

# Design and Control of A Standalone Photovoltaic Power System For Telecommunications In Isolated Regions of Algeria

Sahraoui Hamza<sup>1</sup>, ALI Moussa Mohamed <sup>2</sup>, Hacene Mellah<sup>3</sup>, Amar Maafa<sup>4</sup>, Abdelghani Yahiou<sup>5</sup>, Bessaad Taieb<sup>6</sup>, Farouk Mechnane<sup>7</sup>, Baazouzi Kamel<sup>8</sup>, Drid Said<sup>9</sup>, Larbi Chrifi-Alaoui<sup>10</sup>

<sup>1,8</sup> Laboratory of Science for Mathematics, Computer Science and Engineering Applications. Department of sciences and technology Institut of Sciences University Center of Barika, Amdoukal Road, Barika 05001, Algeria.

<sup>2,6</sup>Electrical Engineering Department, Hassiba Benbouali, University of Chlef, B.P 78C, Ouled Fares Chlef 02180, Chlef, Algeria,

<sup>3,4</sup> Electrical Engineering Department, University Akli Mouhand Oulhadj-Bouira, Rue Drissi Yahia Bouira, 10000, Algeria.

<sup>5</sup>Department of Electrical Engineering, Faculty of Technology, Ferhat Abbas University, Setif – 1, Setif 19000, Algeria

<sup>7</sup>Research Laboratory LSPIE, University of Batna2 Algeria,

<sup>9</sup> Higher National School of Renewable Energy, Environment and Sustainable Development, Batna, Algeria

<sup>10</sup>Laboratory of Innovative technology (LTI). University of Picardie Jules verne, Amiens, 13 Road François mitterrand 02880. Cuffies –Soissons, France

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## ABSTRACT

In this paper, we describe the design, control, and management of a photovoltaic (PV) power supply system for a remote telecommunications facility situated in Bab Ezzouar, Algiers, Algeria, that maintains Base Transceiver Stations (BTS) in remote areas where the intermittent grid is either unavailable or non-existent. The proposal is developed and modeled in MATLAB/Simulink for a freestanding PV-battery hybrid system that utilizes a DC-DC boost converter regulated by a Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm. The proposed system endeavour's to maximize solar energy harvesting while maintaining a constant energy supply for remotely situated telecommunication BTS without grid connection in a variety of environmental conditions. The simulation results indicate effective MPPT and battery charge-discharge management performance, ensuring BTS autonomy and serviceability 24/7, while demonstrating both technical feasibility and operational efficiency associated with the use of PV-based systems to meet the energy needs of isolated telecommunication infrastructure in North African regions, which have considerable solar potential.

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## Corresponding Author:

Sahraoui Hamza,  
Department of sciences and technology Institut of sciences,  
University Center of Barika,  
Amdoukal Road, Barika 05001, Algeria..  
Email: hamza.sahraoui@cu-barika.dz- ORCID: 0000-0002-0827-2559

## 1. INTRODUCTION

It is essential to provide reliable energy source for telecommunication systems, especially in rural or remote areas with insufficient or no access to a reliable electrical network. The Base Transceiver Stations (BTS) stations that make up mobile communication networks have energy demands that require constant accessibility. This study looked specifically at the impacts of electrical delivery stability in Algeria, with the problem most serious in Bab Ezzouar (an Algerian suburb that has rapidly urbanized and industrialized). Therefore, there is a need for other options to provide BTS power. When considering alternatives in light of the high solar irradiation level (annual average of about 5.3 kWh/m<sup>2</sup>/day) in this region, solar photovoltaic

(PV) systems see reduction in their concerns with availability as a reliable energy source [1]. Algiers has ideal conditions for solar installations with over 3000 hours of sunlight annually. PV installations can be a stand-alone power source has little impact on the region's environment. This paper provided a stand-alone PV-battery system to power a BTS station in Bab Ezzouar. MATLAB/Simulink modeling were under taken to validate the system with Maximum Power Point Tracking (MPPT) control using Perturb and Observe. The results are promising with regards to cost effectiveness and reduce emissions, The paper also compares system reliability and best performing system with a similar BTS site using only a diesel generator. There are several studies on integrating renewable energy into a telecommunications system, primarily solar and wind. In order to compare PV performance in a variety of scenarios, Patel and Agarwal modelled a number of techniques in [2]. Having P&O and Incremental Conductance as two of the more commonplace algorithms that optimize the PV output in real-time, more recent investigations note that MPPT algorithms are significant. There are PV-Battery hybrid systems being used on off-grid telecom applications in the Middle East and sub-Sahara Africa that operate well and are cost-effective too. Most studies are not connected to a full simulation environment like MATLAB/Simulink, and have not been tailored for the North African region. Practical considerations like a region's solar profile, temperature amplitudes and actual BTS load profiles are typically ignored in implementation comparisons e.g. hybrid systems with diesel backup demonstrated strong reliability in [3] albeit with much larger emissions and operational costs. This paper provides a simulation and model of a regionally-specific, sustainable solution created for Bab Ezzouar within the hope of catalyzing the state-of-the-art.

Numerous studies have examined how photovoltaic (PV) systems can be integrated into off-grid telecommunications infrastructure; Patel and Agarwal [2] performed much of the foundational research pertaining to modelling PV arrays when partially shaded. In terms of maximum power point tracking (MPPT), Bollipo et al. [4] and Priya and Stonier [5] recently reviewed numerous MPPT methods and classified them into three categories: classical, intelligent, and optimization-based.

While the classical methods (Perturb and Observe (P&O) and Incremental Conductance) are the simplest methods of tracking, they both suffer from convergence speed and steady-state oscillations tradeoffs. Adaptive P&O methods are more balanced and Eltamaly and Abdelaziz [6] demonstrated a 97.5% tracking efficiency using adaptive methods, while still retaining implementation simplicity. The advanced MPPT methods (fuzzy logic and neural networks, Ahmed et al. [7]) had a maximum efficiency of 98.2%, but required a larger amount of computational resources to implement. Lithium iron phosphate (LiFePO<sub>4</sub>) batteries have the longest cycle life and thermal stability of any type of battery used in remote telecom applications [8] so they are the preferred choice for remote telecom applications. Recent literature has shown that proper state-of-charge (SOC) monitoring of batteries can increase their cycle life by 30-40% [9] [10].

Integrating batteries and supercapacitors into hybrid storage configurations [11] or second life electric vehicle batteries [12] is a promising way to lower costs and increase performance. Regional studies development specific to North Africa have been done to address the unique climate issues presented by PV installations in this region; one study by Zereg et al. [13] stated that accurate solar irradiance data is critical for sizing PV systems in Algeria and Kizza and Uzorka [14] showed that temperatures reduced PV performance by 10-15% during peak summer conditions. A number of PV-powered BTS sites have been implemented in southern Algeria and met the reported performance target of 95% availability over a 3-year period [15]. Despite this large body of research, there is a lack of studies that incorporate an integrated design and simulation of PV-battery systems that can specifically address the solar profile, temperatures, and BTS loading characteristics of Northern Algeria along with quantitative comparisons of P&O to other MPPT techniques as they relate to remote telecommunications. In order to fill this void, this paper presents a comprehensive MATLAB/Simulink model for a BTS located in Bab Ezzouar, Algiers that includes an adaptive P&O MPPT and presents performance comparison results and implementation options consistent with the regional characteristics.

Table 1 presents a short comparative analysis of MPPT techniques for PV-battery systems.

Table 1. Comparative Analysis of MPPT Techniques for PV-Battery Systems

| MPPT Method              | Complexity | Convergence Speed | Steady-State Oscillations | Hardware Cost | Suitability for Variable Irradiance |
|--------------------------|------------|-------------------|---------------------------|---------------|-------------------------------------|
| P&O (Fixed Step)         | Low        | Moderate          | Moderate                  | Low           | Moderate                            |
| Adaptive P&O             | Low-Medium | Fast              | Low                       | Low           | Good                                |
| Incremental Conductance  | Medium     | Moderate          | Low                       | Medium        | Good                                |
| Fuzzy Logic Control      | High       | Fast              | Very Low                  | High          | Excellent                           |
| Neural Network           | Very High  | Very Fast         | Negligible                | Very High     | Excellent                           |
| Model Predictive Control | High       | Fast              | Very Low                  | High          | Excellent                           |

While there is a significant performance advantage in using advanced control methods such as FLC, NN and model predictive control, these advanced control methods have a much greater degree of complexity and therefore have a much higher cost in terms of hardware. Adaptive Perturb & Observe (P&O) provides the

best compromise between the need for reliability, relative ease of use, and cost-effectiveness in remote base station applications.

