Novel battery charging regulation system for photovoltaic applications

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Abstract: A battery-charging system for stand-alone photovoltaic (PV) applications is presented. Advantages of the proposed method are: better exploitation of the available PV energy by means of a maximum power point tracking (MPPT) technique employed in the control algorithm, increased battery lifetime due to higher level state of charge operation, and the charging control process does not depend on accurate battery current measurements, reducing the effect of the current sensor sensitivity on the battery final state of charge. Also, since it is based on the battery current regulation principle, it can be effectively used with large battery strings. The experimental results verify that, using the proposed method, a better exploitation of the available PV energy, compared to a commercial battery charger based on the on/off principle, is achieved, and simultaneously a 100% battery state of charge is reached in shorter time.

1 Introduction

Rechargeable batteries are widely used in stand-alone (i.e. not grid-connected) photovoltaic (PV) systems to store the energy surplus and supply the load in case of low renewable energy production. The most common type used is the valve regulated lead–acid (VRLA) battery, because of its low cost, maintenance-free operation and high efficiency characteristics. Although the battery installation cost is relatively low compared to that of PVs, the lifetime cost of the battery is greatly increased because of the limited service time [1]. The expected battery lifetime is reduced if there is low PV energy availability for prolonged periods or improper charging control, both resulting in low battery state of charge (SOC) levels for long time periods. The overall system cost can be reduced by the use of proper battery charging/discharging control techniques, which achieve high battery SOC and, consequently, longer lifetime.

A battery-charging approach, that has been widely applied in PV systems is based on directly connecting the solar array to the battery bank [2]. As shown in Fig. 1*a*, for a six-cell battery, the battery is supplied by the maximum available PV current, which depends on the battery state of charge. When a preset overcharge limit is reached, the battery is disconnected from the power source. In a similar version, the full PV array current is supplied to the battery until the battery voltage increases to a voltage regulation set point. Then it is either regulated at this value [3], or at a lower floating voltage [4], for finishing the charging process, as shown in Figs. 1*b* and *c*, respectively. The disadvantage of these methods is that the overcharge limit or the voltage regulation set point do not always correspond to the battery 100% state of charge condition since, as explained below, the voltage at which battery overcharging begins depends on the charge rate, which varies according to atmospheric

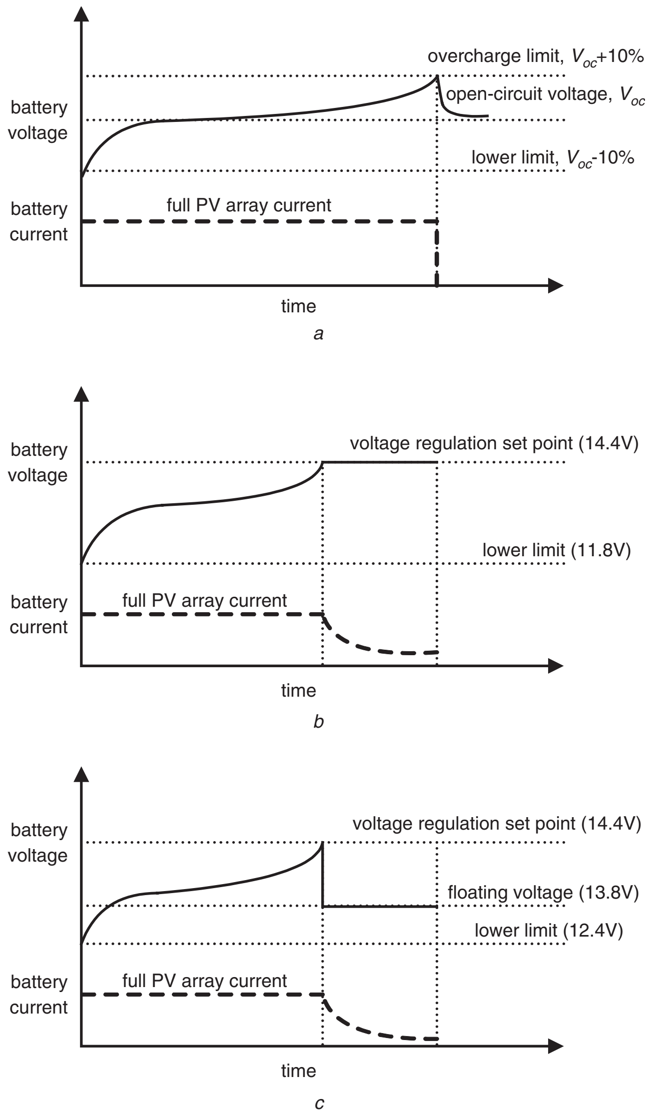

Fig. 1 *Battery charging control schemes*
a Power source disconnection at an overcharge voltage limit
b Regulation at a preset voltage level
c regulation at a lower floating voltage

