \) are the lumped series and shunt resistance of PV array, \( I_{sc} \) is the short-circuit current, \( T \) is the cell temperature in degree Kelvin, \( V_{go} \) is the extrapolated band gap at zero degree Kelvin, \( K \) is Boltzmann's constant, \( N \) is the ideality factor, \( N_s \) is the number of cells in series, \( R_w \) is the lumped series resistance between solar array and battery-bank and \( V_g \) is offset voltage drop of series switch used for charging regulation, and \( V_{bb} \) is the voltage of battery-bank.

The mathematical formulation shows that the effect of different parameters such as photovoltaic generated current \( I_{ph} \), temperature \( T \), lumped series resistance \( R_s \) on the MPP for a PV array can be obtained as follow:

\[
P_a = V_p \times I_p,
\]
where \( P_a \) is power output of the PV array.

Substituting \( V_p \) by \( V_{bb} \) and \( I_p \) by \( I \) in Eq. (2) for the case of PV array connected to battery-bank, we have

\[
P_a = V_{bb}I. \tag{3}
\]

Neglecting voltage drops \( IR_w \) and \( V_g \), and differentiating Eq. (3) with respect to the battery voltage \( V_{bb} \), we get

\[
\frac{dP_a}{dV_{bb}} = \left(1 + \frac{R_s}{R_{sh}}\right)I_{sc} - AT^3e^{(-qV_{go}/KT)}e^{q(V_{bb} + IR_s)/NKTN_s}\times
\left[\frac{1}{R_{sh}} + \frac{AT^3e^{(-qV_{go}/KT)}e^{q(V_{bb} + IR_s)/NKTN_s}}{(NKTN_s)}\times(1 + R_sR_{sh} + \frac{V_{bb}}{NKTN_s})\right],
\]
and \( dI/dV_{bb} \) can be obtained by differentiating Eq. (1)

\[
\frac{dI}{dV_{bb}} \times \left(1 + \frac{R_s}{R_{sh}} + AT^3e^{(-qV_{go}/KT)}e^{q(V_{bb} + IR_s)/NKTN_s}\frac{q}{NKTN_s}\right) = -\left(\frac{1}{R_{sh}} + \frac{AT^3e^{(-qV_{go}/KT)}e^{q(V_{bb} + IR_s)/NKTN_s}g}{NKTN_s}\right).
\]

Since in Eq. (5) \( R_s \) is negligible in comparison to \( R_{sh} \), \( 1 + R_s/R_{sh} = 1 \). Let

\[
AT^3e^{(-qV_{go}/KT)}e^{q(V_{bb} + IR_s)/NKTN_s}(q/NKTN_s) = K_1.
\]

Substituting \( K_1 \) in Eq. (5) reduces Eq. (5) to the simplified form

\[
\frac{dI}{dV_{bb}} = -\frac{K_1}{(1 + K_1R_s)} \tag{6}
\]

since at Maximum Power Point (MPP) \( dP_a/dV_{bb} = 0 \).

Substituting \( dI/dV_{bb} \) from Eq. (6), and \( I_{ph} = I_{sc} \) in Eq. (4) at MPP we get:

\[
I_{ph} = K_1\left\{(NKTN_s/q) + V_{bb}/(1 + K_1R_s)\right\}, \tag{7}
\]
where \( I_{ph} \) is directly proportional to insolation.

From Eq. (7) it is easily seen that the MPP shifts leftward in the \( I-V \) curve of solar panel either if insolation decreases or cell temperature increases or when both occur simultaneously.
The temperature and solar intensity effects on the $I-V$ characteristic of PV modules are shown in Fig. 1. For tropical countries like India, the choice of PV array voltage is very difficult because of large swing in ambient temperature, and also accumulation of dust on PV panel which reduces insolation.

