An Optimized, Low-Cost Off-grid Solar System: Design and Implementation

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Abstract. This paper reports on the design and implementation of a low-cost off-grid solar installation system that maximizes the energy production for any given day. Our proposed solution consists of (1) a double axis solar tracker with electric actuators controlled by an Arduino board, (2) an MPPT (Maximum Power Point Tracking) power controller, with a capacity of 20 A, remotely accessible from a smartphone with a dedicated Android application that uses a Bluetooth connection and (3) a remote data logging system that periodically stores the installation data to an online database server using a Wifi connection. The overall cost of the system is about $215 ($72 for the regular and $143 for the solar tracker).

Keywords: MPPT regulator · Solar tracker · Connected regulator

1 Introduction

Energy has always been vital to the development of nations. It underpins all other sectors such as education, health, agriculture, and information systems. Consequently, when the energy sector is dysfunctional, the whole nation is impacted. This has been the case for Senegal where the population have witnessed a long period of frequent power outages between 2011 and 2016. According a study by the “Direction de la Prevision et des Etudes Economiques”, these outages have had an economic impact of $16,500 per day [11].

As an alternative to unreliable grid power, the populations have turned to renewable energies, specifically solar, which presents many potentials in Senegal (it is free and available throughout the year). However, despite the opportunities it offers, there are several challenges that need to be overcome for an effective use of solar energy in Senegal (and in Africa in general). Two of the main challenges are *efficiency* and *cost*. In this paper, we report on a project that addresses these two issues by the design and implementation of a low-cost off-grid solar installation system that optimizes the production of energy for any given day.

1.1 The Current State of Electrification in Senegal (Africa)

In Africa, the overall electrification rate is quite low. According to the “Global Energy Architecture Performance Index” report (2017) [1], only five African countries

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(Morocco, Egypt, Tunisia, Algeria and Libya) have achieved a 100% electrification rate. The same report ranks Senegal at the eighth position among the 24 African countries in the study, with an electrification rate of 56.5%.

Access to electricity has always been an issue in Senegal. In addition, the existing and limited grid energy is unevenly distributed between rural and urban areas. While people in big cities are living with frequent power outages, the rural population is living in complete darkness; this, despite the many efforts deployed by the successive governments to significantly boost the energy sector. For instance, the PERACOD ("Programme de Promotion de l'Electrification Rurale et l'Approvisionnement durable en Combustibles Domestique") [2] program aims at expanding the electrical grid and increase the electrification rate to 60% by 2022. In the meantime, the majority of the Senegalese population is using oil lanterns and candles at night.

In the last decade, the populations have been increasingly turning towards renewable energies (in particular solar) because of the many potentials they offer. In fact, the amount of yearly solar radiation received in Senegal, could fill the energy deficit experienced by the SENELEC ("Société Nationale d'Electricité") and help remove the disparities in the energy distribution between urban and rural areas.

1.2 Solar Energy Potential in Senegal

Senegal has one of the highest solar potential in the world, with an average of 5.5 kWh/m^2/day raw energy (with some variations between the north and the south parts of the country: the average raw energy is equal to 5.8 kWh/m^2/day in the north, while it is equal to 4.03 kWh/m^2/day in the south) [3, 4]. This average raw solar energy is equivalent to 395 thousand billion of kWh per year, or 33.83 million PET (Petroleum Equivalent Tons). This is equivalent to 15 million times the total current energy consumption of the country [4]. If exploited with some minimal efficiency, the entire country can be powered solely by solar energy throughout the year.

In addition, sunshine is pretty stable throughout the year in Senegal. It is slightly less sunny during the rainy season, with August having the smallest sunshine rate. However, compared to March (which is the sunniest month of the year), the drop of the sunshine rate is less than 25%. As a contrast, in Europe, the drop between December and June can be as high as 250%.

Encouraged by this high solar potential, the government of Senegal has recently launched a campaign to motivate the population to adopt off-grid solar installations.

