Modeling, Control and Simulation of a Power Conditioning System for Solar Street LED Light

Mahrous Elsamman, M. K. Metwally
Faculty of Engineering, Taif University, 21974 Taif, KSA

***Abstract*— Recently enhancing the grid reliability during the peak instant is gained a lot of attentions. In addition, using renewable energy systems to feed remote areas which are not preferred to be fed from the utility because they are far from it is a another goal of many researchers. One out of these loads is the street lighting especially. Therefore, this paper proposes a standalone solar energy-free system for street lighting as there is no power demanded from the grid. The proposed system consists of a PV panel, storage system, LED lamp, power conditioning system (PCS) and the controller which can manage the power direction and system operation. Using LED in lighting applications has many advantages compared to other lamp. It is very efficient (very high efficiency lighting source) and cost effective (the life time is very long compare to other lamps). In additions to, it needs low dc voltage source to be operated. The storage system will be charged during the day time using the available sunlight. On the other hand, during the night time the controller will give a signal to the system to connect the LED lamp to be ready for use. Since the LED needs a low dc voltage to be operated, so a simple dc-dc converter will be enough for this system resulting in decreasing the cost of the overall system. Selected of simulation results have been provided to validate the proposed system.**

***Index Term*-- Energy free system, LED, PV system, street lighting, battery storage system.**

I. INTRODUCTION

Recently PV systems have found fairly wide applications from large scale PV plants with cumulative power reaches approximately a few tenths of GWp were connected to the grid of a small scale PV reaches approximately a few tenths of Watts in applications such as Camera, watches, Mobiles, etc. One of these PV applications is the standalone systems which considered the most economic solutions to provide the required power service. Street lighting system using the most efficient and a cost effective LED lamps is one of these standalone PV systems applications. This system consists of PV panel, high quality battery, LED lamp, dc-dc converter, and the controller.

PV system is not only an environmentally friendly option (requiring no power input plus free of pollution), but can also be located anywhere regardless of local grid availability. The power source is solar power which is recognized as being an environmentally "clean" form of energy production point of view. PV arrays utilize the sun radiation to produce electricity. These modules do not require fuel to operate.

On the other hand, most current street lighting uses high intensity discharge lamps. Recently, searching for new street lighting modules has gained a lot of attention to reduce the amount of energy consumed by this type of lamp and also to reduce the amount of CO2 emissions. Light Emitting Diodes (LEDs) with their current performances have proved themselves to be the most suitable solution for LED Street Lighting, [1] and [2]. The LED lamp offers many advantages such as: extremely long life, 100,000 hours, extreme robustness as there are no glass components or filaments, no external reflector, a modular construction, no emissions like HID lamps and most importantly their high efficiency. LEDs are a good light source conversion; their efficiency is 160 Lm/W. So using this type of lamps enables the reduction of more than 50 % of the total energy used by HID lamps; that by its order reduces the required PV arrays. Therefore, applying the proposed system, streets can be illuminated with lower power lamps, no operating costs, no CO2 emissions and environmentally friendly [3] and [4].

Due to the importance of the issue, there are many companies around the world are now involved in developing, building, and producing these products of street light. Also there is a variety of products with wide range of power and wide range of lamp type used. One example of the solar street LED light system is produced by GEO-Technik [5]. It is a sandstorm- and weatherproof PV street lighting fixture, equipped with high power LED Chip with power range of 100 W and 120 W, respectively. By the use of LED lamps and microcontroller system control, they have a very long maintenance-free system life time.

The following are some examples of using LEDs in lightening applications with the PV system:

- street light LED lamp of EverGEN™ 1500 Series produced by Solar Street Lights Company [6].
- The Solar Illumination Project in Beijing Olympic Wrestling Venue Lamps LSL0733-7325LD30W/24 Pole height:7 meters Distance between two poles: 15 meters Road width: 10 meters Solar energy system: 80W Quantity:10 PCS.
- The Lingqiu County Solar Illumination Project in Datong of Shanxi Province Pole height : 7meters, Distance between two poles) 20m, Road width:15m, LSL0733-7325LD30W/24, quantity: 150pcs.
- The Shipai Wetland Park project. The park is located at the West part of Dongguan with a planned area of 280,000 square meters. Base on Kingsun Solar-Wind LED Street Light Project in Songshan Lake, Dongguan Government decides to use Kingsun Solar-Wind LED Street Light in

this project. The pole in this area is 10 meters height, we suggest our client to using the KS-E108TX Solar-Wind LED Street Light system in this paper.

