Energy Management of an Autonomous Photovoltaic System under Climatic Variations

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ABSTRACT

Predictable and unpredictable variations are two major causes of renewable energy-related intermittency. Such a drawback could be overcome by applying new energy management strategies, particularly storage systems. This paper investigates the feasibility of introducing a photovoltaic management string, enabling the maintenance of continuous energy supply storage capacity. Accordingly, the PV system is liable to perform at maximum efficiency following the implementation of an MPPT-controlled DC/DC boost converter of the Perturb and Observe (P&O) type. Most of the energy-management approaches target goals lie mainly in optimizing the energy resources' operational and storage capacities. The current MATLAB/Simulink-based simulation study achieved results that turned out to testify well to the advanced design's high performance and efficiency in maintaining the load's energy autonomy while increasing the battery's life span.

Keywords-PV-battery; storage system; energy management strategy; P&O; MATLAB/Simulink

I. INTRODUCTION

Given the increased global demand in energy supply, renewable energy development continues to undergo rapidly frequent changes. In effect, the depletion of fossil fuel reserves has enticed research and development programs to offset the deficit by turning to alternative sources of energy [1-2]. Petroleum-based resources, such as natural gas, coal, and oil, have for long been the unique available energy sources. Still, their uneven and random distribution across territories, along with their limited reserves and supply have spurred international conflict and fierce competitions. Also noteworthy, is the fact that the fossil-based conventional sources are usually available for only a few decades, while nuclear power generating plants often produce dangerous pollutants, including radioactive waste. To meet the world's growing energy demands, it is therefore necessary to find adequate solutions and diversify the sources of energy. The current research is focused on retrieving and developing new environmentally friendly, renewable, and inexhaustible power sources. Still, energy extraction techniques require further research and development strategies to improve efficiency and reliability. The renewable energy sources fall into three categories:

- Mechanical energy (wind, waterfall, and wave hydrodynamics).
- Electrical energy (photovoltaic (PV) and thermoelectric conversion).
- Heat energy (geothermal and solar thermal).

It is worth noting that most of these power sources rely predominantly on the sun as a major source. Indeed, as a viable source of renewable energy, the sun has been the focus of intensive global research for several decades [3]. It is worth mentioning, in this respect, that the PV panels' drawn energy is not only powerful, but also convertible into electricity thanks to an array of PV installations: isolated "stand-alone" installations, grid connected installations, and hybrid facilities [4]. Regarding the present paper, the modeling and simulation of an autonomous renewable-energy electrical system are treated with respect to the following main axes:

- The theoretical study is focused on the detailed analysis of the boost converter.
- Highlights of an advanced stand-alone PV system with Maximum Power Point Tracking (MPPT) control and the relevant energy management strategy are outlined.
- Analysis and comparison with various storage technologies allow us to identify the load necessary power requirements, the climatic conditions, and the most convenient storage modes fit for an autonomously sustained PV.

The energy management strategy is used to optimize the system's regulatory and supervisory tasks while controlling the charge and discharge status to extend the battery's life. Actually, such a process is deemed critical in an environment where electrical energy consumption is constantly increasing, due to the remarkable growth of industrial development, communication, and transport. In this context, we put forward special battery-stand-equipped indirect storage systems. Similarly, a backup power supply seems essential in case of energy shortage in the batteries' stores [5]. Regarding the present work, our choice is set on applying lithium-ion batteries, given the significant advantages they offer (see Table I). More particularly, they display noticeable energy density, very fast charging process, and a diversity of life cycles. The proposed PV system involves a PV generator, lithium-ion battery, and resistive load. To this end, a special energy management strategy is enrolled to ensure the system's perpetual continuity and improve the battery's life cycle.

TABLE I. BATTERY TECHNOLOGIES AND PERFORMANCE

Technology	Lead-acid (Pb-ac)	Lithium-ion (Li-ion)	Nickel cadmium (Ni-Cd)
Energy density (Wh/kg)	25–45	80-150	20-60
Power density (W/kg)	80–150	500-2000	100-800
Discharge time (h)	0.3-3	0.3-5	0.3-3
Return (%)	A few days	A few months	Less than 1 month
Efficiency (%)	60-98	90-100	60-80
Cycle life	300-1500	>1500	300-1500
Cost ($/kWh)	100-300	500-1200	200-800

The advanced PV system exhibits not only a high power output, but also an abrupt response to climate as well as load variations. Accordingly, a relevant energy management strategy is considered, whereby the system's continuous functioning and battery's life cycle could be maintained. The strategy is so simple to implement that it requires a low processing amount, and enhances the system's overall storage efficiency and lifetime while allowing to avoid total load disconnect.