## 2. SYSTEM DESIGN METHODOLOGY

A daily energy consumption of 3.5 kWh, typical for a base transceiver station (BTS) operating in rural or semi-urban contexts, is used to determine the size of the PV array. The size and design requirement is lowered to around 4.2 kWh/day with a 20% safety margin allowing for system losses and securing a high reliability factor. The battery storage unit size is equivalent to a 48V, 100Ah Lithium Iron Phosphate (LiFe PO<sub>4</sub>) bank, which provides a minimum of 18 hours of autonomy. This chemistry has a significant advantage of extended cycle life, higher thermal stability, and deep discharge capability, making it conducive for remote maintenance-free deployment [8].

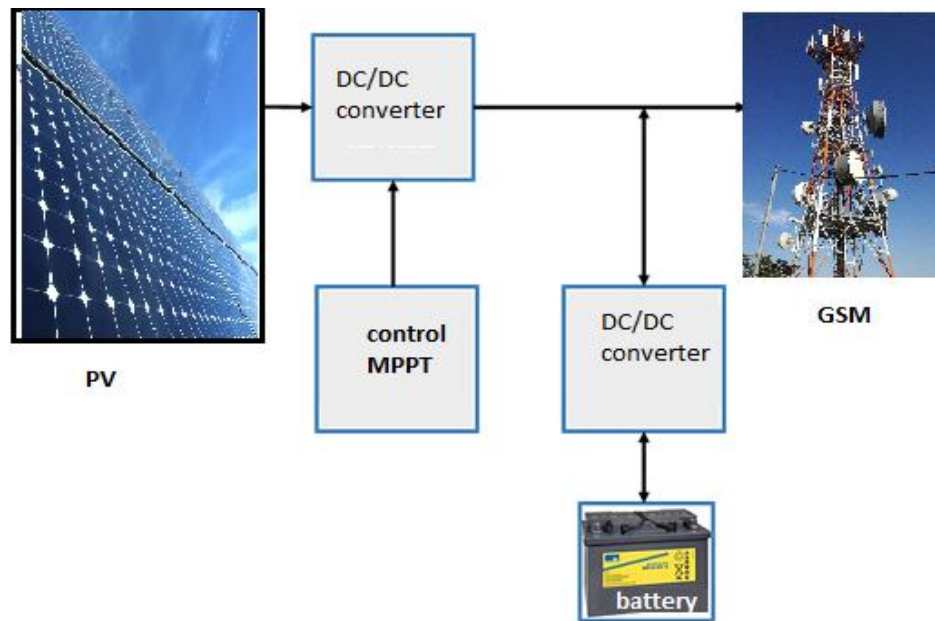


Figure 1. Structure of the photovoltaic conversion chain of our system.

The boost converter is controlled in continuous conduction mode (CCM) to improve the Boost converter efficiency and decrease output voltage ripple, to maintain the voltage reference error to the output of the buck-boost converter. The permanent monitoring of the PV array's instantaneous maximum power point by the MPPT control signal results in continuous duty cycle changes that move the operating point to be coincident with the PV array's immediate maximum power point [16]. Each unit's modularity provides the capacity for more PV strings or battery banks to be added so that they will accommodate projected future increases in load or hybridization with other renewable energy resources (i.e. wind or fuel cells), on a as needed basis. The electrical connections between the PV source, DC-DC converter, MPPT controller, battery bank, and BTS load are depicted schematically in Figure 1. This integrated system is modeled and validated in MATLAB/Simulink to assess performance under dynamic solar conditions using actual irradiance data from Bab Ezzouar.

### 2. 1. Geographic and Climatic Data

Bab Ezzouar is situated in the Algerian region of Algiers at 36° 43' 34.14" N Longitude: 3° 10' 58.48" E. The climate of Bab Ezzouar is classified as Mediterranean, characterized by hot, dry summers and mild, rainy winters – all under perfect conditions for producing solar energy. The region receives a daily average of about 5.3 kWh/m<sup>2</sup> of solar irradiance, making it an excellent candidate for the installation of PV systems (NASA Surface Meteorology and Solar Energy, SSE database [13]). According to the NASA surface irradiance models, this region receives more than 3000 hours of sunshine annually with ideal conditions producing peak irradiance above 1000 W/m<sup>2</sup>. With changes in the amount of sunlight available each day, simulations provided the BTS with realistic profiles of energy generation and consumption using historical irradiance data.



Figure 2. Bab Ezzouar location

A PV array, a DC-DC boost converter, a battery storage and a BTS load make up the system. The battery supplies energy in periods of low irradiance whilst a MPPT controller of the Perturb and Observe (P&O) type maximizes the output of the PV system. All components are sized using an average BTS daily energy demand of 3.5 kWh and a reserve margin of 20% to cover variation in load.

## 2.2. Telecommunications Context and Power Requirements

The PV-battery power system's design, a primary objective of the paper, requires knowledge of telecommunications context for accurate sizing and operational planning. This section provides basic information on the Base Transceiver Station (BTS) in mobile networks and discusses power requirements for the BTS.

The BTS acts as a telecommunications network component that supports mobile-device-to-network communication via radio waves in the Global System for Mobile Communication (GSM) network. The BTS contains radio transceivers, antennas, and signal-processing equipment that determine a cell's coverage area [17]. In a situation where the provision of electricity to a remote or isolated site is impractical or not feasible, the BTS could become an independent communications point that will be entirely reliant on local power generation.

The energy consumption of a typical BTS is based on the configuration of the BTS, capacity of the BTS (i.e., number of sectors and carriers being served), and the condition (age) of the BTS equipment. In order to develop a reference for energy consumption for this study, a typical load profile for a rural or semi-urban area (i.e., Algeria) was developed through industry practice and literature review [18]. The key parameters for the BTS used for the study are the following: an average daily energy consumption of 3.5 kilowatt-hours (kWh) per day, nominal operating voltage of 48 volts (V) DC (i.e., the telecommunications industry standard), and average total continuous power drawn of approximately 146 Watts (3.5 kWh divided by 24 hours).

Peak power demands are approximately 200 watts during periods of high demand or burst operations.

Due to the need for continuous, reliable, and 48Vdc power, the proposed PV-battery system is to provide this level of power. The size and amount of autonomy provided by the system for telecommunications load requirements are a direct result of telecommunication load demand. 18 hours of autonomy allows the BTS to function at night and during long periods of low solar irradiation; thus, allowing for the continual provision of "24/7" service availability, as required by today's telecommunications.

## 2.3. Application to the Sizing of PV Systems for BTS Sites

Watania Télécom Algérie - OOREDOO (WTA) conducted a feasibility analysis to explore the implementation of solar (PV) panels to power one of its Base Transceiver Stations (BTS) in an effort to enhance and modernise its mobile telecommunications network. Variability, with peak. The BTS is one of the components in the GSM infrastructure and is composed of the radio transmitters and receivers that facilitate communication between mobile user equipment and the core network. The proposed stand-alone PV-based energy system we conceived to operate autonomously and reliably, thus reducing its reliance on the conventional grid electricity from the utility grid in some parts of the country where access to electricity fails on a regular basis, or has never been consistently available. At the same time, this commitment aimed to fulfill the sustainability agenda by either substituting or reducing diesel generators to maintain full operational performance and reducing the environmental impact through lower carbon emissions and costs while ensuring the BTS remains operational.

