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Conception and regulation of Battery Charging Using PI Controller

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***Abstract*— This paper deals with the use of *PI* controllers to charge a lead acid battery using a *PV* generator as input source and a buck converter. For the safety of the battery, the voltage and the current must be limited in their nominal values, for this purpose two regulation loops (voltage loop and current loop) are proposed and simulated using Matlab/Simulink software and implemented in Arduino Board. The first loop regulates the voltage of the output buck converter at the reference voltage and gives the reference current to the second loop, which regulates the output current of the converter at its reference and generates a variable duty cycle for the control of the Pulse Width Modulation *(PWM)* buck converter. Simulation and experimental results are presented to illustrate the efficiency of the proposed design.**

***Keywords*— Battery, PV, Buck converter, PI controller.**

I. INTRODUCTION

Due to fossil fuel depletion and the greenhouse gas problems caused by conventional energy production, renewable energy sources are being extensively used, such as photovoltaic sources, fuel cells, wind generation, etc [1]. In our work, we propose the use of photovoltaic energy, which induces the concept of power storage due to the intermittent availability of such a resource (variable solar illumination) [2]. Nowadays rechargeable batteries are generally used in isolated sites (i.e. which are far of the power network), to store the energy excess and supply the load in case of low PV energy production [2]. Lead-acid battery is widely used in these applications because of its low cost and its easy maintenance. However it has a short lifetime (300 to 800 cycles of charge and discharge), in addition the charge and the discharge need to respect the limits given by the manufacturer (maximum and minimum voltage, maximum current of charge) in order to preserve a long lifetime of the battery, for this purpose a battery charger is indispensable. In the literature, various circuit systems are used between the PV source and the battery, to insure safety charge and discharge of this last [3-6]. In this paper we propose a DC to DC buck converter [3-11], as battery charger, this choice is justified by the fact that the PV output voltage is greater than that of the battery. To insure a safety charge and discharge of battery, the DC to DC buck converter is controlled using PI controllers [3-9]; two loops are needed, the voltage loop is implemented to charge the battery at its nominal voltage provided by the constructor in three steps (bulk, absorption and float), the current loop is implemented to respect the maximum current charge, equal to C/5, where C is the cell capacity in ampere-hours and the minimum current of charge is equal to C/100 [3]. The overall system composed by the PV system, the buck converter, the control loops and the lead acid battery is modelled and simulated by Matlab/Simulink. Moreover, experimental results are given using a cheap arduino mega card for the implementation of the PI controllers and drive the buck converter.

II. MODELLING OF PHOTOVOLTAIC ARRAYS

A photovoltaic cell has an equivalent behaviour to a current source shunted by a diode [12] Fig.1.

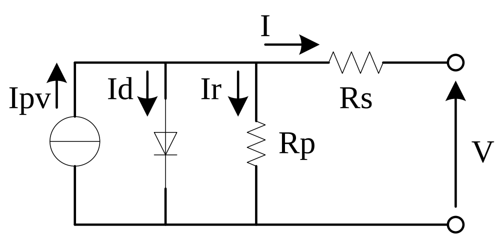

Fig. 1 Electrical equivalent circuit of a photovoltaic cell.

The *I-V* characteristic of a practical photovoltaic array is derived by equation 1:

$$I = Ipv - Id - Ir \quad (1)$$

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Where:
I_{pv}: is the photovoltaic currents of the array.
I_d: is the current of diode.
I_r: is the derived current by shunt resistor.
It follows that [12]:

$$I = Ipv - Io\left[\exp\left(\frac{V + Rs\left(\frac{N_{ser}}{N_{par}}\right)I}{Vt \cdot a \cdot N_{ser}}\right) - 1\right] - \frac{V + Rs\left(\frac{N_{ser}}{N_{par}}\right)I}{Rp\left(\frac{N_{ser}}{N_{par}}\right)} \qquad (2)$$

