

PV-Powered LED Street Lights Optimization Using the Zeta-Sepic converter and Photo-Electro-Thermal Theory

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Nowadays, using photovoltaic-powered Light Emitting Diode (LED) street lights is spreading owing to their higher efficiency and longer lifetime. In this paper, the Zeta-Sepic converter is used to manage an LED light, a PV panel, and a battery storage in these systems since it offers compact and single-stage power conversion. The PV panel and LED light are connected to the converter input port using a simple relay, while the battery source is put at the converter output port. During the day, the PV panel energy is saved in the battery through the converter forward direction power flow. Besides, by the converter reverse direction power flow the battery supplies the LED light with the required power during night. For these operation cases, voltage regulation is realizable at both converter input and output ports. This performance provides MPPT to the PV panel, State of Charge (SOC) control for the battery and light control with the LED light. For the LED lights, there exist a relationship between light, electricity and thermal energy that is optimized to achieve the highest luminal flux to the input power ratio. As a result, this paper uses the photo-electro-thermal theory and heatsink characteristics and bidirectional Zeta-Sepic converter to drive the LED lights at the operating voltage, in which the LED light optimal luminous flux occurs. Finally, the proposed LED light system is analyzed and validated in different operational conditions using MATLAB/SIMULINK. As useful experimentation, a photo collector sphere was built in the laboratory to calculate and validate the optimal working point of the light by measuring the LED light intensity through sensors installed on it.

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I. INTRODUCTION

The excessive use of fossil fuels to supply electrical energy will make these valuable and national assets come to the end in the near future. So, the world is looking for resources that can be used to replace fossil fuels. In addition, the problems associated with these sources, including contamination and greenhouse gases, are aggravating. Renewable energy is the best option to solve these problems. Among renewable energies, solar energy is the most important energy because it is available everywhere, clean, free, and never-ending.

This energy is used on a large scale in, say, solar power plants and water pumps and on a small scale in, for example, street lighting, mobile charging, and watches [1]. Street lighting systems can be fed independently using a photovoltaic system without being connected to the power grid. Fig. 1 shows a block diagram of a street lighting system powered by a photovoltaic (PV) system.

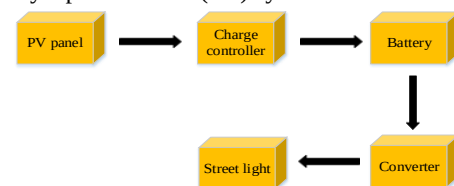


Fig.1. The block diagram of a standalone PV-powered street light.

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By this system, solar energy is intercepted by a PV panel and stored in a battery by a dc-dc converter and at night, light is powered by the battery through another dc-dc converter. Bidirectional dc/dc converters are among the most important energy conversion systems with industrial applications such as fuel-cell vehicles, renewable energy systems, battery charging/discharging converters, and uninterruptible power supply systems. In the renewable energy systems, including fuel cell systems, PV systems, and wind power systems, the bidirectional dc/dc converter is necessary for electric power conversion between a low voltage battery and load [2], [3].

With respect to lighting loads, high-intensity-discharge (HID) lamps are commonly used as sources of street lighting because they have better vision, higher luminous efficiency, and longer lifetime [4]-[6]. But, these lamps have some disadvantages, such as excessive glare, containing harmful substances (metallic mercury), and needing some seconds to get to full brightness. High brightness Light Emitting Diodes (LED) can be a good replacement for these lamps as they do not have these problems. They have high reliability, high lifetime, high luminous efficiency, and energy-saving, they do not emit ultraviolet and infrared rays, and they are environmental-friendly.

The two parameters of LED voltage and current are very effective in the design of such systems. Indeed, it should be tried to drive these systems in almost constant current and voltage because any increase in these parameters increases the junction temperature and reduces the optical flux and efficiency. LEDs have optical, electrical and thermal characteristics that are dependent on one another. So, in order to design a proper LED system, the relationship between these three characteristics should be considered to drive the LED light at the point of current and voltage, in which the maximum luminous flux and hence the highest optical efficiency is achieved. In [7] and [8], two street LED light systems powered by solar energy and a battery are proposed. In [9], a lighting system is controlled by a microcontroller and a bi-directional buck-boost converter is used to charge and discharge the battery. In all of these lighting systems, there is no proper design to feed the lights at the optimal point and the relationship between light, electricity and thermal energy. On the other hand, the high number of elements increases the size of the converter. In [10], a solar smart LED street lighting system is used. This smart system uses the Internet, which is a complex and costly process.

An LED device model has been proposed to model the thermal resistance and light output [11]. But, this model is for the LED device and not for the LED system including the thermal design of a heat sink and the electric power control. In [12], an integrated model which links the optical, electrical, and thermal aspects of LEDs is presented to show how the current is achieved for maximum luminous flux.