## 2.4. PV Generator

The PV generator, a fundamental energy source in the system proposed herein, is composed of an array of mono-crystalline silicon solar panels that convert incoming solar radiation into direct current (DC) electricity using the photovoltaic effect. For the case study in Bab Ezzouar, Algeria, the PV array we designed to deliver electricity to meet the daily energy requirement of the Base Transceiver Station (BTS), which is an anticipated to be around 3.5 kWh. To consider energy security, the system we designed to consider a 20% reserve to cater for fluctuations in solar irradiance from daily and seasonal variations and uncertainties. Therefore, the design was able to enhance energy security by compensating for days of cloudy weather, dusty solar panels, and any other events that could reduce the system performance [19].

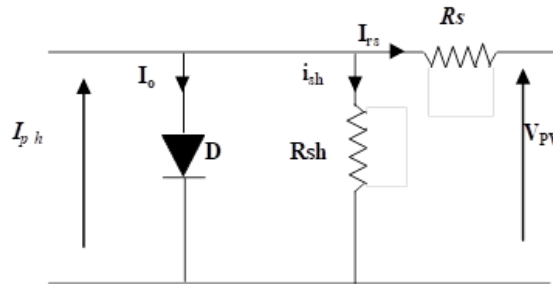


Figure 3. The PV cell equivalent circuit

The behaviour of the PV generator is given in a cell-level configuration comprising an equivalent electrical circuit containing a current source (photocurrent), a diode (p-n junction behaviour), and the series ( $R_s$ ) and shunt ( $R_{sh}$ ) resistances to account for additional parasitic losses. The PV array used in the system consists of monocrystalline silicon modules due to their high efficiency and longevity. The PV array has a total capacity of approximately 1.5 kW specifically meant for the energy consumption of the Base Transceiver Station (BTS) to operate despite low solar availability occurring during the night and when it is cloudy. The PV array tilts at an angle to approximate annual daily solar irradiance capture with respect to seasonal variation (Tilt angles effect daily solar irradiance).

## 2.5. Energy Production Modeling

The energy produced by the PV array will be affected by solar irradiance, which is how much sunlight falls on the solar panels, and by the efficiencies of the solar panels themselves. Solar irradiance throughout the day and year will be different and usually peaks at midday. Using the formula below, the amount of energy produced each day by the PV array is determined:

$$E_{PV} = A \cdot G_{avg} \cdot \eta_{PV} \quad (1)$$

Where:  $E_{PV}$  is an energy from the PV array (kWh/day),  $A$  is a surface area of the solar panels ( $m^2$ ),  $G_{avg}$  is an average daily solar irradiance in Bab Ezzouar ( $kWh/m^2/day$ ),  $\eta_{PV}$  is a conversion efficiency of the PV modules (15-20% typical). Based on a 1.5 kW PV array and considering an average solar irradiance of  $5.3 kWh/m^2/day$  for Bab Ezzouar, the amount of energy that can be obtained from the PV system in a day can be calculated:

$$E_{PV} = 1.5kW \times 5.3kWh/m^2/day \times 0.18 = 1.428kWh/day$$

This calculation confirms that the PV system generates sufficient energy to meet the daily BTS energy requirement ( $3.5 kWh/day$ ) while also providing other energy that can be stored in the battery for low irradiance periods or overnight.

## 2.6. Impact of Environmental Factors

Performance of the PV array is affected by various environmental parameters:

- Solar radiation: The amount of sun falling on the panels will change with the time of day and time of year. Peak energy production occurs near the noon hour, with decreasing amounts on the day of the summer solstice, and an increase during the early morning and late evening hours (including all other times of day when it is cloudy/raining).
- Also the Temperature: As temperatures rise the efficiency drops (increased temperature lowers the output of Photovoltaic modules). Most commonly the coefficient for mono-crystalline panels is about a -0.4% for each degree of Celsius increase in temperature. meaning for every  $^{\circ}C$  of temperature increase there is a decrease in the output power of 0.4%. Bab Ezzouar has hot summers where the ambient temperature reaches  $40^{\circ}C$ . Because of this, it might negatively affect the PV output possibility in the summer months [14] [10].

- Shading: PV Panels can experience partial shading when nearby objects (e.g. trees or buildings) will cause the panels to underperform. The system design uses this as part of the assurance that a suitable installation location was chosen and uses panels that have a better shade tolerance.

## 2.7. Modeling of PV Output

In the simulation, the output of the PV array is modeled as a function of irradiance and temperature. The basic output power of the PV array is given by the equation:

$$P_{PV} = P_{max} \cdot (1 - \alpha(T_{cell} - T_{ref})) \cdot \left(\frac{G}{G_{ref}}\right) \quad (2)$$

Where:

$P_{PV}$  is the power output of the PV array (W),  $P_{max}$  is the rated maximum power (W) under standard test conditions (STC),  $\alpha$  is the temperature coefficient (typically  $0.0045/^{\circ}\text{C}$  for monocrystalline panels),  $T_{cell}$  is the operating temperature of the solar panel ( $^{\circ}\text{C}$ ),  $T_{ref}$  is the reference temperature (usually  $25^{\circ}\text{C}$ ),  $G$  is the actual solar irradiance ( $\text{W}/\text{m}^2$ ),  $G_{ref}$  is the reference irradiance ( $1000 \text{ W}/\text{m}^2$ ). Through the incorporation of both irradiance and temperature, this model realistically replicates the actual performance of the PV array during the entire day. In addition to the overall efficiency of the PV array itself, system losses such as wiring loss, inverter loss, and panel mismatch loss also affect the overall efficiency of the system. To account for these losses, the overall efficiency of the PV array is reduced by a factor of approximately 80% to 85%. The efficiency losses can be calculated as:

Where:

$$\eta_{total} = \eta_{PV} \times \eta_{losses}$$

$\eta_{total}$  is the total system efficiency (after accounting for losses),  $\eta_{losses}$  is the combined losses from wiring, inverter, and other system inefficiencies. For a system with 85% efficiency losses, the total efficiency of the system would be reduced accordingly.

## 2.8. Array Sizing and Simulation Results

The PV array is sized to provide enough energy to meet most of the BTS' daily energy needs during peak solar conditions and has enough battery capacity that excess energy is stored when conditions are favorable for consumption during cloudy periods and nighttime. The sizing accounts for:

- Average daily energy consumption of the BTS (3.5 kWh/day),
- Daily average changes in solar irradiance (5.3 kWh/m<sup>2</sup>/day),
- Seasonal variation in irradiance (i.e. summer and winter),
- Required margin for energy reliability (20%);

The PV generator output is simulated continuously so its performance is adjusted in real-time depending on the irradiance and temperature conditions to meet the BTS load requirements. Figures 5 (A) and (B) show the change in characteristics of the PV panel, operating at temperatures ranging from 25 to 75° C and irradiation from 200 to 1000 w/m<sup>2</sup> respectively.

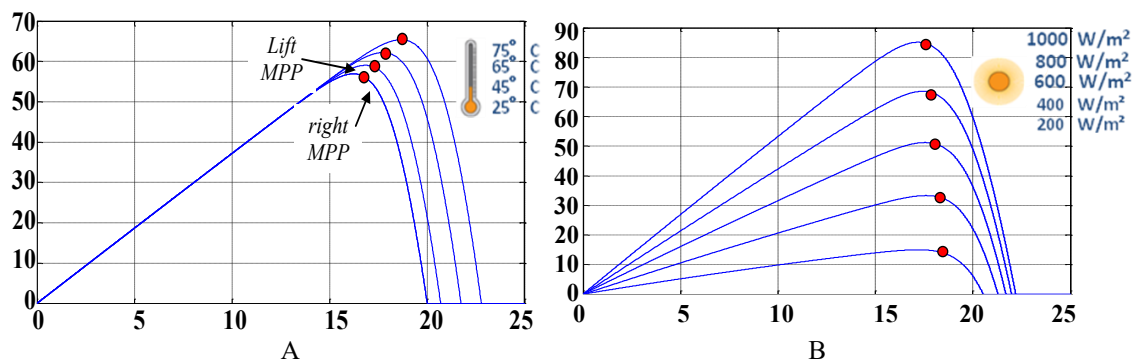


Figure 4. A; P-V characteristics of the PV panel under variation of temperature B; P-V characteristics of the PV panel under irradiation variation

## 2.9. Boost Converter

Also called a step-up DC-DC converter, the Boost Converter is an essential part of the system, as it will adapt the PV arrays voltage output to the charging voltage level required by battery charging circuitry and the Base Transceiver Station (BTS). It is vital for the excellent energy transfer from the PV generator, especially when solar irradiation fluctuates. The output voltage level of a PV array oscillates between 18 and 30 volts; however, the nominal voltage for the battery bank and BTS load is 48V. Therefore, the voltage must be boosted using a boost converter. The converter also interfaces with the MPPT controller, which dynamically

varies its duty cycle to extract as much power as possible from the PV modules [11]. The scheme of the boost converter is given by the Figure. 5.

