DESIGNING SUSTAINABLE HYBRID HIGH-BRIGHTNESS LED ILLUMINATION SYSTEMS

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Abstract

In this paper, the author presents a road map for the design and development of sustainable hybrid High-Brightness Light Emitting Diode (HB LED) illumination systems controlled by a Field Programmable Gate Array (FPGA). The proposed hybrid system design represents the foundation for future sustainable high-efficiency illumination systems. The system design presented here individually controls an array of HB LEDs. Each HB LED operates in a different mode defined by the user. Photovoltaic (PV) panels were used as the primary source of energy in this hybrid system, while the electric grid was used as a backup source to supply power to the HB LEDs only when the PV system could not sufficiently power all of the system HB LEDs, and when the PV system batteries would be depleted below the minimum level set in the system design.

The hybrid illumination system design presented here is an important link between the current AC-based illumination systems and future sustainable DC-based solar illumination systems. Since computer simulation is an important tool for future illumination system design and analysis, it was used here to assist designers in analyzing different designs and in optimizing the one to be implemented.

Introduction

The demands for utilizing alternative power sources have increased due to rising oil prices and more stringent environmental regulations. Alternative energy and its applications have been heavily studied for the last decade, and solar energy is the preferred choice in many applications. Among solar energy applications [1], photovoltaic (PV) technology has received much attention and is being used in many applications [2], [3].

Presented here is a plan for the design of a sustainable hybrid FPGA-controlled high-brightness LED illumination system that can be used to replace current illumination systems in order to improve system efficiency and reliability. In the proposed system, a single-ended primary-inductor converter (SEPIC) DC-DC converter is used to deliver solar energy via PV-cell modules to a battery bank in charging mode during the daytime. At night, it drives an LED lighting system. An FPGA is used to individually control an array of LEDs. The main reason for choosing HB LEDs as the illumination source in this system is due to their high efficiency as compared with incandescent and fluorescent lamps.

Hybrid HB LED Illumination

The principal motivation for this hybrid system is the clear shift to DC systems with more use of alternative energy sources. The AC vs. DC battle raged when Edison promoted DC power while George Westinghouse felt that AC was the way to go. AC won the battle, since it was so much easier to step the voltage up and down using transformers, and higher voltages greatly reduce resistive loss. This study explored the continued growth of DC power distribution in buildings, for which LED-based illumination has been a major driver.

Since photovoltaic panels are used to power the illumination system, there is a need for a second source of power for the system when the sun is out for a period of time beyond the capability of the batteries to serve as a backup source. Some products that are appearing on the market use HB LEDs with built-in converter that can be connected directly to the AC line. Those products take advantage of the high efficiency of HB LEDs, but they do not use a sustainable source as the main supply for those LEDs.

The hybrid HB LED-based illumination system design presented here incorporates an automatic transfer switch, as shown in Figure 1. Through the use of this switch, the hybrid system uses solar as the primary source of energy, and it switches to the AC line only for the time when the primary source cannot supply the required power to the illumination system.

In the system of Figure 1, LEDs are powered by the solar panel during the daytime as the primary source, with the battery in charge mode, and by the battery at night. If the battery is fully discharged, the HB LED system operates from the AC line as the secondary source. The design of DC-DC converters, DC-AC rectifiers, and DC-AC inverters are well understood and can be followed using senior-level or graduate power electronics textbooks [4-7].