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conditions. Thus, the battery remains in a floating charging state for a longer time, until it is fully recharged. Additionally, voltage regulation is not effective in large battery strings, as it results in a non-uniform charging of the individual cells, thus degrading the battery service time performance.

An alternative charging method is based on on/off control [5], applying either the full array current or no current to the battery bank. In [6], the on/off current control process, shown in Fig. 2*a*, is initiated after the battery voltage rises above the end point charge voltage and aims to regulate the battery voltage to a lower floating voltage level. In [7], a battery charger limits the battery current, using on/off control, to regulate the battery voltage to an upper set point after the battery voltage rises above a lower set point, as shown in Fig. 2*b*. A disadvantage of on/off control algorithms is that, during the off time, which increases according to the battery state of charge, no energy is transferred to the battery, resulting in a prolonged time required to finish the charging process. Thus, for highly variable atmospheric conditions, the battery may not reach the 100% state of charge at the end of the day.

Although, charge equalisation algorithms have been proposed [8], application of such control schemes is not always feasible, as access to individual cells or blocks of cells is required.

In [9], a battery-charging algorithm based on ampere-hour measurements was proposed. The battery state of charge is estimated as:

$$SOC_{k+1} = SOC_k + \frac{\sum_t \left(I_{bat}(t) - I_{gas}\right)\Delta t}{C} \qquad (1)$$

where SOC_k, SOC_{k+1} are the battery state of charge at steps k and $k+1$, respectively, $I_{bat}(t)$ is the battery current, I_{gas} represents the battery losses, Δt is the time interval and C is the nominal capacity in ampere-hours. However, using this method, the determination of both SOC and battery lifetime are highly affected by the current measurement error.

The effectiveness of methods using linear models, artificial neural networks or Kalman filters [10] for determining the battery state of charge, is based on exact battery characteristics reference data and accurate battery models, which in most cases are not available.

In this paper, an alternative battery charging control technique for PV applications is presented. The block diagram of the proposed system is shown in Fig. 3. A PV array is interfaced to a buck-type DC/DC power converter, and a microcontroller-based unit is used to control the battery charging process. The charging regulation concept is presented in Fig. 4, where the voltage against state of charge characteristics of a VRLA cell [11], for various charge rates, are also depicted. It is observed that cell overcharging starts at about 2.4 V/cell, irrespective of the charge rate, and the 100% state of charge condition coincides only with the overcharging at a $C/100$ charge rate, where C is the cell capacity in ampere-hours. The battery current is continuously monitored and a limit is set on the maximum permissible charging current, indicated by the bold line in

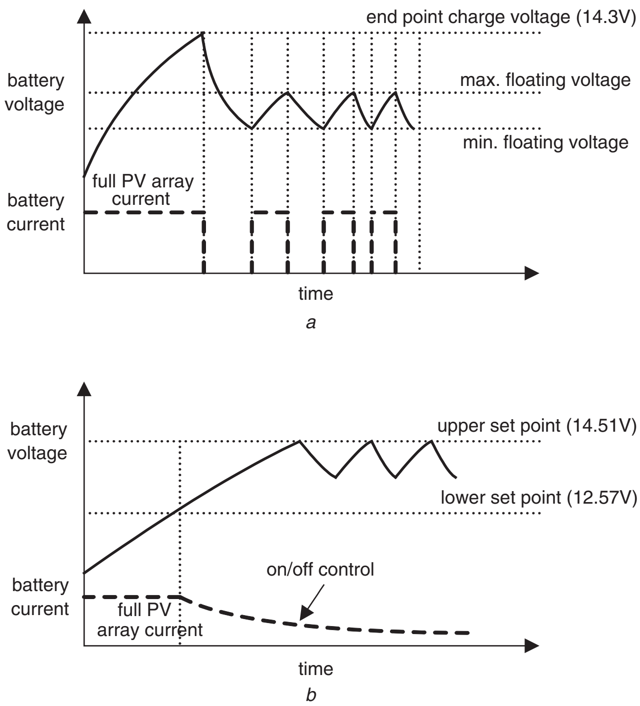

Fig. 2 *On/off control based battery charging*
a battery voltage regulation at a floating voltage
b battery voltage regulation at an upper set point