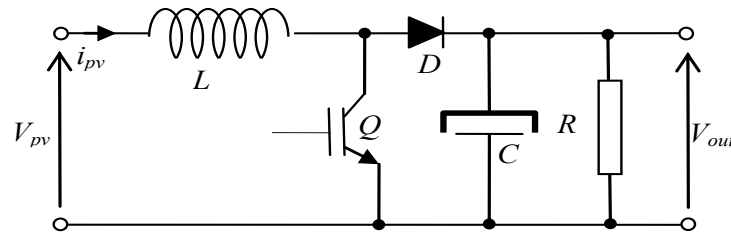


Figure 5. DC-DC Boost Converter

Under CCM, the average model of buck converter can be written as given by following equations

$$\begin{cases} \dot{x}_1 = \lambda_1 V_{pv} - \lambda_1 x_2 u \\ \dot{x}_2 = \lambda_2 x_1 u - \lambda_3 x_2 \end{cases} \quad (3)$$

where  $\lambda_1 = \frac{1}{L}$ ;  $\lambda_2 = \frac{1}{C}$ ;  $\lambda_3 = \frac{1}{RC}$ ;  $u = (1 - \alpha)$  and  $[x_1 \ x_2] = [ipv \ V_{out}]$ .  $T$  is the switching period and  $\alpha$  is the duty cycle. The boost converter in this system uses a traditional single-switch boost topology. The components of the classic configuration include:

- The Switch is a power MOSFET
- A high-frequency Inductor (L).
- A freewheeling Diode (D).
- An Output filter capacitor (C).

The boost converter uses a switching frequency between 20–100 kHz to rapidly on/off the switch (MOSFET). While the switch is in the on position, the L (inductor) stores energy in the L. After enough energy is stored, the L will release its energy via the D (diode) to the load and hence raise the output voltage beyond the input supply voltage.

The output voltage of an ideal boost converter is derived from the following equation:  $V_{out} = V_{in} / (1 - D)$

Where:  $V_{in}$  is the input voltage provided by the PV array,  $V_{out}$  is the output voltage (for example ~48V),  $D$  represents the duty cycle of the converter; and also indicates that  $0 < D < 1$ . In Bab Ezzouar's stand-alone PV system, As  $D$  increases, the output voltage rises. The MPPT algorithm to track the maximum power point of the PV array continuously adjusts the duty cycle. Typical boost converter efficiency ranges from **90% to 96%**, depending on the quality of components and switching frequency. In the simulation, an efficiency of 94% was observed under nominal load and irradiance conditions.

## 2.10. Control and MPPT Integration

In this work, we will use the P&O method since it is simple to use, can be implemented digitally in real-time, and performs well in moderate scintillation environments, like Bab Ezzouar, PV systems are characterized by a nonlinear power-voltage (P-V) characteristic, with a clear maximum power point (MPP) that varies with temperature and solar irradiance, the goal of an MPPT algorithm is to continuously monitor and operate a PV array at its maximum power point, If you do not have MPPT, then the system can be operating at a point on the P-V curve that is not the MPP, and your losses can be significant; for example, in northeastern Algeria, like Bab Ezzouar, variable irradiance, which is evident when clouds or atmospheric dust pass through the system can lead to considerable losses. The P&O algorithm works off the premise of perturbing (increasing or decreasing) the PV array voltage and then measuring the change in power produced (from the PV array). If the power produced increases after the perturbation, then the new operating point can move a little further in that direction, if the power decreases, the direction of perturbation is reversed. In general, the accuracy and dynamic response speed represent the primary performance criteria for MPPT algorithms. Nevertheless, approaches employing a fixed step size inherently exhibit a compromise between convergence speed and steady-state stability. Specifically, a small step size effectively minimizes oscillations around the MPP, yet it considerably slows down the tracking process [5]. In contrast, adopting a larger step size accelerates convergence toward the MPP, but it also increases oscillatory behaviour around the operating point and may consequently reduce the overall efficiency of the system; the algorithm can therefore be formulated as follows:

$$\begin{cases} V_{ref}(t) = V_{ref}(t-h) - K \cdot \text{sign}\left(\frac{\Delta P_{pv}}{\Delta V_{pv}}\right) \\ \Delta P = P_{pv}(t) - P_{pv}(t-h) \\ \Delta V = V_{pv}(t) - V_{pv}(t-h) \end{cases} \quad (4)$$

The sampling interval is represented by "h", "K" denotes the fixed step size gain and "V" denotes the controllable output voltage. In the current work, the fixed step size gain's original value "K" will now be replaced with an adaptive step size gain "Ka", which will vary based upon dynamic variations in both output power and terminal voltage. In addition to enhancing the flexibility of the MPPT methods, this change will improve the converging behaviours of these methods. Therefore, the algorithm proposed in this study can be

$$\text{defined as: } V_{ref}(t) = V_{ref}(t-h) - K_a \cdot \text{sign}\left(\frac{\Delta P_{pv}}{\Delta V_{pv}}\right) \quad (5)$$

Where Ka is an adaptive gain and can be given as flows:

if  $(\Delta P_{pv}(t-h) > 0 \ \& \ \Delta P_{pv}(t) > 0)$  then  $K_a = k_1$

if  $(\Delta P_{pv}(t-h) > 0 \ \& \ \Delta P_{pv}(t) < 0)$  then  $K_a = k_2$

if  $(\Delta P_{pv}(t-h) < 0 \ \& \ \Delta P_{pv}(t) < 0)$  then  $K_a = k_3$

if  $(\Delta P_{pv}(t-h) < 0 \ \& \ \Delta P_{pv}(t) > 0)$  then  $K_a = k_4$

where  $\Delta P_{pv}(t-h)$  and  $q$  are the PV power variation at  $(t-h)$  and  $(t)$  respectively.

Figure 6 represents the comparative between classical PO

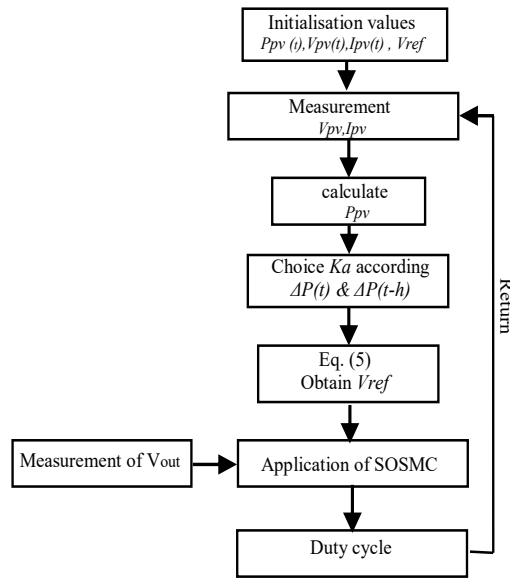


Figure 6. The flow chart of the adaptive M&O

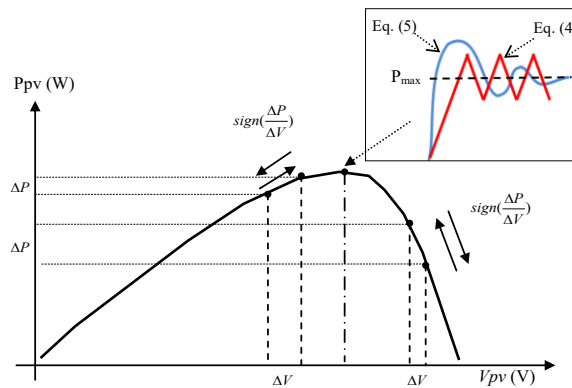


Figure 7 . the classical PO

$K_a$  is step size of P&O algorithm,

Using a variable perturbation step size—larger when far from MPP, smaller near MPP to reduce oscillations—improves tracking performance, particularly in situations with rapidly changing irradiance.