1.3 Architecture of an Off-grid (Autonomous) Photovoltaic System

One of the main characteristics of off-grid solar systems is that energy can be produced *only* during the day time. Therefore, there is a need to store (part of) the produced energy for night time consumption.

Figure 1 shows the architecture of an off-grid solar installation system. The energy production is done by the solar panels that use the photoelectric effect to produce a direct current. A solar charge controller is then used to control the associated voltage. Energy storage is performed by using this voltage to charge batteries. The controller also protects the batteries against overcharging which is known to dramatically reduce battery lifetime. At sunset, the panels stop producing current and the stored energy starts getting consumed for household needs. For that, an inverter is used to convert the direct current (DC) of the batteries to the alternative current (AC) needed to power most household apparels (TV, PC, Refrigerators, etc.).

Given that only the quantity of energy stored during the day is available for consumption at night, it is crucial for any solar installation to be able to charge the batteries at their maximal capacity before the sun goes down. That is one of the two objectives we have set in this project.

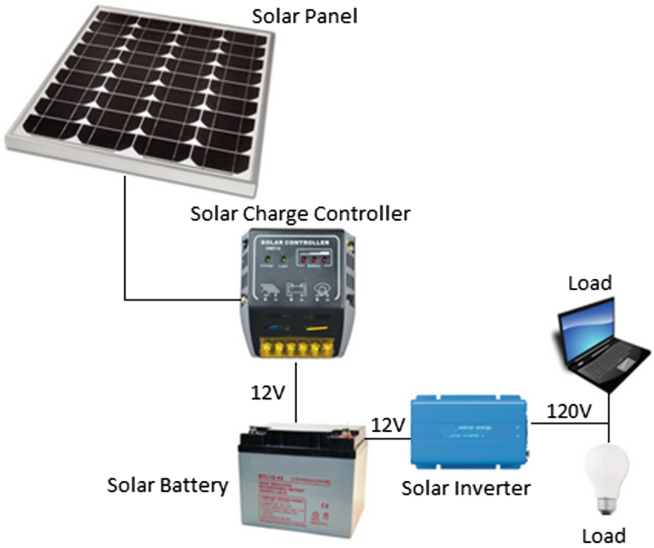

Fig. 1. Architecture of an autonomous photovoltaic system

2 Our Proposed Solution

In this section, we present our proposed solution. For recall, our goal is to design and implement a low-cost photovoltaic system with optimized efficiency. We start by relating some facts gathered from a survey conducted with solar installations professionals in Senegal and visits made to household installation units.

2.1 Observations from Field Visits

Because of the government's ongoing campaign to encourage populations to adopt off-grid solar energy, an increasing number of Senegalese households are acquiring solar installations. In December 2017, we surveyed installation and maintenance professionals and visited several households installations to study the performance of the installed units. At the end of our filed visits, our main observation was that most installations have a deficit of production. For instance, at the end of each day, the batteries are usually not fully charged. The main reasons found for this deficit in production are the following:

1. The panels are usually not well dimensioned, which leads to insufficient power production,
2. The charge controller is often of very low quality,
3. The batteries used are often inappropriate (most of the time car batteries are used).

Among these causes of inefficiency, the low-quality charge controller is the most widespread. This is principally due to the very high cost of the controller (in the Senegalese market), which makes people to turn toward cheaper but very *low-quality* controllers. Unfortunately, the quality of the controller is very crucial for the efficiency of the overall system.