- BBE LU2 in Calama city of Chile, solar LED street light is a very good choice for the clean energy with the sustainable development.

Looking into the practicality of the idea and its suitability for Kingdom of Saudi Arabian, no doubt that it should be applied. The main reasons behind that: KSA is one from the main counties where PV can be connected and have high power generation at anywhere and the Sun is available for long day time. The problems of CO2 emissions and a lot of pollutions can be reduced. In addition to, KSA has many long roads far away from the grid which will be too costly to connect them to the grid. All these factors are pushing the direction of using the proposed system. However, it should be manufactured locally to reduce the system manufacturing cost from one side. Also, to create a locally expect and cheap maintenance system. Therefore, its design steps and modes should be understood and adopted based on every country requirements and sources.

This paper concern with modeling, control and simulation of a power conditioning system for solar street LED light in addition to a battery storage system with a bidirectional DC/DC converter is inserted to balance between PV and load.

II. THE PROPOSED STANDALONE HYBRID PV/BATTERY SYSTEM

Figure 1 shows a schematic of the proposed PCS which operates to charge the battery at day time and also it powers the LED lamp at night time. The proposed system consists of PV module of BP485 [7] type, dc-dc boost converter, battery, dc-dc bidirectional converter and LED load. The control system is devoted to track the maximum power from the PV module beside a bidirectional converter controller is devoted to balance the power supplied to the load in addition to battery charge/discharge system. The overall system is explained in details in the following sections.

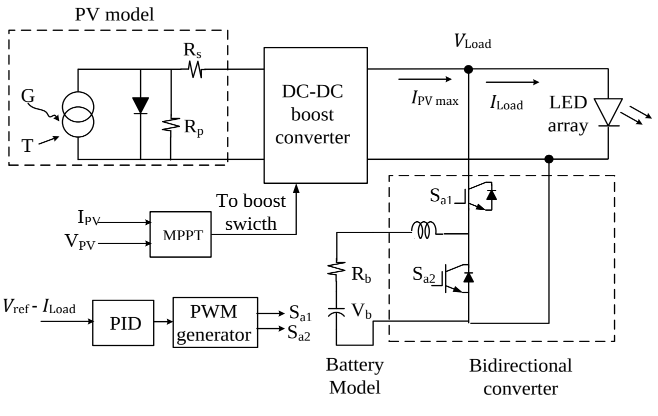


Figure 1. A schematic diagram of the proposed system and its control

A) Modeling the PV module

The simplest equivalent circuit of a solar cell is a current source in parallel with a diode. The output of the current source is directly proportional to the light falling on the cell. The diode determines the I-V characteristics of the cell. Increasing sophistication, accuracy and complexity can be introduced to the model by adding for example temperature dependence of the diode saturation current I_0, temperature dependence of the photo current I_{ph}, series resistance R_s and shunt resistance RP in parallel with the diode.

To implement the solar cell in MATLAB/SIMULINK, The basic equation from the theory of semiconductors that mathematically describes the I–V characteristic of the ideal PV cell [8] is:

$$I = I_{ph} - I_0(e^{\frac{qV}{akT}} - 1) \tag{1}$$

where I_{ph} is the current generated by the incident light (it is directly proportional to the Sun irradiation), I_0 is the reverse saturation or leakage current of the diode, q is the electron charge (1.60217646 × 10^{-19}10 C), k is the Boltzmann constant (1.3806503 × 10^{-23} J/K), T (in Kelvin) is the temperature of the p–n junction, and a is the diode ideality constant.

Practical arrays are composed of several connected PV cells and the observation of the characteristics at the terminals of the PV array requires the inclusion of additional parameters to the basic equation:

$$I = I_{ph} - I_0(e^{\frac{V+IR_s}{aV_t}} - 1) - \frac{V + IR_s}{R_p} \tag{2}$$

Where $V_t = N_s kT/q$ is the thermal-voltage of the array with Ns cells connected in series. This equation originates the I–V curve in figure 2. Table 1 gives real solar module specifications of BP485 type which will be used in simulation.

