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Autonomous Street Lighting System based on Solar Energy and LEDs

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Abstract: This paper introduces a solar-powered autonomous street lighting system designed primarily for areas without access to the grid, such as rural roads and intersections. It utilizes solar panels as the primary energy source, with batteries serving as backup, and employs light-emitting diodes (LEDs) for illumination. The proposed system is optimized for efficiency by employing direct current (DC) power at all stages. To replace a 70W high-pressure sodium (HPS) lamp, an LED fixture design is discussed, considering human scotopic vision. Experimental outcomes for the LED driver and battery charger are provided, demonstrating features such as maximum power point tracking (MPPT), constant current, and constant voltage modes. The system ensures MPPT under varying solar irradiance and temperature conditions by analyzing the battery charger input impedance.

I. INTRODUCTION

Brazil's energy sector relies heavily on hydroelectric power due to its abundant water resources. However, the vast geographical size of the country results in an extensive and costly energy distribution network, leaving many remote areas without electricity supply【1】【2】. T

The aim of this study is to develop an autonomous, energy-efficient, and long-lasting street lighting system powered by alternative energy sources. This solution is also proposed as a substitute for traditional street lighting in urban environments.

Over the last two decades, the cost of solar-electric technology has steadily declined by 20%-25% annually, primarily driven by advancements in solar cell efficiency, improved manufacturing techniques, and economies of scale【3】.

High-pressure discharge lamps, such as mercury vapor, HPS, and metal halide lamps, are commonly used for street lighting and require ballasts to operate effectively【4】. LEDs, although traditionally used for signaling, have emerged as a viable alternative for lighting systems due to technological advancements that enhance their efficiency and color quality【5】.

The key advantages of LEDs in this application include their long lifespan, which aligns with the lifespan of solar panels (approximately 25 years), and their compatibility with DC power, eliminating the need for inverters. This increases overall system efficiency and reduces costs. Examples of LED-based street lighting systems have already been documented【6】.

Figure 1 illustrates the proposed system, comprising a photovoltaic panel that charges the batteries via a DC/DC converter during the day. At night, the batteries power the LED lamp through a driver that adjusts the current and enables dimming when required. The use of DC throughout the system minimizes energy losses associated with additional power conversion stages.

II. PROPOSED LIGHTING SYSTEM - LEDS

The design of the LED fixture is a crucial aspect of the proposed lighting system. It directly impacts the specifications of the photovoltaic panels and battery bank. Several factors influence the number of LEDs required:

1) Lamp Replacement Objective: Identifying the characteristics of the existing lighting system.
2) Human Visual Perception: Addressing the differences between photopic and scotopic vision.
3) LED Model Selection: Choosing the most suitable LED variant.

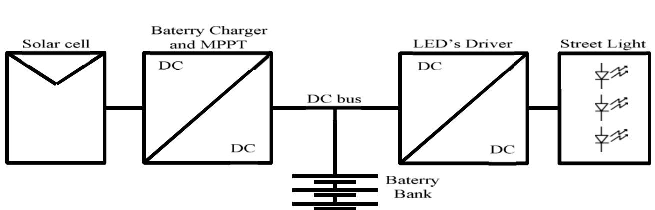

Figure 1. Proposed system

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A. Replacement of Conventional Lamps

Public High-pressure sodium (HPS) lamps are commonly used in public lighting. However, replacing them with LEDs necessitates a precise design methodology. This study demonstrates the substitution of a 70W OSRAM Vialox Nav-E Standard HPS lamp with an LED-based solution, achieving comparable luminous efficiency. The selected HPS lamp has a luminous flux of 5600 lm, a color rendering index (CRI) of ≤25, and an average lifespan of 28,000 hours, with fixture efficiency rated at 80%

B. Photopic Vision versus Scotopic Vision

The human eye has two types of photoreceptors in the reti- na, rods and cones, responsible for sending visual signals to the brain. In high levels of light, daylight, for example, the cones are the majority photoreceptors, qualifying this vision as photopic. At low light levels, the rods are the majority photoreceptors, qualifying this vision as scotopic. In an in- termediate light level, people deal with the called mesopic vision, where both cones and rods are responsible for light perception. Figure 3 presents the human eye sensitivity as a function of the light wavelength, for the photopic and scotop- ic conditions [7].

