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Design and Comparative Study of Three Photovoltaic Battery Charge Control Algorithms in MATLAB/SIMULINK Environment

Ankur Bhattacharjee
Bengal Engineering and Science University, Shibpur West Bengal, India

Abstract

This paper contains the design of a three stage solar battery charge controller and a comparative study of this charge control technique with three conventional solar battery charge control techniques such as 1. Constant Current (CC) charging, 2. Two stage constant current constant voltage (CC-CV) charging technique. The analysis and the comparative study of the aforesaid charging techniques are done in MATLAB/SIMULINK environment. Here the practical data used to simulate the charge control algorithms are based on a 12Volts 7Ah Sealed lead acid battery.

Keywords

PV panel, DC-DC buck converter, Lead acid battery, Constant Current (CC) charging, Two stage Constant Current Constant Voltage (CC-CV) charging, Three stage charging.

1. Introduction

The conventional energy crisis and increasing rate of environmental disorder such as air pollution and global warming; lead to rapidly increasing rate of use of non-conventional or renewable energy sources as they are clean and free from many hazardous effects. One of the most promising renewable energy sources is solar energy. Solar photovoltaic systems can be divided into two main classes;

1. Stand-alone solar photovoltaic system, 2. Grid connected solar photovoltaic system. In this paper the concentration is towards stand-alone photovoltaic system. Stand-alone PV systems are
2. used in various household applications such as solar Inverter, UPS charger, simple solar battery charger, solar Emergency Lantern, Solar Pump and solar vehicle. Battery is the primary energy storage in a stand-alone PV system. For the reliable and safe operation of these systems efficient battery charging is required so that the system performs well even when the solar panel is not working at night or cloudy weather. A dc-dc buck converter

topology is used here as the power conditioning unit between the PV panel and the battery to be charged. This paper is organized as follows; section 1. Includes the introduction of the paper. Section 2.Includes the study of equivalent circuit, mathematical model and MATLAB /SIMULINK model of PV cell, generic model of battery, and Buck converter. Section 3.Contains the control logic, MATLAB/SIMULINK models of the three charge control techniques, Section 4. Consists the comparative study of the four charge control techniques through simulation results, Section 5. contains the conclusion of the paper and at the end the references of the paper is included.

2. Equivalent circuit, Mathematical model and MATLAB/ SIMULINK model of PV CELL AND Buck converter

A. *Equivalent circuit, mathematical model and MATLAB/SIMULINK model of PV cell:* [1-3]

An ideal PV cell is modeled by a dc current source in parallel with a diode. There are losses associated with the working of a PV cell or solar cell. Voltage drop due to external contacts are represented by the drop across the series and shunt resistance. Here an equivalent circuit of a solar cell or photovoltaic cell is shown in figure 1,

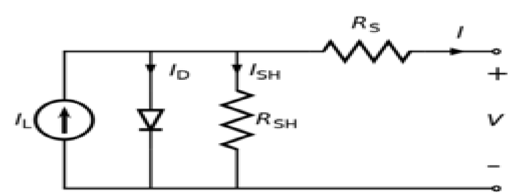

Figure.1: Equivalent circuit of a PV cell

Solar cell or Photovoltaic cell consists of a p-n junction fabricated in a thin wafer of semiconductor. There are two commonly used materials for solar cell. These are, 1. Monocrystalline silicon, 2. Polycrystalline silicon. A typical solar cell is approximately 10×10 cm in size, protected by transparent anti-reflection film. The solar panels are connected in series and parallel combination to form a solar array. Each of the PV cell produces around 0.5V (for Silicon). The voltage across a solar cell is primarily dependent on the design and materials of the cell, while the current depends primarily on the incident solar irradiance and the cell area. A solar array is formed by combination of series and parallel solar modules. From the equivalent circuit in fig. 1 we can get the following mathematical equations of a solar cell, From the above circuit, the output current of the PV cell,

$I = I_L - I_D - I_{Sh}$ (1)

Where, I_L is the photocurrent or the current generated by sunlight imposed on the PV cell.
I_D is the diode current.
I_{Sh} is the current through the shunt resistance.