Nowadays, using the PV-powered LED street lights is

spreading owing to their higher efficiency and longer lifetime. In this paper, the Zeta-Sepic converter is used to manage an LED light, a PV panel, and a battery storage in these systems since it offers compact and single-stage power conversion. The PV panel and LED light are connected to the converter input port using a simple relay, while the battery source is put at the converter output port. During the day, the PV panel saves energy in the battery through the converter forward direction power flow. Then, in a reverse direction power flow of the converter, the battery supplies the LED light with the required power during the night. For these operation cases, voltage regulation is realizable at both converter input and output ports. This performance provides MPPT to the PV panel, State of Charge (SOC) control for the battery, and light control with the LED light. In LED lights, there exist a relationship between light, electricity and thermal energy that is optimized to achieve the highest luminal flux to the input power ratio. As a result, this paper uses the photo-electro-thermal theory and heatsink characteristics and the bidirectional Zeta-Sepic converter to drive the LED lights at the operating voltage, in which the LED light optimal luminous flux occurs. Finally, the proposed LED light system is analyzed and validated in different operational conditions using MATLAB/SIMULINK. Also, a photo collector sphere was built in the laboratory that could achieve the optimal working point of the light by measuring the photo through sensors installed on it.

The paper is organized as follows: LED device system structures based on the general PET (photo-electro-thermal) theory is analyzed in section II, the proposed system operational modes, proposed control system, and battery SOC control unit are described in sections III, IV, and V, respectively, the MATLAB/SIMULINK results are presented in section VI, and the experimental results and conclusions are expressed in sections VII and VIII, respectively.

II. LED LIGHT GENERAL PHOTO-ELECTRO-THERMAL THEORY

A general LED system with N LED devices placed on a heatsink is considered in Fig. 2. According to the PET theory, the relations between current, voltage, junction temperature, flux, and efficiency can be written as below [13]:

$$\Phi_v = N \times E \times P_d \quad (1)$$

in which E is the luminous efficiency (lumen/watt) and P_d is the rated power of each LED (watt). The emission intensity with the temperature has an inverse relationship, and it follows an exponential decay function near room temperature [14]:

$$I = I_{25^\circ C} \exp \frac{-(T_j - 25^\circ C)}{T_i} \quad (2)$$

in which T_i is the characteristic temperature. Since the LEDs should not operate at junction temperatures above $125^\circ C$, the

luminous efficiency is as follow:

$$E = E_0[1 + k_e(T_j - T_0)] \text{ for } T_j \geq T_0 \text{ and } E \geq 0 \quad (3)$$

where E_0 is the rated efficacy at the rated temperature ($T_0 = 25^\circ\text{C}$) and k_e is the rate of reduction of the efficacy. In the LEDs, much of the power is converted to heat by:

$$P_{\text{heat}} = k_h P_d = k_h V_d I_d \quad (4)$$

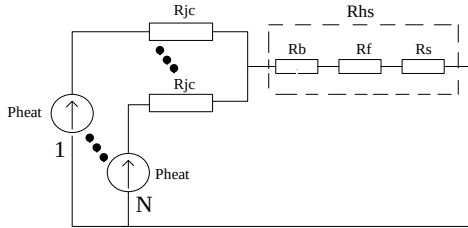


Fig.2. Thermal equivalent circuit with N LEDs mounted on the same heatsink.

where k_h is a constant less than 1 and it represents the portion of LED power that turns into heat. The measurement of k_h can be found in [15]. Before considering the relationship between heatsink temperature and junction temperature, it is necessary to calculate the heatsink thermal resistance [16]. The parallel Plate-Fin heatsink model in Fig. 3 is considered for the current analysis. In general, each heatsink contains three resistors, R_b (thermal resistance of base), R_s (spreading thermal resistance), and R_f (thermal resistance of fins), each of them is calculated as follows:

$$R_b = \frac{t_b}{k_{hs} A_{\text{base}}} = \frac{t_b}{k_{hs} WL} \quad (5)$$

where t_b is the thickness of the heatsink base, k_{hs} is the thermal conductivity of the heatsink material, W is the heatsink width, and L is the heatsink length. The thermal resistance from the fins to the air R_f can be expressed as:

$$R_f = \frac{1}{h_{\text{air}} (A_{\text{base}} + M \eta_{\text{fin}} A_{\text{fin}})} \quad (6)$$

where M is the number of fins, h_{air} is the air convective heat transfer coefficient, A_{base} is the area of base surface, η_{fin} is the heat exchange efficiency of fin, and A_{fin} is the area of fin surface. The fins efficiency for the heatsink can be calculated by:

$$\eta_{\text{fin}} = \frac{\tanh(H_f)}{m H_f} = \frac{\tanh(H_f \sqrt{\frac{2h_{\text{fluid}}}{k_{hs} t_f}})}{H_f \sqrt{\frac{2h_{\text{fluid}}}{k_{hs} t_f}}} \quad (7)$$

in which H_f is the fins height, t_f is the fins thickness, and h_{fluid} is the convective heat transfer coefficient. For non-circular shapes, the radius equivalent to the base of the heatsink and the heat source is as follows:

$$r = \sqrt{\frac{A}{\pi}} \quad (8)$$

where A is the area of the base plate for the heat source or heatsink base and r is the equivalent radius for the heat source or heatsink base [17].