The dead-band threshold around the MPP minimizes small disturbances that continuously cause inefficiencies in the form of ripple, while a low-pass filter smooths the power readings to eliminate noise and to prevent erratic switching, this type of adaptive strategy is perhaps more favorable in coastal areas like Bab Ezzouar, where solar irradiance can rapidly fluctuate from quickly passing clouds and marine haze. The algorithm is put into practice as a control subsystem that is connected to the boost converter and PV array module, a comparison between tracked and theoretical MPP curves confirms the algorithm's effectiveness. The algorithm also ensured consistent BTS operation without power interruptions even under partially cloudy conditions.

## 2.11. Battery Storage

The battery storage helps maintain continuous power supply to the Base Transceiver Station (BTS) during the night, when solar irradiation is low, and in cases of sudden load change. By acting as a reserve for excess energy, the Bab Ezzouar PV System can maintain a reliable supply of power while reducing reliance on the utility grid. To provide this level of reliability, we chose to implement Lithium Iron Phosphate batteries because of their extended service life (greater than 2000 cycles), high power density, stable operation over wide temperature ranges, and improved safety characteristics over both lead acid and other lithium battery chemistries. The storage technology includes lithium iron phosphate batteries rated at 48 volts, 100 amp hour capacity providing 4.8 kilowatt hours of actual capacity (80% depth of discharge). The design gives approximately 1.1 days of usable storage based on a daily load of 3,500 watt hours (3.5 kWh) from the base station and adds a 20% safety factor to minimise cycles and improve performance. SOC will be the reference point for the operation and maintenance of energy management for all of these batteries. SOC is dynamically updated using the Coulomb Counting method [13]:

$$\text{SOC}(t) = \text{SOC}_0 - \frac{1}{C_{\text{bat}}} \int_t^0 I_{\text{bat}}(t) dt \quad (6)$$

Where:  $\text{SOC}_0$  is the initial state of charge,  $C_{\text{bat}}$  is the nominal battery capacity (Ah),  $I_{\text{bat}}$  is the battery current (positive for discharge, negative for charge), Where SOC thresholds are implemented in the control system to: Prevent deep discharge (<20%) to avoid overcharging (>95%) to Activate alerts for maintenance or faults.

## 2.12. Battery Management System (BMS)

A The Battery Management System (BMS) is a key component of the PV-BTS, making certain that the battery portion of the PV-BTS is safely, accurately, and efficiently charged and discharged. The BMS's key functions include monitoring the status of each cell in the battery pack, managing the charge and discharge process, providing overvoltage, undervoltage, and overtemperature protection, and ultimately extending the life of the battery. Voltage Monitoring: The BMS continuously monitors the voltage of each cell to ensure that all cells remain balanced. Thermal Management: The BMS ensures that the battery operates within safe temperature limits. The safe operating temperature range is typically between 0°C and 45°C for Lithium Iron Phosphate ( $\text{LiFePO}_4$ ) batteries. Current Limiting: The BMS limits the maximum amount of current that can flow into or out of the battery during charging or discharging. This protects the battery and ensures its long-term reliability. State of Charge (SOC) Estimation: The BMS determines the amount of capacity that remains in a battery at any given time, this is called the "State of Charge" (SOC). Fault Detection: If anything goes wrong with a battery; for example, there is a short circuit, it has been overvoltage, or it has been overtemped, the BMS will detect and isolate the fault. Daily Operational Example ; [10] A Typical Summer Day in Bab Ezzouar ,In the next section, we will review the operation of the BMS as we follow a real 24-hour solar generation profile for Bab Ezzouar :

Table 2. a real 24-hour solar generation profile for Bab Ezzouar

| Time interval | Operating mode                 | PV input     | bts load (~150 w)   | Battery action                                             | SOC variation          | Temperature notes              |
|---------------|--------------------------------|--------------|---------------------|------------------------------------------------------------|------------------------|--------------------------------|
| 00:00– 6:00   | Nighttime – Battery Discharge  | 0 W          | Supplied by battery | BMS allows discharge, monitors SOC closely                 | 95% → 75%              | Cool (~-22°C), no thermal risk |
| 06:00– 8:00   | Sunrise – Low Irradiance       | 500–1000 W   | Partially supplied  | Battery discharges at lower rate, blended mode             | SOC stable/slower drop | Moderate, stable conditions    |
| 08:00– 4:00   | Peak Sun Hours – Charging Mode | Up to 1.3 kW | Fully covered by PV | Excess charges battery, BMS manages C-rate, cell balancing | 65% → 100%             | Safe charging, float mode      |

| Time interval | Operating mode                     | PV input      | bts load (~150 w)                 | Battery action                            | SOC variation | Temperature notes              |
|---------------|------------------------------------|---------------|-----------------------------------|-------------------------------------------|---------------|--------------------------------|
| 14:00– 8:00   | Post-Peak – Idle/Partial Discharge | Decreasing PV | Supplied by PV, partial discharge | BMS balances load, maintains SOC ~95–100% | ~95–100%      | Hot (~35–38°C), thermal checks |
| 18:00– 0:00   | Sunset – Night Discharge           | 0 W           | Supplied by battery               | Battery powers BTS, SOC managed safely    | 95% → 80%     | Stable night temperature       |

The battery management system (BMS) tracks daily operation metrics for usage analysis and predictive maintenance. Due to moderate to high temperatures and high humidity associated with the coastal environment of Bab Ezzouar, performance of batteries may be affected. Selected LiFePO<sub>4</sub> cells (Lithium Iron Phosphate) should preferably be maintained in passive ventilation thermally insulated compartments. These systems have protections against short circuits, overload, and thermal runaway; therefore, they can tolerate ambient air temperatures of 45°C.

### 3. MATLAB/SIMULINK IMPLEMENTATION

The PV-battery hybrid system is modelled and simulated in MATLAB/Simulink to evaluate its performance under varying irradiance conditions and real-world operating constraints. The simulation integrates solar irradiance inputs, PV module characteristics, MPPT controller (P&O algorithm), DC-DC boost converter, battery storage with BMS, and the BTS load.

