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SOLAR BASED SOFT SWITCHING DC -DC RESONANT CONVERTER FOR LED DRIVING APPLICATIONS

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ABSTRACT

The availability of DC grids necessitates the development of LED drivers for both low and high voltages. A full-bridge configuration is proposed for LED drivers suitable for housing and street lighting applications. This approach is effective for current handling with minimal conduction losses and allows for easy extension to higher wattage solutions. It offers advantages such as lower component count, PWM dimming, and compatibility with various loads. To enhance performance, a modified version of the conventional bidirectional boost converter is introduced, integrating an auxiliary circuit comprising a capacitor, inductor, and switch. This configuration supports soft switching in both operation modes. During the day, the system operates in buck mode, storing solar energy in the battery. At night, the system uses the battery to power LED lighting via boost operation. This approach is grounded in PET theory, coupled with insights on heat sink design and soft-switching. This integrated system ensures efficient operation by maintaining the optimal voltage. An extensive analysis is performed, and the proposed solutions are verified through simulations using the PSCAD/EMTDC version 4.2.1. The study explicitly presents a practical solution for cascade-based LED lighting, with good results.

Keywords: *optimal flux; buck-boost converter; soft switching; LED streetlights; PET theory; photovoltaic technology.*

INTRODUCTION

As the world moves forward, with the continual progress in technology, the expansion of the population, and the increasing use of electrical devices, the demand for electricity is growing. If this trend continues, we will ultimately face a potential crisis in meeting energy demands. To address this challenge, researchers have suggested the use of renewable energy sources. Solar energy, in particular, is widely regarded as one of the most promising renewable energy sources due to its accessibility. Power electronic converters are a critical component of these renewable energy systems. Given that solar systems produce direct current (DC), DC/DC converters are essential in photo-voltaic systems [1]. Bidirectional DC/DC converters are commonly used in various applications including fuel cell systems, battery systems, and uninterruptible power supply (UPS) systems. These converters play a significant role in renewable energy systems [2]. There are two main classifications of bidirectional DC/DC converters: isolated and non-isolated [4]. Isolated bidirectional converters, which employ more than four switches and an isolated transformer, have higher conduction losses and lower efficiency compared to their non-isolated counterparts. In contrast, non-isolated DC/DC converters offer higher efficiency due to their simpler design [3]. To further enhance efficiency, a suggested approach is the use of soft-switching techniques, which allow for zero-voltage switching and reduce switching losses, thus improving overall efficiency [2]. In recent years, there have been various research efforts regarding the control methods of DC/DC converters [2]. LED lighting is considered a superior alternative compared to traditional lighting systems due to its high luminous efficiency and long lifespan [1].

The wide range of applications of LED lighting include indoor lighting, roadway lighting, automotive lighting, among others [1]. LED lighting, having unique voltage and current characteristics, requires a dedicated power supply known as an LED driver. For LED drivers, switched-mode power supplies with high efficiency are preferred over linear regulators [2]. AC-DC converters are used in LED drivers with AC supplies, as they are either single-stage [3] or multi-stage [7]. An electrolytic capacitor is commonly used in AC-DC LED drivers to eliminate low-frequency ripple. However, LED drivers incorporating electrolytic capacitors have a relatively short lifespan. Since LEDs have a much longer life span, it is more appropriate to use LED drivers that do not include electrolytic capacitors to match the lifespan of the LED itself and ensure long-term reliability [5]. However, this choice increases the complexity of the circuit. To overcome the lower efficiency and shorter lifespan of traditional LED drivers, it is more feasible to switch toward DC distribution.

The power industry at the utility level is moving toward DC distribution. Most electrical devices operate internally on DC power, and appliances such as electronic chargers, computers, and LED lights all function with DC power. With the development of renewable energy sources like solar panels, which produce DC power directly, the growth of DC distribution is making more sense [5]. LED lighting load has a significant demand for DC power due to the increasing use of LED lamps. LEDs supplied from DC sources are compact, reliable, and more efficient compared to those supplied from AC, as they eliminate the need for an AC-to-DC conversion stage [1-6]. Preferred features for street lighting with LEDs using DC power include:

- Relatively larger power
- Multiple load requirements
- High efficiency
- Reduced component count
- Dimming capability for improved energy efficiency
- Load current regulation.