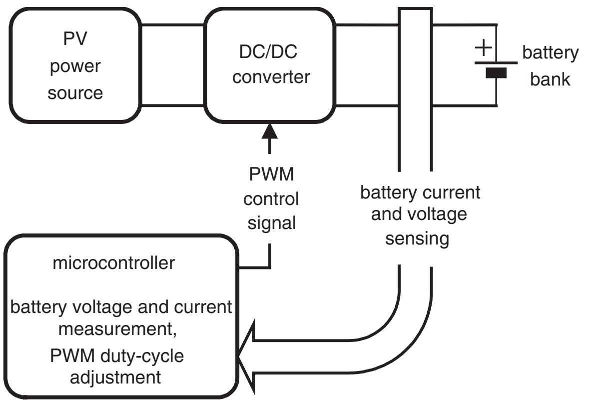

Fig. 3 *Block diagram of proposed system*

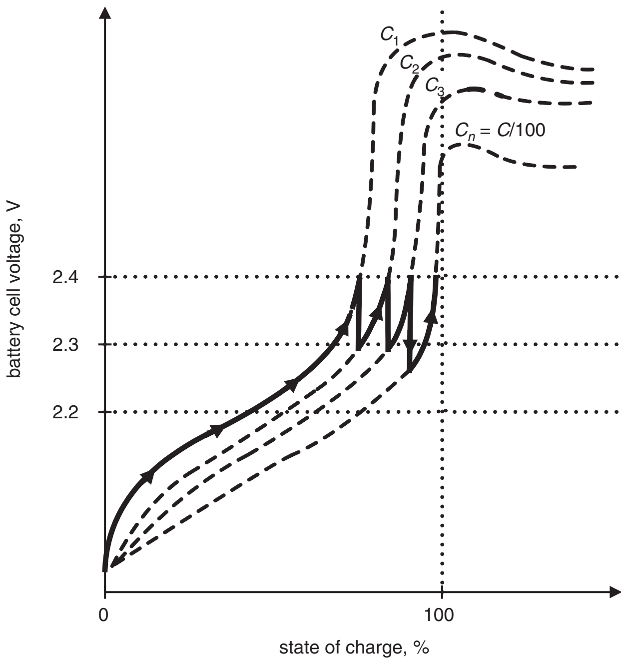

Fig. 4 *Battery-charging regulation concept*
C_1, C_2, C_n are the charge rates and C is the battery capacity in ampere-hours

Fig. 4. The actual charging current is allowed to be equal to or less than this maximum current. The battery-charging current depends on the PV power production and varies according to the atmospheric conditions, and the battery voltage level depends on both the battery-charging current and its state of charge. For low PV output power, a maximum power point tracking (MPPT) algorithm is executed, maximising the energy transferred to the battery bank. For other cases, the battery charging current is regulated to the maximum permissible current.

The battery voltage is also measured and every time it rises above 2.4 V/cell, denoting an overcharging condition, the maximum permissible battery current is decreased. This process is repeated until the maximum battery current is reduced to $C/100$. Then a battery voltage increment above 2.4 V/cell indicates a 100% state of charge. In this case, the battery current is kept to a low value to compensate for the control unit power consumption and the battery self-discharge. The initial value of the maximum battery charging current is restored when a discharging condition is detected.

Advantages of the proposed method over the on/off algorithms described above, are: (*a*) better exploitation of the power produced by the PV power source, (*b*) increased battery lifetime by restoring the maximum possible battery SOC in the shortest charging time, and (*c*) it is less affected by the current measurement errors. Furthermore, in contrast to voltage-regulation methods, as the proposed method is based on battery current regulation, it results in a uniform charging of all cells. Thus it can be effectively used in large battery strings.

2 Proposed system

A detailed block diagram of the proposed system is shown in Fig. 5. The buck-type DC/DC converter is designed according to the system power capability requirements, as analysed in [12].

The control unit in Fig. 5 consists of (*a*) an Intel 80C196KC microcontroller and (*b*) interface circuits required to lead the battery ambient temperature, voltage and current signals to the microcontroller. The microcontroller on-chip 8-bit pulse width modulation (PWM) generator output drives the DC/DC converter, according to the battery charging algorithm analysed below. A liquid crystal display (LCD) informs the user about various parameters of the system operation. The control unit has its power supply from the battery, which is charged by the DC/DC converter.