Fig. 3. The structure of a typical parallel plate-fin heatsink.

The spreading thermal resistance R_s can be expressed as:

$$R_s = \frac{1}{2} \left(1 - \frac{t_b}{r_2}\right)^{3/2} \frac{\tanh(\pi + \frac{r_2}{r_1} \frac{t_b}{r_2}) + \frac{k_{hs}}{r_1 \sqrt{\pi} h_{\text{fluid}}}}{1 + \frac{k_{hs}}{r_1 \sqrt{\pi} h_{\text{fluid}}} \tanh(\frac{r_2}{r_1} \frac{t_b}{r_2})} \quad (9)$$

where r_1 and r_2 are the equivalent radius for the LED source and heatsink base, respectively. So, the total heatsink resistance is equal to the sum of all three resistances.

$$R_{hs} = R_b + R_f + R_s = \frac{t_b}{k_{hs} A_{\text{base}}} + \frac{1}{h_{\text{air}} (A_{\text{base}} + M \eta_{\text{fin}} A_{\text{fin}})} + \frac{1}{2} \left(1 - \frac{t_b}{r_2}\right)^{3/2} \frac{\tanh(\pi + \frac{r_2}{r_1} \frac{t_b}{r_2}) + \frac{k_{hs}}{r_1 \sqrt{\pi} h_{\text{fluid}}}}{1 + \frac{k_{hs}}{r_1 \sqrt{\pi} h_{\text{fluid}}} \tanh(\frac{r_2}{r_1} \frac{t_b}{r_2})} \quad (10)$$

According to Eq. (10), it can be said that the heatsink resistance depends on the geometric properties of the heatsink. In thermal design, if the heatsink thermal resistance becomes greater, the heatsink will be smaller and it will transfer less heat to outside. Based on Eq. (10) and the model in Fig. 1, T_{hs} and T_j can be obtained by:

$$T_{hs} = T_a + R_{hs} (N \times P_{\text{heat}}) = T_a + R_{hs} (N \times k_h \times P_d) \quad (11)$$

$$T_j = T_{hs} + R_{jc} (P_{\text{heat}}) = T_{hs} + R_{jc} (k_h \times P_d) \quad (12a)$$

$$T_j = T_a + (R_{jc} + N R_{hs}) k_h P_d \quad (12b)$$

Putting Eq. (12b) in Eq. (3) will yield the luminous efficiency.

$$\begin{aligned} E &= E_0[1 + k_e(T_j - T_0)] \\ E &= E_0\{1 + k_e[T_a + (R_{jc} + N R_{hs}) k_h P_d - T_0]\} \\ E &= E_0[1 + k_e(T_a - T_0) + k_e k_h (R_{jc} + N R_{hs}) P_d] \end{aligned} \quad (13)$$

So, the total luminous flux Φ_v is:

$$\begin{aligned} \Phi_v &= N \times E \times P_d \\ \Phi_v &= N\{E_0[1 + k_e(T_a - T_0) + k_e k_h (R_{jc} + N R_{hs}) P_d]\} P_d \\ \Phi_v &= N E_0\{[1 + k_e(T_a - T_0)] P_d + k_e k_h (R_{jc} + N R_{hs}) P_d^2\} \end{aligned} \quad (14)$$

Eq. (14) shows that the optical flux, the electrical power, the heat sink resistance, and the LED junction resistance are related to each other. It is an equation that integrates the photometric, electrical, and thermal aspects of the LED system together. On the other hand, using this equation, maximum flux is calculated and the optimum point of the system is obtained. By differentiating Eq. (14) with respect to P_d , we have:

$$\frac{d\phi_v}{dP_d} = NE_0 \{ [1 + k_e(T_a - T_0)] + 2[k_e k_h(R_{jc} + NR_{hs})]P_d \} \quad (15)$$

Therefore, the maximum Φ_v point can be obtained by putting

$$\frac{d\phi_v}{dP_d} = 0 \quad \text{and}$$

$$P_d^* = -\frac{[1 + k_e(T_a - T_0)]}{2k_e k_h(R_{jc} + NR_{hs})} \quad (16)$$

where P_d^* is the LED power at which the maximum Φ_v occurs. Considering the power relationship in the LED ($P_d = V_d * I_d$):

$$I_d^* = -\frac{[1 + k_e(T_a - T_0)]}{2k_e k_h(R_{jc} + NR_{hs})V_d} \quad (17)$$

This current is the optimal point of the system. Sometimes, P_d^* can be greater from the rated power of the LED in which case, it is possible to ignore a few percents of the luminous flux and consider the rated power as P_d^* .