And, $I_L = \left(\frac{I_{sc.stc} \times S}{1000}\right) + \left((T - T_r)K_i\right)$ (2)

where $I_{sc.stc}$ is the short circuit current of the PV cell at standard test condition (S=1000W/m^2, T=25^{0}C).
K_i is the temperature coefficient for I_{SC}.
T_r is the reference temperature.
T is the ambient temperature.
S is the solar irradiance (W/m^2).
The diode current,

$I_D = I_0\left[\exp\left(\frac{q}{AKT(V+IR_S)}\right) - 1\right]$ (3)

And, $\frac{AKT}{q} = V_T$ (4)

where, I_o is the Reverse saturation current of the diode ; q is the charge of electron (1.6×10^{-19} C).
K is the Boltzman constant (1.38×10^{-23} J/K).
A is the quality factor (lies between 1.2-1.6 for crystalline silicon).
V_T is the thermal voltage of diode.
V is the terminal voltage of the PV cell.
I_o can be expressed by,

$$I_0 = I_{rr}\left(\frac{T}{T_r}\right)^3 \exp\left[\frac{qE_g}{KA\left(\frac{1}{T_r} - \frac{1}{T}\right)}\right] \quad (5)$$

where, E_g is the band gap energy (1.12 ev for crystalline silicon).
I_{rr} is the I_o at standard test condition(STC).

And the shunt current, $I_{sh} = \frac{(V+IR)}{R_{sh}}$ (6)

Then combining the equations (2) to (6) and putting them in equation (1) we get the total output current source.
The PV cell temperature depends on the ambient temperature and the solar insolation in this way,

$T_{cell} = T_{ambient} + (T_{NOCT} - 25)\frac{S}{1000}$ (7)

where T_{NOCT} is the cell temperature at 23^{0}C and insolation of 1000W/m^2.
PV cell open circuit voltage is expressed by,

$V_{OC} = V_{OC.STC}\{1-K_V(T-T_r)\}$ (8)

where $V_{OC.STC}$ is the cell open circuit voltage at standard test condition.K_V is the temperature coefficient for open circuit voltage (0.012/^{0}C).

From the above mathematical equations of PV cell the of PV cell is modelled in MATLAB/SIMULINK environment shown in figure2 where 1000W/m^2 and 25^{0}C are the standard test conditions of insolation and temperature.

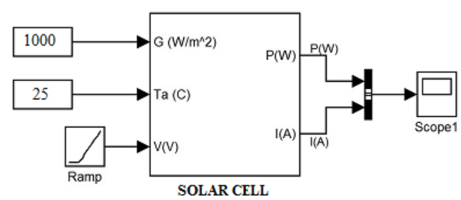

Figure. 2: MATLAB/SIMULINK model of PV cell

Here the ramp function of voltage represents the profile of current and power output from PV cell with respect to change in voltage.
The solar panel current varies linearly with solar insolation and logerithmically with temperature. The figure 3 and figure 4 Show the variation of solar cell I-Vcharacteristics[4] curve for different insolation and ambient temperature level,

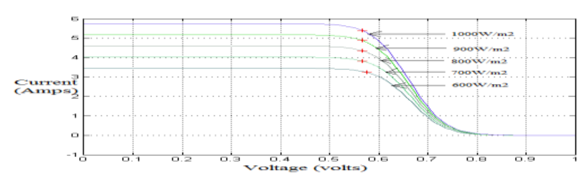

Figure 3: I-V curve of solar cell for different insolation level

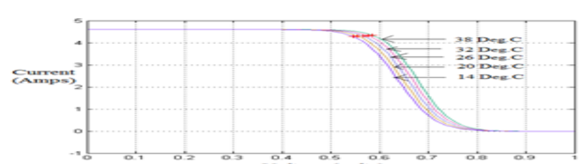

Figure 4: I-V curve of solar cell for diffrent ambient temperature level

In the above two figures 3and 4 the 'red' coloured points are the the point of maximum power at different insolation and ambient temperature.The simulation results of power vs voltage curve of solar cell for different insolation and ambient temperature level is also shown here in figure 5 and figure 6.It is seen that the power output of solar cell is greater in 14^0C temperature than that of 38^0C. Hence the performance of Solar panel is better in winter season rather than in summer.