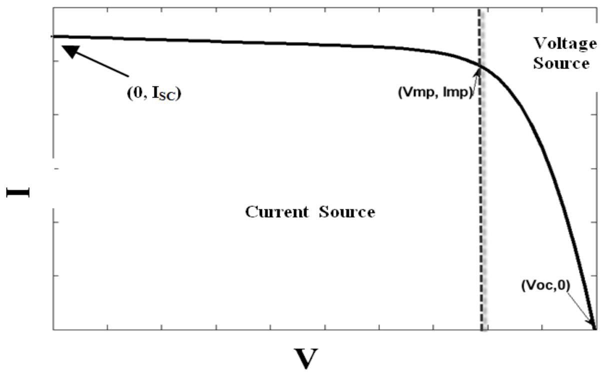


Fig. 2. The I–V Characteristic curve of a practical PV device and the three remarkable points: short circuit (0, I_{sc}), MPP (V_{max}, I_{max}), and open circuit (V_{oc} , 0).

Table I
BP485 Solar cell specifications

Specification	
PV module type	BP485
Rated Power (P_{max})	85W
Voltage at P_{max} (V_{mp})	17.8V
Current at P_{max} (I_{mp})	4.9A
Short circuit current (I_{sc})	5.48A
Open circuit voltage (V_{oc})	22V
Series resistance (R_s)	0.2 Ω
shunt resistance (R_{sh})	63 Ω

B) Maximum Power Point Tracking (MPPT) Algorithm

To get fast tracking for maximum power, it is preferable to use incremental conductance method [9] which is based on the fact that maximum power occurs when the variation of $dP/dV = 0$. Since the dc power across uncontrolled rectifier is governed by this equation $P = VI$, from which the following equation:

$$\frac{dP}{dV} = I + V\frac{\Delta I}{\Delta V} \qquad (3)$$

The following constraints are used to calculate the MPPT using the incremental conductance method:

$$I + V\frac{\Delta I}{\Delta V} = 0 \quad \text{at MPP} \qquad (4)$$

$$I + V\frac{\Delta I}{\Delta V} > 0 \quad \text{left of MPP} \qquad (5)$$

$$I + V\frac{\Delta I}{\Delta V} < 0 \quad \text{right of MPP} \qquad (6)$$

Equations (3) –(6) are used to determine the location of the operating point. Based on these equations the controller can easily determine increasing or decreasing the operating voltage to reach maximum power point. Figure 3 shows the flow chart for MPPT employed.

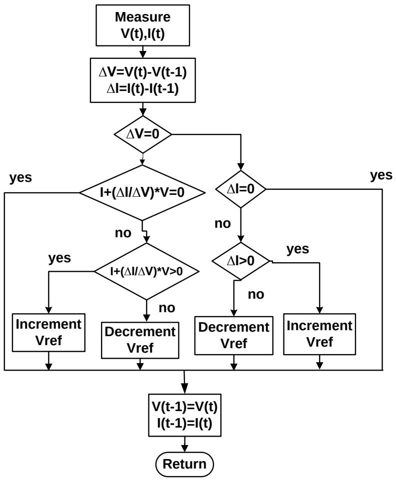


Fig. 3. Flow chart of incremental conductance MPPT method.

A. Bi-directional dc/dc Converter

The bidirectional control of the battery energy storage system (BESS) is carried out based on the modified hysteresis control [10] – [12] shown in figures 4 and 5. When the wind power is larger than the load power, the buck switch (S_1) is activated to charge the battery pack. On contrary, when the PV power is smaller than the load power the boost switch (S_2) is activated to discharge the battery pack. The MPPT calculation technique is used to feed the reference signal to the voltage controller to adjust the dc-link voltage to operate PV module at its maximum power. The power flow controller determines which switch buck switch (S_1) or boost switch (S_2) should be activated to make the power balance between the PV module and the load power. In achieving both power flow control and maximum power point control, the dc bus voltage will be variable. In this case, the buck switch (S_1) is activated only when the input PV power is larger than the specified load power. The control circuit should guarantee that the two switches don't operate at the same time.