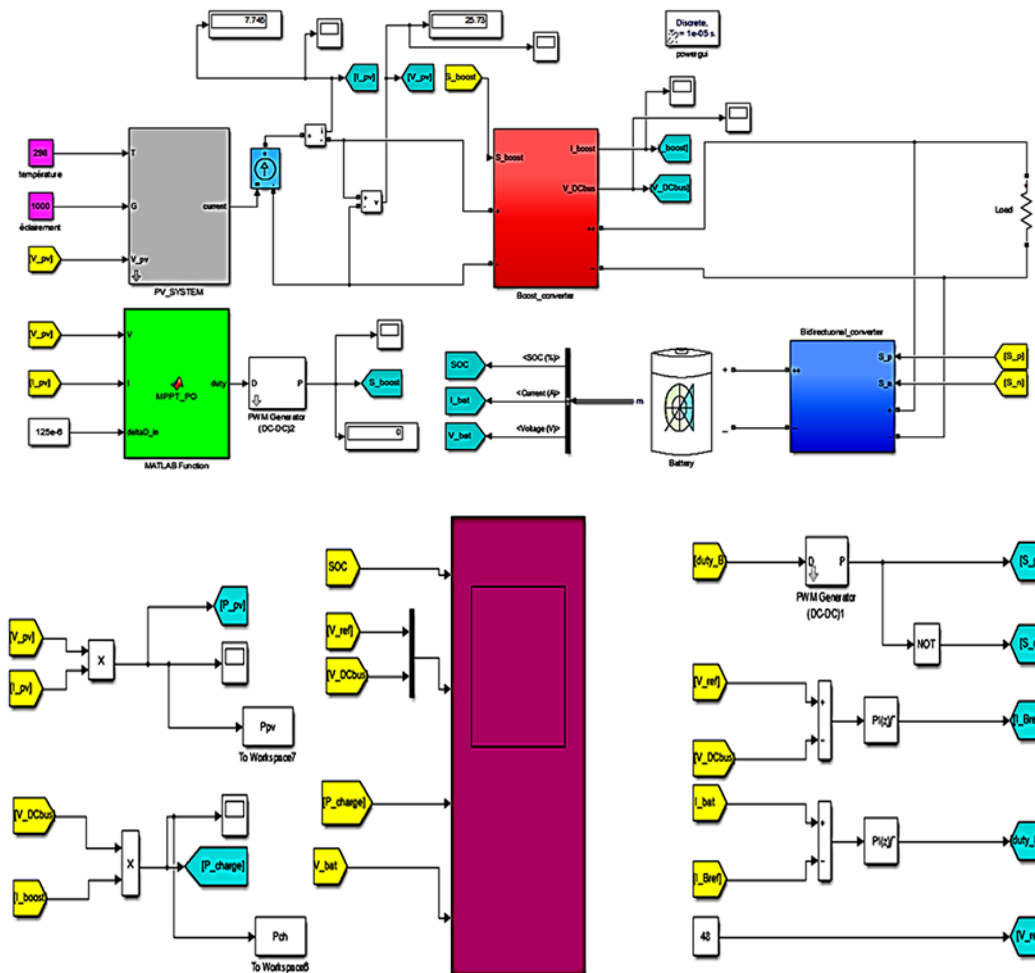


Figure 8. Overall block diagram of the system under MATLAB SIMULINK.

MATLAB/Simulink was selected to model and simulate the dynamic behaviour of the proposed PV-battery hybrid through different environmental and load conditions for the system outlined in this section which provides an overview of the simulation environment and the procedures used to conduct component modelling, select parameters and validate the hybrid system with regard to dynamic performance analysis.

### 3.1. Overview of System Architecture

The overall simulation was created by integrating five primary subsystems that will be discussed in detail as outlined in Figure 8 of this report.

**PV Array subsystem:** This subsystem provides the electrical characteristics of the monocrystalline silicon modules based upon the solar radiation and temperature of the cells.

**DC-DC Boost Converter:** This subsystem will convert the output voltage of the PV array to a regulated 48 V DC Bus for powering the BTS Load as well as for charging the batteries.

**MPPT Controller:** This subsystem provides the adaptive Perturb and Observe (P&O) algorithm to allow continuous tracking of the Maximum Power Point of the PV array by varying the duty cycle of the Boost Converter.

**LiFePO<sub>4</sub> Battery Storage Subsystem:** This subsystem represents the battery bank used for energy storage and provides SOC monitoring functionality for each battery.

**BTS Load:** This subsystem is designed to model the constant load of the BTS Base Transceiver Station as well as provide the capability to simulate dynamic load changes.

The interconnection of these subsystems provides bi-directional flow of energy, allowing for the battery to discharge when there is insufficient PV generation and to charge when excess solar energy is available.

## 4. RESULTS

We carried out a simulation where we maintained a constant temperature of 25° and for different illuminance values (1000 w/m<sup>2</sup> and 500 w/m<sup>2</sup>) and for different load values (100 ohm, 500 ohm). In the case:

Load 100ohm.

Sunshine G (1000 W/m<sup>2</sup> and 500 W/m<sup>2</sup>).

The initial state of charge of the batteries 60%.

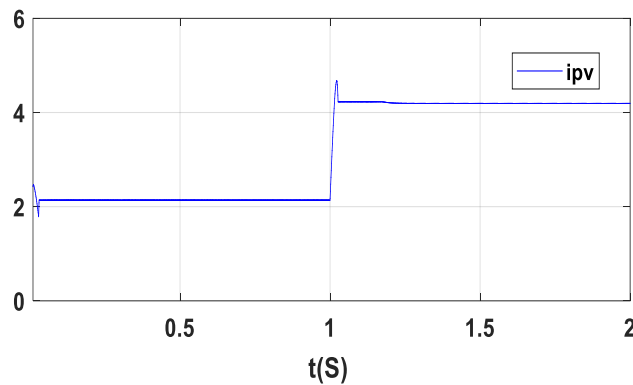


Figure 9. the PV Current.

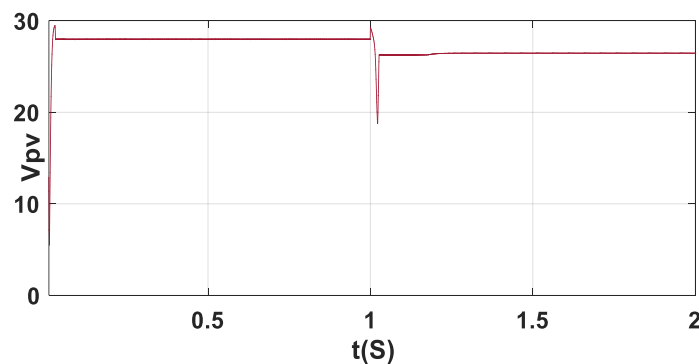


Figure 10. output voltage of PV.

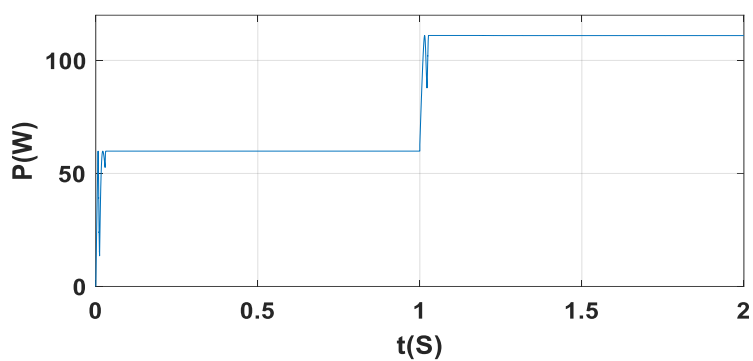


Figure 11. output power of PV

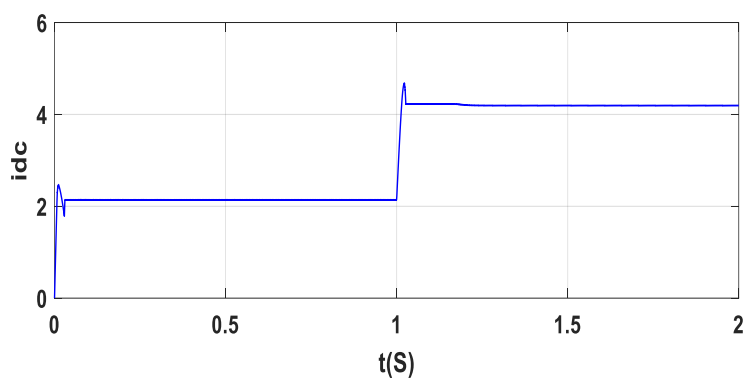


Figure 12. Current of DC bus of boost.