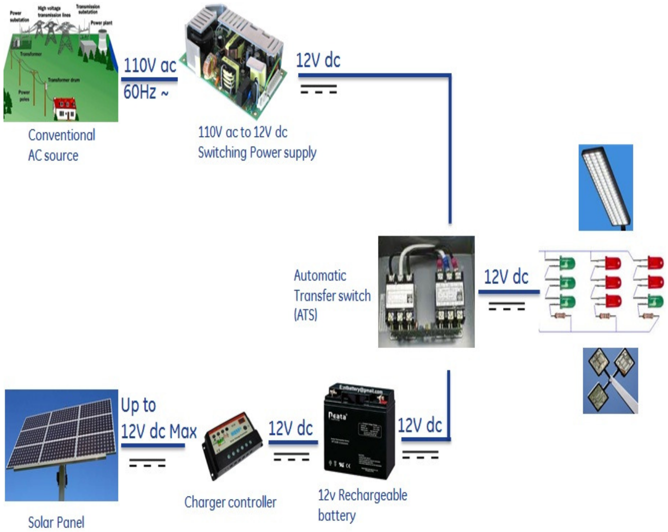

Figure 1. Hybrid High Brightness LED Illumination System

Since LEDs can handle voltage fluctuations, the system can be simplified by using a full-wave bridge rectifier instead of the AC-DC converter. The simplified system is shown in Figure 2, where the DC distribution to power HID LED lamps consists of a solar panel, DC supply distribution, DC supply switching module, battery charger controller, battery bank, DC–DC Converter (Buck-Boost converter), and HID LED lamps. The operation of this buck-boost converter has two operation modes: the first is the buck mode for daytime battery charging operation, and the second is the boost mode for nighttime lighting usage.

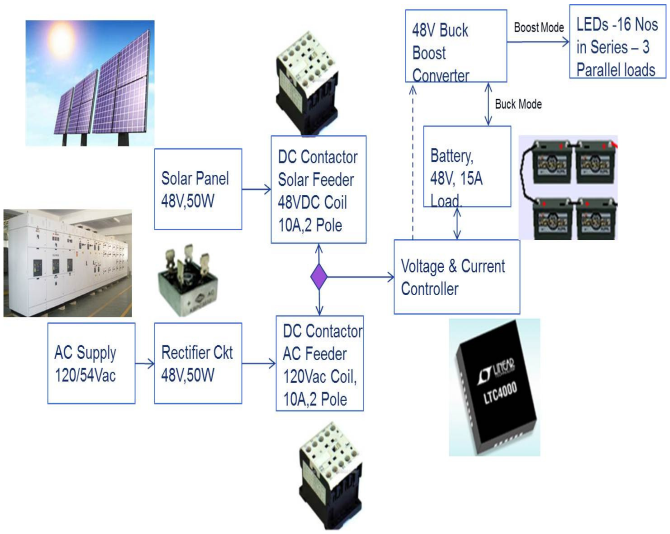

Figure 2. Simplified Hybrid LED Illumination System

The hybrid illumination system presented in Figure 2 is sustainable for many applications that are emerging due to the continued growth of DC power distribution in buildings. The principal force behind this growth is LED-based illumination which was cited as one major driver. The main challenges in building such a system include: the analysis of switching circuits that deal with switching of power between AC and DC distribution; being fed from solar panels; and, switching between the two sources. Figure 3 presents one solution for this problem, where an AC contactor and a DC contactor with mechanical interlock are used; and Figure 4 which presents the relay control for the mechanically interlocked contactors.

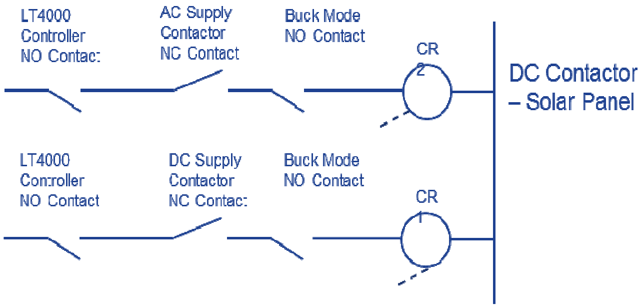

Figure 3. AC and DC Contactors Design to Control the LED Illumination System Switching

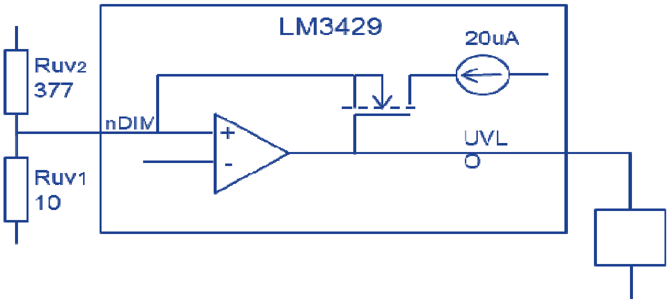

Figure 4. Relay Design to Control the Hybrid Illumination System Switching

The illumination system is designed to be used to individually control an array of HB LEDs. Each HB LED operates in a different mode that is independently defined by the user. The defined sequence of LED illumination is controlled using a controller circuit, i.e. an FPGA. Figure 5 presents the basic control system layout used for this DC illumination control strategy that gives the user more flexibility and control than the flexibility and control level available for standard AC-powered illumination used in incandescent or fluorescent lamps.