The following constraints are used for charging/discharging as follows:

If $V_{dc} > V_{dc-up}$ then charging and $V_{dc-ref} = V_{dc-up}$
If $V_{dc} < V_{dc-lw}$ then discharging and $V_{dc-ref} = V_{dc-lw}$
If $V_{dc-lw} \le V_{dc} \le V_{dc-up}$ then no control = rest

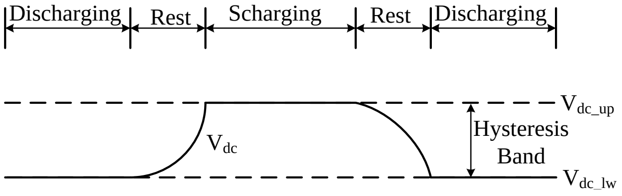


Fig. 4. Modified hysteresis-control strategy

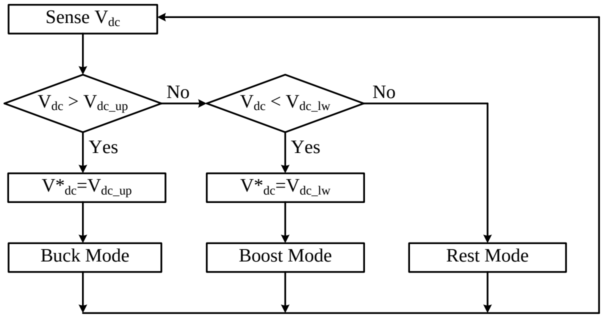


Fig. 5. Battery-mode control block (BESS /modified hysteresis)

III. LED Lamp Design and Selection

A LED driver system has been designed for a LED street lighting lamp of 80 W. Comparing to high pressure sodium lamp, the LED street light can save about 50% - 70% energy. Besides, the life span of LED street lamp is 3 - 5 times to sodium lamps. For example, the 30W, 60W, 100W and 180W LED street lights are good solutions to replace the conventional 80W, 150W, 250W and 160 W high pressure sodium lamps [13]. Because of low power consumption, it's the best candidate light source of solar street lights. And this can be assured by the LED lamp driver that was presented for street lighting system in [14] and [15] for universal AC input. Because the illumination produced by a LED is relatively weak, it is necessary to increase the flux by incorporating strings of LEDs of series and parallel combinations into a module array in order to use them for street lighting. The number of LEDs required for the street light is calculated based on multiples of the light flux produced by a single LED [16]. So it is necessary to increase the flux by incorporating strings of LEDs for series and parallel combinations into a module array in order to use them for street illumination. The LED lamp that will be used consists of 4 branches of 19 LEDs in series. The LEDs are of the type cool white Cree XM LED driven at 400 mA. This type of LED lamp can give overall luminous efficacy of 132 lm/W [17].

A. LED Modeling

The characteristics of LEDs are the same as conventional PN junction, [18 - 20]. Figure 6 shows the current-voltage characteristics of commercial LED. The current to voltage characteristics shown in figure 6 can be approximated by the following equation:
The LED load I-V model can be approximated [20] as follows:

$$V_D = R_{di}\ I_d + V_{\gamma i} \qquad [7]$$

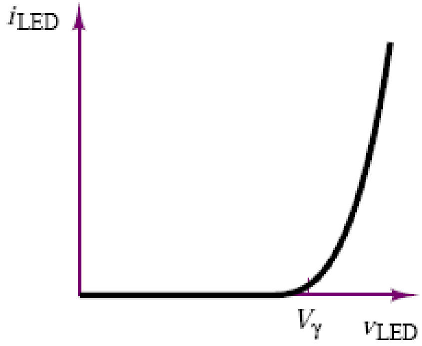


Fig. 6. The I-V curve of commercial LEDs at 40° C.

Where V_D is the forward voltage drop on one LED, R_{di} is its dynamic resistance, I_d is the LED forward current and $V_{\gamma i}$ is the threshold voltage. Considering the whole string in series, the expression for the output voltage is the same, but multiplied by the number of LEDs connected in series as follows:

$$V_o = N(R_{di}\ I_d + V_{\gamma i}) = R_{dI}\ I_d + V_{\gamma I} \qquad [8]$$

Where V_o is the entire string output voltage and N is the number of LEDs connected in series. Linear interpolation of the Cree® XLamp® MC-E [21] LED current voltage characteristics datasheet is shown in figure 7. Therefore R_{di} and $V_{\gamma i}$ are found to be 1.07 ohm and 2.8 V, respectively.