III. PROPOSED SYSTEM OPERATIONAL MODES

In the process of charging and discharging the battery, due to the difference in voltage between the PV panels, the battery and the LED light are required to use simple dc-dc converters such as Buck-Boost, Cuk, Zeta, and Sepic that can increase/decrease the voltage. From these converters, the Zeta-Sepic is the best option because the Cuk converter has a reverse output and problems at system design time. On the other hand, the Buck-Boost converter has several flaws such as discontinuous input current and reverse output [18]. In order to reduce the volume and cost of the two converters for charging and discharging, Zeta and Sepic converters are integrated [19]. Our proposed idea in this paper is so that its outputs are not reversed compared to the Buck-Boost and Cuk converters, and LED lights are powered according to the PET theory at the optimal point where the maximum luminous flux occurs and this is something that has not been done in such works.

Fig. 4 shows the proposed system circuit to feed LED light. During the day as Fig. 5 shows, since the PV panel voltage is higher than the battery voltage, the converter operates with the Zeta circuit. In this case, the relay is closed to PV, the switch Q_1 is switched in PWM with the duty ratio d_1 , and the switch Q_2 is permanently off and instead, the diode D_2 conducts in the Q_1 off times. For this situation, the converter

voltage gain is:

$$\frac{V_B}{V_{PV}} = \frac{d_1}{1 - d_1} \quad (18)$$

On the other hand, at night that there is no PV power, the system works with the Sepic circuit shown in Fig. 6 so as the relay is closed to the LED light and Q_2 is switched in PWM with the duty ratio d_2 while Q_1 is off permanently. In this case, the diode D_1 will conduct in the Q_2 cutting times. The circuit voltage gain is stated as:

$$\frac{V_B}{V_{LED}} = \frac{1 - d_2}{d_2} \quad (19)$$

A useful approach to reduce the conduction losses of the single-switch classical power electronics converters is to utilize them in synchronous rectification performance. With this approach, the non-active antiparallel switch of the converter active diode is turned on for cutting-times of the converters main switch, or simultaneous to the diode conduction times. Therefore, for the proposed circuit, the switch Q_2 is turned on when the switch Q_1 is turned off. In other words, the proposed circuit switches are turned on and off oppositely by using the converter first duty ratio. Therefore, using Eq. (18) and (19), the voltage of the converter in the first capacitor C_1 can be expressed by:

$$V_{C_1} = \frac{1 - d_1}{d_1} V_B \quad (20)$$

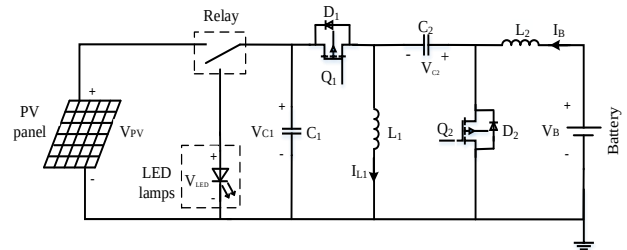


Fig. 4. The proposed integrated zeta-sepic LED light system.

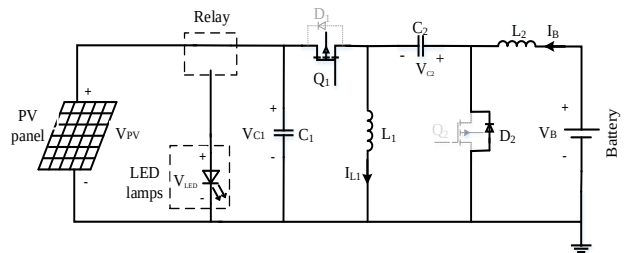


Fig. 5. The day time operation.

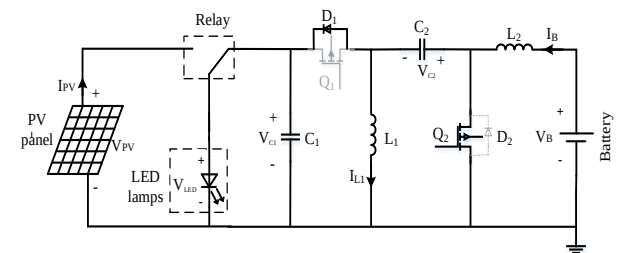


Fig. 6. The night time operation.

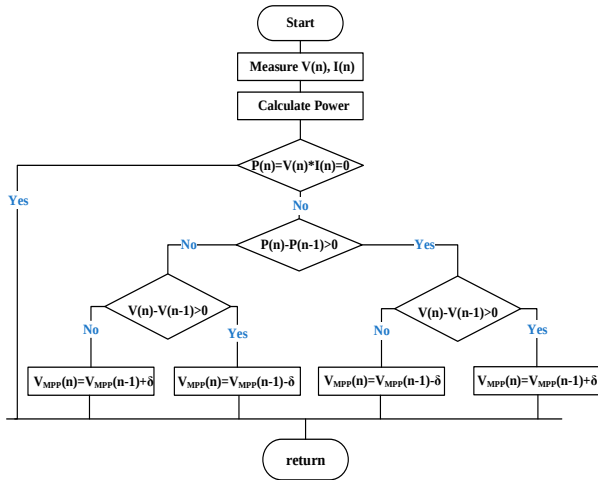


Fig. 7. The flowchart of the P&O algorithm.