In this LED control strategy, an FPGA is used to individually control the LEDs. The FPGA is programmed using Hardware Description Language (HDL). In this case, VHDL is used. [VHDL is a hardware description language used in electronic design automation to describe digital and mixed systems and integrated circuits.] The pattern of the LEDs defined by the user can be modified using this hardware description language. A Basys Spartan 2 FPGA was chosen for this application due to its flexibility, low cost, and ease of use.

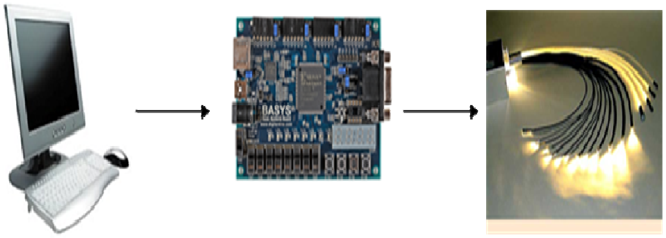

Figure 5. FPGA-Controlled Illumination

The application software used in this study was Adept, which is a powerful program that allows configuration and data transfer with Xilinx logic devices, and can be used as an interface between Xilinx and the Spartan 2 FPGA board. For maximum intensity from the LEDs, the typical forward voltage of 3.9V, with a forward current 700mA, is supplied to the FPGA. A personal computer provided with Xilinx software was used for programming the sequence of the LEDs defined by the user. The programming was done using VHDL. The developed software was tested using a Digilent FPGA board.

High brightness LEDs [8], [9] can be driven at currents from hundreds of mA to more than an ampere, compared with the tens of mA for other LEDs; however, few of the HB LEDs can produce over a thousand lumens. Since overheating is destructive, the HB LEDs may need to be mounted on a heat sink to allow for heat dissipation. If the heat from an HB LED is not removed using a heat sink, the device will burn out in seconds.

A single HB LED can often replace an incandescent bulb in a torch, or be set in an array to form a powerful HB LED system. LEDs can operate on AC power without the need for a DC converter. Each half-cycle part of the LED emits light, while the other part is dark, a pattern that is reversed during the next half cycle. The efficacy of this type of HB LED is typically around 40 LM/W. A large number of LED elements in series may be able to operate directly from line voltage. In 2009, Seoul Semiconductor released a high-DC-voltage LED capable of being driven from AC power with a simple controlling circuit. The low power dissipation of these LEDs gives them more flexibility than the original AC LED design. In this project, the HB LEDs were powered from a DC source.

To control the LED from the FPGA, a circuit driver was needed to boost the power of the FPGA output. An LED driver circuit is an electric power circuit used to power a light-emitting diode or LED. The circuit consists of a voltage source powering a current-limiting resistor and an LED connected in series. The HB LEDs used in this project design had a constant current of 700mA and a supply voltage of +3V. As the current has to be amplified to 700mA for each LED, two transistors were connected together so that the current amplified by the first is amplified further by the second transistor. The overall current gain is equal to the two individual gains multiplied together, i.e., $h_{FE} = h_{FE1} \times h_{FE2}$, where h_{FE1} and h_{FE2} are the gains of the individual transistors. An LED driver circuit for each individually controlled LED is given in Figure 6.

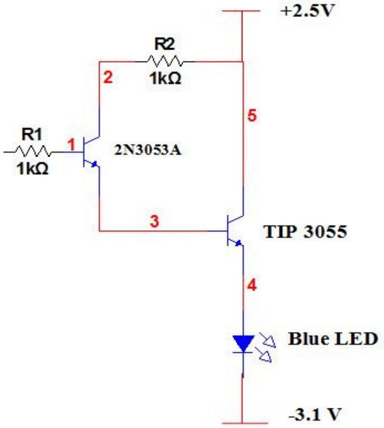

Figure 6. LED Driver circuit

Sustainable PV-Powered Illumination

Since photovoltaic panels are used to power the HB LED illumination systems, there is a need for the development of the DC converter system to power the LEDs. To satisfy this requirement, a forward converter with PV-based LED applied in lighting systems was used. In the proposed DC supply system, SEPIC was used to deliver solar energy via PV-cell modules to a battery bank in the charging mode during the daytime. During the nighttime, the converter (see Figure 7) drives an LED lighting system.