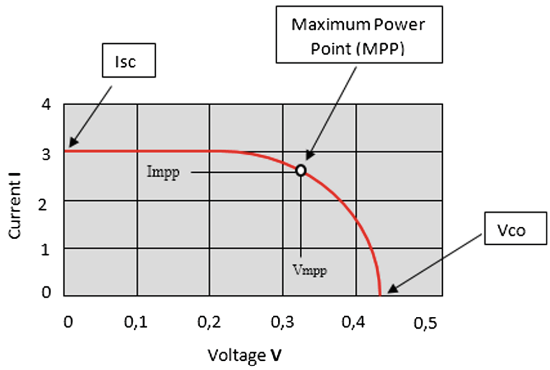

Fig. 2. Characteristics of an MPPT charge controller

The optimal charge controller has been known to be the MPPT, which sets the panels to produce at their optimal power, as shown in Fig. 2. Unfortunately, the MPPT controllers that are available in today's Senegalese market are very expensive. For instance, for a 30 A capacity, the Victron 100/30 controller that is the most available costs around $180. This is more than ten times the lower-quality PWM controller that is found in most installations in Senegal (costs around $15). With these low-quality charge controllers, the batteries are rarely fully charged before the sun goes down. This, combined with the inappropriate batteries, leads to unreliable systems with batteries that usually get discharged before the sun rises again. Not only this causes a deficit in energy, but it also can damage household apparels.

As a solution, we propose a low-cost implementation of the MPPT by using an Arduino board (which is quite cheap). To further enhance the production of the system, we build a solar tracker that maintains the panels oriented in the direction of the sun, at all times. With this, the maximum (possible) power production is guaranteed, whether it is very sunny or not.

2.2 The Automatic Solar Tracker

The solar tracker is built with two rotations axes, each equipped with a servomotor. The two axes guide the movement of the tracker in order to maintain a 90 degrees incidence angle at all times. The overall system is controlled by an Arduino microcontroller board on which we have implemented the "Perturb and Observe" (P&O) tracking algorithm. The algorithm dynamically re-computes the *average* position of the panels by making use of data gathered by four photoresistor sensors (Light Dependent Resistors—(LDR)) placed in the four corners of the support unit. Figure 3 shows a picture of the positioned LDRs.

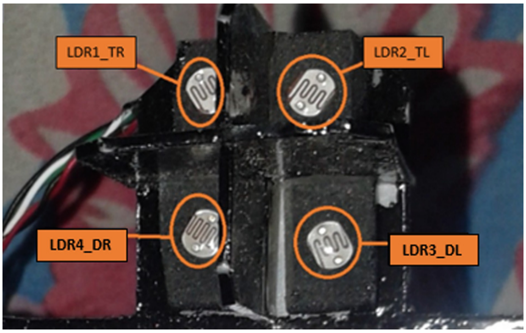

Fig. 3. Photoresistor sensors positioned on the support of the panel

The tracking algorithm continually executes the following steps:

- First, it computes the averages as follows:
  - Top average: ***avgt = (LDR1_TR + LDR2_TL)/2***;
  - Down average: ***avgd = (LDR4_DR + LDR3_DL)/2***;
  - Left average: ***avgl = (LDR1_TR + LDR4_DR)/2;***
  - Right average: ***avgr = (LDR2_TL + LDR3_DL)/2.***
- After that, the differences between averages are computed as follows:
  - ***dv = (avgt – avgd),***
  - ***dh = (avgl – avgr).***
- Finally, the algorithm compares the values of dv and dh to a tolerance level t and uses the result to update the position of the panel. The updates are done as follows:
  - ***If (dv>t or dv < −t),*** then
    If (avgt > avgd), then, orient the support towards the top,
    Else, orient the support towards the bottom;
  - ***If (dh>t or dh < −t),*** then
    If (avgl < avgr), then, orient the support towards the right,
    Else, if (avgl < avgr), then, orient the support towards the left;
    Else If (avgl == avgr), then, maintain current position.

It is possible to tune the sensitivity to the fluctuations of the luminosity by varying the tolerance value (**t**) using a potentiometer. This allows us to control the precision of the tracker.

Figure 4 shows the circuit diagram of the tracker, while Fig. 5 shows a picture of the panels mounted on top of the support of the tracker.