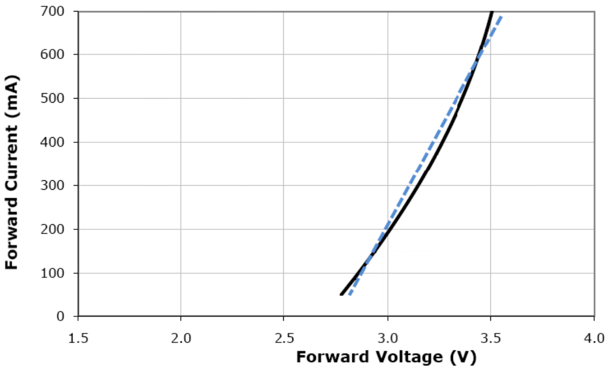


Fig. 7. Linear interpolation of LED load.

IV. SIMULATION RESULTS

The proposed system has been modeled and simulated using MATLAB/SIMULINK software to verify the performance of the proposed idea using the designed component values. Simulation parameters of the proposed system are given in table 2. It should be noted that the LED load has been modeled as a simple resistive load in series with battery. A step change in the PV is assumed after 0.2 s of simulation time. Normally the operation of the proposed system is simple which called the day and night operation modes and is suitable for lightning applications. In this case the PV and the load lamp are operated in complementary modes. During the day time, the lamp is disconnected and the PV will charge only the battery and the load current in this case equals zero. Therefore the two switches S_1 and S_2 are synchronously switched with pulse width modulation (PWM) signal. Switch S_2 with the coil and the switch S_1 are forming a simple boost converter system. This is because of the PV panel voltage supposes to be larger than the battery voltage. However the proposed system has been studied for the general case where the PV, the load and the battery are connected and the load can receive its power from either the PV or battery or both.

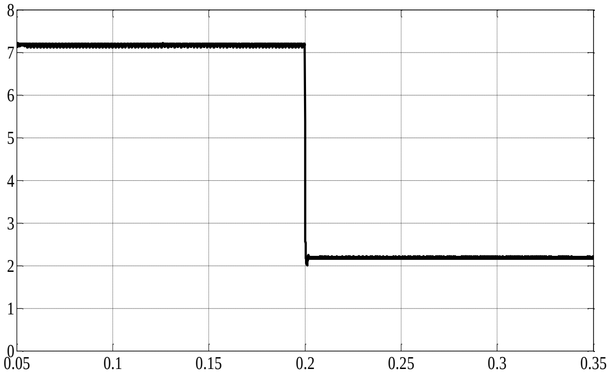
Figures 8 to 10 give the simulation performances of the proposed system. Figure 8 shows the PV response with MPPT control algorithm. The PV current, PV voltage and PV power are almost very close to the maximum power given in the data sheet of the PV module type BP845 in table 1. A step change is assumed due to the weather condition. Figure 8 (d) gives the MPPT algorithm duty cycle which indicates that the duty cycle oscillates around steady sate values approximately 0.53 and 0.45 respectively.

Figure 9 shows the simulation results of the LED load. The load current, load voltage and load power are shown in figures 9(a), (b) and (c), respectively. It can be noted that the load voltage is decreased after the sudden change because of the battery changes from charging to discharging modes due to the decreased in the power comes from the PV. Also the load voltage values are set by the battery storage system control described in figure 4.

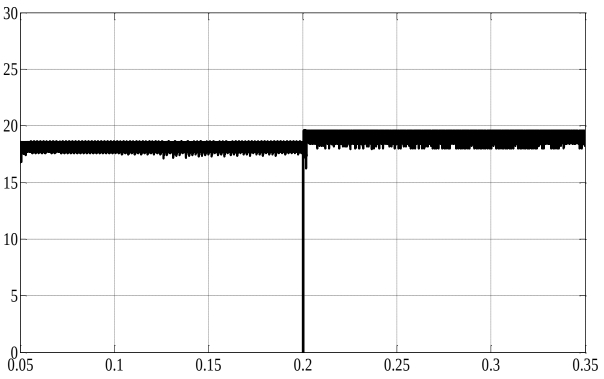
Figure 10 shows the performance of the battery storage system. Figure 10(a) gives the bidirectional converter switches S_1 and S_2 signals. This figure indicates that the bidirectional dc-dc converter operates as a buck converter in the first period from 0 to 0.2 s because the PV power is greater than the load power; and it operates as a boost converter in the second period from 0.2s to support the load voltage due to the load power is greater than the PV power. The battery voltage, battery current and battery state of charge (SOC) are shown in figures 9(b), (c), and (d). It can be noted that the battery charges in the second period from 0.2s to balance the power of the load and the PV power and discharges to the load in the first period from 0 to 0.2 s to support the PV power. Also it can be noted that small change in the SOC is due the very short period of simulation.

