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Hybrid MPPT-Controlled LED Illumination Systems

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Abstract

This paper presents a road map for the design and development of sustainable hybrid High Brightness Light Emitting Diode (HB LED) illumination systems with maximum power point tracking (MPPT). The proposed hybrid system design presents the foundation for future sustainable high efficiency illumination systems. The system design presented in this paper individually controls an array of HB LEDs. Each HB LED operates in a different mode defined by the user. Photovoltaic (PV) panels-based systems are used as the primary source of energy in this system while the electric grid is used as the backup source that supplies power to the HB LEDs only when the power of the PV system is not sufficient to supply all the system HB LEDs and the PV system batteries are depleted below the minimum level set in the system design. A matlab/ Simulink model is proposed for studying the system behaviors and operation modes.

Keywords: *MPPT, High Brightness LED; Hybrid; Matlab/ Simulink; DC Chopper*

1. 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 [1]. Among solar energy applications, the photovoltaic (PV) technology has received much attention, and it is being used in many applications [2&3].

This paper presents a sustainable hybrid high brightness LED Illumination System that can be used to replace current illumination systems in order to improve the 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.

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. A second factor is that the world of DC Application is fast expanding with the requirements of data storage and high efficiency requirements in supply distributions. Compact fluorescent lamps are becoming obsolete, and replaced with HB LED lamps driving the efficiency of lighting systems. The system presented in this paper expands on the continued growth of DC power distribution in buildings, and driving this trend toward that end LED-based lighting has been cited as a factor.

2. Hybrid 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. As we know, 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 paper explores the continued growth of DC power, and the force driving the trend; LED-based lighting has been cited as one 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 in the market use HB LED with build-in converter that can be connected directly to the AC line. These 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 authors present this new hybrid HB LED-based illumination system design with automatic transfer switch as given in figure 1. This hybrid system uses solar as the primary source of energy, and it switches to the AC line only when the primary source can’t supply the required power to the system.

In the system given in figure 1, LEDs are powered from the solar panel during the daytime as the primary source, with the battery in charge mode, and they operate from 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 [4-8]

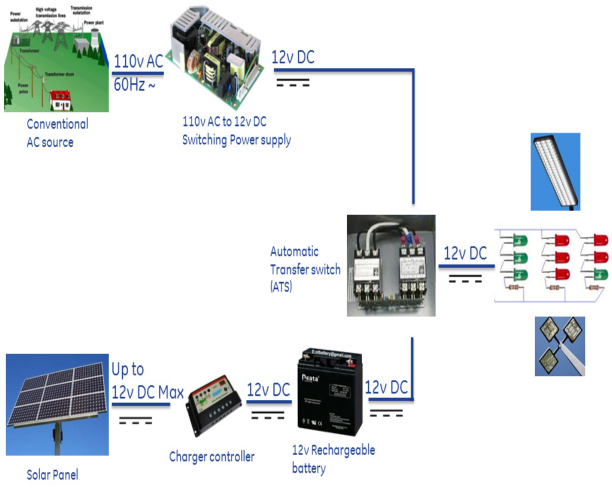


Figure 1: Hybrid High Brightness LED Illumination System

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 given in figure 2 where components can be classified into two different categories. The first one is high tension parts which consist of photo cells and high power LED, and the other is the low tension side which consists of L, C, and battery. The operation of this buck-boost converter has two operation modes: the first is the buck mode for day time battery charging operation, and the second is the boost mode for evening time lighting usage.

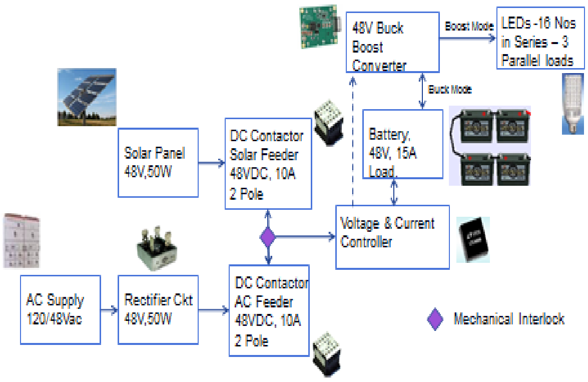


Figure 2: Simplified Hybrid Illumination

This simplified system is sustainable for many applications emerging due to the continued growth of DC power distribution in buildings, and the principal force behind this trend is LED-based lighting which we have cited as one major driver. The main challenges in building such a system include analysis of a switching circuit that controls alternating of power between the AC and DC distribution systems, being fed from Solar panel 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 presents the relay control for the mechanically interlocked contactors.