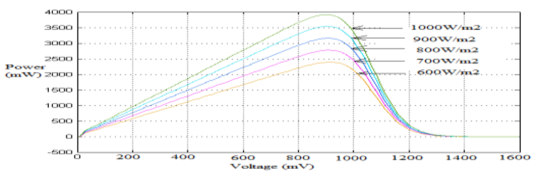

Figure 5: P-V curve of solar cell for different insolation level from 600W/m^2 to 1000W/m^2

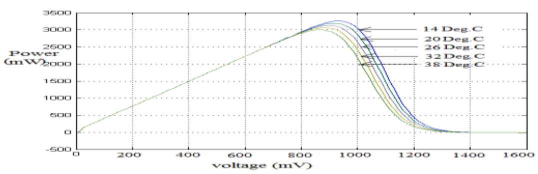

Figure 6: P-V curve of solar cell for different ambient temperature level from 14^0C to 38^0C

B. DC-DC buck converter topology:[5]

A dc-dc converter is used as a power interface circuit between the PV panel and the battery. The DC/DC converter connects/ disconnects conveniently the solar panel from the battery based on PWM (Pulse Width Modulation) signals. Here the buck converter topology is used due to two main advantages of it, 1. The required input current to the converter is small, hence the rating and the size of the PV panel becomes smaller, 2. The charge control operation remains uninterrupted even when the PV panel gives low output current at low level of insolation because the buck converter will boost the current up to the required level of charging. The equivalent circuit representation of the buck converter is shown in figure 7,

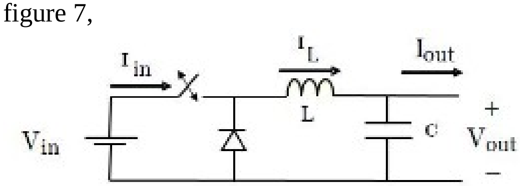

Figure 7. Equivalent circuit of dc-dc Buck converter

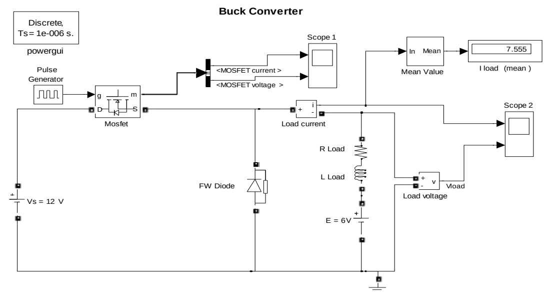

Figure 8. MATLAB/SIMULINK model of Buck converter

The average output voltage of the buck converter is, $V_{out} = \frac{1}{T}\int_0^T V_{out}(t)dt = V_{in}\frac{\partial T}{T} = V_{in}D$Where D is the duty cycle of the buck converter.

The duty cycle varies between 0 and 1. Therefore the output voltage will always be less than the input voltage. Here in this topology,V_{sa} is the V_{in} of the proposed buck converter. That means the output of the solar panel is the input to the buck converter.

3. Control logic, MATLAB/SIMULINK models of the three charge control techniques:[6-7]

A. Constant current charging technique:

In constant current charging technique the converter gives a constant charging current to the battery which means whatever variation of current the PV panel is supplying according to different solar insolation levels, is fed to the converter and the charge controller then gives the required PWM signal to the converter to supply constant current to the battery throughout the charging process. Hence the problem of irregular charging current can be avoided in this method. The schematic of this charging topology is given in figure 9,