II. SIZING AND MODELING OF PHOTOVOLTAIC CHAIN COMPONENTS

The general diagram of the PV convention chain under examination is depicted in Figure 1.

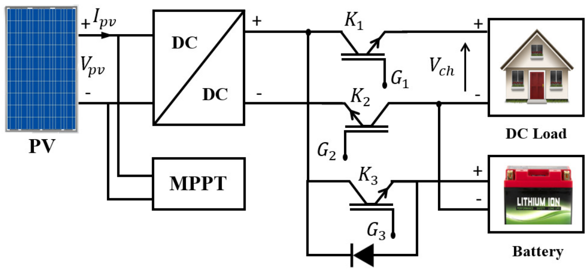

Fig. 1. Block diagram of the PV conversion chain.

A. PV System Modeling

For an effective PV design to be achieved, accurate measurements and a reliable mathematical approach are necessary. More particularly, the design control rests on the knowledge of the subsystems' various technical characteristics. Basically, the design background requires fulfilling the following steps [6]:

- Selecting the PV modules: the voltage to be delivered, the appropriate technology, and the peak power.
- Determining the storage capacity and battery type.
- Pinpointing the power converters' fit sizes.

B. Photovoltaic Single Model

The single-diode PV cell corresponding circuit displays two resistors: A shunt resistor R_{sh} connected in parallel, designating the leakage current in the PN junction, and a series resistor R_s connected in series, which stands for the connections' various resistances [7]. On substituting the two currents I_d (diode current) and I_{sh} with their relevant expressions, the following equation is drawn:

$$I_{PV} = I_{ph} - I_s \times \left(\exp\left[\frac{V_{PV} + R_s I_{PV}}{V_t} \right] - 1 \right) - \frac{V_{PV} + R_s I_{PV}}{R_{sh}} \quad (1)$$

where $V_t = k \cdot T / q$, k is the Boltzmann's constant, T the cell temperature, and q the electron's charge.

C. Boost Converter Model

A step-up boost converter is frequently used to transform a low-input voltage into a high output value [8]. It incorporates a continuous input voltage U, an inductor L, a diode D, and two capacitors C_e and C.

D. P&O MPPT Control Strategy

Thanks to its simplicity, exclusively requiring current and voltage measurements of the PV array, the Perturb and Observe (P&O) method is considered an effective strategy frequently applied in the MPPT research area. The idea of this approach lies in regularly changing the voltage of the PV array, by comparing the previously delivered power to that actually delivered, following a particular disturbance. Due to this technique, identifying the power peak turns out to be a feasible procedure, regardless of temperature or irradiation fluctuations. Figure 2, depicts the P&O approach corresponding algorithm [9-10]. The associated duty cycle $d(t)$ is highlighted by the following expression:

$$d(t) = d(t-1) + q * \delta_d \tag{2}$$

where q is either equal to 0 or ±1, depending on the PV power and voltage variation, and δ_d denotes the disturbance value.

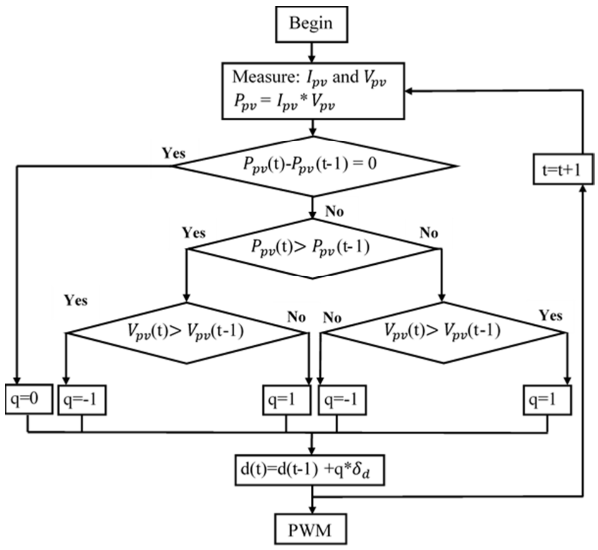

Fig. 2. Flowchart of the P&O MPPT technique.