Several DC-DC converter-based LED drivers have been suggested in research. A full-bridge resonant DC-DC converter for regulating LED current and providing PWM dimming is introduced in [7]. It uses a constant duty ratio and fixed frequency, but current regulation is handled by an extra buck converter, which adds more components. An autonomous LED street lighting system is proposed in [8], but it uses hard-switching. A buck-boost integrated half-bridge series resonant DC-DC converter for LED drivers with current regulation and PWM dimming for multiple loads is proposed in [9]. This design provides high gain, but LED current is controlled using frequency control, which involves a complex component design and an additional switch for PWM dimming. A full-bridge ripple-free LED driver with current regulation and PWM dimming for street lighting is presented in [10]. It has smaller magnetic components but uses an auxiliary buck-boost converter for current regulation and an extra switch for dimming. A half-bridge series resonant converter-based LED driver for current regulation and PWM dimming is proposed in [11]. It reduces voltage stress on components, but it has more components. A switch-controlled capacitor-based LED driver for multiple loads is introduced in [12], using constant frequency for current regulation and dimming. However, it needs additional switches, diodes, and capacitors, which increases component count and complexity. A single inductor multiple output LED driver for dimming is proposed in [13]. It offers a high dimming range but has a high dimming frequency and requires more components for dimming. An asymmetrical half-bridge LED driver with multiple output for street lighting is introduced in [14]. It operates with constant frequency but uses analog dimming, and it has more components. A three-leg series resonant converter-based LED driver for current regulation and dimming is proposed in [15], operating with fixed frequency, but it requires more components for multiple loads. A constant current LED driver to regulate LED current is suggested in [6]. It has low ripple content, but it requires more inductors, diodes, and capacitors, increasing component count. A DC-fed resonant switched capacitor topology-based LED driver is proposed in [7]. It is simple, robust, and low-cost, but uses analog dimming for illumination control, which affects the color of LED lighting. Current is regulated using a variable inductor, whose design is complex. A single inductor half-bridge LED driver with magnetic control for DC-grid is introduced in [8]. It operates with constant frequency, but current regulation uses a variable inductor that is hard to implement. A half-bridge series resonance LED driver with two outputs is presented in [9]. It has fewer switches, but more diodes and capacitors, and it has higher current and voltage stress.

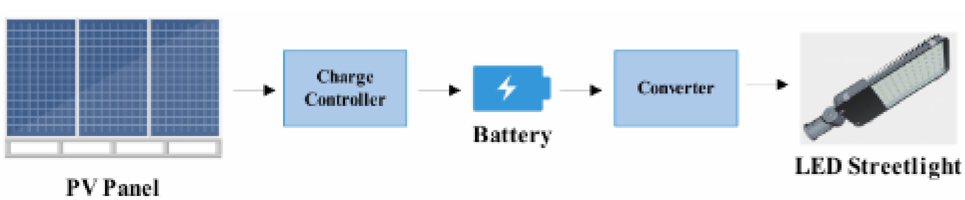

Figure 1:PV-powered LED streetlight system.

PROPOSED SYSTEM COFIGURATION AND OPERATION

The proposed system is shown in Figure 2. This system uses a soft-switching bidirectional dc/dc converter to collect energy from the PV panel and provide power to the LED light. As you can see in the figure, the converter sends current through both its input and output ports, which is a good feature for the battery, PV panel, and LED light. The PV source and LED light have higher voltage levels compared to the battery, so the high-voltage side of the converter is connected to them via a static relay. Because of this, during the day, the converter uses its buck mode to store PV energy in the battery, and at night, it uses its boost mode to power the LED light from the battery. As shown in Figure 3, during the day, the converter operates in buck mode because the PV panel voltage is higher than the battery voltage[9].