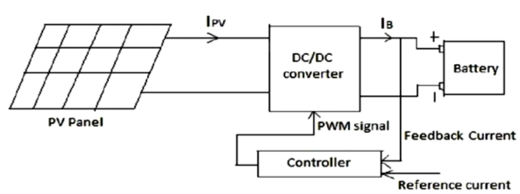

Figure 9: Constant current PV battery charging

The charging profile of the constant current charging is shown in figure 10,

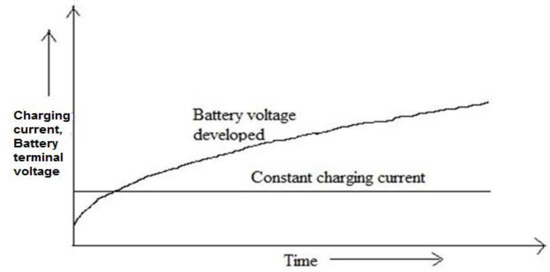

Figure 10: Charging profile for constant current PV battery charging

The MATLAB/SIMULINK model for constant current charging algorithm and the charge control logic is shown below in figure 11,

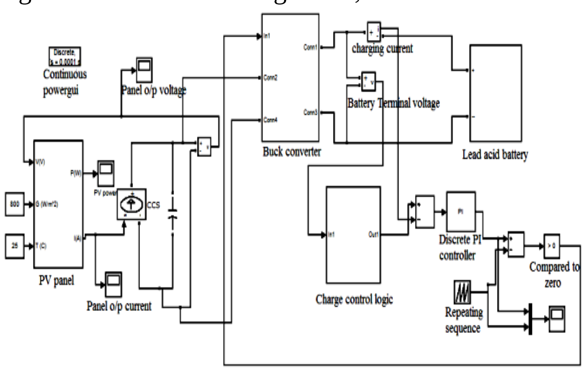

Figure 11: MATLAB/SIMULINK model of constant current PV battery charging

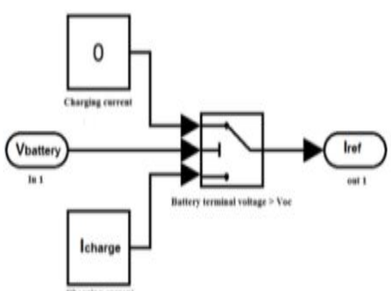

Figure 12: Control logic for constant current PV battery charging

In the above MATLAB figure 12 of control logic the battery is charged with a constant current until the battery terminal voltage is reached to a certain threshold value of V_{OC}. The In 1 is the sensed battery terminal voltage ($V_{battery}$) and out 1 is the reference charging current (I_{charge}) fed to the PI controller. When the battery voltage crosses the threshold value of V_{OC} as shown in the switch block used in the control logic, the charging process is terminated and it is shown in the control logic by setting reference charging current as zero shown in the figure 12.

B. Two stage Constant current constant voltage (CC-CV) charging technique :

The conventional Constant current constant voltage (CC-CV) charging method is applied to avoid the shortcomings which come in the constant current charging method as described earlier. Here, the entire charging process is divided into two modes, first one is constant current mode and second one is constant voltage mode. In constant current mode the battery is provided a high charging current called bulk current until the preset overvoltage limit is reached. After this threshold value of voltage is reached the mode shifts to constant voltage mode where the upper threshold voltage is maintained across the battery until the current decreases to a preset very small value called float value. If the current decreases beyond that threshold, then the charging process is terminated. The topology of this charging process is shown in the figure 13,

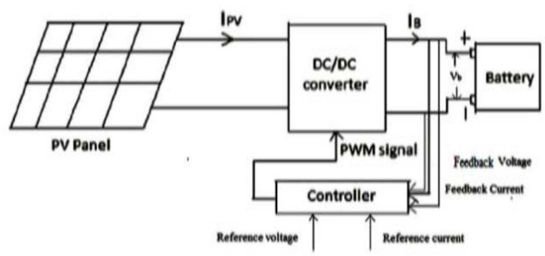

Figure 13: Two stage Constant current Constant voltage PV battery charging topology

The charging profile of this two stage charging method is shown in the figure 14,

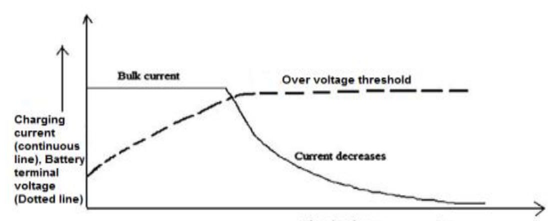

Figure 14: Charging profile of two stage Constant Current Constant Voltage PV battery charging