IV. PROPOSED CONTROL SYSTEM

As is clear from Fig. 4, the main control target of the proposed converter is to regulate the first capacitor voltage V_{C1} , since it is the voltage smoothing element in parallel with the PV module and the LED light during days and nights, respectively. Accordingly, the proposed control system is shown in Fig. 8. By the selection switch Night/Day, during the days, V_{C1ref} is chosen to be V_{sel} for the PV module and is chosen to be V_{opt} of the LED light during the nights. Then, a PI procedure is applied to control V_{C1} by regulating the converter controlling duty cycle d_1 . The signal V_{sel} is determined by the MPPT and the battery SOC units, which is described in the next section.

During days, the converter controlling duty ratio d_1 is chosen as the controlling variable to regulate the PV module voltage and hence its generated power. Based on this, first the maximum power operating voltage (V_{MPP}) of the PV module is detected using the P&O algorithm illustrated in Fig. 7. Then, it is applied to the PI control procedure to determine the duty cycle d_1 . Also, during nights, first the optimal operating voltage (V_{opt}) of the LED light is detected using the PET theory. It is then applied to the PI control procedure to determine the converter controlling duty cycle d_1 .

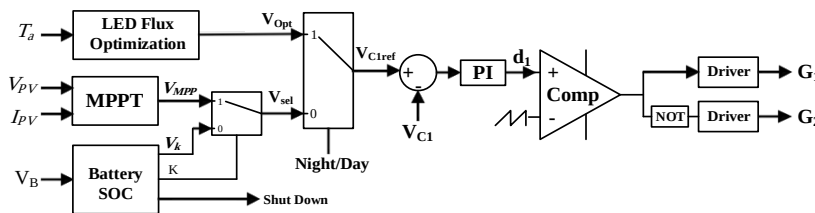


Fig. 8. The proposed system control.

V. BATTERY SOC UNIT

. In order to remain the battery voltage within the allowed band of $V_{Bmin} < V_B < V_{Bmax}$ (i.e. $V_{Bmin}=11V$ and $V_{Bmax}=13.5V$ for lead-acid batteries) the battery SOC control block is designed to supervisory analyze and determine the converter power flow. The decisions of SOC unit are applied to the converter by the two controlling signals of K and V_K , incorporating the V_{sel} selection switch. The flowchart of the battery SOC is illustrated in Fig. 9 and its rules are discussed as follows:

$V_{Bmin} < V_B < V_{Bmax}$

In this condition, the signal V_{sel} is chosen to be V_{MPP} by $K=1$, and hence regulating the PV voltage at V_{MPP} by d_1 leads to changing the battery with $P_B=P_{MPP}$.

$V_B > V_{Bmax}$

In this condition, since the battery is fully charged, the PV module is not put on MPP by setting the K signal of SOC at zero ($K=0$). Therefore, the signal V_{sel} is chosen to be the SOC output signal of V_K , which is usually greater than V_{MPP} . The signal V_K is instantly adjusted by the SOC unit so that the battery voltage remains constant at V_{Bmax} , resulting in the battery average current of about zero.

$V_B < V_{Bmin}$

This condition occurs for night times when the LED light is supplied by the battery source for a long time. Therefore, the battery does not have enough charge and its voltage falls lower than V_{Bmin} , so the SOC unit makes the shut-down signal active for the system. Coming to the shut-down signal results in disconnecting the relay from LED and setting the converter duty ratio at zero.

TABLE 1

Simulation parameters of the LED street light

Symbols	Simulation Parameters	Symbols	Simulation Parameters
W_{LED}	0.14 (m)	M	18
L_{LED}	0.16 (m)	k_e	-0.0045
W_b	0.20 (m)	k_{hs}	200(w/m.k)
L_b	0.22 (m)	E_0	78.5(lm/w)
t_b	0.015 (m)	h_{fluid}	95 (w/m.k)
t_f	0.005 (m)	R_{jc}	8 (°C/W)
H_f	0.01 (m)		

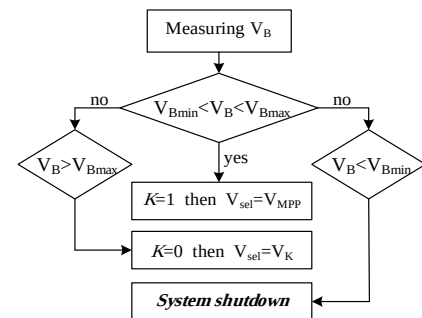


Fig. 9. The flowchart of the battery SOC unit.

I. SIMULATION RESULTS

In order to investigate the proposed system, an assumed LED street light of 60W, a PV module, and a 12V battery source are considered. Due to the single LED weak brightness, it can be multiplied in series and parallel [16]. A number of 20 LEDs are used in the simulation arranged in two LED strings, each containing 10 LEDs in series. Data about the LED street light used in the simulation are listed in Table 1.