In this situation, the relay is connected to the PV panel, and the Q1 switch is turned on using a PWM signal, while the Q2 switch remains off. When Q1 is off, the diode D2 allows current to flow. On the other hand, as seen in Figure 4, at night, the converter uses boost mode since there is no PV power available, and the battery has to power the LED light, which requires a higher voltage. In this situation, the relay is connected to the LED, and Q2 is turned on using PWM, while Q1 remains off. When Q2 is off, the diode D1 allows current to pass[6].

Now, if during the time each diode is conducting, the corresponding inverse parallel switch of that diode is also turned on, the circuit functions as a synchronous rectifier for both the buck and boost circuits, which reduces conduction losses[6].

Therefore, a PWM signal is applied to the Q1 switch with a duty ratio of d1, and the Q2 switch operates in the opposite state of Q1 with a duty ratio of 1 - d1. This means when Q1 is on, Q2 is off, and when Q1 is off, Q2 is on. In this setup, the voltage across the capacitor C1 is given as[9]:

$$v_{C_1} = \frac{v_B}{1-d1}$$

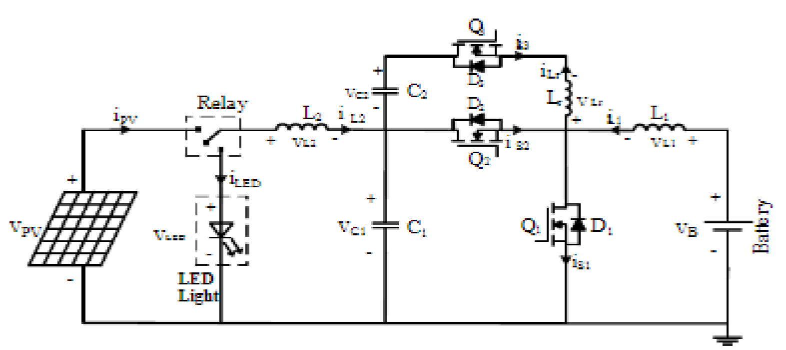

Figure 2. Proposed soft-switching bidirectional DC/DC converter for LED streetlight system.