The battery voltage is measured by means of a voltage divider interfaced to an op-amp-based voltage-follower, and a Hall-effect based sensor is used to measure the battery current. A LM35 precision centigrade temperature sensor is employed to monitor the battery ambient temperature.

The control algorithm flowchart is shown in Fig. 6. A set of variables is used to store the following parameters of the system operation:

- the minimum and maximum permissible battery voltage and current levels
- the desired power control action (variable *UP* in Fig. 6, taking values 1 and 0), indicating whether the MPPT process must be performed or the PV output power must be decreased.

Their initial values are given in Table 1. The maximum battery current is set to $C/5$, where C is the battery capacity in ampere-hours, for protection of the battery from overheating, and the minimum current is set to $C/100$, corresponding to a battery 100% state of charge, according to Fig. 4. When the battery is fully charged, the battery-charging current is regulated to $I_{trickle}$, to compensate for the control system power consumption and the battery self-discharge, according to the battery manufacturer's specifications. For the case study under consideration, the maximum battery voltage is set at 28.8 V, as overcharging starts at 2.4 V/cell at 25°C and the battery stack consists of 12 cells. The minimum voltage level is set at 25.4 V, which is the battery open-circuit voltage at 90% state of charge at 25°C.

With reference to the flowchart shown in Fig. 6, the program variables and the microcontroller special function