2.2. Loss of PV energy due to mismatch with battery-bank

The charging and discharging characteristic of a Lead Acid (LA) battery is shown in Fig. 2 [12]. From Fig. 2, it can be seen that for a typical 2 V cell of a lead-acid battery, voltage varies from 1.9 V to 2.4 V. Also occasionally for boost charging the voltage is allowed to rise up to 2.5 V. The percentage variation in voltage profile over a mean voltage 2.15 V is ±11.6%. Therefore, if the MPP of PV array is matched at 2.5 V, the loss due to voltage variation will be around 11.6% if the PV array current is constant.
However, the PV array current decreases with an increase in PV array voltage or vice versa. Therefore, the loss increases if the battery voltage is more than MPP and decreases if $V_{ss}$ is less than MPP. Hence, the MPP of PV array is matched with maximum allowable battery voltage 2.5 V, so that the decrease in battery voltage is offset by an increase in charging current. The limit of mismatch can be calculated using the $I-V$ curve of a typical 35 Wp solar panel connected to a discharged battery (1.9 V/cell) and comparing the PV output power with MPP power. In this case the operating current will be 2.35 A and the power output will be 26.79 W against the maximum power output under standard test condition (STC). The loss of available PV power output is 23.45%.

For the sake of standardisation, it is assumed that the solar panel voltage at MPP under STC has to be fixed and cannot be changed from one climatic zone to other. Even for the temperate climatic zones, MPPT is relevant because even if the solar array design is optimised to battery-bank voltage at the time of installation, there will be mismatch due to ageing because of increase in lumped series resistance $R_s$ and reduction in short-circuit current $I_{sc}$ [8]. Therefore, the MPP of PV array will decrease with time and it is difficult to predict PV array degradation which will depend on many variables, i.e., production process, temperature, and humidity cycle from one place to another. In Indian climatic condition the MPP usually shifts 4 V to 5 V leftward for a typical 35 Wp solar panel connected with battery-bank because high insolation period being associated with high ambient temperature or vice versa. In these conditions, the loss of available PV energy is more than 10%. Therefore, there is much need for maximum power point tracker (MPPT) to be integrated with PV system coupled to battery-bank against the general assumptions and practices that MPPT is only required for those PV systems which are directly coupled to resistive or inductive loads.

2.3. Experimental verification of charge equalisation problem

To verify the charge equalisation problem the following experiments were performed. Two sets of 6 V/120 AH battery bank (from same batch of production), were connected in series. The battery-bank was charged with the help of PV array (70 Wp) and standard power supply for alternate charging cycles. In order to have comparative study of the behavioural pattern of battery-bank by charging with the PV array and a standard power supply. In between every charging cycle, battery-bank was discharged at $C/10$ rate. Before charging the battery-bank, the differences in specific gravity of each cell were equalised. The charging and discharging cycles were repeated three times. During charging and discharging, measurement of voltage as well as specific gravity of individual cell were recorded at an interval of one hour. And the temperature of electrolyte was also monitored. The total ampere-hour input or output from battery-bank was recorded with the help of Ampere-Hour meter, fabricated and tested in house. The accuracy of the instrument is $\pm 3\%$, and least count 0.01 AH. The performance of battery-bank was similar for all the completed cycles irrespective of the charging source. The observation of one of the complete cycle for charge and discharge of battery-bank is given in Table 1a and 1b, respectively. From the tables the following observation are obtained.
Table 1
(a) Charging cycle of lead-acid battery-bank

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Voltage (V)</th>
<th>Overall voltage (V)</th>
<th>AH</th>
<th>/ (Amp)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cell 1</td>
<td>Cell 2</td>
<td>Cell 3</td>
<td>Cell 4</td>
</tr>
<tr>
<td>1.</td>
<td>1.901</td>
<td>2.089</td>
<td>2.116</td>
<td>2.118</td>
</tr>
<tr>
<td>2.</td>
<td>1.913</td>
<td>2.129</td>
<td>2.165</td>
<td>2.170</td>
</tr>
<tr>
<td>3.</td>
<td>2.133</td>
<td>2.142</td>
<td>2.181</td>
<td>2.189</td>
</tr>
<tr>
<td>4.</td>
<td>2.148</td>
<td>2.157</td>
<td>2.207</td>
<td>2.234</td>
</tr>
<tr>
<td>5.</td>
<td>2.156</td>
<td>2.166</td>
<td>2.241</td>
<td>2.326</td>
</tr>
<tr>
<td>6.</td>
<td>2.158</td>
<td>2.169</td>
<td>2.330</td>
<td>2.436</td>
</tr>
<tr>
<td>7.</td>
<td>2.179</td>
<td>2.193</td>
<td>2.435</td>
<td>2.439</td>
</tr>
<tr>
<td>8.</td>
<td>2.190</td>
<td>2.202</td>
<td>2.444</td>
<td>2.492</td>
</tr>
<tr>
<td>9.</td>
<td>2.207</td>
<td>2.217</td>
<td>2.466</td>
<td>2.515</td>
</tr>
<tr>
<td>10.</td>
<td>2.231</td>
<td>2.232</td>
<td>2.502</td>
<td>2.551</td>
</tr>
<tr>
<td>11.</td>
<td>2.247</td>
<td>2.249</td>
<td>2.513</td>
<td>2.557</td>
</tr>
</tbody>
</table>