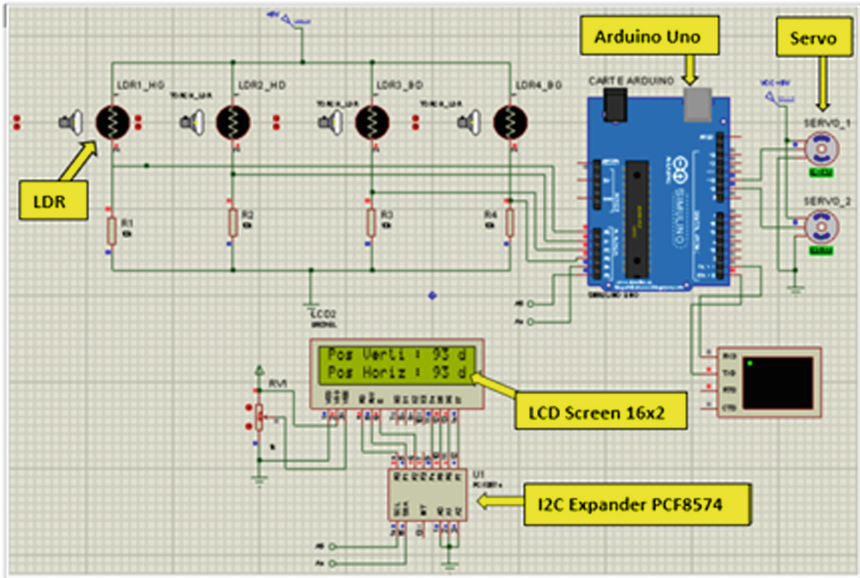

Fig. 4. Diagram of the solar tracker

2.3 The MPPT Charge Controller

MPPT is a technic used in off-grid solar installations to maximize the power extraction under all conditions [3, 4]. It is composed with an algorithm embedded into an electronic circuit [5–7]. In our case, we use an Arduino board as microcontroller on which we implement the MPPT algorithm as well as the P&O algorithm. The controller regulates the output voltage toward the batteries to protect them against overcharging but also against overvoltage (by use of a diode TVS at input and at output) and overcurrent (by use of a fuse). To allow remote access, the controller is also equipped with a Bluetooth module (HC-05) and a Wifi module (ESP-01). The Bluetooth module is used to communicated with a dedicated Android application that gives to the users the possibility to remotely access the installation data via a smartphone. The Wifi modules serves as a channel to periodically log the system data onto an online database server. These added functionalities enable the user to access the system data from anywhere and at any time.

Fig. 5. Miniaturized implementation of the solar tracker

2.4 The DC/DC Converter

The role of the DC-DC converter is to optimize the match between the voltages of solar array (PV panels) and the battery bank. It does it by maintaining the nominal functioning point (FP) *on or very close to* the maximum power point (MPP), independently of the conditions (temperature, solar radiation, battery charge, etc…).

In this project, we have used a DC-DC converter of type BUCK to control the input voltage. On the other hand, the reference voltage is fixed or set by the P&O algorithm that varies the cyclic ratio (*D*) of the static converter.

The whole conversion process works as follows: The Arduino board generates a 5 V PMW signal. An associated embedded circuit (Half-Bridge Driver IR2014) then enables the switching of the MOSFET transistor (IRFZ44N) of the converter. This allows to vary the cyclic ratio which maximizes the power transfer towards the output of the controller. The BUCK controller always gives an output voltage that is lower than the input. The value of this output voltage is given by the following formula:

$$\boldsymbol{Vout} = \boldsymbol{Vin} * \boldsymbol{D},$$

where, ***Vout*** is the output voltage, ***Vin*** is the input voltage and ***D*** is a cyclic ratio.

The value of the inductance is an important parameter for the efficiency of the system. The optimal value is compute using the following formula:

$$L = \left(\mathrm{V_{in}} - \mathrm{V_{out}}\right) * \mathrm{D} * \frac{1}{f} * \frac{1}{dl}$$

where, **L** is the inductance, ***f*** the switching frequency, and ***dI*** is the ripple current (*here **dI** is chosen between 30 and 40% of the output current*). The circuit diagrams of the converters are shown in Figs. 6 and 7.