Where:
$V_t=N_s.K.T/q$ is the thermal voltage of the array with N_s cells connected in series, R_s is the equivalent series resistance of the array, R_p is the equivalent parallel resistance and N_p is the number of cells connected in parallel.
The photovoltaic current of the array depends directly on the solar irradiation level and temperature according to the equation 3:

$$Ipv = \left(Ipv,n + Ki \cdot \Delta T\right) \cdot \frac{G}{G_n} \qquad (3)$$

Where:
$I_{pv,n}$ [A] is the light-generated current at the nominal condition (usually 25 ° C and 1000W/m^2), $\Delta T = T - T_n$ (being T and T_n the actual and nominal temperatures [K]),
G [W/m^2] is the irradiation on the device surface, and G_n is the nominal irradiation.

III. Battery charger system

In this study, the coupling of a PV panel with a battery via a DC/DC converter is considered, as shown in Fig. 2. The PV panel is made of two series cells KD135GH from Kyocera, where each has a 17.7 voltage at 1000 W/m^2 irradiance. The load is made of 6 series OPzV type batteries with 2 volts each. A DC/DC converter is used to step down the PV potential to the battery limit as represented in Fig 2.

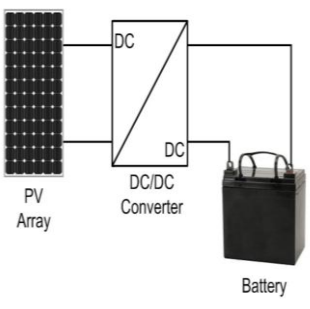

Fig. 2 Schema of Batteries charger system.

IV. Description of Buck converter

The step-down *DC/DC* converter, commonly known as a buck converter, is shown in Fig. 3. It consists of: a *DC* input voltage source VS, a controlled switch *Mosfet*, a diode *D*, a filter inductor *L*, a filter capacitor *C*, and a load resistance *R*.

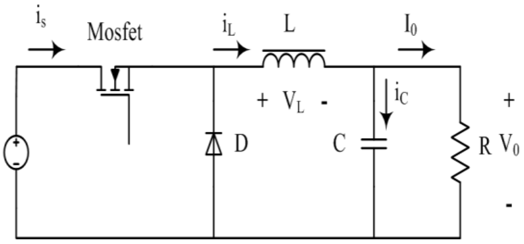

Fig. 3 Schema of buck converter.

The DC–DC converter can operate in two distinct modes with respect to the inductor current I_L: the continuous conduction mode *(CCM)* and the discontinuous conduction mode *(DCM)*. In the *CCM* the inductor current is always greater than zero. When the average value of the input current is low (high value of the load *R*) and/or low value of the switching frequency *f*, the converter may enter the *DCM*. The CCM is preferred for high efficiency and good utilization of semiconductor switches and passive components [7-11].

For the buck converter, the value of the filter inductance that determines the boundary between *CCM* and *DCM* is given by [7-11]:

$$L_b = \frac{(1-d) \cdot R}{2 \cdot f} \qquad (4)$$

Where: L_b is the boundary inductance, *d* is the switch duty ratio, *R* is the maximum résistance that give the minimum current load and *f* is the switching frequency.

For $L > L_b$, the converter operates in the CCM, in which, the filter inductor current I_L consists of a DC component I_O with a superimposed triangular *AC* component. Almost the entire AC component flows through the filter capacitor as a current i_c; this component causes a small voltage ripple across the dc output voltage V_O. To limit the peak-to-peak value of the ripple voltage below a certain value V_r, the filter capacitance *C* must be greater than [7-11]

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$$C_{\min} = \frac{(1-d)V_O}{8V_r L f^2} \quad (5)$$

V. PROPOSED SYSTEM CONTROL OF BATTERY CHARGER

The battery charger using the PV array includes basically 2 parts: the power stage and the control stage as represented in Fig.4 [7].