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 operated by means of 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.

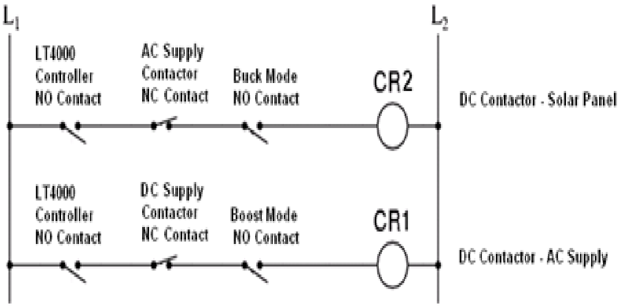


Figure 3: AC and DC Contactors Design to Control the LED Illumination System Switching

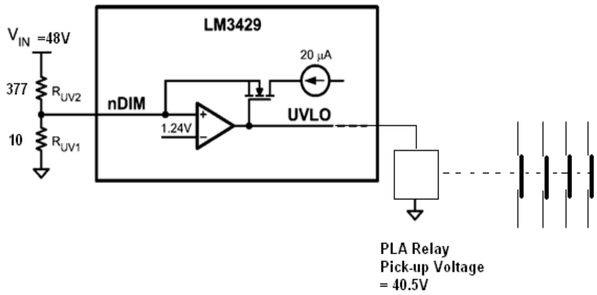


Figure 4: Relay Design used to Control the Hybrid Illumination Switching

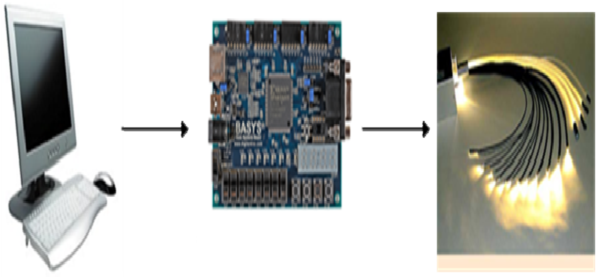


Figure 5: FPGA-Controlled Illumination

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 language. Basys Spartan 2 FPGA is used for this application due to its flexibility, low cost, and ease of use.

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

High brightness LEDs [9&10] 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 HP 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 with the other half cycle being dark, and this 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 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 are powered from a DC source.

To control the LED from the FPGA, a driver circuit is needed to boost the power of the FPGA output. An LED driver circuit is an electric 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 our design have 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 are 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.

3. 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, the SEPIC is used to deliver solar energy via PV cell modules to a battery bank in charging mode during the daytime. During the nighttime, the converter 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 throughout the step-up transformer and full bridge rectifier.

SEPIC circuits find widespread application when the input voltage fluctuates above and below average value, while the output voltage must be kept at a constant value with minimum tolerances. One of most important applications of SEPIC circuit is the 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 from above to 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 changes directly affect the generated output voltage. The standard SEPIC topology [11&12] requires two inductors in additional to step-up transformer, making the power-supply footprint quite large.

Photovoltaic (PV) cells are used to convert the sunlight into electrical energy. On the other hand, it is also an important issue to save the energy demand and increase the energy efficiency [13-15]. High brightness light emitting diodes (LEDs) [16&17] are becoming more widespread for the lighting applications such as automobile safety and signal lights, traffic signals, street lighting and so on. LED power circuitry is discussed thoroughly in the literature [18].

In lighting applications with solar energy, the charger is adapted to convert the solar irradiations for storing in the battery during the daytime. In the nighttime, a discharger is used to release energy in the battery and drive the LED lighting system. Low-power DC-DC converters can be used for the charger and discharger mode. Since the PV voltage from the solar panel is unstable, the buck-boost converter is more suitable for the charger circuit. This converter can also be used in the discharger circuit.