The maximum power of each LED is 3W, while its optimal power is obtained by Eq. (16) to be about $P_d = 2.27W$ and $P_d = 2.77W$ for the ambient temperatures of $T_a = 35^\circ C$ and $T_a = -5^\circ C$, respectively.

Also, the P-V output characteristics of the used PV module is shown in Fig. 10 for the three different examined environmental conditions. Moreover, a 12V lead-acid battery source is considered for the proposed system. The simulation goal is to charge the battery by the PV module under the MPPT condition of the PV panel during days, while at nights, it is expected to supply the LED light in its optimal voltage by the battery source. All the simulation stages are so considered to happen for the possible minimum and maximum levels of the solar irradianations and ambient temperatures. The system was simulated using the Simulink/Matlab software for day and night mode of the proposed system; the day mode and the night mode include three and two operation stages, respectively, which are discussed below.

Day Mode Operation: The simulation is done in three different stages. In all stages, V_{C1ref} is chosen to be V_{MPP} of the PV module switch. The PV current, voltage and power, V_{C1ref} , duty cycle d_1 and the battery current are shown in Figs. 11, 12, 13, and 14, respectively.

First simulation stage: $0 \leq t < 0.5sec$: At this stage, the maximum amount of solar radiation ($G = 1000W/m^2$) at the ambient temperature ($35^\circ C$) is considered. First, the maximum power operating voltage (V_{MPP}) of the PV module is detected using the P&O algorithm.

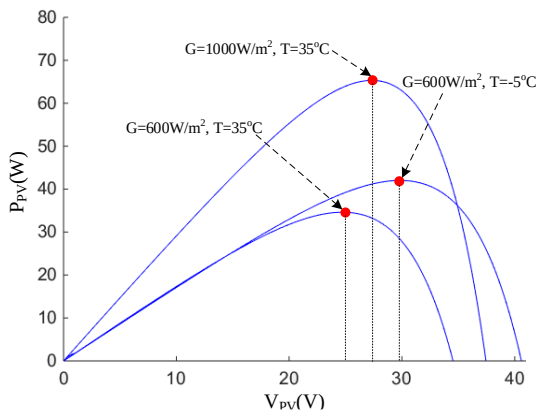


Fig. 10. The P-V output characteristics of the used PV module.

Then, it is applied to the PI control procedure to determine the converter duty ratio d_1 . Voltage and current $V_{PV} = 27.5V$, $I_{PV} = 2.4A$ are regulated for the PV panel by duty ratio $d_1 = 0.28$. In this case, $P_{PV} = 65.3W$ is transmitted through the Zeta converter to charge the battery with the charging current of $I_B = -5.4A$ for the battery.

Second simulation stage $0.5 \leq t < 1sec$: At this stage, the amount of radiation is reduced ($G = 600W/m^2$), but the temperature is still $35^\circ C$. Since the radiation affects the current and voltage of the array, the magnitude of these values is reduced ($V_{PV} = 25V$, $I_{PV} = 1.4A$) by the duty ratio $d = 0.32$. Therefore, with the lower radiation, the power output of the PV is reduced ($P_{PV} = 34.6W$). For this condition, the charging current of the battery reduces to about $I_B = -2.85A$.

Third simulation stage $1 \leq t < 1.5sec$: As approaching to the night and cooling the air, the temperature drops to below zero, so the radiation level of $600W/m^2$ and temperature of $-5^\circ C$ govern to the PV module. The MPPT control sets these values to the system $V_{PV} = 29.5V$, $I_{PV} = 1.43A$, $P_{PV} = 42W$ with the duty ratio $d_1 = 0.28$. In this condition, the battery is still charged by the current of $I_B = -3.5A$.

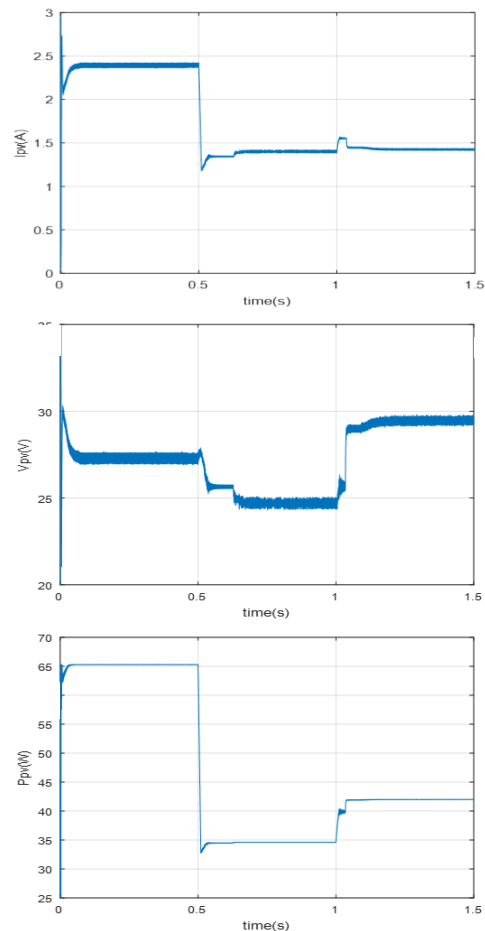


Fig. 11. The PV current, voltage, and power during the day.