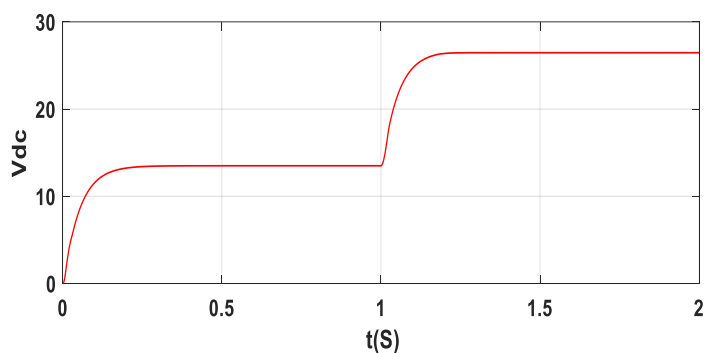


Figure 13. output voltage of DC bus of boost

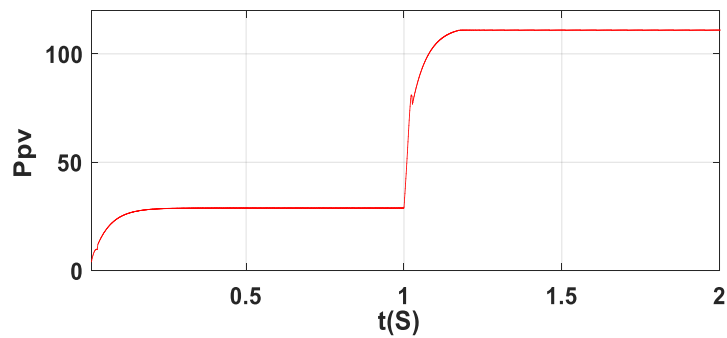


Figure 14. Power of charge

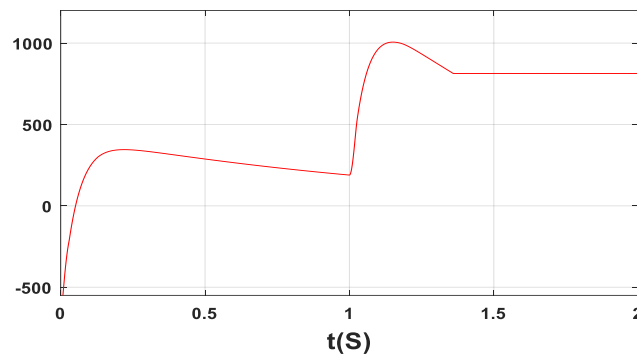


Figure 15. State of charge (soc)

Table 3. Parameter of simulation

| Parameter       | Initial Value | Final Value                   | Notes                           |
|-----------------|---------------|-------------------------------|---------------------------------|
| $P_{pv}$        | 25W           | 110 W                         | Simulates increasing irradiance |
| $I_{pv}$        | 2.2A          | 4.25A                         | As PV power rises               |
| $V_{pv}$        | 28 V          | 30V                           | Held constant for test          |
| $V_{boost}$     | 12 V          | 28V                           | Regulated                       |
| $I_{boost}$     | ~2.1A         | ~4.1 A                        | Stable under converter          |
| $P_{load}$      | 120W          | 120W                          | BTS fixed consumption           |
| $V_{DC Bus}$    | 50 V          | 50 V                          | Constant                        |
| $I_{DCBus}$     | ~2.2A         | ~4.2A                         | Shared between load + charging  |
| Battery Current | -3 A to +4 A  | +5 A max                      | Negative = discharging          |
| Battery Voltage | 48 V → 52 V   | Charging profile              |                                 |
| SOC             | 60% → 100%    | Charged fully over simulation |                                 |

## 5. RESULTS AND DISCUSSION

The dynamic response and energy control of the proposed PV-battery system were clearly demonstrated by the MATLAB/Simulink simulations at different levels of solar irradiance. The P&O algorithm showed a high degree of responsiveness to changes in solar input. The system operated very close to the Maximum Power Point (MPP) during the simulation, achieving an average of around 96% MPPT efficiency. The enhancement of adaptive step-size promoted quicker convergence rates with irradiance ramps while reducing the amplitude of steady-state oscillations found in typical P&O implementations. Power flow control was seamless as the PV source, DC-DC boost converter and battery storage operated in unison. The PV system increased the proportion of energy supply as irradiance transitioned from 25 W to 440 W, allowing the battery to transition from discharge mode to charge mode. The 120 W BTS load received uninterrupted power throughout the simulated day as it autonomously transitioned to and from power supply modes. Throughout the test scenario, the boost converter maintained a regulated DC bus voltage of 30 V while stabilizing the output current at approximately 4 A, effectively fulfilling the simultaneous load supply and battery charging requirements.

In this research study's simulated environment, cumulative error analysis of estimated state of charge (SOC) was performed using sensitivity analysis. With a current sensor accuracy ( $\pm 2\%$ ), a sample rate of 10 Hz, and a simulation duration of 24 hours under a pulsed BTS load, the predicted maximum total cumulative SOC error would be  $\pm 4.2\%$ . This value is acceptable for use because the battery management system (BMS) has implemented a 20% safety factor (SOC cannot be de-rated below 20%), providing a buffer against estimation errors. In cases where an extended autonomy requirement exists or sites have poor solar conditions, an attempt to achieve a tighter SOC estimation error ( $\pm 2\%$  or less) will require the use of more complex methods of SOC estimation (i.e., Kalman filtering [21], machine learning methods [22]).

**Tracking Efficiency:** The adaptive P&O approach has demonstrated performance levels that are 1-3% higher than conventional P&O solutions currently used in the field with an efficacy rate of approximately 96.3%. (Performance referenced in [9] is comparable to complex neural network techniques.)

**System Efficiency:** The average efficiency of the system, including losses associated with the inverter and battery management system, is 94.2%, which shows significant improvement over earlier study results (88-91% [6]).

**Regional Relevance:** Unlike most previous studies, our study utilizes site specific solar resources data from Bab Ezzouar, Algeria to quantify solar potential for applications in North Africa and other locales with similar renewable generation potential (average irradiance = 5.3 kWh/m<sup>2</sup>/day).

**Comprehensive Validation:** The 24-hour simulation cycle, with full charge-discharge cycling, provides a more thorough evaluation of the performance of the system than shorter, instantaneous evaluations as reported in previous studies.

The converter achieved effective energy transfer at high efficiencies (>94% under full load) by using a high switching frequency (20 kHz) and appropriately sized passive components, yielding low voltage ripple. The battery behavior tracked closely with theory. When irradiance conditions were low, the battery continued to supply nearly 3 A to the BTS load. The battery transitioned to charging mode as solar energy increased, pulling current at 5 A. The battery's SOC improved steadily from 60% to 100% during the simulation horizon, demonstrating the system's ability to fully recharge the battery under adequate solar conditions while regulating to prevent overcharging and deep discharge, as proposed through the BMS strategy. Although the P&O MPPT is a relatively simple and low-cost method, the results for battery charging with the P&O algorithm are compared against sophisticated solutions (e.g., Incremental Conductance and Fuzzy Logic Control). Simulation results confirmed that, based upon the proposed PV–battery hybrid system, BTS operation could be sustained autonomously, with no reliance on the grid.

## 6. CONCLUSION

This work created, planned for and tested a stand alone hybrid Photovoltaic (PV)/Battery Energy System for a Telecom Base Transceiver Station (BTS) within Bab Ezzouar, Algeria as a technical alternative energy source for off-grid telecom infrastructure in comparison to current diesel generator systems. Using meteorological data from Northern Algeria, the MATLAB/Simulink model provided 96% Maximum Power Point Tracking (MPPT) efficiency through an Adaptive Perturb and Observe algorithm while supplying continuous power on a 48VDC Bus with 18 hours (1.1 days) of power autonomy supplied by the battery bank. The Battery Management System (BMS) prevented over-discharge and excess deep discharge therefore extending the overall life of the batteries. The Modular Design allows the system to be easily expanded as needed, and fits well into Algeria's high levels of solar resource (greater than 5.3 kWh/m<sup>2</sup>/day). The possible challenges to the successful operation of the completed systems are; High Ambient Temperature reducing the PV Efficiency, Dust build-up that requires regular cleaning, Logistical problems transporting the materials to the remote sites, and Security concerns (Theft or Vandalism) affecting the systems. In order to deal with the challenges identified above, future systems should include a Hybrid System with Diesel or Fuel Cell backup power options to cover extended periods of low irradiance, Predictive Maintenance by using Remote Monitoring capabilities and complete technical-economic site specific analysis on future sites throughout Algeria.

### Practical Implementation Challenges

Although simulation results appear encouraging, numerous obstacles will have to be solved to practically deploy the proposed system in remote areas of Algeria.