E. Energy Computation Requirement of a Standalone PV System

The first step to follow when sizing a PV installation consists in estimating the energy consumption amount and determining the load-specific profile [11]. Hence, the consumed energy corresponding expression turns out to be:

$$E_{DC} = P_{DC} \times t_j \tag{3}$$

where E_{DC} denotes the energy consumed on a daily basis, t_j stands for the daily usage time, and P_{DC} designates the daily-consumed power.

F. Sizing a Photovoltaic Generator

The total number of modules necessary for maintaining the load provision constitutes an initial step in sizing a solar generator [12].

The PV generator's peak power is determined by:

$$P_C = \frac{1000 \cdot E_{Tot}}{G \cdot F_{CG}} \tag{4}$$

where E_{Tot} denotes the total energy consumed on a daily basis, G refers to the irradiation, and F_{CG} designates the global factor correction.

The total number N_{Tot} of PV modules is computed as:

$$N_{Tot} = \frac{E_{Tot}}{\eta_M \cdot G \cdot S_M \cdot F_{CG}} \tag{5}$$

where S_M denotes the module area and η_M the module efficiency.

Depending on the load and module peak power, N_{tot} is determined by:

$$P_C = G_0 \cdot S_M \cdot \eta_S \Rightarrow N_{Tot} = \frac{P_C}{P_{CM}} \tag{6}$$

where P_{CM} designates the PV module's peak power.

The number of modules in series is:

$$N_{MS} = \frac{V_{bat}}{V_{\max}} \tag{7}$$

where N_{MS} represents the number of PV modules connected in series and V_{bat} and V_{max} are the battery voltage and the maximum power voltage, respectively.

The number of parallel modules is determined by:

$$N_{MP} = \frac{N_{Tot}}{N_{MS}} \tag{8}$$

The size of the photovoltaic surface is computed as:

$$Surface = N_{MP} \cdot M_{MS} \cdot S_M \tag{9}$$

The peak PV power is calculated as:

$$P_{pv} = \frac{E_{ch}}{G \cdot (1 - pertes)} \tag{10}$$

The storage system capacity is sized by:

$$C_{batt} = \frac{E_S \cdot N_j}{U_{batt} \cdot \eta_{batt} \cdot P_{db}} \tag{11}$$

where P_{db} denotes the battery discharge depth and N_j the number of autonomy days.

III. ENERGY MANAGEMENT ALGORITHM

An adequate operation of the autonomous PV system entails optimal management of the energy flows exchanged among the system's various components. At this level, it is necessary to introduce our special management system architecture [13-16]. We anticipate that the batteries are fully charged at the start of the PV installation to monitor the entire system [13]. The energy management strategy is mainly concerned with monitoring the charge state and protecting the battery (minimum charge state EDC_{min} = 30% and maximum charge state EDC_{max} = 95 %) as depicted in Figure 3. It should be also noted that the PV/battery system involves 4 operating modes, as illustrated in Figure 4, where P_{Ava} is the difference between the power of the PV generator and the load.

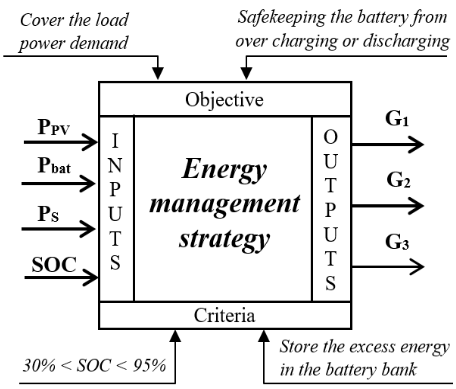

Fig. 3. ULM diagram of the energy management algorithm.