Figure 7 illustrates the principle PV-SEPIC-LED circuit applied in street illumination, where the produced PV voltage is stored in a battery bank throughout the charging unit during the daytime; at night, the discharger activates and the LEDs are energized with appropriate voltage through a step-up transformer and full bridge rectifier.

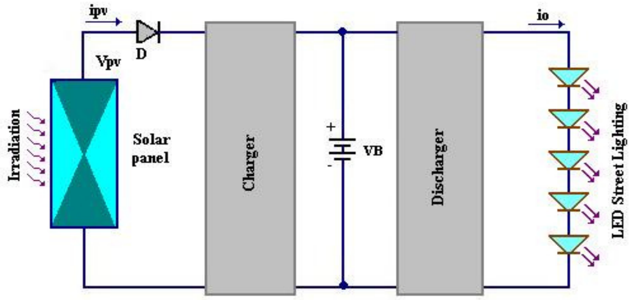

Figure 7. PV-based Sustainable Illumination

SEPIC circuits find widespread application when the input voltage fluctuates above and below an average value, while the output voltage must be kept at a constant value with minimum tolerances. One of the most applications of a SEPIC circuit is in integration with the photovoltaic system (PV system) and illumination load of series- and parallel-connected LEDs.

The SEPIC converter is a DC/DC converter topology that provides a positive regulated output voltage from an input voltage that varies above and below the output voltage. This type of topology is needed when the voltage from an unregulated input power source—such as solar, where the sun irradiation, temperature and weather change—directly affects the generated output voltage. Standard SEPIC topology [10], [11] requires two inductors in additional to a step-up transformer, making the power-supply footprint quite large. Photovoltaic (PV) cells are used to convert sunlight into electrical energy. On the other hand, it is also an important issue to save the energy demand and increase the energy efficiency [12-14]. High-brightness light-emitting diodes (LEDs) [15], [16] are becoming more widespread for lighting applications such as automobile safety and signal lights, traffic signals, street lighting, and so on.

In lighting applications with solar energy, the charger is adopted to convert solar irradiation for storage in the battery during the daytime. In the nighttime, a discharger is used to release energy from the battery and drive the LED lighting system. Low-power DC-DC converters can be used for the charger and discharger modes. So, since the PV voltage from the solar panel is unstable, the buck-boost converter is more suitable for charger circuits. This converter can also be used in the discharger circuit.

DC-DC Converter Control Design and Analysis using Computer Simulation

Computer simulation is an important tool for future illumination systems design. The HB LED-based illumination system was simulated using a circuit simulation program. In this section, the DC-DC converter control loop simulation results are presented. The most common control method, shown in Figure 8, is pulse-width modulation (PWM). This method takes a sample of the output voltage and subtracts it from a reference voltage to establish a small error signal (V_{ERROR}). This error signal is compared to an oscillator ramp signal. The comparator is used to generate a digital output (PWM) that controls the power switch.

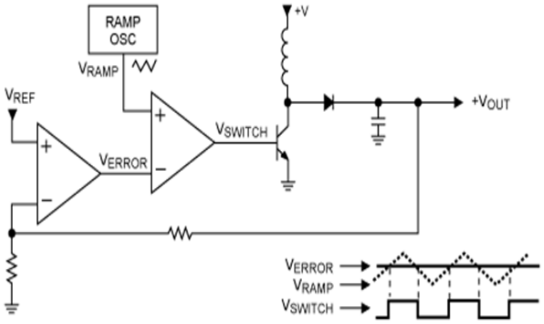

Figure 8. PWM controller for Switching Buck Controller

When the circuit output voltage changes, V_{ERROR} also changes causing the comparator threshold to change. Consequently, the PWM also changes. This duty cycle change then moves the output voltage to reduce the error signal to zero, thus completing the control loop.