4. DC-DC Converter MPPT 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 matlab/Simulink environment [19]. In this section, we present the complete simulation model including the solar PV module, Maximum Power Tracking module (MPPT), DC-DC boost converter and storage unit (Battery). These modules are going to be described as follows:

4.1 Characteristics of PV Array

Basically, PV cell is a P-N semiconductor junction that directly converts light energy into electricity. It has the equivalent circuit shown in Figure1 as represented in [20-22].

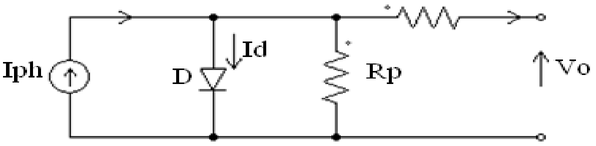


Figure 6: Equivalent circuit for PV cell

Where I_{ph} represents the cell photocurrent; R_p and R_s are the intrinsic shunt and series resistance of the cell respectively; Id is the diode saturation current; V_o and I_o are the cell output voltage and current respectively.

The following are the simplified equations describing the cell output voltage and current:

$$V_o = \frac{A.K.T_c}{q} \ln\left(\frac{I_{ph} + I_d - I_o}{I_o}\right) - R_s.I_o \qquad (1)$$

$$I_o = N_p(I_{ph} - I_d\left(e^{\frac{q.Vo/Ns}{A.K.Tc}} - 1\right) \qquad (2)$$

$$I_d = I_{or}\left(\frac{T_c}{T_r}\right)^3 .e^{\frac{q.Eg}{B.K}\left(\frac{1}{Tr}-\frac{1}{Tc}\right)} \qquad (3)$$

$$I_{ph} = N_p.\{I_{sc}.\phi_n + I_t(T_c - T_r)\} \qquad (4)$$

Where, K- Boltzmann constant; N_p and Ns are the number of parallel and series connected cells respectively; E_g is the band gap of the semiconductor; T_c and T_r are the cell and the reference temperature respectively in Kelvin, A and B are the diode ideality factors with values varies between 1 and 2; Φ_n is the normalized insulation; I_{sc} is the short circuit current given at standard condition; I_t and I_{or} are constants given at standard conditions.

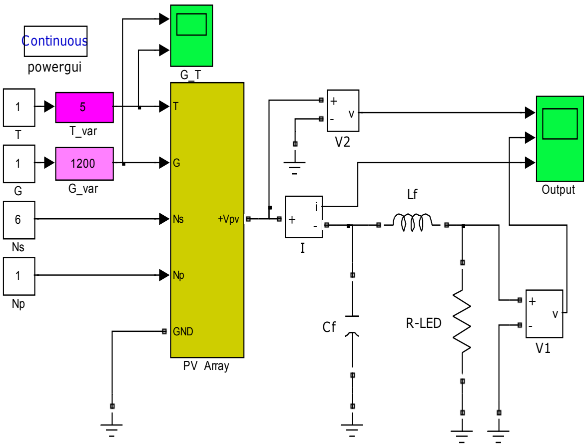
4.1 Photovoltaic I-V Performance

In order to study the I-V performance of the PV circuit and to look for appropriate dc chopper for boosting up the output voltage to predetermined value it is necessary to illustrate the obtained PV voltage and current for boost chopper according to specifications given in table 1 at reference irradiation 1000W/m2.

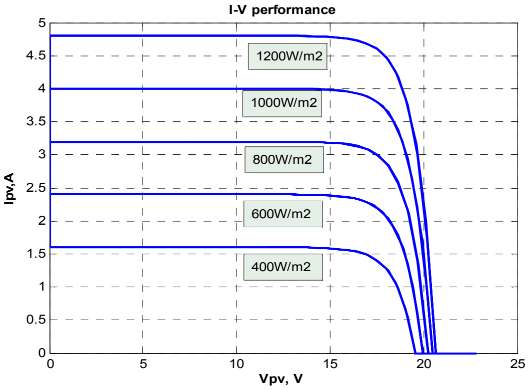
The PV Array voltage can be obtained by multiplying the module voltage and current by N_{sm} and N_{pm} that represents number of series and parallel connected modules respectively.

Table 1: Data specification for PV Array.