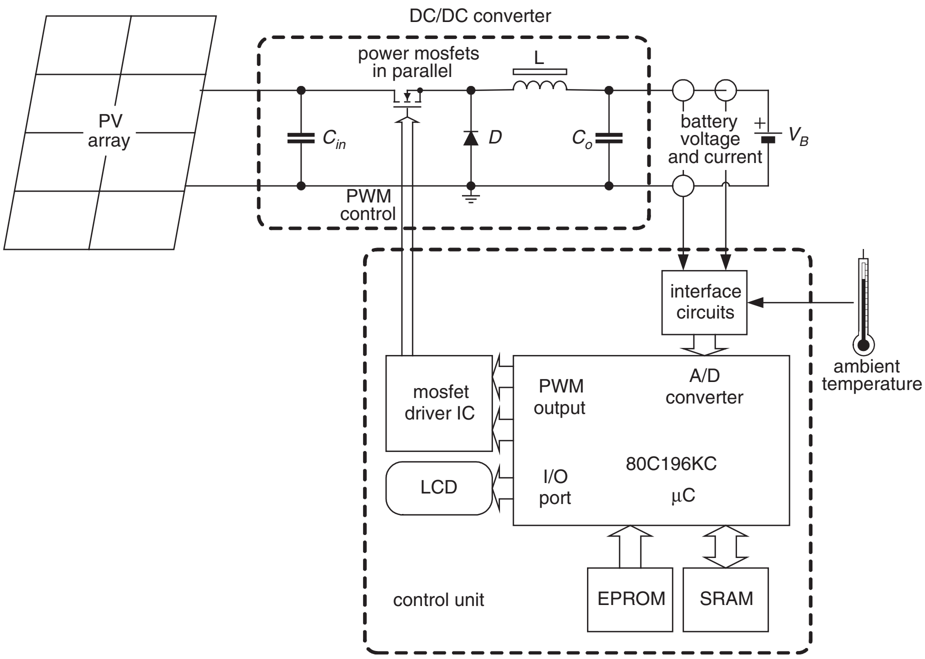

Fig. 5 *Detailed diagram of the proposed system*

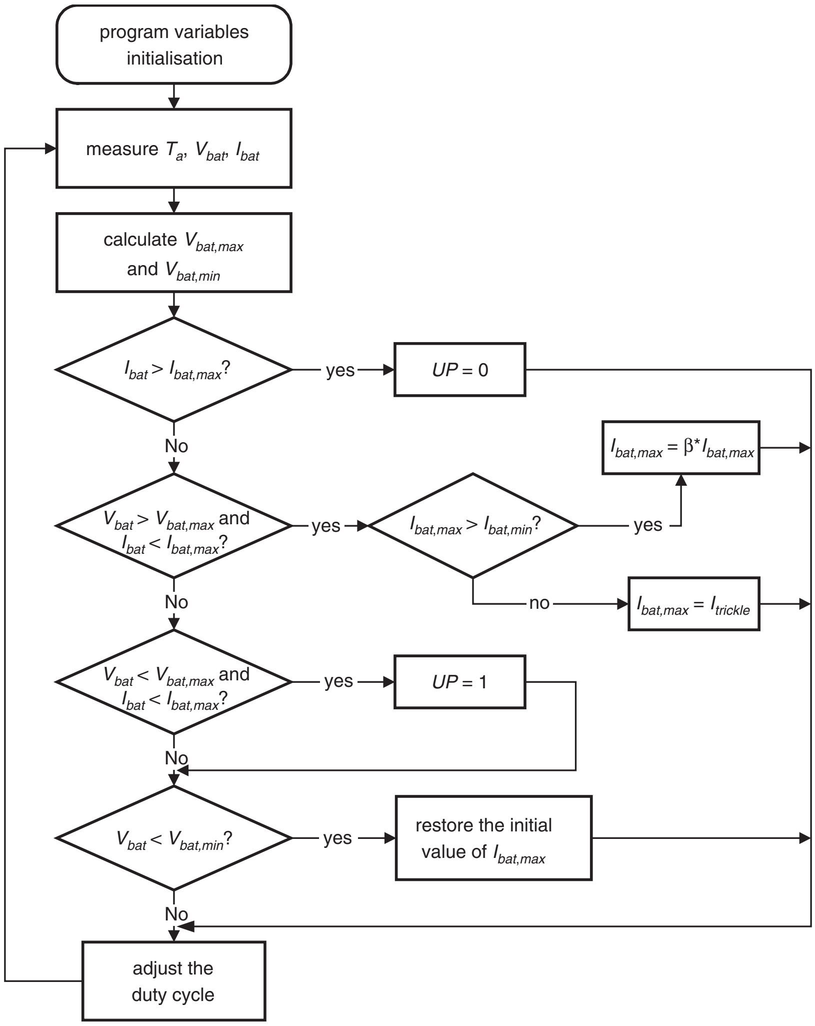

Fig. 6 *Control algorithm flowchart*

Table 1: The initial values of the program variables

Variable	Initial value
Minimum battery current ($I_{bat,min}$)	$C/100$
Maximum battery current ($I_{bat,max}$)	$C/5$
Trickle current ($I_{trickle}$)	0.2 A
Minimum battery voltage ($V_{bat,min}$)	25.4 V at 25°C
Maximum battery voltage ($V_{bat,max}$)	28.8 V at 25°C
Control direction (UP)	1

registers (SFRs) are initialized, while the ambient temperature and the battery voltage and current are measured.

The minimum and maximum battery voltage levels are then calculated as:

$$V_{bat,max} = 28.8 + (T_a - 25)N_C\alpha \quad (2)$$

$$V_{bat,\min} = 25.4 + (T_a - 25)N_C\alpha \quad (3)$$

where T_a is the ambient temperature, $N_C = 12$ is the number of cells of the battery stack and $\alpha = -3.5\,\text{mV}/^\circ\text{C}/\text{cell}$ is the temperature compensation coefficient [11].

Then a sequence of control actions are performed, to regulate the battery charging process:

- If the battery current is higher than the maximum battery current, then the variable UP is set to zero, indicating that the battery charging current must be reduced.
- If the battery voltage rises above the maximum voltage level, meaning that it is in overcharge state, the maximum battery current is reduced. Thus, at the next iteration of the algorithm, the actual battery current will be reduced according to the previous control action. When the maximum battery current reaches the $C/100$ level, indicating a 100% battery state of charge, the maximum battery current is set to $I_{trickle}$, as described above.
- If the battery voltage is below the maximum voltage level, then the variable UP is set to 1 so that the duty cycle is adjusted such that the PV output power is maximised (MPPT process). Additionally, if the battery voltage is below the minimum voltage level, indicating a discharging condition, the maximum battery charging current is restored at its initial value.