The MATLAB/SIMULINK model of the two stage constant current constant voltage charging method is shown in the figure 15.The MATLAB/SIMULINK model in figure 16 shows the control logic of the two stage constant current constant voltage charging algorithm. The first switch block 'Switch1' that creates condition whether the battery voltage is less than the V_{OC} or not. If it is true means the battery voltage is less than the overvoltage limit, then the constant current charging is enabled. A high charging current (bulk current) is supplied to charge the battery. The PI controller minimizes the error between the actual charging voltage and the desired charging voltage and generates the required duty cycle to trigger the converter.

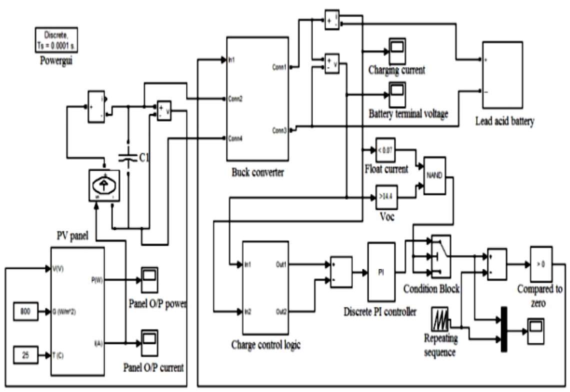

Figure 15: MATLAB/SIMULINK model of two stage constant current constant voltage PV battery charging

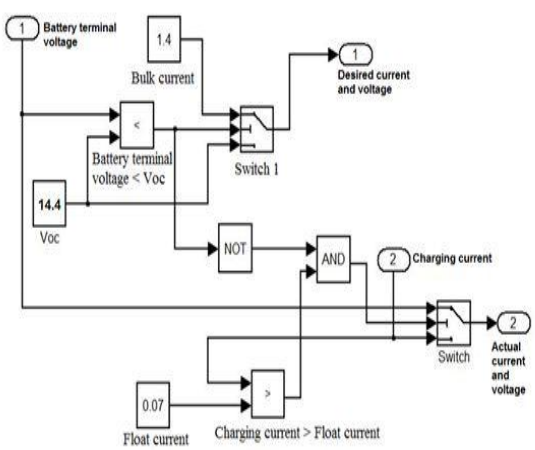

Figure 16: Control logic of two stage Constant Current Constant Voltage charging

If the condition is false means the battery voltage is greater than or equal to the V_{OC} then the constant voltage mode is enabled. The PI controller again generates the required duty cycle for the converter to track the desired constant charging voltage which is 14.4 volts for the battery considered. The second switch shows the condition whether the battery charging current falls below the threshold called float charging current rated as C/100 where C is the rated capacity of the battery. Here the lead acid battery being used has the capacity of 7Ah. Hence the float charging current threshold will be 0.07 Amperes. If the condition is true, means the charging current is greater than 0.07 Amperes. Then the constant voltage of V_{OC} is maintained by the converter across the battery terminal. If the condition is false means the charging current falls below the threshold value of 0.07Amperes the PI controller generates zero duty cycle for the converter and the battery charging is terminated.

C. Three stage charging technique:

The three stage battery charging technique is a modified two stage constant current constant voltage (CC-CV) charging method. Instead of two charging stages it has three charging stages. The topology of the circuit used to implement this charging algorithm is similar to the two stage CC-CV charging technique as shown below in the figure 17,

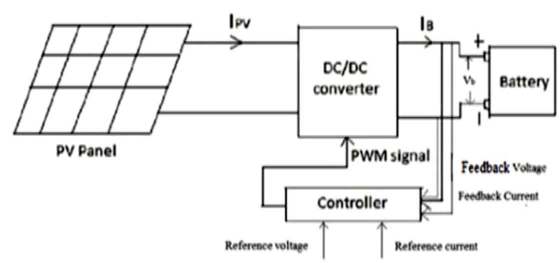

Figure 17: The three stage charging topology

The desired charging profile of the proposed three stage charging method is shown in the figure 18,