The current system of photometry, which determines the luminous flux of light sources, is based on the photopic vi- sion. In other words, the lamp to be replaced, characterized in the previous section, has 5.600 lm (nominal flux) in photopic vision conditions. However, when people deal with public illumination of remote localities, as the application discussed in this work, the scotopic vision characteristics are more ade- quate to be considered. The perceptual equivalence of a no- minal (photopic) luminous flux in a specific visual condition is called effective flux or effective lumens [8].

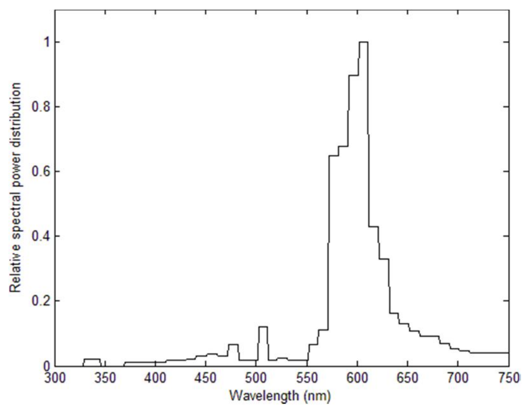

Figure 2 –Spectral power distribution of the OSRAM Vialox Nav-E Stan- dard.

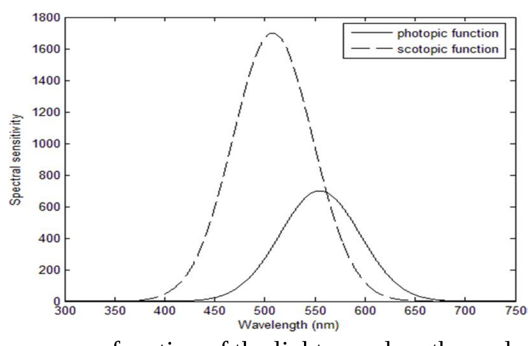

Figure 3 – Sensitivity of the human eye as a function of the light wavelength, under photopic and scotopic conditions.

C. LED Model Selection

Nowadays, a large variety of high power LEDs is commer- cially available and, therefore, a careful study is required before a specific model could be chosen. The most common method to obtain white light is by using a blue LED coated with phosphor that, when excited by the blue light, emits a broad range spectrum, producing the white light. By this method, it can be obtained LEDs of colors known as cool white, neutral white and warm white, by varying the amount of phosphor. The cool white LEDs are considered the most efficient in scotopic conditions, since they require fewer phosphor and produce light with wavelengths close to the peak of sensitivity of the human scotopic vision. By this way, cool white LEDs were chosen.

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It is also important to notice that LEDs are commercially available for 350, 700 and 1000mA (nominal mean current). From a brief market analysis, it was noticed that the 700mA LEDs certainly yield the lowest price per lumens, among the high power LEDs. By this way, the model Luxeon Rebel – Cool White Lambertian – 145 lm @ 700 mA was chosen. An approximation of its spectral power distribution is illustrated in Figure 4. Other important characteristics of this model are:

a) Luminous flux = 145 lm.
b) CRI ≥ 70.
c) Average life = 50000 h.
d) Fixture efficiency = 100%.
e) Average power = 2.4 W.

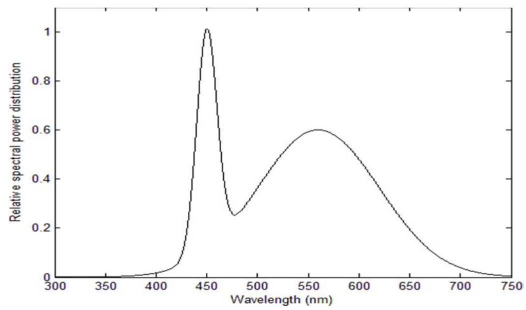

Figure 4 – Spectral power distribution of the Luxeon Cool White Lambertian LED.