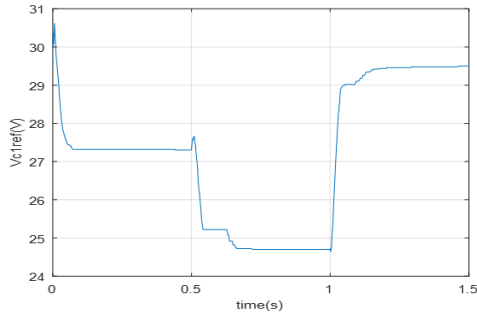


Fig. 12. The curve of V_{C1ref} during the day.

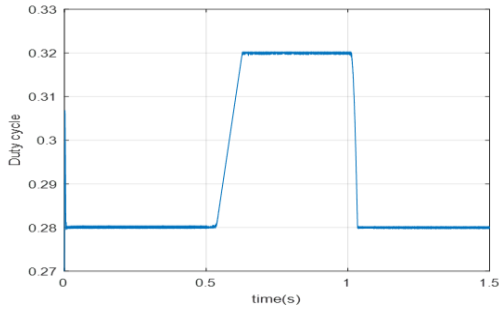


Fig. 13. The converter controlling duty ratio of d_1 during the day.

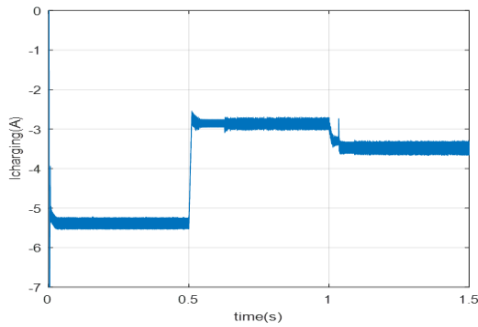


Fig. 14. The charging current of the battery during the day.

Night Mode Operation: This simulation scenario is done in two different stages. The curves of LED optimal current and voltage, V_{C1ref} and the battery current are shown in Figs. 15, 16, and 17, respectively.

First simulation stage $0 \leq t < 0.5\text{sec}$: At night, the relay is closed to the LED light. Because of the temperature effect on the LED light, ambient temperature is considered to be 35°C . First, the optimal operating voltage (V_{opt}) of the LED light is detected using the PET theory. Then, it is applied to the PI control procedure to determine the converter duty cycle d_1 . So, the street light is driven in the optimal current and voltage of $V_{LED} = 38\text{V}$, $I_{LED} = 1.2\text{A}$, which results in the discharging current of $I_B = 3.8\text{A}$ for the battery.

Second simulation stage $0.5 \leq t < 1\text{sec}$: This section is similar to the previous stage, except that the ambient temperature is dropped to -5°C . By reducing the temperature, the optimum operating point of the LED light changes to $V_{LED} = 37\text{V}$, $I_{LED} = 1.5\text{A}$, causing the discharging current of $I_B = 4.6$ for the battery. Also, according to Fig. (8), the V_{C1ref} is successfully set at V_{Opt} of the LED light during the night.

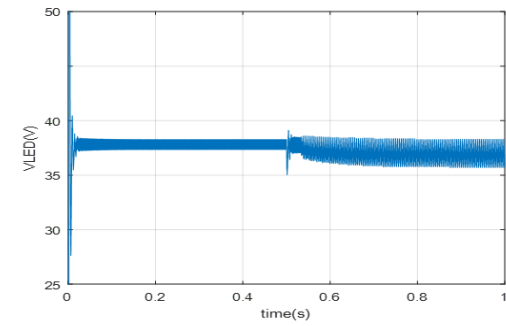
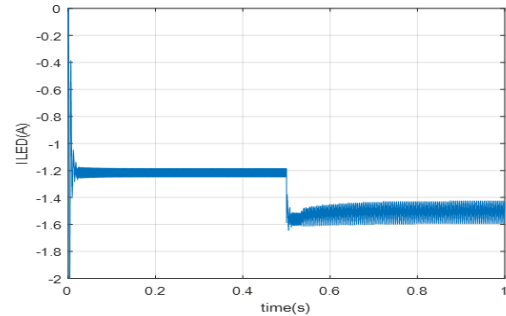


Fig. 15. The optimal current and voltage of the LEDs.

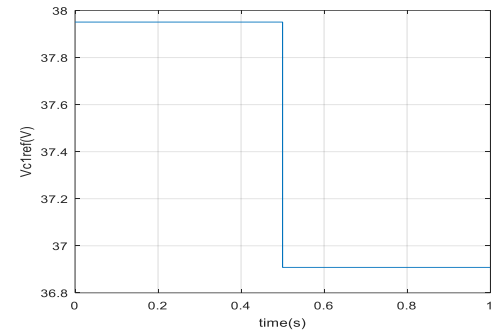


Fig. 16. The curve of V_{C1ref} at night.