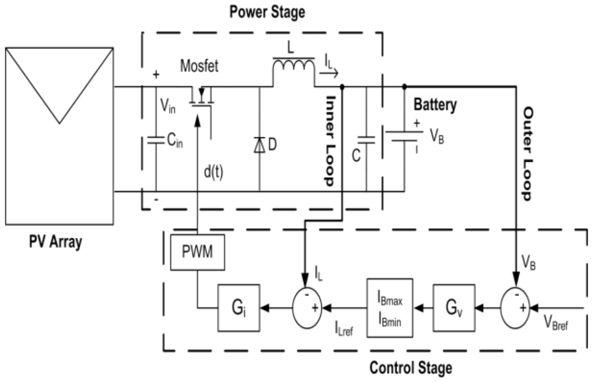


Fig. 4 Block diagram of proposed system.

The outer voltage loop is used to charge the battery at its nominal voltage given by the constructor (*14 V* in our case) and to provide the reference current to the inner current loop. The signal of the control loop is shown in Fig 4. The reference current is limited to avoid the maximum charging current accepted by battery (*C/5*) and/or the maximum current of coil filtrate (*1.5 A)*.

In order to study the system stability and transient behavior, the relationship between the input and the output is required. For the inner loop, the transfer function is $I_L/d(s)$ given by relation (6) and for outer loop the transfer function is V_B/I_L given by (7) [7].

$$\frac{\tilde{I}_L}{\tilde{d}} = \frac{V_{in}}{R}\frac{(1+RCs)}{\left(1+\frac{L}{R}s+LCs^2\right)} \quad (6)$$

$$\frac{\tilde{V}_B}{\tilde{I}_L} = R\frac{1}{1+RCs} \quad (7)$$

It is thus possible to design the current controller $G_i(s)$ and the voltage controller $G_v(s)$. In particular it has been defined so that the overall open loop system should satisfy the expected performance and stability of the power converter. The desired criteria of the open loop system are: stability (a phase margin not lower than 45 degrees) a minimum stationary error, a crossover frequency as high as possible (high bandwidth), but suitably much lower than the switching frequency (at least one order); in our case Sisotools of MatLab/Simulink is used to design the parameter of $G_i(s)$ and $G_v(s)$[9].

$$G_i(s) = \frac{K_{ii} + K_{ip}s}{s} \quad (8)$$

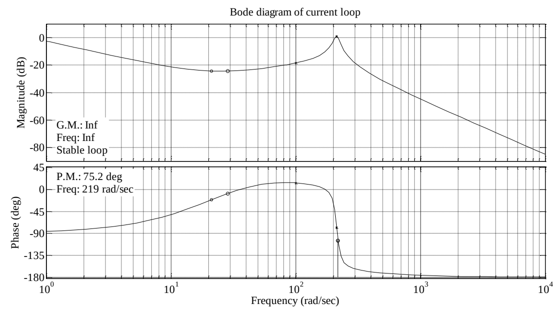
$$G_v(s) = \frac{K_{vi} + K_{vp}s}{s} \quad (9)$$

Where: K_{ii} and K_{ip} are the integral and the proportional gains of current loop respectively. Also, K_{vi} and K_{ip} are the integral and the proportional gains of the voltage loop respectively.

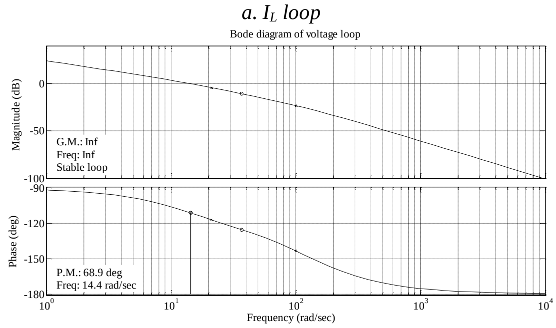
The parameters of the *PI* controllers are:

K_{ip}=0.002, K_{ii}=0.08, K_{vp}=0.14, K_{vi}=4.