D. LEDs Arrangement Design

The efficiency of a light source can be evaluated by the power spectrum distribution of this source (figures 2 and 4) weighted by the human visual spectral sensitivity function (Figure 3). As it was discussed in Section II.B, the human visual perception depends on the lighting and viewing condi- tions (photopic or scotopic), and the nominal luminous flux of a source (the standard commercial characteristics) is usually determined considering the photopic human visual sensitivity. In this section, the number of LEDs is calculated based on the efficiency of the lamp to be replaced and on the efficiency of the previously modeled LEDs, both in scotopic conditions.

The efficiency of a light source under specific lighting conditions can be evaluated by integrating the power spec- trum distribution weighted by the human visual spectral sensi- tivity function [9]. This methodology leads to a figure of merit that is called source effective illumination:

$lm(cond, source) = \int P(source, \lambda)V(cond, \lambda)d\lambda$ (1) where *cond* is the lighting condition (photopic or scotopic), *source* identifies the light source, λ is the wavelength,
P(*source*,λ) is the power spectrum distribution function and *V*(*cond*,λ) is the human visual spectral sensitivity function for a specific lighting condition.

Notice that the power spectrum distribution characteristics, when informed by the manufacturer, usually correspond to a family of sources, which can assume distinct nominal power and luminous flux. Considering it, these characteristics are usually available in a normalized form, as illustrated in fig- ures 2 and 4. Thus, it is necessary the power spectrum distri- bution to be weighted by a constant that leads to the nominal luminous flux value (effective illumination under photopic conditions).

The effective illumination relation, of the lamp to be re- placed, between scotopic and photopic conditions, calculated using (1), leads to a value approximately equal to 0.73. This value means that a source model Vialox Nav-E Standard has 73% of its nominal efficiency when used in scotopic condi- tions, which represents a source effective illumination of approximately 4088 lm. This same relation, when the LEDs modeled in Section II.C are considered, leads to a value of approximately 2.23, which represents an efficiency in scotop- ic conditions 2.23 times greater than in photopic (nominal) conditions. This result shows that this model of LEDs reaches approximately 323 effective lumens in scotopic conditions.

To replace the Vialox lamp, observing the lighting condi- tions of the application considered in this work, the effective lumens in scotopic condition should be 4088 lumens. Thus, 13 units of the chosen LEDs are enough to reach this lumin- ous flux. Considering that LEDs have 20% of its initial (no- minal) light decreased during its average life, the number of LEDs must be raised to 15 units. Finally, since nominal val- ues of a LED are obtained under a junction temperature of 25ºC and they use to decrease when temperature increases, resulting in 20 units of LEDs (30% of safety margin) in the proposed fixture.

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III. LEDS DRIVER DESIGN

The LEDs driver design depends on the input voltage, which is supplied by the batteries, being 24 V; the number of LEDs (output power) and their connection too. In section II it was defined that 20 LEDs are enough for the proposed sys- tem. LEDs series connection was chosen due to its simplicity and low cost. Then, the design parameters are listed below:

- Input: 24 Vdc.
- Output: 68 Vdc, 700 mA, 47.6 W.
- Switching frequency: 50kHz.
- Input current ripple: 25%.

The selection of the power converter that will perform the LEDs supply is based on the design parameters above. Among the possible power converters available, the most indicated is the boost converter, due to its simplicity and low cost. This power converter can be observed in Figure 5.

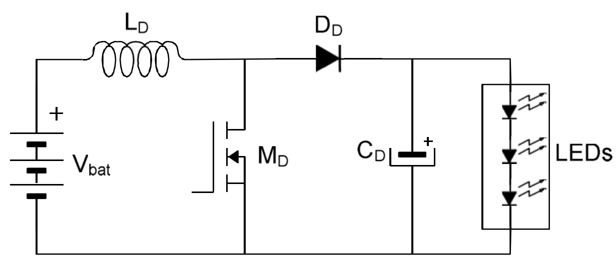

Figure 5 – LEDs driver – boost converter (50W@50kHz)

A. Experimental Results

A laboratory prototype was implemented, in order to prove the theoretical analysis presented in former sections. The design equations for this converter are well known in the literature and the driver parameters, according to Figure 5, are presented in Table I.