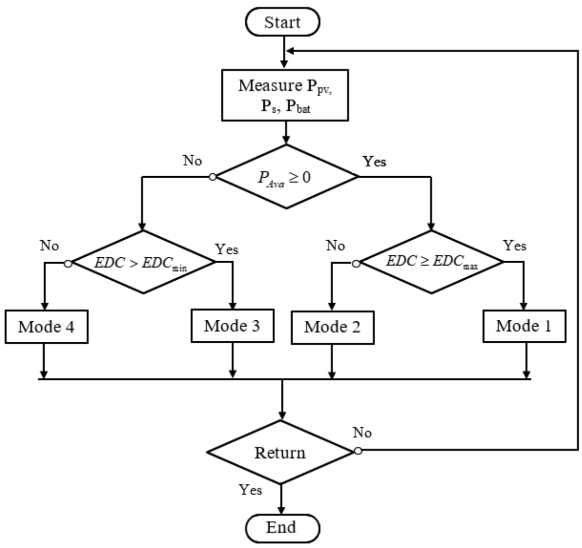

Fig. 4. Operating mode management flowchart.

In case of excessive PV energy:

- MODE 1: The batteries are charged. The PV generator is adequately ready to meet the demand.
- MODE 2: The PV generator is fit to satisfy the load. The produced energy excess is to be stored in the batteries.

In case of lack of PV energy:

- MODE 3: Only the batteries are to supply the charge.
- MODE 4: The batteries are completely discharged with no PV production.

The management algorithm helps supervise the energy exchanges between the installation elements, depending on the two scenarios highlighted in Figure 4:

- Supply of receivers and storage by PV panels if PV energy is sufficient
- Supply of receivers exclusively by the storage system if the PV energy is insufficiency.

IV. GLOBAL SYSTEM SIMULATION

Figure 5 shows the system corresponding diagram for a 5kWp PV field, 220V (50Ah) storage lithium-ion battery, and a boost converter, modeled and simulated in MATLAB/ Simulink.

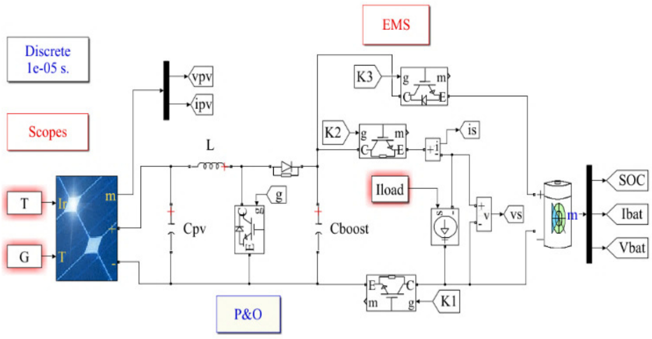

Fig. 5. The global system's diagram in MATLAB/Simulink.

A. *Simulation Results Considering One-day Profiles*

Figure 6 depicts a day-long sunshine and temperature actual representations, as applied for the subsequent simulation results. To analyze the system's operation during the interval [5h, 18.5h], a simulation of the global system was performed over a sunny day. As proof of the management algorithm's effective robustness, Figure 7 outlines two different curves:

- The first curve depicts the maximum power drawn by the P_{pv} photovoltaic panels.
- The second curve highlights the load power profile P_s.

The open state (Level 0) or closed state (Level 1) operating moments, relevant to the three power switches (K_1, K_2, and K_3), are illustrated in Figure 8. Based on Figure 8:

- Suppose that the PV panels' generated power is greater than that of the load, which is the case for the intervals [(6h-7h24), (7h36-9h), (9h54-10h54), (11h54-16h36), and (17h-18h30)]. In this case, an excess production mode will be adopted at these intervals considering modes 1 and 2. As shown in Figure 8, the power switches K_1 and K_2 are off, and K_3 is on during Mode 1 operation, and K_1, K_2, and K_3 are closed during operation in Mode 2.
- Suppose that the consumption amount is lower than the production rate (i.e. when the panel's generated power proves to be lower than the load required power), as it is the case for the intervals [(7h25-7h35), (9h-9h53), (10H55-1153), (16H37-17h), modes 3 and 4 will then be applied, as

the consumption rate turns out to exceed the production rate. The curve depicted in Figure 8 shows that in mode 3 the switch K_1 is off and the switch K_2 is on, while in mode 4, all the switches K_1, K_2, and K_3 are on.

- Once the system's power consumption and production rates are equal to zero, the system will be disconnected from its load, as is the case during the period span [18:30-6:30].

