Modelling and study of energy storage devices for photovoltaic lighting

Marwa Ben Slimene¹,² and Mohamed Arbi Khlifi³

Abstract
The electricity production via these sources of energy, offers a bigger safety of supply to the consumers while respecting the environment. For that reason, the principal objective of this paper is to study and control the photovoltaic lighting energy storage system. We presented the study of the whole PV system such as solar panels, DC chopper, batteries with account of all conditions of the sites of installation (period of sunshine and temperature). This study analyzed the integration of a photovoltaic power plant, super capacitor energy storage system, and lighting system. Our approach of sizing is based on the modeling of various components describing the functioning of every part of the installation among others. We can mention the production, the consumption and the storage of energy through solar battery.

Keywords
Lighting and electrification, solar charge controller, Maximum Power Point Tracking, battery, energy storage, Energy Efficiency

Introduction
With the ever increasing demand for energy, the search for alternative energy sources has increased. The worldwide use of fossil fuels has led to the critical situation of global warming, significantly affecting our health, environment and climate. Extensive emphasis has been put on the development of renewable energy systems. In this context, photovoltaic systems are considered as one of the best solutions for the production of electricity. However, these systems are subject to the variations in the amount of solar energy available throughout the day and throughout the year. This poses a major challenge in terms of energy storage, which is essential for the continuous operation of the system.

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on the implementation of renewable energy sources. Solar energy is by far the most abundant form of renewable energy and has the potential to partially replace fossil fuels. The amount of solar radiation striking our earth’s surface is about ten thousand times higher than the current global electrical energy consumption. Photovoltaic (PV) cells are one of the ways to harness solar energy. PV cells convert sunlight directly to electricity and can be influential in meeting the world’s energy demand. Photovoltaic technology (PV) is an important technology that can convert solar irradiance directly to electrical energy through a PV panel (Arias et al., 2012; Gago et al., 2013; Gil-de-Castro et al., 2013; Wang et al., 2014).

Nowadays, much of the world’s energy is provided from fossil sources. The consumption of these sources gives rise to emissions of greenhouse gases and thus to an increase in pollution. Thus, renewable energy from the sun, wind, heat, earth, water or biomass, represent the future of the planet and represent an unlimited energy resource. However, electricity from renewable sources is intermittent and dependent on weather conditions. To do this, these renewable generators are usually coupled to a storage system providing continuous availability of energy (Gnanavadivel et al., 2016; Principi and Fioretti, 2014).

Implementation of technologies for harvesting renewable energy sources faces several challenges (Li et al., 2016). Some of the questions which considerable effort is spent on worldwide are: uncertainty in political decisions regarding actors’ responsibility for the energy transition, lack of developed optimization tools to manage high penetration of intermittent energy sources, limitations of energy storage solutions. A target of 100% renewable energy supply will only be achieved if consumers are convinced to become more efficient and environmentally friendly in the way they use energy. No incentives or rather small ones are supported by a very high payback time of the equipment to manage renewable energy, despite the decreasing price trend (Aneke and Wang, 2016).

Light-to-light systems are typically solar powered stand-alone lamps using LEDs as light source. The reason the use of a semiconductor laser might be interesting for general lighting is not the stimulated coherent emission typical of a laser, but the high light intensity, luminous efficiency and optical management of the light beam (Sędziwy and Kotulski, 2016). Park lights and bollards are examples of L2L systems and these systems offers lighting solutions, for places where lighting is not feasible due to very high cabling costs of e.g. 500 €/m in Copenhagen. At low latitudes dimensioning of such products is relatively easy, since there is plenty of sun and the difference between day length between summer and winter is small. However, in locations further away from equator, the difference in day length between summer and winter increases, and the solar potential is less. Therefore, construction of reliable lighting with feasible dimensions requires intelligent harvesting and efficient usage of energy becomes crucial (Ghaib and Ben-Fares, 2017; Mohamed, 2016; Rashwan et al., 2017; Schratz et al., 2016).