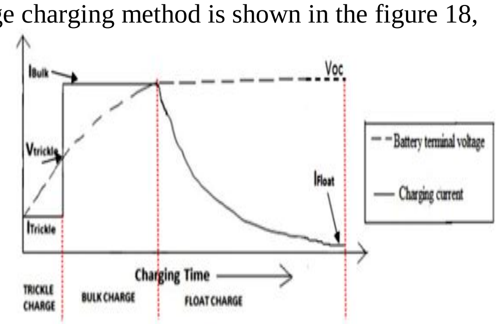

Figure 18: Charging profile of the three stage Constant current Constant Voltage charging technique

The MATLAB/SIMULINK model of the three stage charging topology is shown in the figure 19,

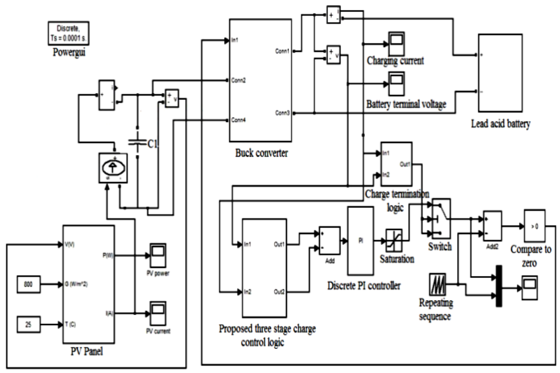

Figure 19: MATLAB/SIMULINK model of the three stage PV battery charge controller

The three stage charge control logic is shown in figure 20,

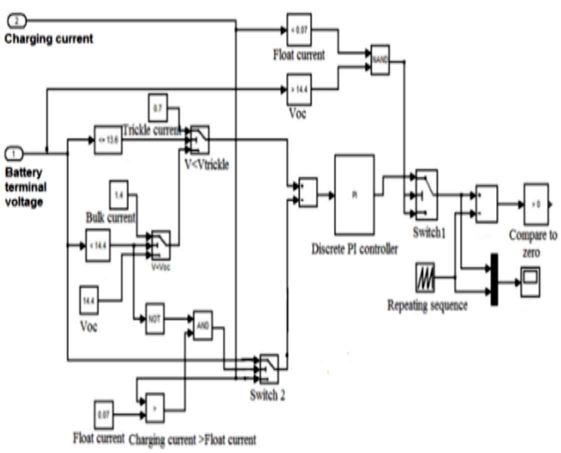

Figure 20: Control logic with PI controller for the three stage charge control algorithm

The function of the proposed control logic shown in the above MATLAB/SIMULINK model is described below. Initially the discharged battery terminal voltage is compared to the trickle charge voltage threshold at the beginning of the charging process. If the battery voltage is less than the trickle charge voltage threshold (Specified by battery manufacturer) then the trickle charging stage is enabled. Here in the above figure20, the switch condition named V $<V_{Trickle}$ is decides whether the charging current to be supplied in trickle mode or not.If this condition is true then the upper case (0.7 ampere) is enabled and if this is false then the next switch condition comes into action. The PI controller is designed in such a manner that it minimizes the error between the actual and the desired/reference value of charging current and according to that PWM (Pulse Width Modulation) signal is given to the dc-dc buck converter. The buck converter then supplies the preset trickle current to the battery. The trickle charge current reference is set to C/10 amperes where C is the battery capacity in Ampere-hour (Ah). The lead acid battery used here for experiment has capacity of 7Ah. Hence the trickle charging current set for it is 0.7 Ampere. The battery voltage starts increasing and the trickle charge current is supplied to the battery until the battery voltage reaches the Trickle voltage threshold $V_{Trickle}$. Here for the 12 volts 7Ah lead acid battery the trickle voltage threshold is set to 13.6 volts as shown in the logic in MATLAB/SIMULINK. Once the battery voltage reaches $V_{Trickle}$then the bulk charging stage is enabled. In this stage, the battery is charged by a higher current I_{Bulk}until the battery voltage is less than its overvoltage threshold $V_{OC.}$ Here also the battery voltage is compared to the reference V_{OC} and the PI controller again minimizes the error between the actual current and bulk charging reference current set as $I_{Bulk.}$ Likewise the previous condition, PWM operation is performed to give required pulse to the converter. The converter then supplies constant current I_{Bulk} to the battery. In the figure 20 the switch condition $V < V_{OC}$ is performed in this stage of charging and if it is true then the upper case (1.4 ampere) is enabled. In the bulk charging stage the reference charging current is set based on the battery rating specification. The bulk charging current is set equal to the maximum permissible charging current of the battery. Here the lead acid battery which is selected has the maximum safe charging current level of 1.4 amperes. The battery voltage increases rapidly in this charging stage because of high charging current and the I_{Bulk} is supplied to the battery until the battery voltage reaches the overvoltage limit V_{OC} specified as 14.4 volts for a 12 volt lead acid battery. Once the battery voltage reaches the overvoltage threshold V_{OC} then the charge controller changes its mode of charging from constant current to constant voltage mode called float charging stage. Here in the above figure the third switch condition comes into operation when the second switch condition fails. If this condition is true then the voltage across the battery terminal is maintained at V_{OC} and the battery takes charging current in a decreasing fashion. This V_{OC} is maintained until the battery charging current goes down to a lower threshold value I_{Float}. This