The next step is the PWM signal duty cycle adjustment, according to the decisions taken at the previous steps of the algorithm. When the battery charging current must be reduced, indicated by the variable UP value mentioned above, the duty cycle must be reduced, i.e.:

$$D_{k+1} = D_k - |\Delta D| \quad (4)$$

where $|\Delta D|$ is set to 1/256, which is the maximum precision allowed by the 8-bit PWM word length. On the other hand, if the MPPT process must start, the duty cycle is adjusted as follows:

$$D_{k+1} = D_k + |\Delta D| sign(\Delta D_k) sign(P_{in,k} - P_{in,k-1}) \quad (5)$$

where D_{k+1} and D_k are the duty cycle values at steps $k+1$ and k respectively ($0 < D_k < 255$), ΔD_k is the duty cycle change at the k step, $P_{in,k}$ and $P_{in,k-1}$ are the converter input power levels at steps k and $k-1$, and the function sign(x) is defined as:

$$\begin{aligned} \text{sign}(x) &= 1, \quad if\ x \geq 0 \\ \text{sign}(x) &= -1, \quad if\ x < 0 \end{aligned} \quad (6)$$

Because of the relatively long battery time constants, the battery state of charge is considered to be invariable between consecutive steps of the control algorithm. The $I_{bat,max}$ reduction coefficient, β in Fig. 6, is selected so that, during the total time required to reduce $I_{bat,max}$ from $C/5$ to $C/100$, the battery state of charge change is less than 1% of the battery nominal capacity, to prevent battery overcharging.

The following analysis proves that the duty cycle reduction results in regulation of the battery current to the desired level. When the converter operates in the continuous conduction mode [12], the input and output voltage levels are related as follows:

$$D = \frac{V_o}{V_{in}} \quad (7)$$

and

$$\frac{dD}{dV_{in}} = -\frac{V_o}{V_{in}^2} < 0 \quad (8)$$

where V_{in} and V_o are the DC/DC converter input and output voltage levels, respectively, and D is the PWM control signal duty cycle value.

When the converter operates in the discontinuous conduction mode the input/output voltage relation is described as follows:

$$\frac{V_o}{V_{in}} = \frac{D^2}{D^2 + \frac{I_{in}}{I_{LB,\max}}} \quad (9)$$

$$I_{LB.\max} = \frac{V_o}{2 f_s L} \quad (10)$$

where I_{in} is the converter input current, L is the power inductor value and f_s is the switching frequency. Rearranging (9) gives:

$$D = \sqrt{\frac{V_o I_{in}}{(V_{in} - V_o) I_{LB,\max}}} \quad (11)$$

and consequently:

$$\frac{dD}{dV_{in}} = \frac{1}{2} \sqrt{\frac{(V_{in} - V_o) I_{LB,\max}}{V_o I_{in}}} \frac{V_o}{I_{LB,\max}} \frac{d f(V_{in})}{dV_{in}} \quad (12)$$

where:

$$f(V_{in}) = \frac{I_{in}}{V_{in} - V_o} \quad (13)$$

and

$$\frac{df(V_{in})}{dV_{in}} = \frac{-I_{in} + \frac{dI_{in}}{dV_{in}}(V_{in} - V_o)}{(V_{in} - V_o)^2} = \frac{-\frac{I_{in}}{(V_{in} - V_o)} + \frac{dI_{in}}{dV_{in}}}{(V_{in} - V_o)} \quad (14)$$

Considering the PV array current/voltage characteristic [13], it holds that $\frac{dI_{in}}{dV_{in}} < 0$ and as $V_{in} > V_o$, (12) yields:

$$\frac{dD}{dV_{in}} < 0 \quad (15)$$

Considering (8) and (15), it holds that $\frac{dD}{dV_{in}} < 0$ in both the continuous and discontinuous conduction modes. Thus a duty cycle reduction causes a PV array output voltage increment. As shown in Fig. 7, continuously increasing the input voltage results in successively moving on the hill-shaped power characteristic at power levels $P_{in,1}$, $P_{in,2,..,}$ $P_{in,k}$. Because the power transferred to the battery is equal to the PV output power at each step, it holds that:

$$I_{o,k} = \frac{P_{o,k}}{V_o} = \frac{P_{in,k}}{V_o} \quad (16)$$

and

$$I_{o,k} < I_{o,1} < I_{o,2} \quad (17)$$

where $I_{o,n}$, $n = 1,2,\ldots,k$, is the battery current and $P_{o,k}$, $P_{in,k}$ are the battery and PV source power levels, respectively, at the kth step of the regulation process.