The migrating to LED (Light Emitting Diode) lighting allows considerable energy savings due to its superior efficacy compared to halogen and fluorescent lighting; further improvements are soon expected. The initial cost of purchasing LED lighting has plummeted in recent years, often making it the most economical choice. For those reasons, LED lighting is becoming omnipresent (Touitou et al., 2017). With the invention of LED (light emitting diode) technology as low power lighting sources, PV systems find an ideal application in remote or mobile lighting systems. PV systems combined with battery storage facilities are mostly used to provide lighting for billboards, highway in formation signs, public-use facilities, parking lots, vacation cabins, lighting for trains. Lightning is an electrical discharge in the atmosphere and typically occurs during thunderstorms. Lightning can
be categorized as intracloud lightning (sheet lightning), cloud-to-cloud lightning (heat lightning), cloud-to-air lightning and cloud-to-ground lightning. Intracloud lightning is the most common type of lightning and appears completely within a cloud. Cloud-to-cloud lightning occurs between two or more separate clouds without contact to the ground. Cloud-to-air lightning refers to a discharge jumping from cloud to clear air. Lastly, cloud-to-ground lightning occurs between a cloud and the ground and is initiated by a downward-moving leader stroke and upward-moving leader stroke (Ibrahim and Ahmed, 2017).

The commercial systems can light the streets from 4 to 12 hours depending of the size of PV panel and battery. The structural scheme of the solar street light system is presented in Figure 1.

Solar photovoltaic (PV) lighting systems have provided a practical and cost-effective solution for powering a diversity of lighting applications. Thousands of PV lighting systems are being installed annually throughout the world, including applications for remote area lighting, sign lighting, flashing and signaling systems, consumer devices and for home lighting systems. PV lighting systems are simple, easy to install, and if properly designed and maintained, can provide years of exceptional service.

Renewable generator selected for this study is a photovoltaic (PV) with storage system is ensured by battery. This system is called PV-battery systems. The storage type generally used in this system is the lead-acid battery. However, the use of such battery on a seasonal scale is unfeasible. To protect against excessive charging, we must disconnect them from the system, so it is impossible to use all of the renewable resource. To this end, our paper is structured in three parts: A general description and also the principle of operation for each element constituting the photovoltaic system presented. After that, we propose two type of control PV lighting System, we present and model each part of the system. Finally, the design and simulation of the solar storage is presented.

**Modeling of the PV lighting system**

The solar irradiance could be considered the most important climatic variable that determines correct performance of a PV. A photovoltaic system represented in the figure 2 is an alternative energy generation technique that takes advantage of solar irradiation to produce electrical energy through the photoelectric principle and can be used in two main ways:
direct consumption and energy storage into a battery bank of deep cycle, this allows to have energy availability at any time. A photovoltaic lighting system is an alternative energy generation technique that takes advantage of solar irradiation to produce electrical energy through the photoelectric principle and can be use.

**PV system design**

A photovoltaic cell can be modeled as a current source in parallel with a diode. However, when the intensity of light incident increases the current is generated by the photovoltaic cell.

The mathematical equation of the circuit in the ideal model is:

$$I_{pv} = I_{cc} \frac{E}{E_r} + k_{isc}(T - T_r) \frac{E}{E_r} - I_s \left[ \exp \left( \frac{V_{pv}}{V_T} \right) - 1 \right]$$

(1)

The mathematical equation of the circuit in the real model is:

$$I_{pv} = I_{cc} \frac{E}{E_r} + k_{isc}(T - T_r) \frac{E}{E_r} - I_s \left[ \exp \left( \frac{V_{pv} + R_s I_{pv}}{V_T} \right) - 1 \right] - \left( \frac{V_{pv} + R_s I_{pv}}{R_{sh}} \right)$$

(2)

**Modeling of a PV generator**

The PV generator is a series/parallel combination of photovoltaic cells. The Photovoltaic module used in this system is a 36 multi-crystalline solar cell in series able to provide 53.32 W of maximum power. A mathematical model of a solar cell can be treated as a current source parallel with a diode; the model is completed by a parallel resistor $R_{sh}$ and a series resistor $R_s$ as shown in Figure 3.

