Performance Evaluation of an Autonomous Photovoltaic System for Recharging Electrical Vehicle Batteries

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Abstract **– This paper deals with the performance evaluation of an autonomous photovoltaic system for recharging (with electrical power produced by photovoltaic panels) Lithium-ion batteries for an electrical vehicle. In this system, the power flow control is performed via a DC-DC converter using a Maximum Power Point Tracking (MPPT) technique. The performance evaluation is according to two operations modes: under degraded and optimal conditions.**

Keywords – Autonomous photovoltaic system, DC-DC converter, Electrical vehicle, Lithium-ion battery, MPPT control

I. Introduction

For the last two centuries, emissions of certain polluting gases from human activities have intensified the phenomenon of greenhouse effect and leads to warmer temperatures on Earth. Consequently, the international community is mobilized to limit atmospheric concentrations of greenhouse gases with the goal of halving global emissions by 2050. Several solutions have been proposed by researchers and the Electrical Vehicle (EV) is one of the most promising alternatives for the transportation problem.

Unlike the conventional vehicles on road today which are major consumers of fossil fuels like gasoline, an EV is propulsed by electricity which can be stored in rechargeable batteries. The EVs are becoming more attractive with the advancement of new battery technologies that have higher power and energy density and allow matching the requested autonomy and vehicle dynamics. Electrical vehicle batteries are recharged using either the grid (G2V: Grid to Vehicle) or using renewable energies in a stand-alone recharging point (H2V: Home to Vehicle).

II. Batteries Technologies and Recharging Topologies

A battery is a device which converts chemical energy directly into electricity. It is an electrochemical galvanic cell or a combination of such cells which is capable of storing chemical energy. The first battery was invented by A. Volta in the form of a voltaic pile in the 1800's. Batteries can be classified as primary batteries, which once used, cannot be recharged again, and secondary batteries, which can be subjected to repeated use as they're able of recharging by providing external electric current.

TABLE I
DIFFERENT BATTERIES TECHNOLOGIES [2]

	Lead-Acid	Ni-Cd	Ni-MH	Li-Ion	Li-Po
Specific Power [W/kg]	80-150	150-400	200-1000	500-4000	315
Cycle Life	500	1350	1350	1000	600

Batteries are more desirable for the use in vehicles, and in particular traction batteries are most commonly used by EV manufacturers. Traction batteries include Lead-Acid type, Nickel-Cadmium (Ni-Cd), Lithium-Ion (Li-Ion), Lithium-Polymer (Li-Polymer), Sodium-Nickel Chloride (Na-Ni-Cl), Nickel-Zinc (Ni-Zn).

Although some storage technologies could work for several applications, the most part of the different options is not economically applicable to different functional categories. Their assessment must be done on the basis of several parameters which establish their applicability: power level (nominal, pulsed), energy storage level (at different charge and discharge rates), memory effect, power density, energy density, overall cycle efficiency, life-time (number of cycles and performance), operative characteristics, environmental impact, recycle opportunity, investment and maintaining costs. Table I summarize some of the commonly used batteries and their properties [3-4].

Most of EV batteries need to incorporate onboard or offboard chargers allowing the battery recharging anywhere there is an electric outlet.

The onboard chargers are limited in output power because of size and weight restrictions dictated by the vehicle design.

The output power of an offboard charger is limited by the capacity of battery to accept the charge. Although these chargers are outside of the vehicle (lighter weight) and have high power (less time to recharge the batteries), adaptability to charge at different places is limited [5].

In this work, Authors are interested to replace discharged Lithium-ion batteries by other recharged from the daily produced photovoltaic energy.

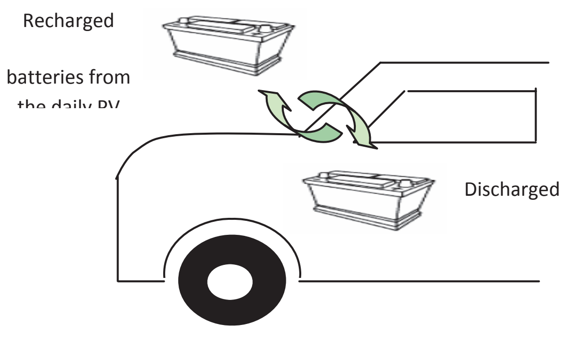

Fig. 1 Substitution batteries possibility

III. Structure of the Autonomous Photovoltaic System

Fig. 2 shows, in block diagram, the autonomous photovoltaic system composed of:

- A PV source, consisting of several photovoltaic panels, one panel provides a maximum power of 38.39W, a voltage of 17.45V and a current of 2.2A.
- A DC-DC buck converter with a Maximum Power Point (MPPT) control allowing to operating the photovoltaic source under the maximum available power.
- Lithium-ion batteries which are the main source assuring the vehicle traction.