The output voltage of the solar panels is stepped down using a buck, step-down converter. The closed-loop control circuitry for the buck converter consists of an Error Amplifier (ERR), oscillator, and PWM circuits. The ERR and oscillator outputs drive the PWM circuit. The EER circuitry is given in Figure 9, where the automatic control measures how close V_{OUT} is to V_{REF}.

The measurement of error is the Error Voltage, which is the difference between V_{OUT} and V_{REF}, Error Voltage = (V_{REF} - V_{OUT}). Since $\mathbf{V_{OUT} \sim V_{REF}}$, Error Voltage is close to zero, which means that this circuit maintains the Error Voltage and the PWM duty cycle, regardless of variations in the input voltage. If $\mathbf{V_{OUT} > V_{REF}}$, then the Error Voltage is negative, thereby decreasing the Error Voltage and the PWM duty cycle. If $\mathbf{V_{OUT} < V_{REF}}$, then the Error Voltage is positive, which increases the Error Voltage and the PWM duty cycle. The oscillator circuit, given in Figure 10, is used to generate the ramp signal used as an input to the PWM circuit.

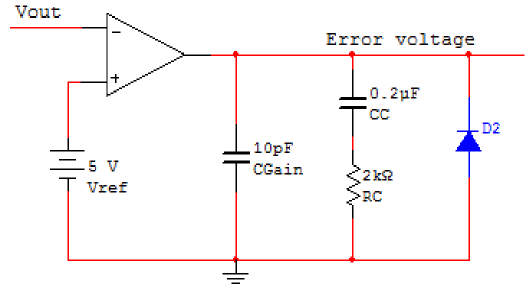

Figure 9. Error Amplifier Circuit

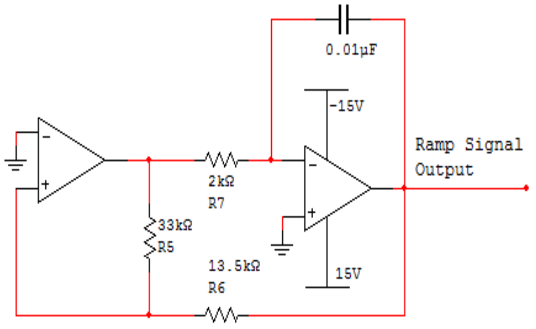

Figure 10. Oscillator Circuit

The PWM comparator circuit, given in Figure 11, compares the Error Voltage, generated by the ERR amplifier circuit, to an oscillator ramp signal which in turn is generated by the oscillator circuit. This comparator produces a digital output (PWM OUT) that drives the MOSFET.

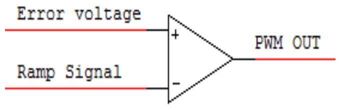

Figure 11. PWM Comparator Circuit

When a DC-DC converter circuit output voltage, Vout, changes, the Error Voltage also changes, thereby causing the comparator threshold to change. Consequently, the PWM OUT also changes.

Conclusion

A sustainable hybrid FPGA-controlled HB LED-based illumination system was developed and tested. This illumination system can be used for many lighting applications since it is more efficient and more reliable than existing traditional lighting systems based on incandescent or fluorescent lamps. The initial cost of the system due to the high cost of solar panels is the main disadvantage in the new design when compared with current illumination systems. While the use of the solar panels and HB LEDs adds to the initial cost of the system, the use of the solar panel will result in energy savings, and the use of HB LEDSs will be paid off in the long term due to their higher reliability, flexible control, and long life time.

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Biography

AKRAM ABU-AISHEH is an Associate Professor of Electrical and Computer Engineering at the University of Hartford where he has served as the assistant chair of the Electrical and Computer Engineering Department and director of the electronic and computer engineering technology program for two years. Dr. Abu-aisheh has a doctorate in Optical Communications from the Florida Institute of Technology and Master of Science and Bachelor of Science degrees in Electrical Engineering from the University of Florida. His research interests include Fiber Optic Communications, Solar Energy, Power Electronics, and Engineering Education. He has published a book, a book chapter, and several international journals and conference papers. Dr. Abu-aisheh may be contacted at abuaisheh@hartford.edu