(b) Discharging cycle of lead-acid battery-bank

<table>
<thead>
<tr>
<th></th>
<th>Voltage (V)</th>
<th>Overall voltage (V)</th>
<th>AH</th>
<th>/ (Amp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>2.104</td>
<td>2.096</td>
<td>2.119</td>
<td>2.112</td>
</tr>
<tr>
<td>2.</td>
<td>2.033</td>
<td>2.033</td>
<td>2.049</td>
<td>2.046</td>
</tr>
<tr>
<td>3.</td>
<td>2.027</td>
<td>2.027</td>
<td>2.043</td>
<td>2.040</td>
</tr>
<tr>
<td>4.</td>
<td>2.020</td>
<td>2.020</td>
<td>2.037</td>
<td>2.034</td>
</tr>
<tr>
<td>5.</td>
<td>2.012</td>
<td>2.014</td>
<td>2.030</td>
<td>2.027</td>
</tr>
<tr>
<td>6.</td>
<td>2.001</td>
<td>2.005</td>
<td>2.022</td>
<td>2.018</td>
</tr>
<tr>
<td>7.</td>
<td>1.986</td>
<td>1.994</td>
<td>2.012</td>
<td>2.005</td>
</tr>
<tr>
<td>8.</td>
<td>1.932</td>
<td>1.981</td>
<td>2.003</td>
<td>2.001</td>
</tr>
<tr>
<td>9.</td>
<td>1.921</td>
<td>1.979</td>
<td>2.002</td>
<td>2.000</td>
</tr>
</tbody>
</table>

(i) Cell 1 is the weakest.

(ii) The difference in cell voltages become disproportionately high after battery-bank is charged to 70% to 80% of its total capacity. This may be concluded from Fig. 2 also because beyond 2.35 V, the voltage of an individual cell changes rapidly.

(iii) The voltage difference between the weak and fully charged cell (cell 1 and cell 4) at 84 AH is 302 mV. Assuming that in a battery-bank only one cell is weak and all others are at same voltage, the cumulative effect of this difference for 12 V battery-bank will be approximately around 1.5 V. For effective charging of the battery-bank the charging source has to be at a relatively higher potential. In case of situation explained above, the potential difference between charging source and the battery is rather utilised for augmenting the storage capacity of already overcharged cells rather than augmenting the capacity of weaker cell. Similarly for 24 V or higher voltage battery-bank this difference will still be higher so the potential difference between individual cells in battery-bank makes charging inefficient. In addition, this leads to the higher rate of loss of electrolyte in those cells which are overcharged particularly when the cell voltage tends to increase [9].

(iv) From the discharge Table 1b it can be observed that cell 1 discharges faster than other cells. Since in conventional BVR, only the terminal voltage is monitored, there is a possibility that cell 1 will be discharged below 30% state of charge (SOC). Due to this
the cell loses the operational life cycle or may be damaged permanently [10]. Therefore, it is important to charge weaker battery cells at higher rate, so that the life and performance of the battery-bank do not deteriorate. Charge equalisation is also important because statistical variation of energy may accentuate the problem when the difference of potential between individual cell tends to increase.

2.4. Design of proposed BVR with multiple output switch mode power supply

The theoretical analysis of PV array coupled to a battery-bank clearly illustrates that MPPT is required to operate the PV array near MPP. Similarly it is seen from the experimental observation that different cells of battery-bank require different amount of charging current depending upon the SOC of individual cells. Thus, the conventional charging method of the battery-bank is inadequate and inefficient.

Therefore, two different control schemes are required to overcome both problems. In our proposed BVR, both the control schemes are integrated together to yield desired results. Multiple output switch mode design is used for charge equalisation and analog positive feedback control together with pulse width modulation (PWM) is used for MPPT.

The integrated scheme is illustrated in Fig. 3. In this figure a transformer is shown with three secondary windings with equal number of turns N2 connected to different block of cells. A blocking diode is connected in series between each transformer winding and blocks of cells. The electromagnetic force (e.m.f.) induced in the secondary winding will be identical, i.e., $E_{s1} = E_{s2} = E_{s3}$.