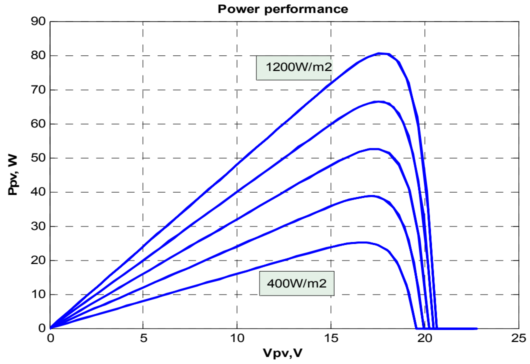
q	K	I_{ph}	I_d	R_S	R_P	T_C
1.602e-19 C	1.38e-23J/°K	4 A	0.2mA	23mΩ	0.65kΩ	25°C
N_S	N_P	V_O	V_{OC}	I_{SC}	V_{MPP}	I_{MPP}
38	4	0.6V	21.5 V	4.7A	17.5V	3.7A
N_{Sm}	N_{Pm}	R_{load}				
1	1	4.5Ω(Set of Series connected LED Diodes)				



a) Matlab/Simulink module for PV Array



b) I-V Performance of PV module.



c) Power performance of proposed module

Figure 7: PV Array module & main charaterestics.

Figure 7 illustrates the proposed PV array with R load presenting the equivalent resistance of complete LED set, where the obtained results for different variation levels are presented. From these performances it is shown that the total output PV voltage and current varies according to irradiation level with approximated 65W maximum power at G=1000W/m2.

4.2 Maximum power point derivation

In order to operate the module at maximum extracted power, it is necessary to calculate the coordinates of the maximum power point (V_{MPP}, I_{MPP}). For this, and to simplify the model in Simulink, the coordinates of the maximum power point are given by the following equations:

$$I_{MPP} = I_{ph} - I_d.\left(e^{V_{mpp}/V_T} - 1\right) \qquad (5)$$

$$V_{MPP} = V_T.\ln\left(1 + \frac{I_{ph} - I_{m\,pp}}{I_{ph}}\left(e^{V_{OC}/V_T} - 1\right)\right) \qquad (6)$$

Where V_T and Voc are the thermal voltage and the cell open circuit voltage respectively and given by:

$$V_T = \frac{K.T_c}{q}$$

$$V_{OC} = V_T.\ln\left(\frac{I_{sc}}{I_d} + 1\right) \qquad (7)$$

The maximum power that can be obtained can be expressed as follows:

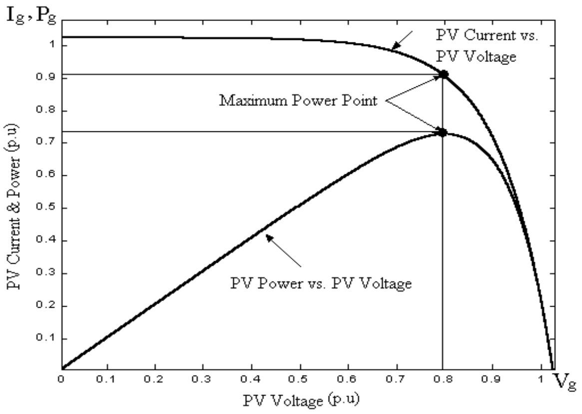
$$P_{MPP} = V_{MPP}.I_{MPP} \qquad (9)$$

Obtaining ng the maximum obtained power form the PV for given solar irradiation requires controlling the duty cycle D of DC Buck-Boost Chopper toward operating the chopper in mode where the extracted from the system power will be maximum. There are several approaches used for realizing MPPT operation mode, one of the most popular and simple approach de is called Perturbation & Observation model (P&O MPPT model).

The mathematical equations realized MPPT approach are expressed as follows:

$$\begin{aligned}
&\mathrm{Vo} = \mathrm{Vpv}.\frac{1}{1-\mathrm{D}}\\
&\mathrm{Po} = \mathrm{Vo}^2/\mathrm{RI}\\
&\mathrm{dPo} = \mathrm{Po}(k+1)-\mathrm{Po}(k);\\
&\mathrm{dVo} = \mathrm{Vo}(k+1)-\mathrm{Vo}(k); \qquad (10)\\
&(\mathrm{dPo}/\mathrm{dVo}) = ?\ldots.. \rightarrow \mathrm{D} = ?\\
&\mathrm{dPo}\begin{cases} >0 \rightarrow \mathrm{dVo}\begin{cases} >0 \rightarrow \mathrm{D} = \mathrm{D}-\Delta\mathrm{D}\\ <0 \rightarrow \mathrm{D} = \mathrm{D}+\Delta\mathrm{D}\end{cases}\\ <0 \rightarrow \mathrm{dVo}\begin{cases} >0 \rightarrow \mathrm{D} = \mathrm{D}+\Delta\mathrm{D}\\ <0 \rightarrow \mathrm{D} = \mathrm{D}-\Delta\mathrm{D}\end{cases}\end{cases}
\end{aligned}$$