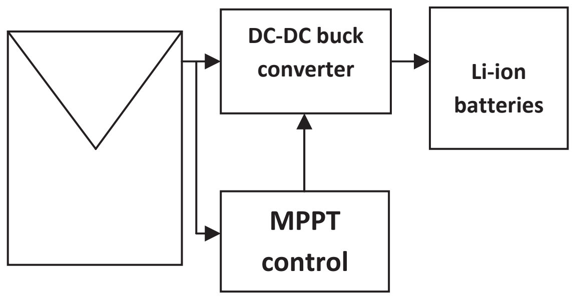

Fig. 2 Block diagram of the photovoltaic system

IV. Modeling and Sizing

For testing electrical vehicles, driving cycles have been normalized. European light-duty vehicles have to face the New European Driving Cycle (NEDC) which represents the typical usage of a small car in Europe. The NEDC consists of repeated urban cycles (ECE-15 driving cycle) and Extra-Urban driving cycle. Figure 3 shows the ECE-15 cycle with the speed and the power demand of a small electric vehicle following a flat road. Sudden power changes are caused by the speed change. In this example, the vehicle peak power reaches about 50kW.

Considering the 1200 seconds of the NEDC vehicle simulation, the Lithium-ion batteries power is of 50kW and the energy demand is about 16.67kWh. A safe margin of 10% gives a total of 18.34kWh.

From the PV source production, this amount of energy needs to be stored in the embarked storage device.

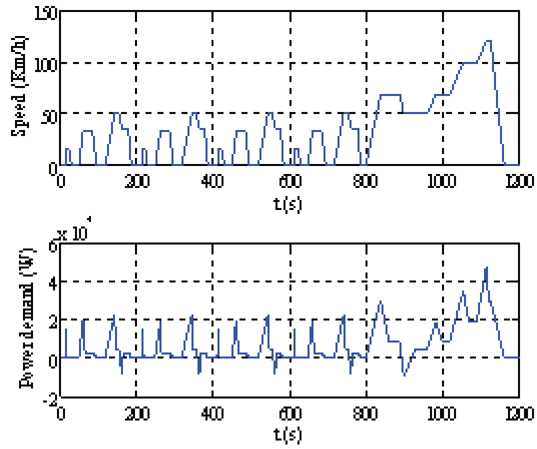

Fig. 3 ECE-15 driving cycle

A. The photovoltaic source

The mathematical model associated with a cell is deduced from that of a diode PN junction. It consists on the addition the photovoltaic (PV) current I_{ph} (which is proportional to the illumination), and a term modeling the internal phenomena. The current I in the output of the cell is then written:

$$I = I_{ph} - I_{od}\left(e^{\frac{q(U+R_S I)}{kT}} - 1\right) - \frac{U+R_S I}{R_{sh}} \quad (1)$$

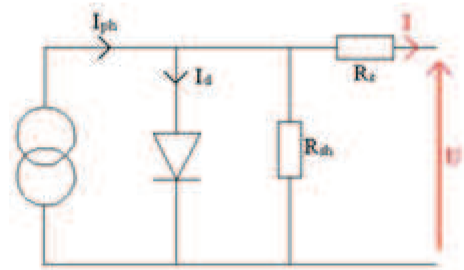

Fig. 4 Equivalent circuit of a photovoltaic cell

The diode models the behavior of the cell in the darkness. The current generator models the current I_{ph} generated by illumination. Finally, the two resistors model the internal losses:

- The serial resistance R_s models the ohmic losses of material.
- The shunt resistance R_{sh} models the stray currents passing through the cell.

As the shunt resistor is much higher than the series resistance, one can neglect the current deflected in R_{sh}. It follows:

$$I = I_{ph} - I_{od}\left(e^{\frac{q(U+R_S I)}{kT}} - 1\right) - \frac{U}{R_{sh}} \quad (2)$$

As the shunt resistance is much higher than the series resistance, one can neglect the current deflected in R_{sh}.

$$I = I_{ph} - I_{od}\left(e^{\frac{q(U+R_S I)}{kT}} - 1\right) \quad (3)$$

Simplified equivalent circuit is represented figure 5.

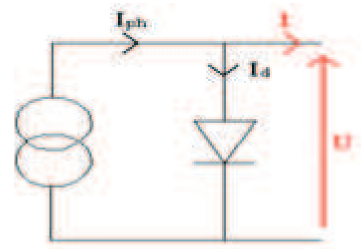

Fig. 5 Simplified equivalent circuit of a photovoltaic cell

Selected PV panel properties are given in Table II.