Table **II**
parameters of the simulated system

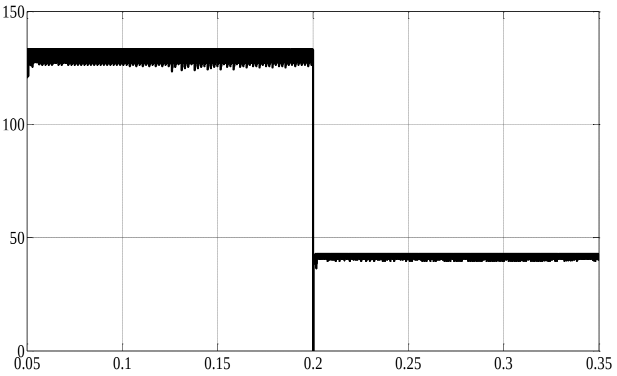
Specification	
Single LED	$R_{di} = 1.07\Omega$
	$V_{\gamma i} = 2.8$ V
dc-dc converter inductance	5 mH
dc-dc converter capacitance	380μF
Switching frequency of dc-dc converter	40 kHz
Bi-directional converter inductance	5mH
Switching frequency of the bi-directional converter	40kHz



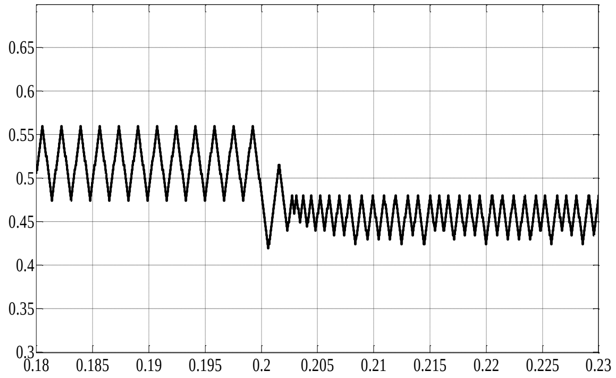
(a) The PV current



(b) PV voltage panel

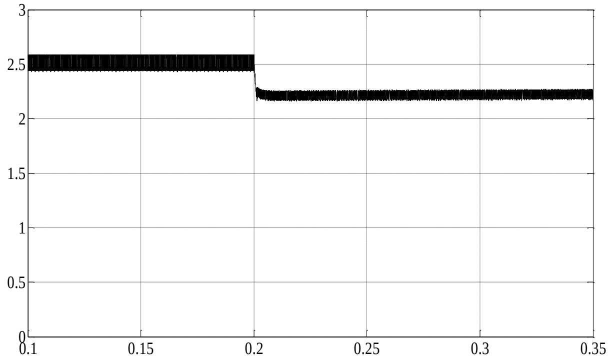


(c) PV panel power

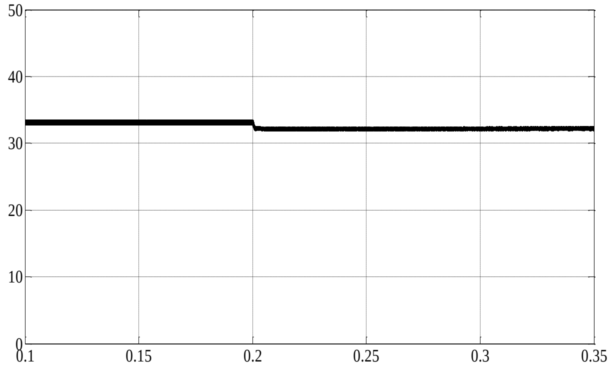


(d) Duty cycle for MPPT

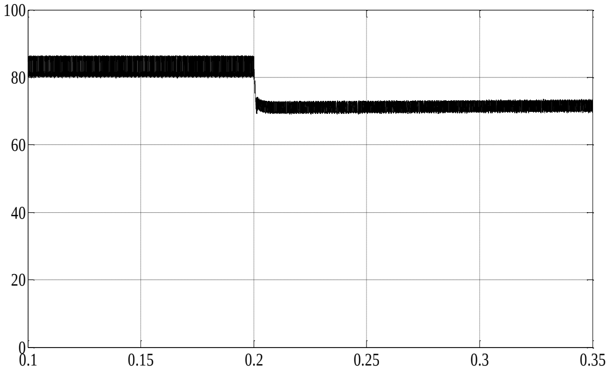
Fig. 8. Simulation results of PV with MPPT performance