Thus, to achieve the desired current and voltage, an association of $N_s$ modules in series and in parallel $N_p$ connected modules gives rise to a $P_{pv}$ generator; its output current voltage characteristic is given by (3).

$$I_{pv} = N_p I_{ph} - N_p I_0 \left( \exp \left( \frac{V_{pv} + R_s I_{pv}}{N_p} \right) \frac{R_s}{aV_T} - 1 \right) - \left( \frac{V_{pv} + N_s R_s I_{pv}}{N_p} \right)$$

(3)
Modeling of the buck converter

In order to convert DC to DC, a DC chopper becomes necessary. Currently, there are exclusive buck converter models for isolated systems which already have an integrated battery charger and controller. Depending on the DC voltage and power consumption, the voltage of the charger and the same voltage of the buck converter vary from 12, 24 or 48 V. There are also DC converters for isolated systems with voltages that exceed 48 V.

When the temperature increases, we see the importance of voltage variations; moreover, the current intensity increases slightly. The topology of a buck converter is shown in Figure 4. When the switch is on position 1 the circuit is connected to the dc input source resulting an output voltage across the load resistor. If the switch changes its position to position 0, the capacitor voltage will discharge through the load.

Controlling switch position the output voltage can be maintained at a desired level lower than the input source voltage. The buck converter shown in Figure 6 can be described by the following set of equations

\[ L \frac{di_L}{dt} = uV_o - V_s \]  

\[ C \frac{dv_s}{dt} = i_L - i_s \]  

**Figure 3.** Modeling of the PV generator.

**Figure 4.** Schematic diagram of a “Buck” converter.
Where $i_L$ is the inductor current, $V_s$ is the output capacitor voltage, $V_e$ is the constant external input voltage source, $L$ is the inductance, $C$ is the capacitance of the output filter and $R$ is the output load resistance. $U$ is the control input taking discrete values of 0 and 1 which represents the switch position. $U = 0$ if switch is at position 0, and 1 if switch is at position 1.

**Modeling of the battery**

Household electricity use pattern is out-of-phase with the solar irradiation intensity along the day. Thus, large portion of electricity is generated during the hours of low household electricity demand. Storage facilities are essential when it comes to the use of intermittent energy sources like solar power. Therefore, reliable and cost-efficient energy storage is needed in order to increase self-consumption and contribute to the possible peak shaving and shifting. Batteries used in this research are electrochemical storage systems which consist of the cathode (positive part) and the anode (negative part) separated by the porous separator. This way the ions flow between electrodes via the electrolyte. The current is either supplied into the battery in charging mode or drawn from the battery in the discharging mode. External supply or demand sources are used in this case. Currently market is shared by different types of battery storage technologies and depending on the application, one or another technology appears to be the most cost-efficient (Hadjipaschalis et al., 2009).

The energy from PV is stored in batteries and there are several types of them according to the technical specifications for photovoltaic lighting system. There are four types of batteries: electrolyte absorbed amid fiberglass and gelled electrolyte for small systems; Stationary armored plate liquid electrolyte type and flat plate liquid electrolyte for bigger systems. Recently the batteries, which refers to a flooded type of tubular-plated, lead acid and deep cycle batteries, have reached 20 years of service life at 20°C. Some aspects must have considered like battery banks, service life, autonomy days, input and output charge voltage, efficiency and deep cycle discharge.

The electrical model of the battery is presented in the Figure 5. In this model the constant resistance is no longer constant but varies with the depth of discharge. The variation upon depth of discharge is either linear or nonlinear.

$$V_{bat} = V_{co} - I_{bat}R_b$$ (6)

![Figure 5. Electrical schematic of the battery.](image-url)
The variation upon depth of charge is nonlinear which is given below:

\[ C_{bat}(t) = C_{bat}(t-1)(1-\sigma) + (P_{pv}(t) - P_L(t)).n_{bat} \]  \hspace{1cm} (7)

The variation upon depth of discharge is nonlinear which is given below:

\[ C_{bat}(t) = C_{bat}(t-1)(1-\sigma) + (P_L(t) - P_{pv}(t)) \]  \hspace{1cm} (8)

The Battery voltage is given below:

\[ V_{bat}(t) = n_b.V_{co}(t) + n_b.I_{bat}(t).R_{bat}(t) \]  \hspace{1cm} (9)

The Battery current is given below:

\[ I_{bat} = \frac{P_{pv}(t) - P_L(t)}{V_{bat}(t)} \]  \hspace{1cm} (10)

The study of the various models is done from a very simple battery model to a complex battery model. The study is done in order to gain in depth knowledge of the electrical behavior of the battery.