Table I – LEDs Driver Component Values

Vbat	24V - 2 x 12MF63
LD	640µH, 80 turns on core EE30/14
CD	1µF / 100V polypropylene
MD	IRF530 – V_{DS} = 100V, I_D = 14A
DD	MUR120
LEDs	20 x Luxeon Rebel – Cool White – 145 lm @ 700 mA

Figure 6 shows the converter input voltage and current, which corresponds to the batteries output voltage and current waveforms. Figure 7 shows the LEDs lamp voltage and cur- rent, where it can be observed that the LEDs instantaneous current is below 1 A, which is the maximum value recom- mended by the manufacturer.

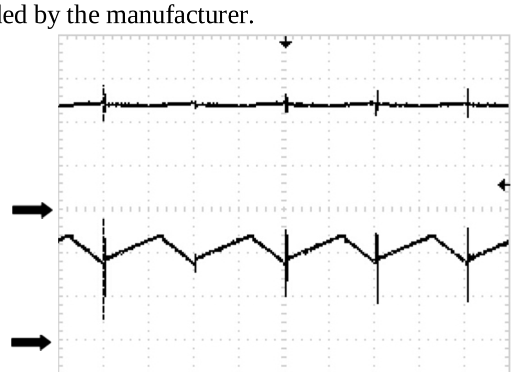

Figure 6 – Batteries voltage (UP) and current (DOWN) (10V/div; 1A/div; 10µs/div).

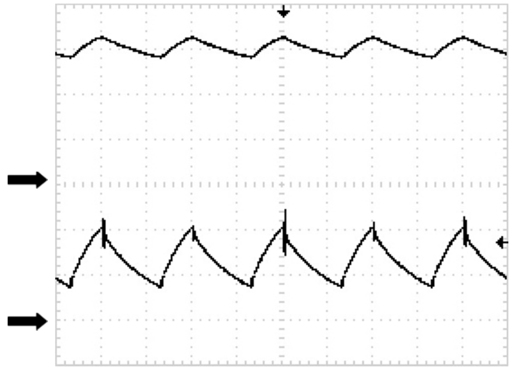

Figure 7 – LEDs lamp voltage (UP) and current (DOWN) (20V/div; 0,5A/div; 10µs/div).

In order to perform the power measurements, the current sensing resistors were short-circuited. Then, P_{in} = 47.6 W and P_{LEDS} = 44.2 W and the converter efficiency was 93%.

IV. BATTERY BANK

Taking into account the costs of each component, the bat- tery bank becomes the most onerous in a photovoltaic system [14], representing as much as 15% [15] of the initial costs for installation of the photovoltaic system, or even up to 46% [15] if maintenance costs are taken into account. This ex- pense increase is mainly due to the lower batteries lifetime, compared to the other system components. In cyclic applica- tions, where the battery is charged and discharged daily, the battery is the most expensive element of the system through- out its useful life.

The recommended charge method is one current and one voltage level (IU) as shown in Figure 8. The current value has direct influence in the charge time, which should be up to 20% of the capacity of the battery (C_{Ah}) being charged.

In this specific application, and taking into account the changes of solar radiation during the day and, consequently, the energy available, the battery bank charge algorithm will present three different modes:

1) If the panel available current is lower than $0.1C_{Ah}$, the converter will find the maximum power point (MPPT) in order to provide the highest current possible for the battery bank (area under the current level, see figure 8).
2) If the panel available current is higher than $0.1C_{Ah}$, the converter limits the current to $0.1C_{Ah}$, and disables the search for the maximum power point.
3) If the batteries are already charged, the control algorithm will apply a constant voltage level, in order to keep the batteries charged.

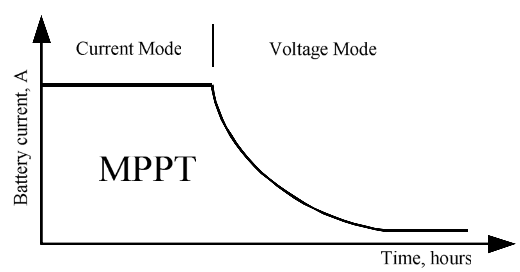

Figure 8. Proposed charge method.