(a) LED current

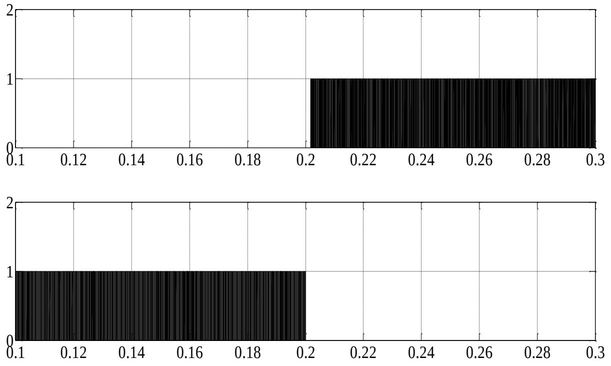


(b) LED Load voltage

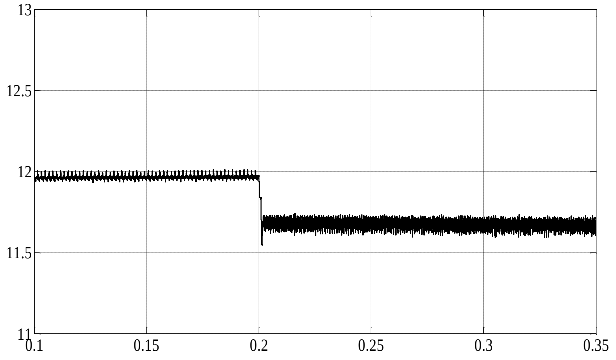


(c) LED power

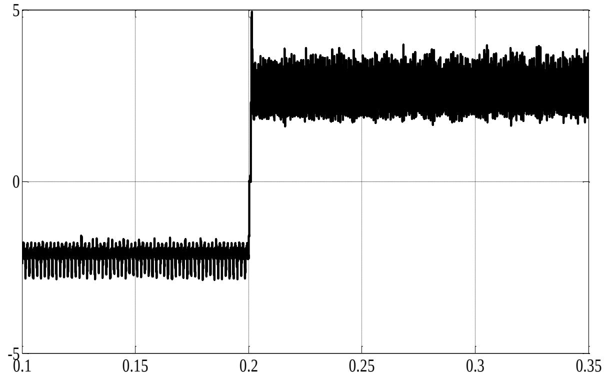
Fig. 9. Simulation results of LED performance



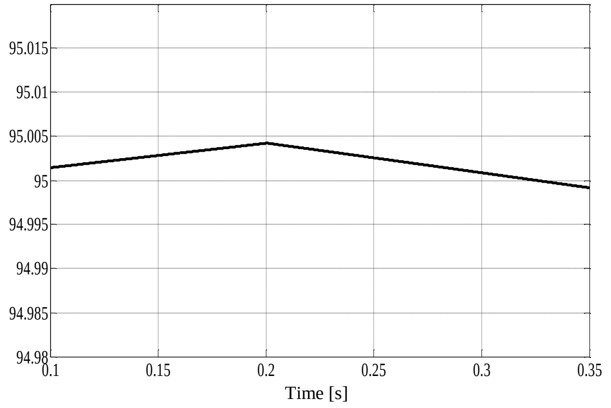
(a) Switches S2 and S1



(b) Battery voltage



(c) Battery current



(d) Battery SOC (80%)

Fig. 10. Battery voltage, charge/discharge current, state of charge

V. CONCLUSION

In this paper a standalone solar street LED light system has been proposed. The source is a PV module that is a clean renewable energy. The load is a LED street lighting module with 80 watt LED lamp is used which equivalent to 150W of HPS sodium lamp. The major benefits of the proposed system are summarized as follow:

- A PV system simulation model with MPPT control is developed using MATLAB/SIMUINK to validate the proposed system.
- A battery model is developed.
- A bi-directional dc-dc converter with a judicious control is developed using of energy balance control.
- Simulation results are provided to verify the applicability of the proposed system.
- Hardware implementation and results are left for future work to be compared with simulation results for supporting the proposed concept.

VI. ACKNOWLEDGMENT

The authors would like to acknowledge the Taif University project. The research has been carried out under the Project no. 1-434-2744.