When $V_{s1}$ is less than $V_{s2}$ and $V_{s3}$ the e.m.f. $E_{s1}$ will be clamped at the voltage equal to summation of $V_{s1}$ and $V_{s2}$. And, thus, diode d2 and d3 will be reverse biased and
entire current will flow to the block 1 till $V_{s1}$ becomes equal to $V_{s2}$ and $V_{s3}$. Once they are equal, the current will be equally distributed into three loops of secondary transformer circuits. Therefore, cell voltages of different block of cells will be automatically equalised.

The operation of PV array at MPP is based on PWM technique which is regulated by APFC. This is achieved by changing the duty-cycle of switch S1 shown in figure, provided the frequency of ON-OFF cycle remains constant.

The switch S1 provides the optimum load to PV array. When the switch S1 is operated with variable duty cycle the effective load of PV array changes from the one value to another value. Where as in case of PV array connected to battery-bank through conventional BVR, load depends upon the battery bus voltage. For the case either $V_{s1} = V_{s2} = V_{s3}$ or $V_{s1} < V_{s2} < V_{s3}$. Load voltage connected to the PV array is given by

$$V' = V_{s1} + V_{d1} = (V_{s1} - V_{d1})N1/N2. \quad (16)$$

Considering switching frequency $f$, the time period $T$ will be $1/f$. If the switch S1 is ON for a period $T1$, then the effective PV array voltage will be

$$V' = (T/T1) (N1 (V_{s1} + V_{d})/N2). \quad (17)$$

From Eq. (17), it is clear that $V'$ can be adjusted to desired value by changing $T1$. This can be done by adjusting $T1$ with the help of PWM control, so that $V'$ can be operated near MPP voltage $V_m$. The PWM control for adjusting $T1$ is generated, by assuming secondary voltages $V_{s1}$, $V_{s2}$, and $V_{s3}$ constant for time under consideration and the maximum power transformation will occur when summation of the current $I$ flowing into different cells/block of cells is maximised. Therefore, effective current flowing into the secondaries is added and suitable control voltage is generated to control the pulse width $T1$ of switch S1. The generation of control voltage is also automatic and is based on APFC. At the start, control voltage is at the minimum threshold, so that pulse width $T1$ is minimum. Therefore, the load voltage $V'$ is very high and a small current only is delivered to the load. This small current in turn generates a small control voltage over minimum threshold level and, thus, $T1$ increases resulting in decrease of effective load voltage $V'$. This cycle goes on till $V'$ is equal to $V_m$. After this point, the ability to deliver more load current ceases and PV array remains latched to this condition, till $V_m$ changes due to change in insolation and temperature.

3. Circuit description

Fig. 4 shows the circuit diagram of proposed BVR. The circuit consists of four section namely power supply section, multi output switch mode section, PWM and MOSFET driver section, and APFC section.

The power supply section provides stabilised voltage to different control circuits and also automatically shuts down if the PV array voltage decreases below threshold level. The Switch Mode section consists of a ferrite transformer, MOSFETS and diodes. The transformer has two numbers of secondary windings, the PWM & MOSFET driver section is mainly composed of PWM IC LM3524. The various control to generate the
PWM signal is inbuilt in this IC [11]. Since we are using APFC concept, the control voltage is applied at pin no. 9 of this IC and desired PWM signal is obtained. A MOSFET driver IC IR uses the PWM signal for switching MOSFETS $T_1$ and $T_2$. To reduce the switching loss the concept of dual mode forward converter has been used in switch mode section. The APFC section consists of shunt resistances, current summation circuit and voltage amplifier circuit to provide the required control voltage. The shunt resistance $Sh_1$ and $Sh_2$ are connected in series between the (+) ve terminal of one block to (-)ve terminal of another block. The common point of the shunts is connected to the anode of diode which is connected to secondary winding-SW1 and dot marked terminal of SW2. The current $I_1$ in block 1 and $I_2$ in block 2 produces voltage drop $V_{ab}$ and $V_{bc}$ across shunts $Sh_1$ and $Sh_2$, respectively. Thus, the total secondary currents can be also be written as a sum of the voltage drop across shunts.

\[ V_{ab} + V_{bc} = V_{ac}, \]

or

\[ V_{ab} + V_{bc} = V_a - V_c. \]  \hspace{1cm} (18)