While figure8 illustrates the Power performance and the flowchart procedure for obtaining the appropriate duty cycle needed to operate the chopper at maximum obtained power.



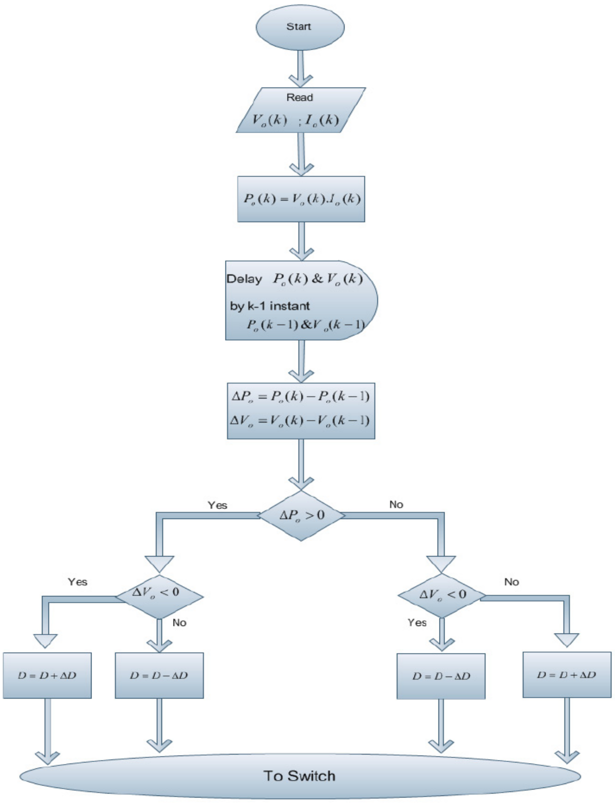
a) Maximum Power Point Tracking procedure

The proposed mathematical equations and corresponds flowchart can be summarized with operation logic as follow:

- (dPo/dVo)<0 ➔ operation at the right hand side of the curve (fig.8a), for D➔ Dmin , then V must be decreased (moving toward decrease).
- (dPo/dVo>0) ➔ operation at the left hand side of the same curve , for D➔ Dmax≈1). Then V must be increased (moving toward increase).

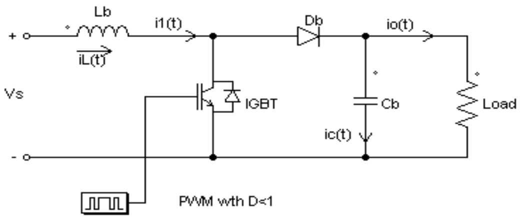
4.3: Boost DC Chopper

The output PV voltage in most of applications is requred to be boost up by applying Boost DC chopper [6]as shown in figure 9, where the principle electrical circuit and the operation mode at continuous current mode (CCM) are illustrated.

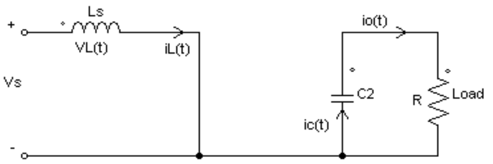


b) Flowchart for tracking procedure

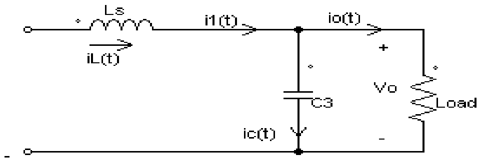
Figure 8: P&O MPPT tracking method.