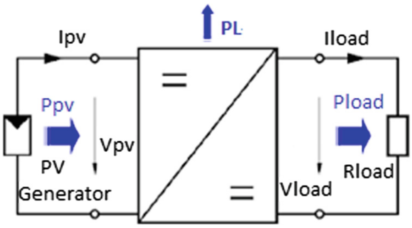

Fig. 6. Circuit of the DC-DC converter

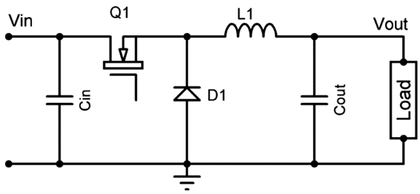

Fig. 7. Circuit of the BUCK converter

2.5 The Arduino Board

The Arduino board represents the brain of the MPPT controller. For our implementation, we use an Arduino UNO model. Its reduced size and weight makes it suitable for usage in systems with limited space. It is equipped with a type B mini USB port that allows it to be programmed via a computer. It is also capable of performing Analog-Digital conversion. The table below shows the main characteristics of our Arduino board.

Table 1. Characteristics of the Arduino board

Arduino Card Name	Microcontroller	Flash memory (Ko) Boot	SRAM (Ko)	EEPROM (Ko)	Voltage (V)	Logical level (V)	Digital I/O	Analog I/O
 Nano	Atmega168/328	16/32 (2)	1/2	0.5/1	7-12	5	14 (6)	9 (10bits)

We use the digital pins (D0 = RX and D1 = TX) for the serial communication with the Wifi model. Pins D4 and D7 are used as virtual serial interface to enable communication with the Bluetooth module.

2.6 Overview of MPPT Controller

Table 1 shows an overview of the different internal components of the MPPT controller. The solar panels produce the photovoltaic energy. The Arduino board generates the PWM signal to control the DC-DC controller. This signal permits to vary the cyclic ratio to adapt the output voltage towards the charges (batteries). The Arduino board also exchanges information with the outside world via the Bluetooth and the Wifi modules. Figure 8 shows a picture of the different components of the MPPT module.

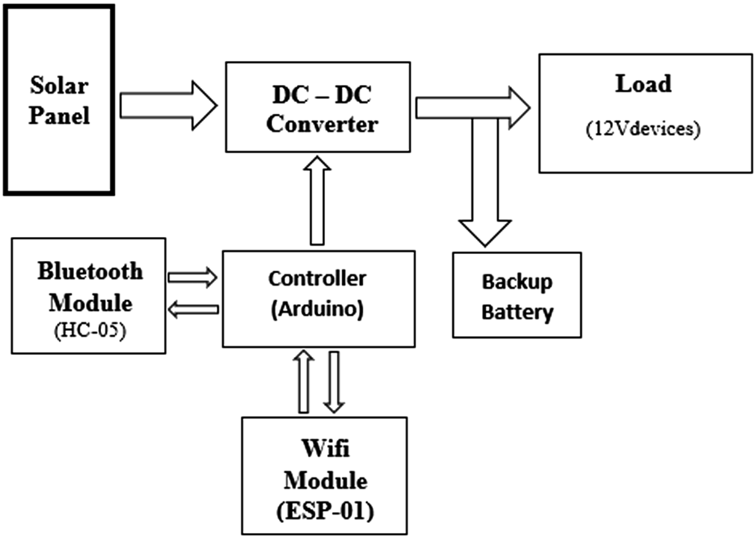

Fig. 8. Overview of the different components of the MPPT charge controller

2.7 The P&O (Perturb and Observe) Algorithm

To vary the cyclic ratio (which leads to the control of the output voltage), we use the P&O algorithm. It is a very simple and easy to implement algorithm. As its name suggests, it perturbs the system, then observes the power generated by the PV to then move the nominal functioning point toward the MPP according to the following dynamic equation:

$$V(k) = V(k-1) + \Delta V \cdot sign\left(\left.\frac{dP}{dV}\right|_{V=V_{k-1}} \right)$$

A flow diagram of the algorithm is shown is Fig. 9, below.