The MPPT chosen algorithm was Disturbance and Obser- vation [16]-[17]. Figure 9 shows the implemented battery charge control algorithm.

This algorithm is composed of three control loops:

- Current Loop: PI regulator with current reference of $0.1C_{Ah}$ (5A);
- Voltage Loop: PI regulator with voltage reference of 2.2V/cell (26.4V);
- MPPT Loop.

Besides, inside the voltage loop, the battery current is also evaluated, in order to detect any problem during this loop (e.g.: damaged battery). If the current is higher than $0.1C_{Ah}$, a protection subroutine is activated.

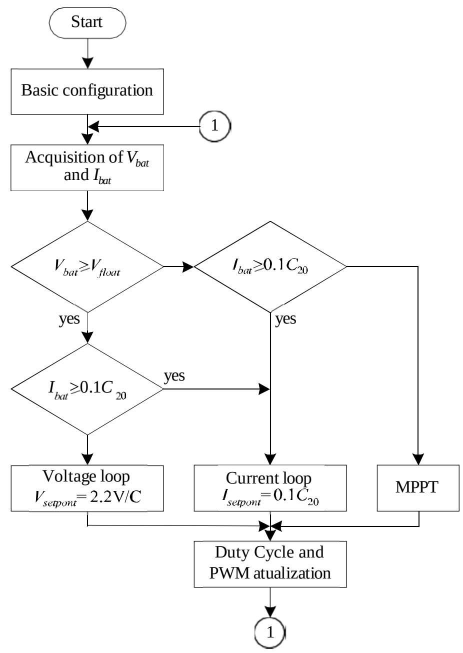

Figure 9. Battery charger control algorithm.

E. Challenges

1) Weather Problems: Solar panels depend on sunlight, so cloudy or rainy days can reduce energy production.
2) Battery Issues: Batteries used to store energy can wear out over time and might not hold enough charge for long periods without sunlight.
3) Maintenance Needs: Solar panels and LEDs need regular cleaning and repair to keep working efficiently.
4) Managing Energy: Balancing how much energy is collected, stored, and used is tricky, especially during bad weather.
5) High Initial Costs: Setting up the system can be expensive, which might limit its use in some areas.
6) Placement Challenges: Finding sunny spots for installation can be hard in cities with tall buildings or lots of trees.

V. CONCLUSION

This work has proposed an autonomous street lighting sys- tem, which uses solar energy as primary source, batteries as secondary source, and LEDs as lighting source. This system is an interesting solution for remote localities, as for roads and crossroads.

The system presents high efficiency, since all the power stages are DC-DC. This kind of conversion yields an easy implementation and control. The LEDs technology has been significantly improved in the last few years, and they have been considered a promising alternative to the illumination systems. The main advantages of using LEDs are: high average life; high luminous efficien- cy; and simple drives, when control and dimming systems are required.

The photopic and scotopic human sensitivity were consi- dered on the design of the lighting system. It was shown that a 70W high pressure sodium lamp (model OSRAM – Vialox Nav-E Standard) can be substituted by 20 LEDs with 145 lm @ 700 mA (model Luxeon Rebel – Cool White Lambertian), resulting in the same effective lumens.

The batteries are the components with highest cost in the system. The main reason is its low average life: usually less than four years. Depending on the operation conditions, the average life of the batteries can still be strongly reduced.

The battery bank charge method is with one level of vol- tage and current. The maximum current never can exceed $0.1C_{Ah}$. The disturbance and observation method, to find the maximum power point of the solar panel, has been imple- mented when the available energy is lower than $0.1C_{Ah}$. The battery charger input impedance was analyzed in order to ensure that the MPPT is obtained for any solar irradiance and panel temperature.

Finally, experimental results of LEDs driver and battery charger were presented, in order to validate the proposed system.

VI. ACKNOWLEDGMENT

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