TABLE II
THE AEG-40 PV PANEL CHARACTERISTICS

Max power [W]	Optimal voltage [V]	Optimal current [A]	Efficiency [%]
38.39	22.2	2.2	10

Figure 6 shows the current-voltage and power-voltage characteristics of the AEG-40 PV panel for different illuminations. Points in red stars on each curve power-voltage correspond to the value of the optimum power point. Every operating point defined on the power-voltage characteristic by the couple "maximum voltage/maximum power" is used to position the panel in its maximum power.

Note that the current and voltage supplied by the panel are proportional to illumination.

The photovoltaic source sizing is considered for the region of Biskra (South-East of Algiers/Algeria), which receives a daily solar energy of 3234 Wh/m^2/day (worse case: month of December) [6].

B. The storage system

Many electrical equivalent circuits of battery are found in literature [7-8]. Batteries are presented with an overview of some much utilized circuits to model the steady and transient behaviour. Thevenin's circuit is one of most basic circuits used to study transient behaviour of battery. This model is shown in figure 8.

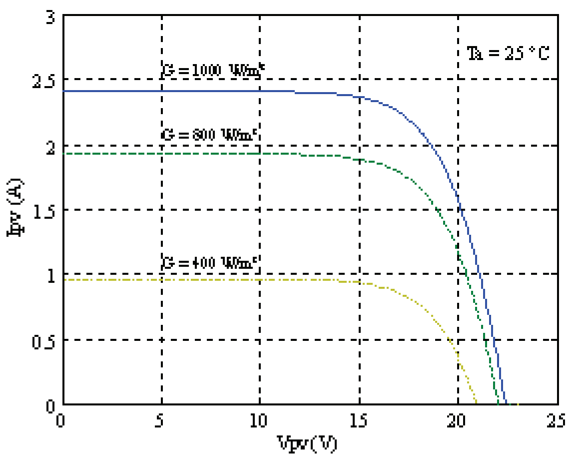

Fig. 6 Effect of illumination on the characteristic current-voltage

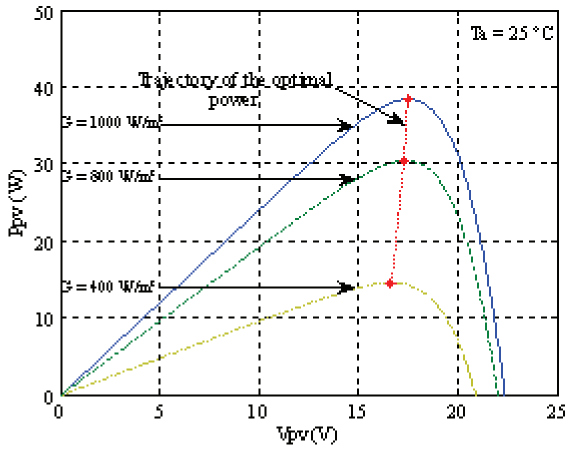

Fig. 7 Effect of illumination on the characteristic power-voltage

TABLE III
THE PHOTOVOLTAIC SOURCE SIZING

Daily produced energy [kWh/jd]	Total surface of PV panels [m^2]	Number of PV panels
30.56	94.5	248

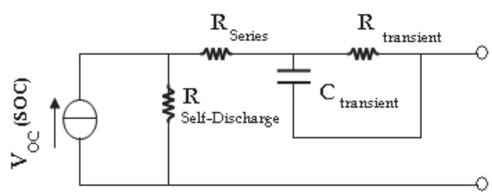

Fig. 8 Thevenin's model [9]

It uses a series resistor (R_{series}) and a RC parallel network ($R_{transient}$ and $C_{transient}$) to predict the response of the battery to transient load events at a particular state of charge (SOC) by assuming a constant open circuit voltage: V_{oc}(SOC) [9].

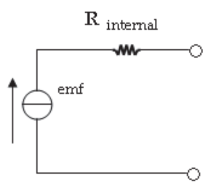

Fig. 9 Circuit showing battery emf and internal resistance $R_{internal}$ [9]

Characteristics of the Lithium-ion batteries are summarized in Table IV.

TABLE IV
THE LITHIUM-ION BATTERIES CHARACTERISTICS

Rated voltage [V]	Rated capacity [kWh]	Depth of discharge [%]
216	18.34	90

C. The MPPT control

Since it is adapted to the unstable weather conditions and does not present a risk of divergence from the maximum power point [10], the incremental conductance method is chosen to search the MPPT. Figure 10 shows the principle of the incremental conductance algorithm.