At each step, after measuring the voltage and current and computing the corresponding power, the following verification tests are performed:

- *If (P(k) > P(k − 1), then:*
  - ***If V(k) > V(k − 1), then** increase the cyclic ration*
  - ***Else,** then decrease the cyclic ratio (V(k) becomes V(k − 1));*
- *If (P(k) < P(k − 1), then:*
  - ***If V(k) > V(k − 1), then** decrease the cyclic ratio,*
  - ***Else,** increase the cyclic ratio (V(k) becomes V(k − 1)).*

This procedure is periodically repeated until a maximum power point is reached.

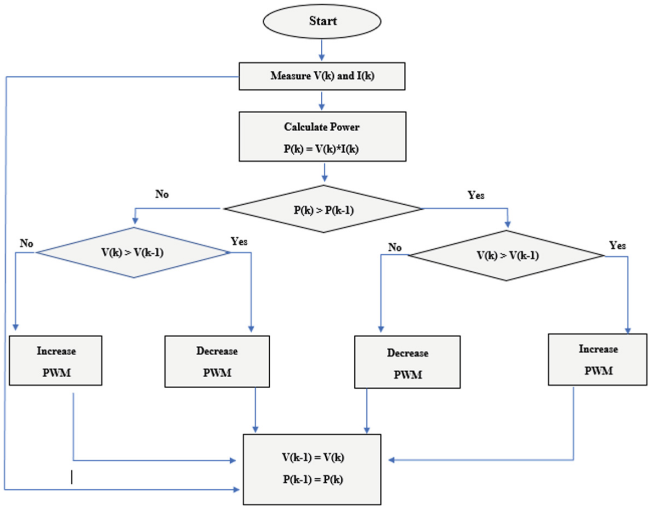

Fig. 9. Flow diagram of the P&O algorithm

3 Related Work

Solar tracking has long been used to increase the efficiency of photovoltaic systems. They have been implemented both with one and two axles. In [8] a double-axle solar tracking system has been used to gather the maximum sun radiation during the day and maximize the produced energy. Unlike our system though, the authors do not use an Arduino board to control the installation. Instead, an PID (proportional integral derivative) controller was implemented to adjust the position of the structure. Using the Arduino allowed us to build a system with similar functionalities at a much lower price.

In [9] a dual-axle solar tracker has been implemented with the additional functionalities of data logging, as in our system. However, the authors use an Atmega 328 microcontroller instead of an Arduino board. Their implementation is *passive* in in the sense that the position of the sun is pre-calculated and hard-coded in the system. Contrary, our implementation dynamically recomputes the position of the sun and hence, is more *active*. This is done using an algorithm that takes as input data acquired by a set of photoresistor sensors placed on the surface of the panels, giving accurate information about the position of the sun at any given time. Finally, our system is also more flexible, as it is able to orient the panels on both axles.

With respect to the implementation of the MPPT technic using an Arduino board, a work similar t ours is presented in [10]. Unlike this work though, ours is not limited to only the design/conception an MPPT controller. Our system is more complete and is embedded with additional functionalities such as remote access to the system data and state of the installation. This can be done via Bluetooth or Wifi. We have also developed a dedicated Android application that enable remote access through a smart phone. Hence, the operator can at any given time and from anywhere consult the system data (online or via their smartphone). In addition, the system data is periodically logged onto a server database, hence providing the possibility of different king of historic studies and data mining.

4 Conclusion and Future Work

In this work, we have designed and implemented a low-cost solar energy system capable of optimizing its production under arbitrary weather conditions. It is composed with an MPPT charge controller and a double axel solar tracker, both controlled by an Arduino board on which we have implemented our algorithms. The whole system is remotely accessible via Bluetooth using a dedicated Android application and via Wifi. Its overall cost is equal to ¼ of the cost of the currently available systems with similar performance.

In perspective, we are considering the manufacture and marketing of connected MPPT controllers and stand-alone mobile devices (solar trackers) for solar panels at very affordable prices in Senegal.

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