REFERENCES

[1] I. L. Azevedo, M.G. Morgan, F. Morgan, "The transition to solid state lighting", *proceedings of the IEEE*, 2009, Vol: 97 issue: 3 pp: 481-510.

[2] X. Long, R. Liao, J. Zhou, "Development of street lighting system-based novel high brightness LED modules", *IET Optoelectronics*, 2009, pp: 40 - 4.

[3] Shur, M.S., Zukauskas, R., "Solid-State Lighting Toward Superior Illumination",*proceedings of the IEEE*, pp: 1691 - 1703, 2005.

[4] Ackermann, B., Schulz, V., Martiny, C., Hilgers, A., Zhu, X.., "Control of LEDs",*Industry Applications Conference*, 2006.

[5] http://www.dimmer.de/shopping/artikelueber.php?sprachnrs=2&wgruppeid=296.

[6] http://www.solarstreetlights.net/.

[7] www.solarcellsales.com/techinfo/docs/bp-485.pdf.

[8] Villalva, M.G., Gazoli, J.R, and Filho, E.R. ," Comprehensive Approach to Modeling and Simulation of Photovoltaic Array," IEEE transactions on power electronics, vol. 24, no.5,pp.1198-1208, 2009.

[9] Seul-Ki Kim, Jin-Hong Jeon, Chang-Hee Cho, Jong-Bo Ahn, and Sae-Hyuk Kwon, "Dynamic Modeling and Control of a Grid-Connected Hybrid Generation System With Versatile Power Transfer", IEEE Transactions on Industrial Electronics, Vol. 55, No. 4, April, 2008, pp: 1677- 1688.

[10] Gordillo, C.; Rodriguez, E.; Lopez, A.; Hurtado, J.; Diaz, J.; Vazquez, N.; Calleja, H.; Nunez, C., "Battery Charger with Maximun Charge Tracking Current for PV Systems", IEEE Twenty-Fourth Annual Applied Power Electronics Conference and Exposition, 2009. APEC 2009, pp: 894 – 898.

[11] S. J. Chiang, Hsin-Jang Shieh, Member, IEEE, and Ming-Chieh Chen, "Modeling and Control of PV Charger System With SEPIC Converter", IEEE Transactions on Industrial Electronics, Vol. 56, No. 11, November 2009, pp: 4344 – 4353.

[12] Gyu-Yeong Choe ; Jong-Soo Kim ; Byoung-kuk Lee ; Chung-Yuen Won ; Tea-Won Lee, "A Bi-directional battery charger for electric vehicles using photovoltaic PCS systems," IEEE Vehicle Power and Propulsion Conference (VPPC), 2010, Page(s): 1 - 6

[13] http://www.ledlightsorient.com/street-lights-c-8.html.

[14] Mokhtar Ali, M. Orabi, Mahrous E .Ahmed, Abdelali El Aroudi "Microcontroller based modified SEPIC converter for driving LED lamp with power factor correction", *IEEE International Conference on Power and Energy* PECON 2010, Nov 2010.

[15] Mokhtar Ali, M. Orabi, Mahrous E .Ahmed, Abdelali El Aroudi "Design considerations of modified SEPIC converter for LED lamp driver", *the 2nd International Symposium on Power Electronics for Distributed Generation* PEDG 2010, June 2010, pp 394.

[16] Rico-Secades M, Calleja AJ, et. al.," Evaluation of a low-cost permanent emergency lighting system based on high-efficiency" IEEE Transactions on Industry Applications, 2005; pp:1386–1390

[17] http://www.cree.com/Products/pdf/XLampXP-G.pdf.

[18] X. Long, R. Liao and J. Zhou, ―Development of street lighting system-based high brightness LED modules," IET Optoelectronics, pp: 40 - 45, 2009.

[19] Y. Aoyama, T. Yachi, "An LED module array system designed for streetlight use", *Energy 2030 Conference*, 2009, pp : 1 - 5.

[20] Mokhtar Aly Ahmed, Mohamed Orabi, Mahrous El-Sayed, "Design of High-Performance Power Converters for LED Lamp Drivers," Master of Science in Electrical Engineering, south valley university, Aswan faculty of engineering, Feb 2012.

[21] Cree® inc™ X-lamp datasheet Available at: http://www.cree.com/products/xlamp_mce.asp