The function given in equation is done by operational amplifier OP1. The voltage amplification is provided by the resistance $R_f$. The operational amplifier OP2 is used to add the minimum threshold voltage with amplified voltage obtained from OP1 to get the
Table 2
Comparison of output PV power through proposed BVR connected to PV system and to the actual measured at MPP

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Output power (W) through BVR</th>
<th>Output power (W) through RHEOSTAT</th>
<th>Variation in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>46.2</td>
<td>47.77</td>
<td>(-) 3.28</td>
</tr>
<tr>
<td>2.</td>
<td>64.9</td>
<td>63.44</td>
<td>(-) 2.24</td>
</tr>
<tr>
<td>3.</td>
<td>58.75</td>
<td>58.13</td>
<td>(-) 0.10</td>
</tr>
<tr>
<td>4.</td>
<td>23.25</td>
<td>23.28</td>
<td>(+) 0.13</td>
</tr>
<tr>
<td>5.</td>
<td>49.02</td>
<td>48.93</td>
<td>(-) 0.18</td>
</tr>
<tr>
<td>6.</td>
<td>65.83</td>
<td>65.55</td>
<td>(-) 0.43</td>
</tr>
<tr>
<td>7.</td>
<td>60.08</td>
<td>60.10</td>
<td>(+) 0.33</td>
</tr>
<tr>
<td>8.</td>
<td>42.50</td>
<td>42.92</td>
<td>(+) 0.98</td>
</tr>
<tr>
<td>10.</td>
<td>56.69</td>
<td>59.36</td>
<td>(+) 4.5</td>
</tr>
<tr>
<td>11.</td>
<td>64.37</td>
<td>65.00</td>
<td>(+) 0.97</td>
</tr>
</tbody>
</table>

required control voltage. As the current increases in either of block or in both, the control voltage simultaneously increases beyond threshold voltage.

4. Discussion and results

4.1. MPPT operation

The input of proposed BVR was connected to a system consisting of a PV array of optimum voltage 33 V and 140 Wp. Two blocks of battery cells (each consisting of 3 number of cells) were connected to the output of BVR. The voltage and current supplied by the PV array was measured with the help of digital multimeter (Fluke, Model-8062A). First measurement was taken with BVR connected in the system. Then the MPP of PV array was determined by using a variable resistance. This experiment was repeated for different values of ambient temperature and insolation. The measured values of MPP

Table 3
Comparison of output PV power between different PV systems. System 1: PV system integrated to battery-bank through proposed BVR, System 2: PV system directly connected to battery-bank

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Output power through BVR (W)</th>
<th>Output power at different battery voltages directly connected to PV array (W)</th>
<th>Maximum power gain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>23.0 (V) 26 (V) 29 (V)</td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>64.9</td>
<td>61 61.1 56</td>
<td>13.76</td>
</tr>
<tr>
<td>2.</td>
<td>49.02</td>
<td>48 46.8 43.66</td>
<td>11.00</td>
</tr>
<tr>
<td>3.</td>
<td>65.83</td>
<td>64 65.2 56.5</td>
<td>15.00</td>
</tr>
<tr>
<td>4.</td>
<td>60.08</td>
<td>59.8 59.0 53.65</td>
<td>11.75</td>
</tr>
<tr>
<td>5.</td>
<td>42.55</td>
<td>42.50 42.9 39.00</td>
<td>8.00</td>
</tr>
</tbody>
</table>
with proposed BVR and MPP obtained with variable resistance are given in Table 2 for comparison. The average variation in power output by PV array is within \( \pm 1.5\% \).

The measurement of output array wattage of PV array when it is connected through proposed BVR and when directly connected to battery-bank is shown in Table 3. The increase in gain observed is between 11\% to 15\%.

The idle current consumption of the circuit is less than 5 mA and becomes negligible when solar radiation decreases below threshold limit. Thus, accounting for the power consumption of the proposed BVR and the voltage drop across connecting leads the overall gain will be around 5 to 6 percent assuming an efficiency of 90\% or more of MPPT. The expenditure incurred in implementation of this concept in PV systems (20 to 100 Wp) is likely to cost $2 to $3 only over and above conventional BVRs. The cost of solar module is approximately $4 per peak watt. Therefore, the concept becomes viable for the systems with array/module capacity of 20 Wp or more.