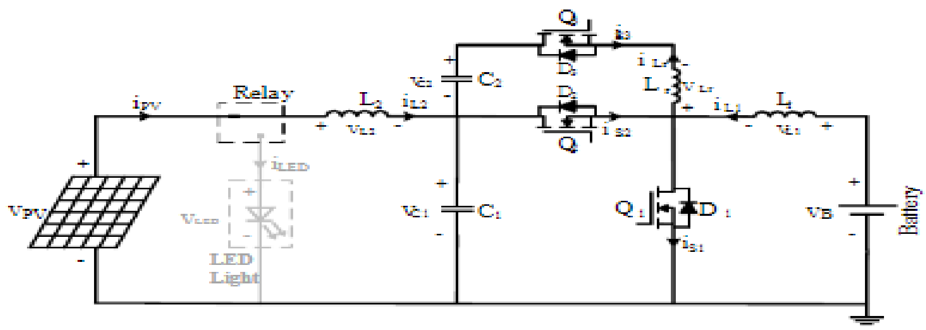

Figure 3. Daytime operation

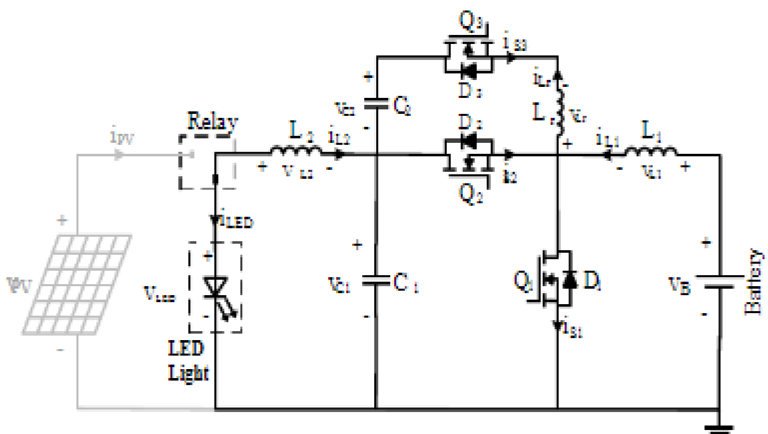

Figure 4. Nighttime operation

PROPOSED CONTROL SYSTEM

Figure 5 shows the proposed converter control system. During the day, the duty ratio d1 is used as the controlling variable to regulate the PV module current at the IMPP, which helps control the generated power at PMPP[9]. By using the MPPT algorithm, the maximum power operating current (IMPP) of the PV module is found. Then, this current is used as input to the PI controller to determine the converter's first switch duty cycle d1. At night, the duty ratio d1 is again used as the controlling variable to adjust the LED light current to its optimal value. To find the duty cycle of the converter d1, the PET theory [4] is used to determine the optimal operating current (IOpt) of the LED light, and this value is then given to the PI controller.

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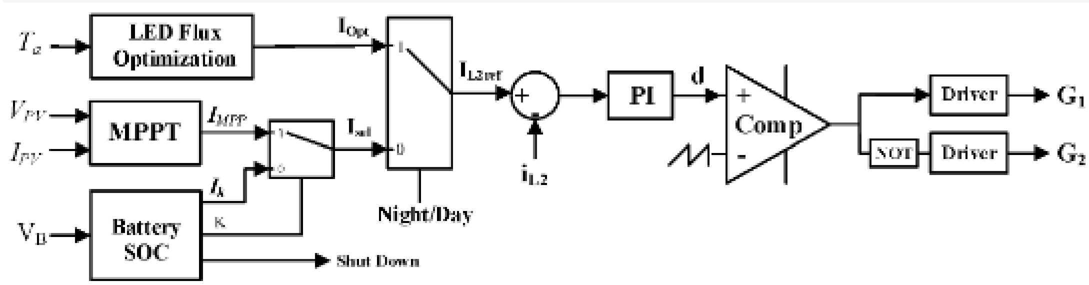

Figure 5: Proposed control system

PROPOSED CONVERTER OPERATION ANALYSIS

In the converter design, by using large enough values for the inductance L2 and capacitances C1 and C2, these components act like nearly constant current and voltage sources for the inductor current IL2 and the capacitor voltages VC1 and VC2. This leads to VC1 being higher than VC2. The inductor currents iL1 and iLr are shown with their small changes in value, known as ripples. During the analysis of the converter, if an inductor current becomes positive, it means the component is charging. If the current becomes negative, it means the component is discharging[9].

ZERO-VOLTAGE SWITCHING (ZVS)

ZVS techniques, which help in making the power switches in a converter switch smoothly, are very popular among designers of power electronic systems these days. The usual way of switching power during the on-time with resonant transitions is known as ZVS. Basically, this works by matching the relationships from the volt/second rule at the start and end of the system. In soft-switching, when a switch is off, the LC circuits vibrate. This helps bring the voltage across the switches down to zero before turning them back on. Another method used is zero-current switching (ZCS). This happens when the switch is turned on when the current through it is zero. Like ZVS, ZCS also lowers switching losses [5,6]. Switching a device when the voltage is zero greatly cuts down on switching losses, which makes the circuit more efficient. Here are the main benefits of using ZVS:

- ❖ Lower switching losses.
- ❖ Higher efficiency.
- ❖ Better ability to handle short circuits.
- ❖ No current going above the peak level.

- ❖ Less electromagnetic interference (EMI).
- ❖ Chance to use high-frequency switching.

Even though ZVS is good, it has some drawbacks.

It may not work well with light loads because it needs a minimum current. Also, there needs to be some time in between when switches turn on and off. For more details on ZVS and ZCS, [7,8].