The number of days that a fully charged battery can meet the system load without recharging is called autonomy. Autonomy can be calculated using the average daily load, nominal battery capacity, and the maximum allowable depth of discharge. The basics for selecting the appropriately sized battery is to Calculate the system load, Select the number of days that the battery needs to deliver autonomy in the system and Use the appropriate depth of discharge to calculate the usable amp-hours.

![Figure 6. Block diagram of a buck converter.](image-url)
Control of the PV lighting system

Sliding mode control

The sliding mode provides a method to design a system in such a way that the controlled system is to be insensitive to parameter variations and external load disturbances. The technique consists of two modes. One is the reaching mode in which the trajectory moves towards the sliding line from any initial point. In reaching mode, the system response is sensitive to parameter uncertainties and disturbances. The other is the sliding mode in which, the state trajectory moves to origin along the switching line and the states never leave the switching line. During this mode, the system is defined by the equation of the switching surface and thus it is independent of the system parameters. The Variable Structure System (VSS) theory has been applied to nonlinear systems. One of the main features of this method is that one only needs to drive the error to a switching surface, after which the system is in sliding mode and robust against modeling uncertainties and disturbances. A Sliding Mode Controller includes several different continuous functions that map plant state to a control surface, and the switching among different functions is determined by plant state that is represented by a switching function.

The main aim is to force the system states to the sliding surface, and the adopted control strategy must guarantee the system trajectory move toward and stay on the sliding surface from any initial condition.

Control for optimal operation of a generator photovoltaic (GPV)

The tracking algorithm of maximum power point (MPPT) the most frequently used and as the name suggests it is based on the perturbation of the system by increasing or decreasing the reference voltage (Vref), or directly on the duty cycle of the converter (DC-DC), and observing the effect on the output power for a possible correction of the duty ratio.

If the value of the current power P (k) of the generator is higher than the previous value P (k-1) when the same direction is kept previous perturbation, if we reverse the perturbation of the previous cycle. The flowchart of the algorithm perturbation and observation (P & O) is given by the following Figure 7:

The simulation result obtained of the proposed control technique (PO) applied to the PV system are presented in the Figures 8 and 9. These characteristics present the evolution of Power voltage and current voltage characteristic by P&O algorithm during a variation transient in solar radiation. It can be seen that the increase of the illumination explained by an increase of the maximum power available and the system track the new maximum power point tracking very quickly when the weather changes suddenly but the operating point oscillates around The MPP, resulting loss in power system. These oscillations would reduce the effectiveness of the photovoltaic power.

Analysis of the irradiation effects on PV system

The Photovoltaic Adjusting a level is to identify its direction and its inclination relative to the horizontal by the angle given. The photovoltaic panel needs to be in an optimum position, so as to capture the maximum of solar energy. In our case, the full south orientation of the panels can capture maximum light during the day.
Figure 7. Flowchart of perturbation method and observation.

Figure 8. Power-Voltage characteristics.
The insolation is important for the period spanning from April to September, while for the other months it is less important but remains significant since it exceeds 2000 Wh/m²/day, Figure 10. Where the global insulation on the inclined plane is given in the equation below:

\[
E^* = \frac{E \cdot K \cos(\theta - \beta - \delta)}{\cos(\theta - \delta)}
\]  

(11)

**Figure 9.** Current-Voltage characteristics.

**Figure 10.** Evaluation of irradiance on an inclined surface.

The insolation is important for the period spanning from April to September, while for the other months it is less important but remains significant since it exceeds 2000 Wh/m²/day, Figure 10. Where the global insulation on the inclined plane is given in the equation below:
With:
N: Number of days since the spring equinox
Ө: Latitude location
K₀: correction factor sunshine
δ: Declination of the sun

The output power and energy generated have been calculated with solar irradiance data recorded every 10 min from Automatic Meteorological Stations (AMSs). Figure 11 shows monthly Global Horizontal Irradiance.