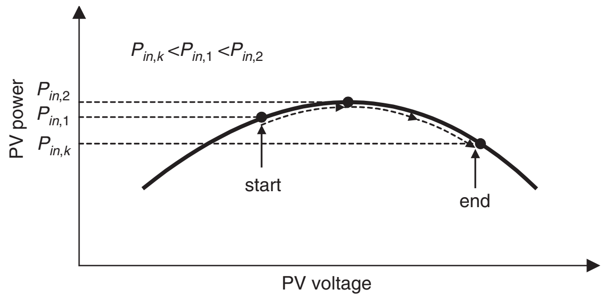

Fig. 7 *Battery-charging current regulation process*

Thus successively decreasing the duty cycle value results in battery charging current regulation below the maximum battery current, according to the control algorithm requirements described above. However, its value might temporarily increase during the regulation process (e.g. during the transition from power level $P_{in,1}$ to $P_{in,2}$ in Fig. 7), but this does not cause battery overcharging, since the control algorithm execution time is less 0.5 ms, and the battery time constants are of the order of seconds [14].

3 Experimental results

The battery-charging method described above was laboratory tested with a PV power source charging two series-connected 12 V, 225 Ah nominal capacity VRLA batteries.

The battery-charging process for a 450 W nominal power PV source is shown in Fig. 8. As can be seen in Fig. 8*a*, the available irradiation, and consequently the available PV power, did not change substantially during the battery current regulation process. During the bulk-charging phase, the maximum available PV power is transferred to the battery stack, according to the MPPT algorithm. The charge-regulation phase is initiated when the battery voltage rises to 28.8 V (Fig. 8*c*) and the battery charging current (Fig. 8*b*) is progressively reduced to 2.5 A at the end of this phase. At the end of the charge-regulation phase, the battery is left in open-circuit condition and the battery voltage measured after 5 h was found to be 25.65 V,

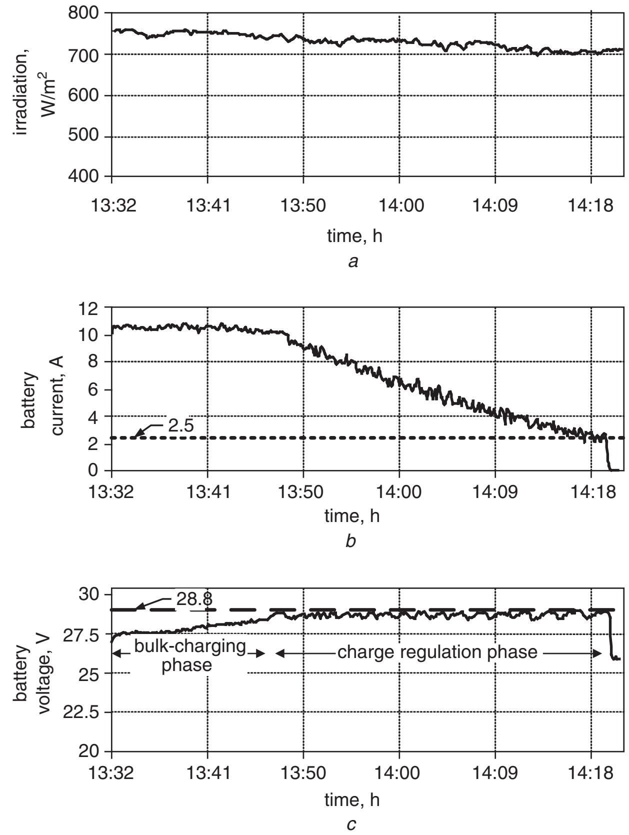

Fig. 8 *Battery-charging process with a PV power source*
a Global irradiation
b Battery current
c Battery voltage

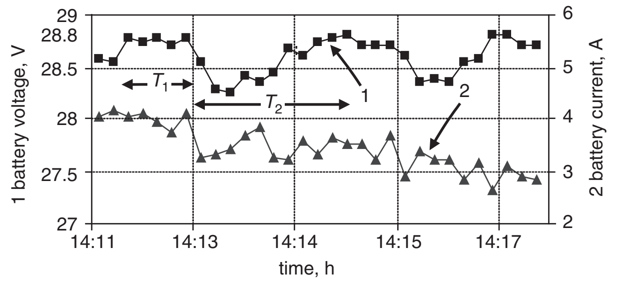

Fig. 9 *Battery voltage and current during a short time interval of the battery charging process shown in Fig. 8*

corresponding to 100% battery state of charge, thus proving the success of the charging algorithm.