**Environmental and Climate** ;The coastal Mediterranean climate in Bab Ezzouar presents many additional environmental challenges than those modeled. Extreme high ambient temperatures (numerous days in the summer exceed 40° C) decrease the efficiency of the PV modules (at a rate of -0.4%/°C) and accelerate the degradation of batteries. The condensation of humidity on the PV surfaces, dust accumulation, exposure from marine aerosols, etc. can all hinder PV performance; therefore all require an ongoing, regular maintenance schedule — however in remote areas such maintenance schedules are prohibitive.

**Logistics and Infrastructure** Many of the BTS sites in remote locations are not accessible by road; do not possess on-site skilled technical personnel; and do not have access to reliable supply chain resources for spare parts. Transporting large components on-site (i.e., each 100 AH LiFePO<sub>4</sub> battery weighs approximately 50-60 kg) to isolated sites is extremely difficult logistically. In addition, due to not having any local technical resources, the only alternative is to train the technical team at an outside location, or remotely monitor the technical team and provide centralized technical support.

**Security and Vandalism** PV panels and battery systems in isolated areas are at risk of theft or vandalism. Providing protective enclosures, including securing mounting structures, and providing community development/engagement programs are all necessary but add to the overall cost and complexity of the project.

### Recommendations for Deployment

The following recommendations are provided for the successful deployment of the system in real-world applications. These recommendations are based on the results of this study and the related challenges to the implementation of the system.

**Hybrid Solutions to Improve Reliability** the existing system can provide long-term (18 hour) autonomy. However, periods of low solar irradiation (i.e., multiple consecutive days with no sun) may render the base transceiver station inoperative due to insufficient solar energy to charge the batteries. Future

deployments of this system should consider using a hybrid configuration (i.e., a small diesel generator or fuel cell) as a back-up source of energy. By using a hybrid design, the amount of battery capacity required (initial cost) will be significantly reduced, while ensuring 100% uptime of the base transceiver stations. The backup generator will only operate during extended periods of cloudy weather, which will decrease both the amount of fuel consumed and the amount of emissions produced by the backup generator.

**Robust Physical Security and Design** PV arrays should be mounted on high, secure structures and should include anti-theft devices. Battery banks should be housed in ventilated, locked enclosures that include thermal management devices (i.e. passive or active cooling) to mitigate the degradation of the batteries due to temperature extremes. Remote monitoring devices, with tamper alerts, should be utilized so that security notifications about the systems can be received in real-time.

**Remote Monitoring and Predictive Maintenance** A web-based monitoring system should be utilized as a platform for tracking key performance indicators for the system on a real-time basis (i.e., PV output, battery state of charge, DC bus voltage, and system efficiency).

### Future Work

Based on this research study using simulation, there are several identified research and development pathways to phase into:

**Technology Validation.** This could include building a laboratory or pilot prototype of the designed system and validating the simulation results in-field. This could involve instrumenting a low-cost or small-scale BTS simulator or doing a pilot with an operator (ex. Watania Télécom Algérie at one of their remote sites).

**Advanced Control Solutions.** The adaptive P&O control algorithm was shown to satisfactorily track the MPPT as a means to maintain the optimal operating point, but future research should evaluate and contrast more advanced MPPT control solutions, such as model predictive control (MPC), neural networks, and fuzzy logic-based controls, particularly as they apply to partial shading and rapidly changing irradiance conditions.

**Multi-objective optimization.** Further research should include developing a MOP (multi-objective programming) model that minimizes LCOE while maximizing system reliability and minimizing environmental impact (embodied carbon). This would provide a more comprehensive design framework than the current technical feasibility objectives.

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## BIOGRAPHY OF AUTHORS



### Sahraoui Hamza

He has a Ph.D. in Industrial Systems Control and Renewable Energy (2016, Batna 2 University, Algeria). Currently he is an Associate Professor. His research focuses on control systems, nonlinear and adaptive control, and renewable energy.



### ALI Moussa Mohamed

was born in Algeria in 1973, he received his Engineer's Degree in Electrical Engineering in 1997 from the University of Laghouat (Algeria). He defended his Magister degree in electrical engineering in 2013 at the University of Khemis-Mliana (Algeria). He is now preparing his doctorate at the University of Science and Technology of Oran (Algeria). His area of scientific interest is the study of interharmonics in the electrical network.


**Hacene Mellah**   

He received the B.S. (2006), Magister (2009), and Ph.D. (2020) degrees from Sétif 1 University, Algeria. Since 2020, he has been an Associate Professor at the University of Bouira. His research interests include control and diagnostics of electrical machines, intelligent techniques, and renewable energy.


**Amar Maafa**

Received the B.S. (2008) and Ph.D. (2017) degrees in Electrical Engineering from the University of Bejaia, Algeria, and a Magister degree from Batna University in 2011. His research focuses on control, modelling, and diagnostics of wind energy conversion systems.


**Abdelghani Yahiou**

Received the B.Eng. (2009), M.Sc. (2012), and Ph.D. (2021) degrees in Electrical Engineering from the University of Setif-1, Algeria. Currently he is an Associate Professor. His research interests include transformer transients, inrush current, ferroresonance, modelling, and measurement systems.


**Bessaad Taieb**

Currently works at University chlef Received Ph.D. degrees in Electrical Engineering from the University of batna, Algeria. Currently he is an Associate Professor. His research Power electronics in Renewable Energies


**Farouk Mechnane**

was born in Batna, Algeria, in 1994. He received his Master degree in Electrical Engineering from the University of Batna, Algeria, 2019. Currently, he is Ph.D Student at the Electrical Engineering Department, University of Batna, Algeria. He is a Member of the “Energy Saving and Renewable Energy” team in the Research Laboratory of Electromagnetic Induction and Propulsion Systems of Batna University, He is also Student Member IEEE. His research interests include Renewable Energies, field theory, and electric machines, nonlinear control for renewable energies and storage system


**Baazouzi Kamal**

Dr. Kamel Baazouzi was born in Batna, Algeria, in 1970. He received the accalaureate degree in Mathematics in 1989, the State Engineering degree in Electrical Power networks from the University of Batna, Algeria, in 1994, and the Magister degree in Electrical Machines and Control Systems from the same university in 2013. He obtained the Ph.D. degree in Sciences from the University of Batna 2, Algeria, in 2023. Since 2023, he has been a lecturer and researcher at the University Center of Barika, Algeria, where he teaches courses related to control systems and renewable energy. His research interests include control of electrotechnical systems, passivity-based control of power converters and induction motors, and optimization of renewable energy systems, particularly photovoltaic and wind energy systems.

**Drid Said**

Received B.Sc., M.Sc. and PhD degrees in Electrical Engineering, from the University of Batna, Algeria, respectively in 1994, 2000 and 2005 respectively. Career history: He is Currently a full Professor at the Electrical Engineering departement at University of Batna 2, Algeria. He is the head of the Energy Saving and Renewable Energy Team in the Research Laboratory of Electromagnetic Induction and Propulsion Systems of Batna University. In 2015, he spent two months as a Visiting professor at Picardie Jules Verne University, France. His research interests include electric machines and drives, renewable energy. He is also a reviewer for several prestigious journals (IET, IEEE, etc.). Prof. Drid is the Vice Chair of the Power & Eenergy chapter and the Treasurer of the IEEE Algeria Section. He serves as an Associate Editor for some international journals, Research interests: His main research interests include Power Quality issues, Power Electronics Devices, Application of Power electronics in Renewable Energies, Electrical machines and drives, Sensorless control, Electrical vehicles and unmanned vehicles, Smart Grid

**Larbi Chrifi-Alaoui**

Larbi Chrifi-Alaoui currently works at Université de Picardie Jules Verne. Larbi Chrifi-Alaoui received the Ph.D. degree in automatic control from the Ecole Centrale de Lyon, Ecully, France, in 1994. Since 1999, he has held a teaching position in automatic control at the Aisne University Institute of Technology, Université de Picardie Jules Verne, Cuffies-Soissons, France, where, from 2004 to 2010, he was the Head of the Department of Electrical Engineering and Industrial Informatics. His research interests include linear and nonlinear control theory, including sliding mode control, adaptive control, and robust control, with applications to electric drive and mechatronics systems