I_{Float}threshold value is set as C/100 where C is the rated capacity of the battery being used. When the battery charging current goes below the threshold value of I_{Float}, then the PI controller sends low(Zero)signal to the converter to terminate the charging process.

4. Simulation results of comparative study and analysis

A. Comparison between the constant current charging and the three stage charging technique:

The simulation results for charging current and battery voltage in the two charge control techniques is shown in figure 21 and figure 22,

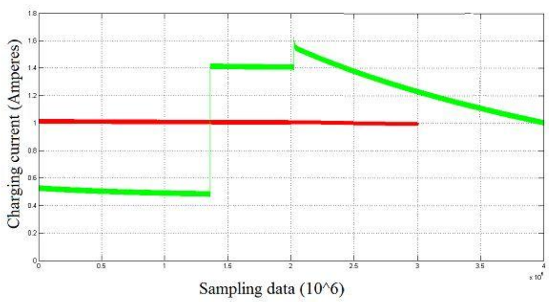

Figure 21: The charging current for constant current charging (Red) and three stage charging (Green) techniques

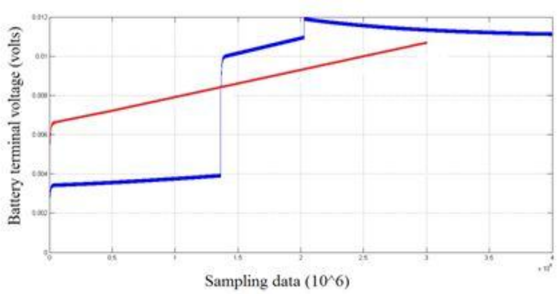

Figure 22: Battery terminal voltage for constant current charging (Red) and three stage charging (Blue) techniques

Here in the proposed three stage charge controller, initially the battery is charged with a current of 0.7Amperes whereas in the constant current charging method if the battery is charged by a constant current of 1 ampere and the constant current is supplied even in the bulk charging phase as described in the proposed algorithm where the battery is charged by 1.4 ampere current. Hence the proposed three stage charging takes much less time to charge the battery in this bulk charging phase as compared to the constant current charging method. Another critical issue is that the battery suffers from incomplete charging in constant current charging method because the charging is terminated when the battery terminal voltage reaches the threshold value Voc as shown in figure whereas in the proposed three stage charging method that threshold voltage is maintained across the battery terminal until the charging current goes down to a lower threshold value of $I_{float.}$ Hence the battery is completely charged and the life cycle of the battery remains unaffected. The three stage charging algorithm is advantageous over the constant current charging method in these critical issues.