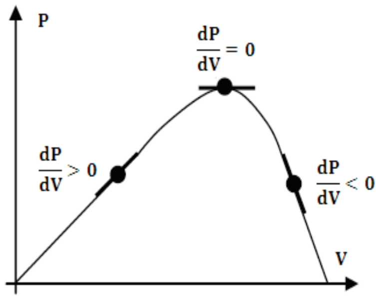

Fig. 10 dP/dV searching principle

Consider the notations V, I, P as variables related to the PV panel. The maximum power is achieved when:

$$\frac{dP}{dV} = 0 \tag{4}$$

To the left of this point, dP/dV is positive; to the right, dP/dV is negative. Since P = I.V, differential calculus gives: dP = V.dI + I.dV. At the MPPT:

$$\frac{I}{V} + \frac{dP}{dV} = 0 \tag{5}$$

From measurements of $I(t_2)$, $I(t_1)$, $V(t_2)$, $V(t_1)$ and assuming that: $dI \approx \Delta I = I(t_2) - I(t_1)$ end $dV \approx \Delta V = V(t_2) - V(t_1)$, it can calculated (I/V) + (dI/dV) and deduced the direction of maximum power point. Then, the convergence direction is always known.

D. The supervision system

To regulate the charging process of the storage element from the PV source daily production, a supervision system based on the batteries voltages is used, and allows disconnecting them after a threshold voltage of 234V corresponding to the full charge voltage. Recharge begins from a threshold voltage of 201.6V corresponding to the voltage when they reach the depth of discharge. The principle of the supervision system can be represented in figure 11.

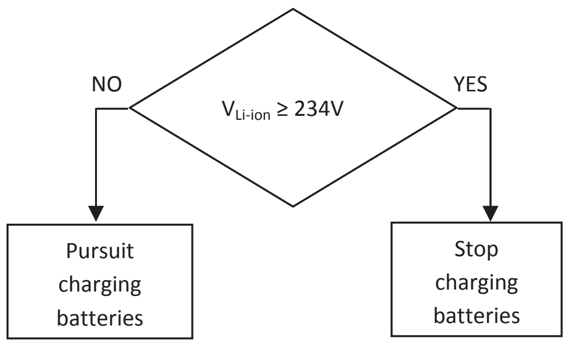

Fig. 11 Principle of the supervision system

V. Simulation Results and Discussion

A. Efficiency of the incremental conductance method

The Efficiency of an MPPT algorithm is judged by its ability to track the maximum power. But also, its robustness in disturbed conditions. To test the chosen method, series of tests with a significant variation in the illumination for about ten hours are conducted.

Average yield η_{mppt} is calculated from the average effective power P_{pvav} and maximum power P_{mpp} can be provided by the PV source. It is given by [11,12]:

$$\eta_{mppt} = \frac{P_{pvav}}{P_{mpp}} \times 100\% \tag{6}$$

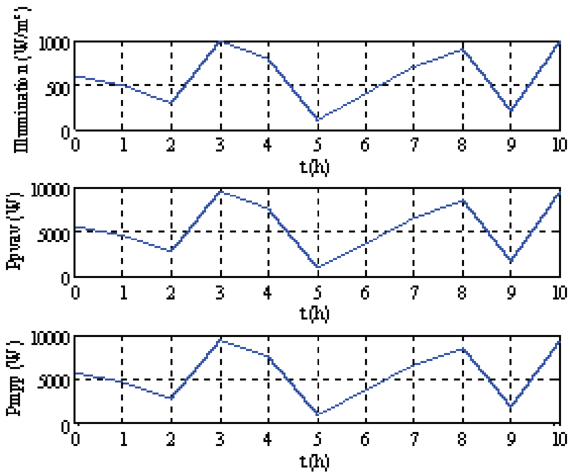

Fig. 12 The MPPT test

With the MPPT algorithm, an efficiency of 98.63% is achieved despite the sudden change of illumination (from 800W/m^2 to 100W/m^2 during one hour).

B. Recharging of the Lithium-ion batteries from the daily produced photovoltaic energy

Two illumination profiles are considered for the region of Biskra: under degraded conditions (December, figure 13), and under optimal conditions (August, figure 15). The daily profiles are obtained using measured data at regular intervals (one hour) throughout a day with a clear sky.