The integration of a PV power plant in the lighting installation area requires an appropriate analysis of the distribution of solar radiation during a year to avoid system requires an appropriate analysis of the distribution of solar radiation during every month to avoid oversizing the storage system. Solar radiation is quite variable during each month. Thus, forecasting is difficult, and it is usually evaluated using statistical data. A correct knowledge of the radiation permits the optimal sizing of the storage systems. Figure 12 reports the average values of solar radiation in one year for the case considered in this paper.

The choice of a storage system with a capacity equal to the maximum recovery energy in summer is oversized with respect to the energy available in winter. Thus, it is necessary to

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**Figure 11.** Irradiance using a standard day of each month.

**Figure 12.** Monthly Global Horizontal Irradiance.
consider the possibility of storing only a part of the energy obtainable by the PV power plant and exchanging the other part with the distribution power system. The energy storage depends on the behavior of the electrical load in the considered lighting energy storage systems.

**Design of PV lighting systems**

Independent, fully integrated power supplies with the primary purpose to control lighting equipment are stand-alone PV lighting systems. The PV power supply may be mechanically integrated with the lighting equipment in various ways depending on the application in question, although the purpose, electrical design and component sizing requirements remain largely the same. The design of PV lighting systems involves a number of steps and possible iterations to select and size the individual components required for a functional system.

**Step 1.** Establish the quantity and quality of lighting needs. Select lighting fixture(s) based on application requirements.

**Step 2.** Determine the magnitude and duration of the lighting electrical load on average daily and seasonal bases.

**Step 3.** Estimate battery storage size based on the desired autonomy period and maximum and average daily depth of discharge. Select a battery based on application requirements.

**Step 4.** Estimate PV array size based on the time of year with the highest average daily lighting load and minimum solar radiation. Select PV modules and array based on application requirements.

**Step 5.** Determine the control strategy to be used for battery protection and lighting control and specify the control set points and conditions. Select system controls based on application requirements.

**Characteristics of PV lighting system**

The information and data presented in this section are intended to provide the reader with some understanding of how a PV lighting system might operate on a typical daily basis. To properly understand the following system operational plots, it is helpful to know how the data were measured. The measured parameters included the solar irradiance (Sun), battery voltage (Vbat) and current (Ibat), and PV array voltage (Vpv) and current (Ipv). The designations in parentheses are used in the legend key for the daily profiles. Each parameter was sampled every ten seconds and averaged over a six-minute period and recorded daily for a total of 240 data points. In addition, the minimum and maximum of the battery voltage (based on 10-second samples) were recorded every six minutes. These minimum and maximum battery voltages are key to understanding how the charge controller operates.

We note that the current of the PV module depends only on the level of sunlight. However, the current from the battery and the load presented in Figure 13 depends on the level of insolation, the state of charge (SOC) and the energy requirement of the system.

Note that the current Ip module exists only during the day and does not depend on changes in the sunshine. The battery voltage and the load exist for 24 hours and constant values.

These drawings represent the shape of the power on the storage system in the highest and least sunny day. We note that the power generated from PV module (Ppv) is proportional to
the sunshine. But the powers of the battery (Pb) and the load (Pch) depend on the level of sunshine, state of battery charge and system power consumption.

**Conclusions**

The integration of PV panels, DC chopper, energy storage systems, and lighting systems was analyzed in this paper. The work focuses on the study and analysis of photovoltaic lighting storage systems for solar low power in lighting in off Grid Street. In general, this work has made the necessary solutions to problems related storage battery. In this regard, we have presented a description of the storage elements of the electrical energy. Generally, the energy storage is provided by lead-acid battery because of their large mass energies of their low cost.

The procedure found the optimal value of the cost functions and demonstrated the technical feasibility of integrating the PV power plant in order to supply a lighting system.

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