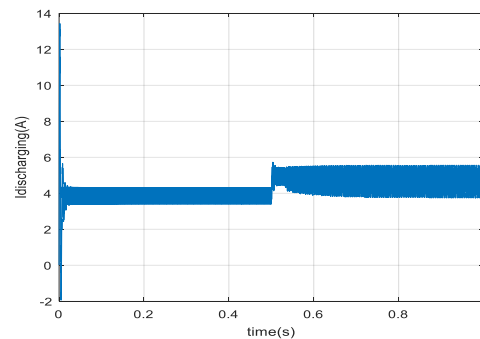


Fig. 17. The discharging current of the battery at night.

II. EXPERIMENTAL RESULTS

When using light sources, especially LEDs, it is important to measure the output radiation power or the luminous flux to determine the optimal point. This parameter can be calculated both theoretically and practically. By theory, the optimal point is determined by using MATLAB/SIMULINK, a Sepic converter, increasing voltage from battery to light, and

inserting photo-electro-thermal information of the light into the simulation. In this case, the 15 LEDs in series are at temperature 28°C. According to Fig. 18, the optimal voltage occurs at $V_{LED} = 56.5V$. Despite theoretical calculations, sometimes the actual conditions are slightly different from the theory, so a photo collector sphere should be used to determine the exact value of the optimal point.

In this way, an LED street light in the lab that contains 15 LEDs in series (Fig. 19) is studied. Other specifications of the LED light comply with those in Table 1. A light collector appliance was built in the laboratory as can be seen in Fig. 20 showing how a hemisphere with a diameter of about 1 m is designed so that its inner surface is completely covered with black color. The reason for using black color is to prevent the reflection of light inside the hemisphere. Several LDR sensors or light-dependent resistive sensors are mounted on a section of the hemisphere for light measurement. By placing the lights on a rotating base (Fig.21) attached to a DC motor and rotating it under the hemisphere, the sensor information goes to the microcontroller and is stored on a memory card.

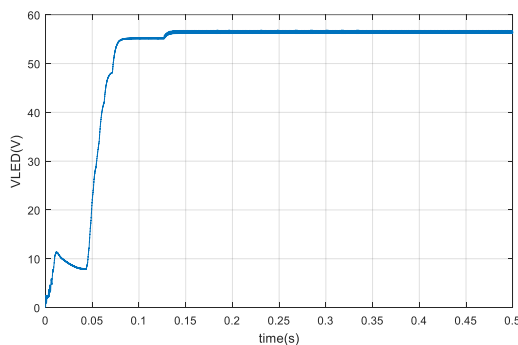


Fig. 18. The optimal voltage of LEDs using the PET theory.

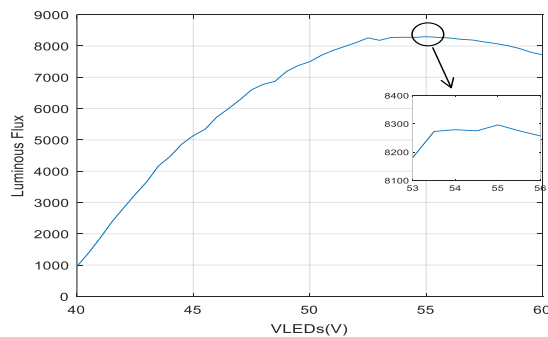


Fig. 22. The voltage-luminous flux curve of the light in laboratory.

The sensors, microcontroller, and memory card are connected as an electrical circuit on a board. The optimal point will be achieved by entering the memory card information into the MATLAB software and performing calculations. As shown in Fig. 22 at different voltages, the maximum flux occurred at a voltage of 55 V. This value is given in real conditions and it is justifiable by the value obtained from the theoretical calculations.



Fig. 19. The LED street light.



Fig. 20. The photo collector sphere.



Fig. 21. The motor and rotating base.

III. CONCLUSION

The bidirectional Zeta-Sepic converter is used to manage a PV-powered LED light and a battery storage. This converter is current fed at the battery port and voltage fed at the common PV/LED port. This characteristic contributes to the exact MPPT for the PV and constant battery current. During the day, the PV energy is saved in the battery through the converter forward direction power flow. Besides during night, the LED light required power is supplied by the battery in the reverse direction power flow. A general theory that communicates the optical, electrical, and thermal characteristics of the LEDs is used. Using this theory, the optimal point of light performance is determined where the maximum luminous flux is obtained.

A simple and suitable control system was designed to perform MPPT, regulate the LED light voltage, and charge the battery. The proposed system offers a compact and single-stage power conversion. Finally, the proposed LED light system is successfully examined and validated in different environmental operation conditions using MATLAB/SIMULINK. Also, a photo collector sphere is made in the laboratory that can achieve the optimal working point of the light by measuring the photo through sensors installed on it.

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