The analysis of I_L and V_B loops, using Bode diagram gives a good margin of stability: the phase margins are 75.2° and 68.9° for I_L loop and V_B loop respectively (Fig.5.a and Fig. 5.b).



a. I_L loop



b. V_B loop

Fig. 5 Bode diagram of current and voltage loop.

The performances of the battery charger to charge a (*12 V*, *7.5 Ah*) lead acid battery from *40 %* of state of charge (***SOC)*** to *100 % SOC* of Fig. 4 based on the proposed *PI* control strategy are given in Fig. 6, while using the parameters calculated previously, the model of *PV* system discussed in section I and

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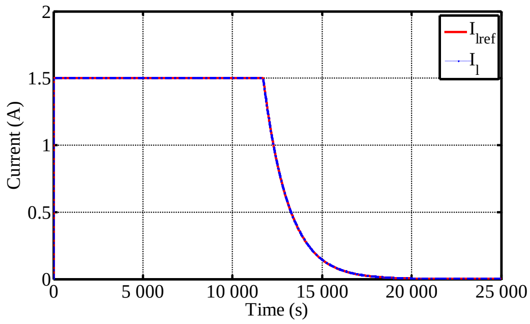
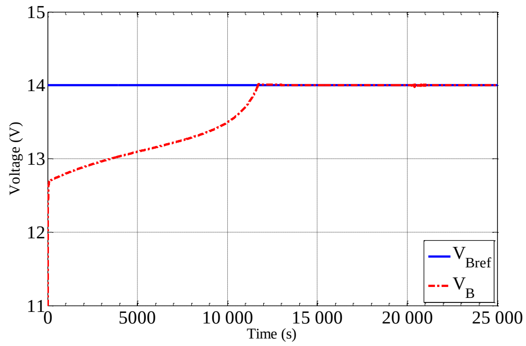
the lead acid battery model of Matlab/Simulink environment.

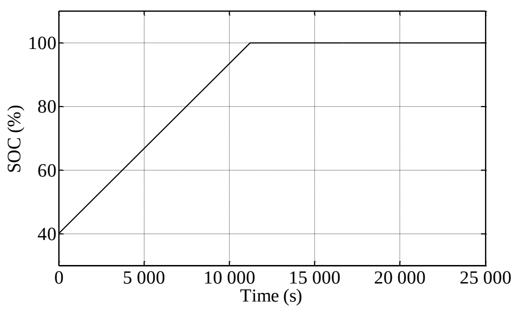
Fig. 6.a shows the battery charging current. In the first time, it is limited at the maximum (1.5A), which depends on the battery maximum current charge that's equal to *C/5* and the nominal current of inductance, until the battery voltage increases to a voltage regulation set point as shown in Fig. 6.b When the set point value is reached, the current of charge decreases to the minimum value. Fig. 6.c represents the state of charge of the battery from *40%* to *100%*.



a. Simulation of inductance current.



b. Simulation of battery voltage.



c. SOC of charge.

Fig. 6 Performance of lead acid battery charger.

VI. Experimental Results

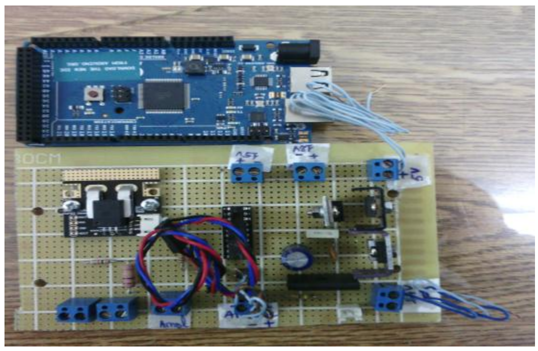
All tests have been done in Matlab/Simulink environment, employing in particular 'Support Package for Arduino Hardword' for the control of the buck converter (Fig 7.a). The experimental implementation of the renewable source simulator is obtained by the set-up of a DC/DC buck converter circuit, using a power Mosfet switched at 1 kHz and a (LC) output filter with the characteristics described in Tab. I, (Fig.7.b).