SIMULATION RESULTS

We assume the use of a 60 W LED streetlight, a PV module, and a 12 V battery source for the proposed system. To address the issue of low brightness from a single LED, multiple LEDs can be connected in series and parallel. In the simulation, 20 LEDs are used in two strings, with 10 LEDs in each string[9]. Table 1 displays the parameters of the LED streetlight used, with each LED having a maximum power of 3 W. In Figure, the P-V output characteristics of the PV module are shown for three different environmental conditions. A 12 V lead-acid battery is used. In the simulation, the PV module should charge the battery during the day under MPPT conditions. At night, the battery supplies the LED light with the optimal current[8]. The proposed converter is switched under soft-switching conditions—ZVS in both operation modes and ZCS. In buck and boost operation modes, as shown in the simulation waveforms, the voltages of Q1 and Q2 were reduced to zero level, indicating successful ZVS conditions for the switches. Additionally, Q3 is turned off when its current is negative, through D3, which provides ZCS conditions for this switch[6-9].

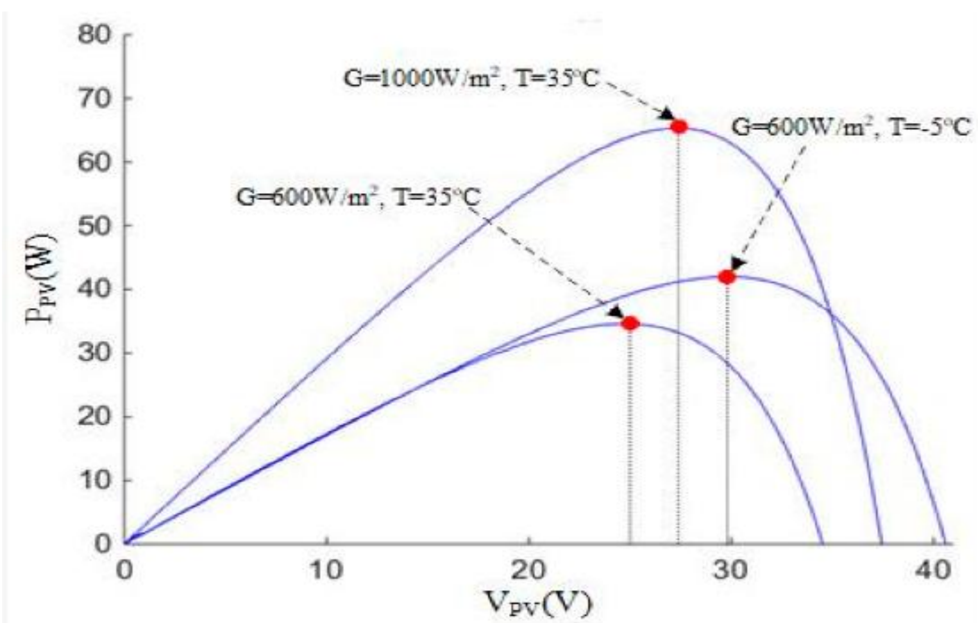

Figure 6: P-V output characteristics of the utilized PV module.

The study accounts for variabilities in solar irradiation and ambient temperature. The system was simulated using the PSCAD/EMTDC software. The system operates in two operational modes: day and night. The system operation involves three and two steps, respectively. The proposed system's operational phases are discussed[8].

Table 1. LED streetlight simulation parameters.

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)	M	18

CONCLUSIONS

This study presents the use of a bidirectional boost converter for the control of PV-powered LED lighting employing battery storage. Design improvement was achieved by introducing an L-C-switch series resonant circuit. This topology provides for soft switching in both buck and boost operations. During daylight, the converter functions to draw MPP solar energy from PV modules and charge the battery in the buck mode. At night, the system would harness stored energy from the battery to power the lighting system. The system's flexibility in operation enables a cost-effective and simplified design. The system integrates electrical, optical, and thermal characteristics of LEDs, optimizing the cycle for maximum luminous flux. A control system enables efficient operability in terms of voltage adjustment, battery charging, and MPPT. The system presents a single-stage: it offers compact and effective power conversion.

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