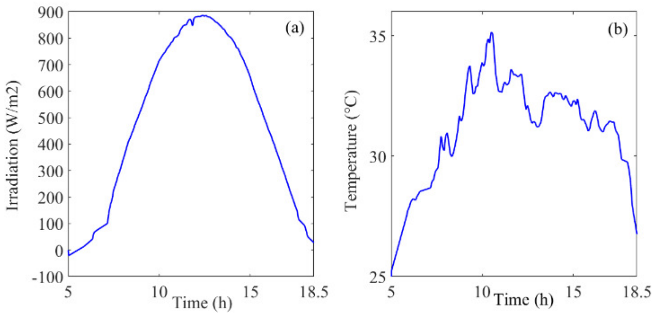

Fig. 6. Sunshine and daytime temperature.

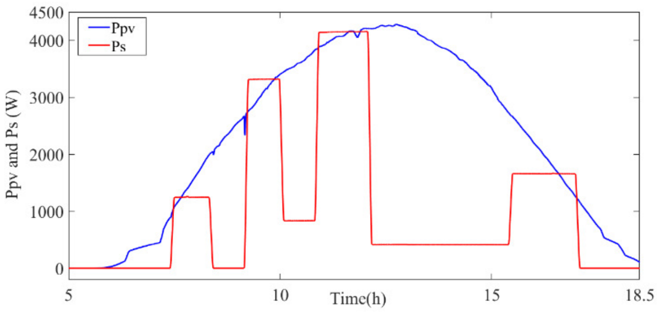

Fig. 7. PV system generated power and load power profile.

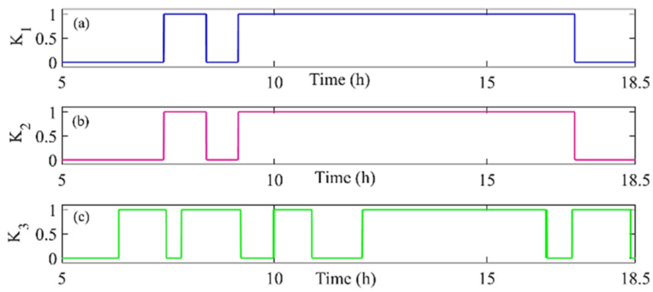

Fig. 8. Operation of the three switches.

The curve appearing on Figure 9 depicts the load as well as the batteries respective voltage V_{bat}, which is almost equal to the standard reference value of 240V. Regarding the illustrated curve in Figure 10, it highlights well the variations in the battery's charge levels over time. Note that the battery's SOC (State of Charge) appears to vary depending on the power demand divergence from the charge and the PV generator's power supply.

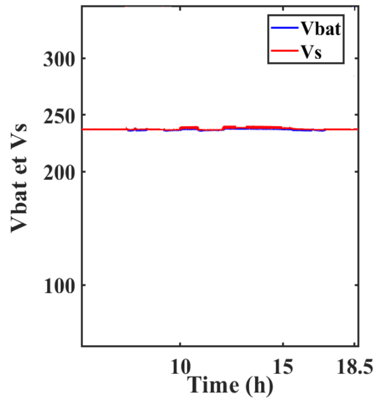

Fig. 9. Load and battery voltage.

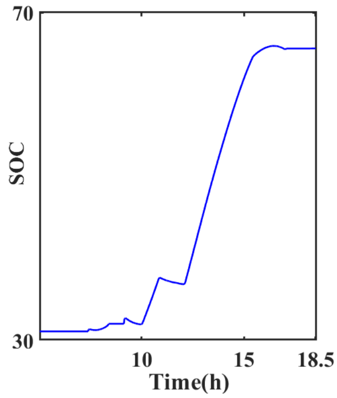

Fig. 10. Battery charge status.

Under the advanced strategy, the continuous bus-provided voltage can be maintained at the desired voltage level of 240V. Accordingly, the DC bus voltage is subject to significant voltage fluctuations on applying this method.

V. CONCLUSION

The novelty of the current study lies in the investigation of the capacity of an autonomous PV-battery conversion system to maintain the load with continuous energy supply under distinct climatic variations. In this respect, a MATLAB/Simulink study context enabled the execution of a simple energy-management technique with various switching modes. The suggested energy management strategy has been able to provide the load with a continuous energy supply, maintained even in the conditions of solar unavailability. In addition, it helps in extending the battery's lifespan, by dealing with the frequent charging and discharging processes. The simulation study results, achieved by the proposed energy-management strategy under distinct operating modes, verified the scheme's remarkable performance and effectiveness not only in maintaining the PV-battery system's continuity, but also in increasing the battery's lifecycle and durability.

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