TABLE I : Output filter parameters

Parameter	Value
L	0.1
C	$220e^{-6}$

In the studied application the battery charger control is implemented using the Arduino mega board, which is a very cheap microcontroller board based on the ATmega1280. It has 54 digital input/output pins (of which 14 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button.

The current and voltage are sensed using a current sensor and voltage divider respectively as represented in Fig. 7.a.



a. Control stage.

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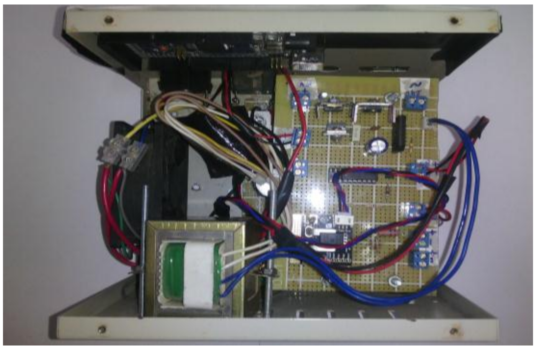
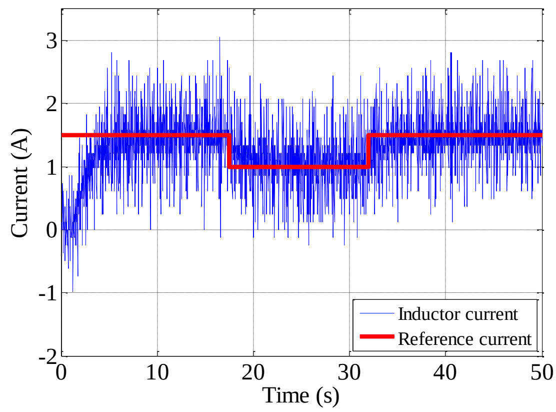


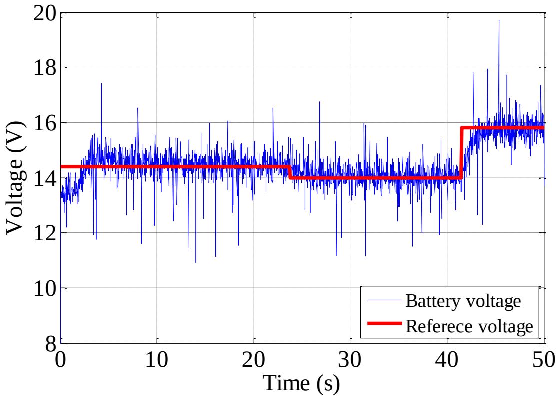
b. Power stage References.

Fig. 7 photograph of the power stage battery charger realised in URAER laboratory.

The performances of the realized battery charger represented in Fig. 7.a and Fig.7.b are given in Fig. 8.a and Fig. 8.b. We see clearly that the current and voltage sensed by the current sensors and voltage divider achieves very closely the current and voltage references, which is the purpose of the control setup.



a. Reference and sensed Current.



b. Reference and sensed voltage.

Fig. 8 Current and voltage sensed at the output of the realized battery charger

VII. CONCLUSIONS

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

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. Some advantages of the proposed method are: (a) a simple PI control technique is employed; (b) the battery lifetime is increased as it is charged while meeting the limit values given by the constructor, with a higher state of charge. Also, since the proposed method is based on battery current and voltage regulations, it can be effectively used in large battery strings.

The experimental results verify that the use of the proposed method, leads to a better exploitation of the PV energy, to charge and discharge the battery according to its limits provided by the constructor (maximum and minimum voltage, maximum current of charge) and to insure the charging and discharging of the battery safely.

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LIST OF SYMBOLS

PI: Proportional Integral.

PV: Photovoltaic.

DC: Direct Current.

Mosfet: Metal Oxide Semiconductor Field Effect Transistor.

SOC: State Of Charge of battery.

CCM: Continuous Conduction Mode.

DCM : Discontinuous Conduction Mode.

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