4.2. Charge equalisation

In the scheme for charge equalisation (Section 2.4) it was shown that entire current will either flow to the block having lowest voltage \( V_s \) or will be divided equally when the voltage of both the blocks are equal to \( V_s \). But contrary to the above theoretical assumption, during testing it was found that the total current flow was not restricted to the lowest voltage block alone. This is because the case discussed is valid for an ideal transformer. In actual practice, the leakage reactance \( (x) \), winding resistance \( (r) \) of the transformer windings limits the current flow in the secondary windings. Therefore, the current flowing in the secondary winding becomes proportional to the difference between induced e.m.f. and \( V_s \). Thus, the current flowing through Sh1 can be given as

\[
I = \frac{(E - V_s - V_d)}{(x + r_1)}.
\]

Since the induced e.m.f. in each secondary winding is equal, i.e., \( E_1 = E_2 \) and also \( V_d_1 = V_d_2 \), the larger current will flow to weak cell, provided the leakage reactance and winding resistance of both the winding are equal thereby providing the charge equalisation. The variation of current in secondary windings with the change in secondary

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Current (A) ((I1))</th>
<th>Voltage (V) ((V_{s1}))</th>
<th>Current (A) ((I2))</th>
<th>Voltage (V) ((V_{s2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>0</td>
<td>6.161</td>
<td>0</td>
<td>6.222</td>
</tr>
<tr>
<td>2.</td>
<td>1.34</td>
<td>6.648</td>
<td>0.81</td>
<td>6.456</td>
</tr>
<tr>
<td>3.</td>
<td>1.36</td>
<td>6.696</td>
<td>0.78</td>
<td>6.487</td>
</tr>
<tr>
<td>4.</td>
<td>1.33</td>
<td>6.716</td>
<td>0.796</td>
<td>6.513</td>
</tr>
<tr>
<td>5.</td>
<td>1.33</td>
<td>6.716</td>
<td>0.782</td>
<td>6.505</td>
</tr>
<tr>
<td>6.</td>
<td>1.41</td>
<td>6.757</td>
<td>1.24</td>
<td>6.588</td>
</tr>
<tr>
<td>7.</td>
<td>1.19</td>
<td>6.712</td>
<td>1.28</td>
<td>6.573</td>
</tr>
<tr>
<td>8.</td>
<td>1.21</td>
<td>6.711</td>
<td>1.25</td>
<td>6.561</td>
</tr>
</tbody>
</table>
voltage $V_s$ is given in Table 4. Initially more current flows to weaker or less charged block of battery-bank. The current in block 1 reduces and block 2 increases with the charging of the battery bank. This is due to the fact that block 1 is charged faster because of the charge equalisation provided. The higher terminal voltage $V_s$ of block 1 (compared to block 2) during the initial phase of charging is due to the difference in the internal resistance in the blocks of the battery bank which is dependent on SOC.

5. Suggestions for further improvements

Due to the voltage drop over diodes connected in secondary windings the proposed circuitry is less efficient. If we take the basic building block of 6 V, then a drop of 0.6 V to 0.8 V in diode will result in loss of over 10%. Again for 2 V and 4 V blocks the losses will increase to around 35% and 15%. Thus, a building block of 6 V was considered an optimum size for a single block of battery-bank. With the incorporation of synchronous rectifier made of MOSFET in parallel to the diode, the voltage drop over diode can be reduced. One such circuit was fabricated by authors and the voltage drop over diode was reduced to around 0.2 V. The use of Schottkey diodes in place of ordinary diodes can also lead to the reduction in $V_d$.

6. Conclusion

A design of the new battery voltage regulator has been proposed for the maximum utilisation of the photovoltaic output power. It provides extra charge equalisation current to the weak block of cells thus immensely contributing toward improving the life span of the battery-bank. The concept is simple and much cheaper compared to other control mechanisms where large number of components are needed. Thus, the desired reliability is obtained at lower cost as less number of components are used. The proposed concept also eliminates the need of keeping the same nominal battery voltage and nominal PV array voltage. Therefore, the system efficiency can be improved by high voltage transmission from field to control room and will be much cheaper because lower current rating cables and junction boxes can be used in the system.

Thus, the proposed BVR will find wide application in PV systems particularly in tropical areas where climatic variations are very high over the year. The simple concept and low idle current consumption makes it viable for being used with low power PV Systems (20 to 100 Wp) which are being used extensively as the basic power source in solar PV application.

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