B. Comparison between the two stage constant current constant voltage charging and the three stage charging technique:

The three stage charging method is compared to the two stage charging by simulating the charge controller models,

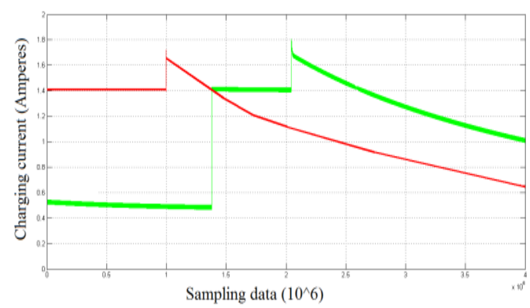

Figure 23: The charging current for two stage charging (Red) and three stage charging (Green) techniques

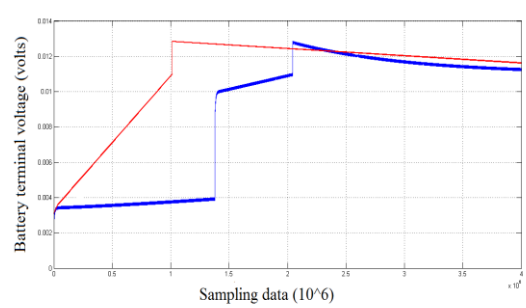

Figure 24: Battery terminal voltage for two stage charging (Red) and three stage charging (Blue) techniques

Here in the above figure the charging current of two stages charging is very high initially when the battery is charged from fully discharged condition. Hence the battery terminal voltage reaches the overvoltage threshold V_{oc} much earlier than the three stage charging technique as shown in the figure where the battery terminal voltage is maintained at V_{oc} until the charging current goes down to the I_{Float} value. But in the three stages charging algorithm the battery is initially charged with a small current and the battery voltage rises up to a certain threshold called trickle voltage and then a high charging current of 1.4 ampere of the charging current is supplied to the battery. Hence it can be stated that although the time taken to fully charge the battery by the proposed charge controller is longer than the two stages charging yet the critical issues like overheating and gassing inside the battery due to high initial charging current can be avoided.

Table 1: Comparative Study of the three Charging Algorithms

Criteria	**PV Battery Charging Algorithms**		
	CC charging	Two stage CC-CV charging	Three stage charging
1.Charging time	Depends upon constant charging current	Lesser time is required	Longer
2.Overheating & gassing	Depends upon constant charging current	Suffers from this phenomena	Overcomes this problem
3.Incomplete charging	Suffers from this phenomena	Overcomes this phenomena	Overcomes this phenomena
4. Battery life	Affected	Affected	Remains unaffected

Here from the table I, it is seen that the three stage charging is more acceptable over the other two charging techniques in the safety criticality issue of the battery life.

5. Conclusion

In this paper a three stage battery charge controller for stand-alone photovoltaic system is designed and a comparative study is done among the three different PV battery charging techniques. The comparative study of the three stage charging topology with the other three charging topologies is done by comparing the simulation results. The three stage charging method is advantageous over the constant current charging in the issues like charging time, required charging current and complete charging. The three stage charging algorithm takes lesser time to charge the battery, provides required charging current and voltage at different phases of charging and leads to complete charging of the battery thus lengthening battery life by providing full charging cycle. The three stage charging is also compared with the two stage charging and it can be concluded that the that the time taken by the three stage charging is more than the two stage charging but looking after the safety of the battery the three stage charging technique is advantageous over the two stage charging technique because the battery is charged with high initial current in two stage charging whereas in three stage charging, initially a small current called trickle current is provided to the battery up to a certain voltage threshold called trickle voltage and then high charging current is provided in the next phase called bulk charging. Hence the battery is safely charged and remains free from overheating and gassing effect caused by over current.

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Ankur Bhattacharjee was born in West Bengal, India in 1988. He received B.Tech in Electrical Engineering from Siliguri Institute of technology in 2010 and M.Tech from Bengal Engineering & Science University, Shibpur in 2012. Currently he is working as Assistant Professor in Electrical Engineering in Birbhum Institute of Engineering & Technology, Suri, Birbhum, West Bengal. His areas of interest are Solar Photovoltaics, Storage batteries, Converter operation, Control System.