A more detailed diagram of the charging process, extending in a short time interval of the charge-regulation stage, is shown in Fig. 9. It is seen that, during the time interval T_1, the battery current is progressively reduced by 0.5 A, resulting in a reduction of the battery voltage from 28.8 V to 28.5 V at the end of T_1. The battery state of charge is constant during T_1 and the voltage change is due to the battery internal resistance voltage drop reduction. During the time interval T_2, the battery voltage rises towards 28.8 V because of the battery state of charge increase. The battery current changes, following the short-term changes of the available solar power, while it is simultaneously limited slightly below $I_{bat,max}$ in order to use the maximum permissible PV power.

The battery-charging process, using a commercial solar charger operating according to the on-off principle described earlier, with the same battery stack and PV power source, is shown in Fig. 10. During the bulk-charge

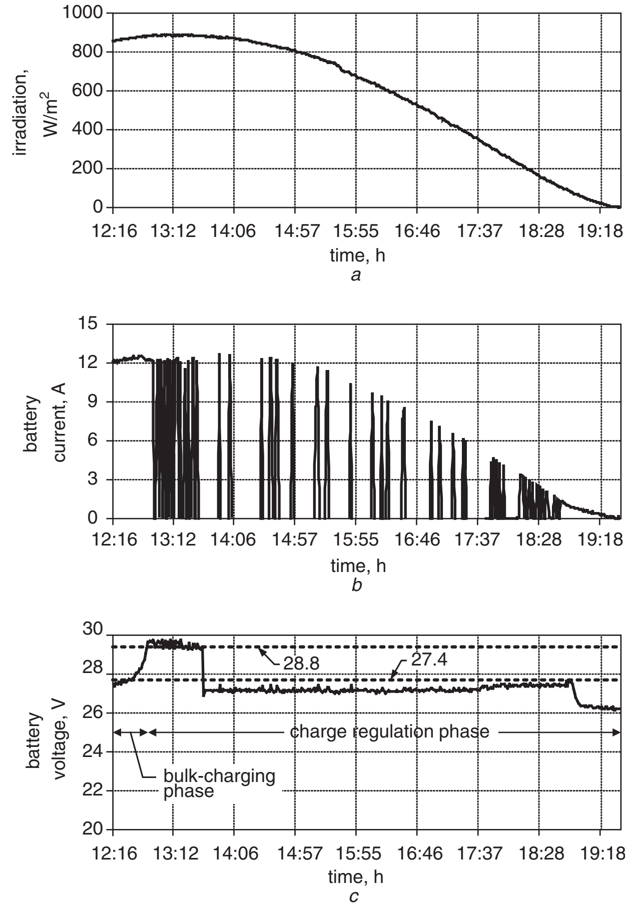

Fig. 10 *Battery-charging process using a commercial solar charger*
a Global irradiation
b Battery current
c Battery voltage

phase, the PV source is directly connected to the battery until the battery voltage rises to 28.8 V. Then, the charge-regulation phase is initiated, where the battery voltage is first regulated at 28.8 V for one hour using on-off control and then regulated at 27.4 V, also implemented with on-off control. The solar power, computed from the measured irradiation (Fig. 10*a*), is comparable to the solar power reaching the proposed system described above. This method also results in a 100% battery state of charge at the end of the charging process. However, comparing Figs. 8*b* and 10*b*, it is observed that the time required to finish the charge regulation is longer. This happens because the on-off control performed by the commercial charger does not fully exploit the available PV power. The result is incomplete charging for low irradiation conditions.

4 Conclusions

The overall cost of a stand-alone PV system can be reduced with proper battery-charging control techniques, which achieve high battery state of charge and lifetime, under continuously varying atmospheric conditions, which give rise to intermittent PV energy production.

In this paper, a novel battery charging regulation system has been presented, consisting of a DC/DC converter controlled by a low-cost microcontroller unit. Advantages of the proposed method are: (*a*) the MPPT technique employed in the control algorithm assures maximisation of the energy transferred to the battery bank, and thus better exploitation of the PV source is achieved; (*b*) the battery lifetime is increased because the battery is operating at higher state of charge; and (*c*) the battery-charging algorithm does not depend on accurate battery current measurements, thus reducing the current sensor accuracy required and subsequently the cost of the circuitry. Also, since it is based on battery current regulation, it can be effectively used in large battery strings.

The experimental results verify that the use of the proposed method results in better exploitation of the available PV energy, compared to a commercial battery charger based on the on/off principle, while simultaneously a 100% battery SOC is achieved in shorter time.

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