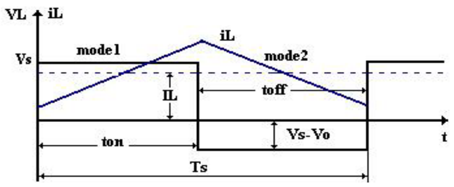
a) Boost DC Chopper



b) Mode#1: IGBT=ON



c) Mode#2: IGBT=OFF

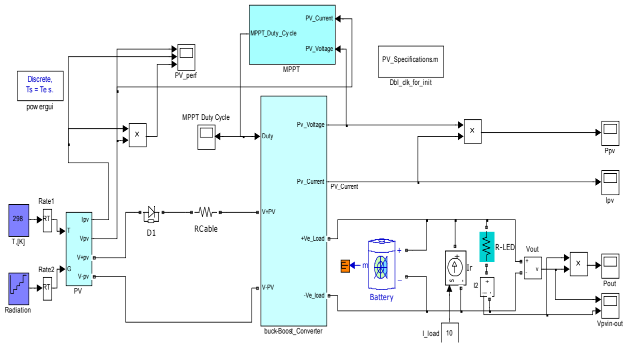


d) Load voltage & current at two operation modes

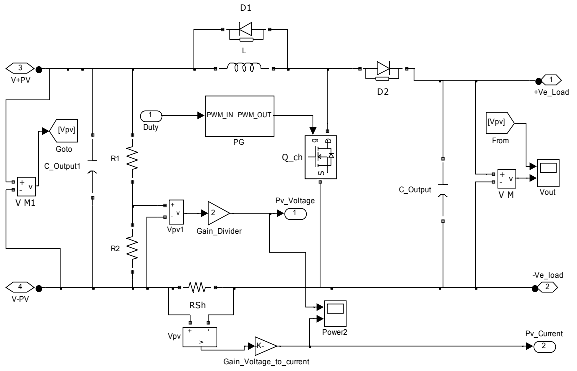
Figure 9: Equivalent circuit for boost converter operating in CCM

4.4: Matlab Simulation of Proposed Model

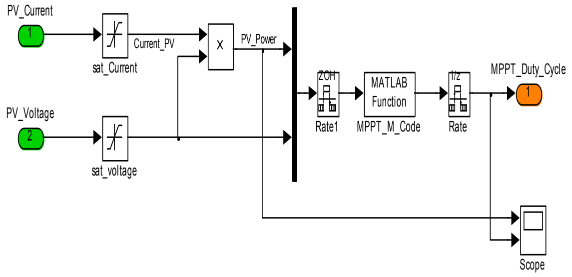
The complete electrical circuit for LED illumination system is simulated in mat lab/simulink environment and illustrated in 10



a) Load voltage & current at two operation modes



b) DC Chopper simulation module



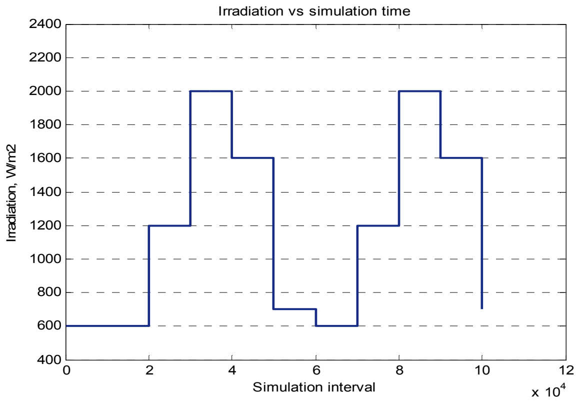
c) MPPT module

Fig.10: Complete Simulation model of PV- LED illumination system.

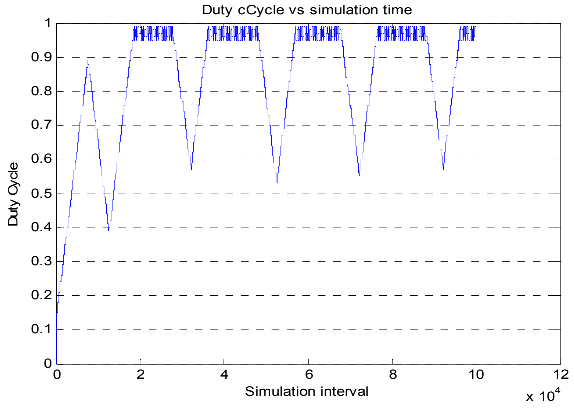
4.5: Simulation Results

There are various PV and chopper paramtetrs that can be described; some of these are illustrated in figure 11 as follows:

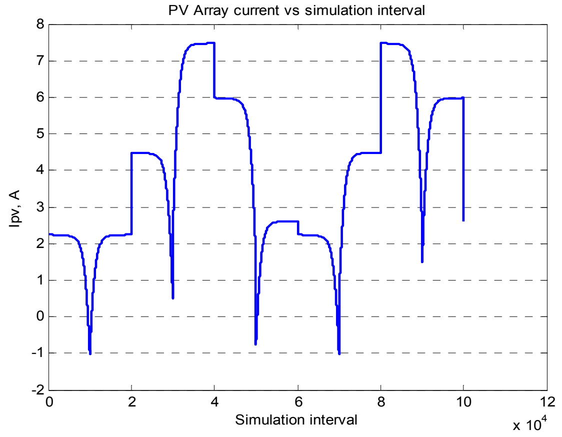
- *Solar irradiation*: Figure 11(a) illustrates the time profile of solar irradiation levels for various periods of daytime in order to show the behaviors of the circuit according to these levels.
- *Chopper duty cycle*: Figure 11(b) illustrates the time profile of calculated dudty cycle , where its shown that for each irradiation level the duyt cycle increases which cause further increase until maximum obtaied power is achieved.
- *PV array current*: Figure 11(c) illustrates the time profile of PV current, where its shown that high irradiation produces large current and power .



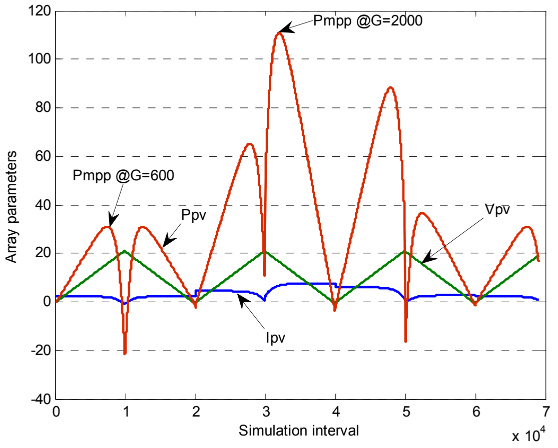
a) Solar irradiations at various daytime intervals.



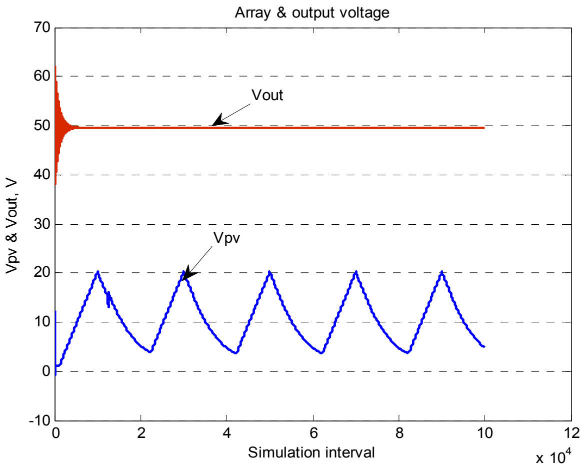
b) Chopper duty cycle.



c) Array current of The PV pannel



d) PV voltage, current and power



e) PV and chopper voltage

Fig.11: Circuit performances at various irradiations

- *PV voltage, current and power*: Figure 11(d) illustrates the time profile of PV voltage , current and power , where its shown how the power being affected by increasing the irradiation level.

- *Input-output voltage*: Figure 11(e) illustrates the time profile of PV input voltage and output chopper voltage, where its shown how the input voltage varies, while the output voltage is boosted up and fixed at appropriate for the elimination system value.

5. Conclusion

A Sustainable hybrid MPPT-Controlled HB LED-Based Illumination System was developed. This illumination system can be used for many lighting applications since it is more efficient and reliable than existing traditional lighting systems based on incandescent or fluorescent lamps. While the use of HB LEDs adds to the initial cost of the system, it will be paid off in the long term due to their higher reliability, flexible control, and long life time. A simulink model for this illumination system was built in order to study the system behaviors at various irradiation level, the effect of MPPT system and generated duty cycle on chopper operation, which in turn causes better utilization, effeciency enehancement and loss reduction.

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