- Profile 1: under degraded conditions of December

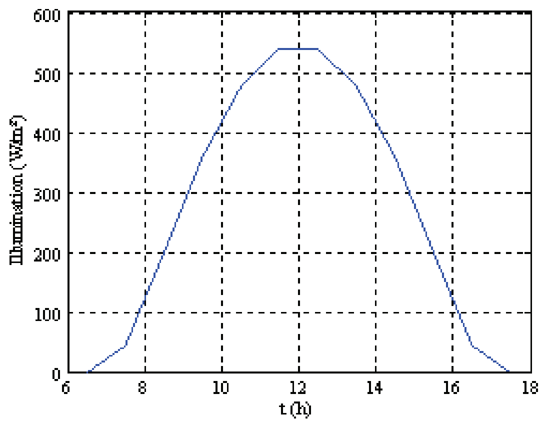

Fig. 13 Illumination profile under degraded conditions

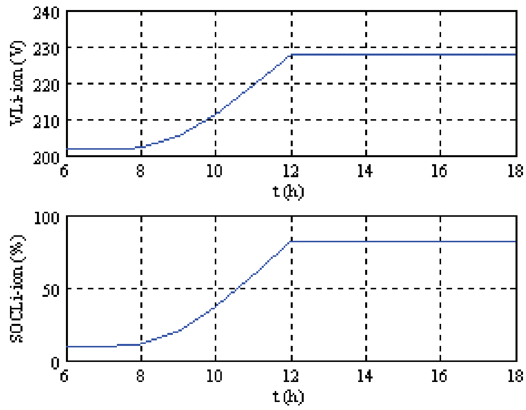

Fig. 14 Batteries voltage and state of charge

Figure 14 presents the Lithium-ion batteries voltage ($V_{Li\text{-}ion}$) and state of charge ($SOC_{Li\text{-}ion}$). Batteries have an initial $SOC_{Li\text{-}ion}$ of 10%. In degraded conditions, it reaches a final $SOC_{Li\text{-}ion}$ of 83.07% during six hours. The charging process is accepted: the batteries voltage is within the interval [201.6, 234V].

- Profile 2: under optimal conditions in August

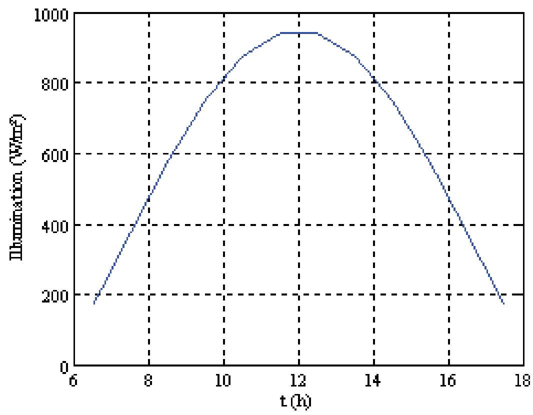

Fig. 15 Illumination profile under optimal conditions

Figure 16 presents the Li-ion batteries voltage ($V_{Li\text{-}ion}$) and state of charge ($SOC_{Li\text{-}ion}$). Batteries have an initial $SOC_{Li\text{-}ion}$ of 10%. In optimal conditions, it reaches final $SOC_{Li\text{-}ion}$ of 96.09% during 4h. Charging process is accepted: the batteries voltage is within the interval [201.6, 234V].

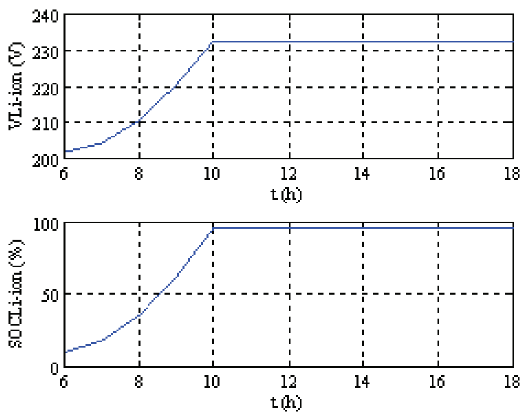

Fig. 16 Batteries voltage and state of charge

VI. Conclusions

In this paper, the design and performance evaluation of an autonomous PV system used to recharge Li-ion batteries of an electric vehicle are given. Using DC-DC buck converter with MPPT control allows to operate PV source to produce continuously maximum available power. During a day of system operation, Li-ion batteries are recharged at 83.07% in 6h (day of December), and at 96.09% in 4h (day of August).

- Li-ion batteries charging process is provided by the supervision system ; - PV model source is accurate and reflects the variation of illumination and temperature ; - The MPPT algorithm tracks the MPP even under disturbed conditions ; - Higher is the illumination power, greater can be the batteries state of charge and less is recharge time ; - Autonomous PV system is able to recharge discharged batteries even during unfavourable environmental conditions. Therefore, the vehicle traction is guaranteed.

VII. References

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