Smart Systems: Development of a Sustainable Eco-Friendly, Efficient, Automated Portable Lighting Source

Sukhbinder Singh Rait[1], P K Singh[2], Namrata Dewan Soni[3], Amit Sehgal[4]
[1,2,3,4]*Department of Physics and Electronics, Hansraj College, University of Delhi, Delhi 110007*

***Abstract*— The aim of the present work is to develop a Solar LED (Light Emitting Diode) bulb with optimized output performance for long hours of operation. The prototype designed is based on integration of the current solar power conversion, energy storage, and solid-state lighting technologies coupled with open-source embedded control into a single accessible unit. Different parts of world are still challenged by the 24 hours of availability of electrical energy; the primary source of inspiration is the need to provide an environmentally clean alternate lighting source for those areas. The module designed is sustainable for its durability and longevity in terms of components used in it. The concept visualized was to design a self-contained single unit consisting of the solar conversion module, energy storage module, control electronics and the solid-state illumination source. The unit has automated control for charging and discharging along with smart control for the illumination levels and ambient light detection for its turn ON and turns OFF operation. A simple but high level of automation has been provided to keep the operation as simple as possible with minimum technical operation requirements from the consumer.**

***Index Terms*— LED Lighting, Renewable energy, Solar energy**

I. INTRODUCTION

According to a report issued by World health organization (WHO) [1], the number of people living without electricity has dropped significantly since last decade. India, Bangladesh, Kenya and Myanmar are few countries that recorded maximum progress since 2010 [2]. But this improvement has been uneven throughout the regions. Moreover, with the onset of financial complications due to COVID-19 and lack of more sustained and stepped-up actions, 650 million people will still be left without access to electricity in 2030 [1]. In the absence of electricity, communities bank upon the pricy and unhealthy alternatives like the use of kerosene lamps for lighting and biomass for cooking [3]. Also, the by-products of these energy sources are harmful to environment [3].

The development of photovoltaic transducers has led to an efficient and clean (no harmful by-products of the energy conversion process) conversion of the solar energy into electrical energy, making solar energy the most sought-after renewable energy source [4-11]. Recent reports highlight the use of light emitting diodes (LEDs) as the most environment friendly, efficient light source with longer lifetimes that incandescent and compact fluorescent lights [12-20]. The energy utilized in manufacturing and operating a LED is much smaller than utilized in incandescent bulbs and even compact fluorescent lamps, and the Light emitting diodes (LEDs) are free from harmful chemicals like mercury (used in CFLs) and provide for a much safer disposal [12-14]. With current improvements in technology, high efficiency white LEDs present an effective and economical source of artificial light [12-20].

In the present work, the authors intend to design a novel lighting solution that uses the combination of solar energy (the most abundant, renewable, clean energy source) and LEDs (solid state light source) coupled with efficient secondary energy storage devices all together combined in a single portable unit. The solar energy available during the day time is harvested and stored for utilization during the dark hours which leads to a very efficient system. To charge the unit, the user just has to place or hang the unit under the sun. The device provides full automated control for the charging process, preventing any overcharging and thereby extending battery life. Various smart features are made available using an open-source embedded solution. The device in question is targeted for the rural areas but keeping in mind its utilization potential, it is a great energy efficient clean solution for the urban areas too.

II. METHODOLOGY

The primary objective of the work was to design a "solar LED bulb" basically comprising of a photovoltaic cell, a rechargeable battery, and a light emitting diode integrated using a low-cost open-source embedded solution. The unit design is such that it provides for efficient solar energy absorption, robustness, uniform light distribution along with aesthetic design. Typical methodology is outlined in a flow chart given in Fig. 1.

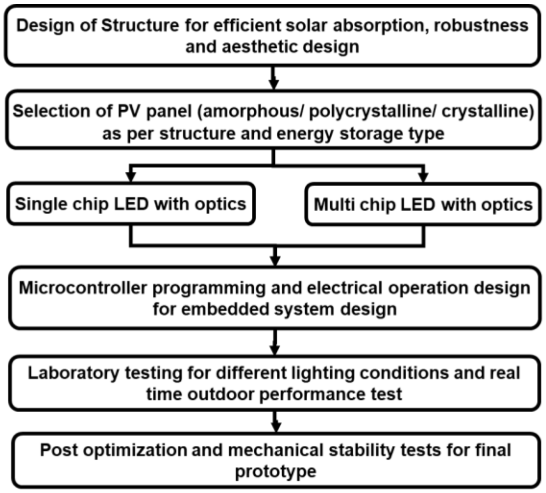

Fig. 1: Methodology used in the present work to design a solar LED bulb

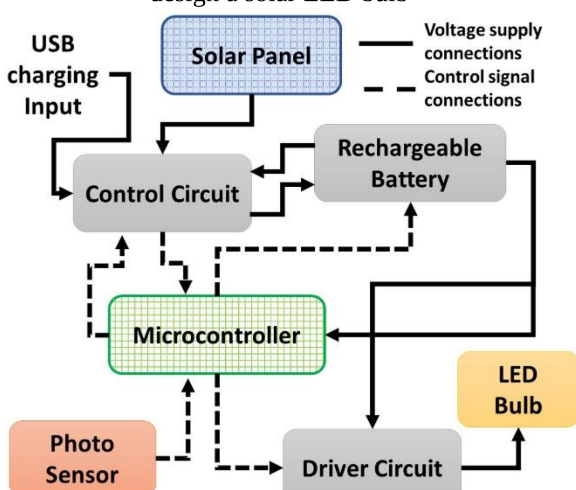

Fig. 2: Block diagram of solar LED bulb.

The Fig.2 shows the block diagram of LED bulb prototype. The device was integrated with sensors to automate the bulb for maximum performance, maximum power saving and component protection due to over consumption. The solar panels are selected as per their mechanical sturdiness and efficiency along with their compatibility with the secondary energy storage type. Different bulb designs were worked out to provide for efficient charging. The complete system is housed in a single unit for portability and ease of operation. Solid state illumination source selection i.e. the LED source and optics design for uniform illumination is also taken care of. The battery selection depends on the cost effectiveness and energy packing density. The charging time vs operation time was studied along with the expected operation life of the complete unit. The complete system is controlled using low-cost open-source embedded solutions based on the award-winning Arduino IDE which provides for the automated features, and smart control of the device, including ambient light sensing and 3 level illumination intensities. The LEDs are driven using a generic logic MOSFET controlled using a digital modulation scheme. The solar LED bulb also has a 5V external electrical charging so that the unit can charge in absence of the sun and be used a conventional light source. The complete unit needs to be sealed to prevent ingress of water & dust.

A. Smart Control Optimization

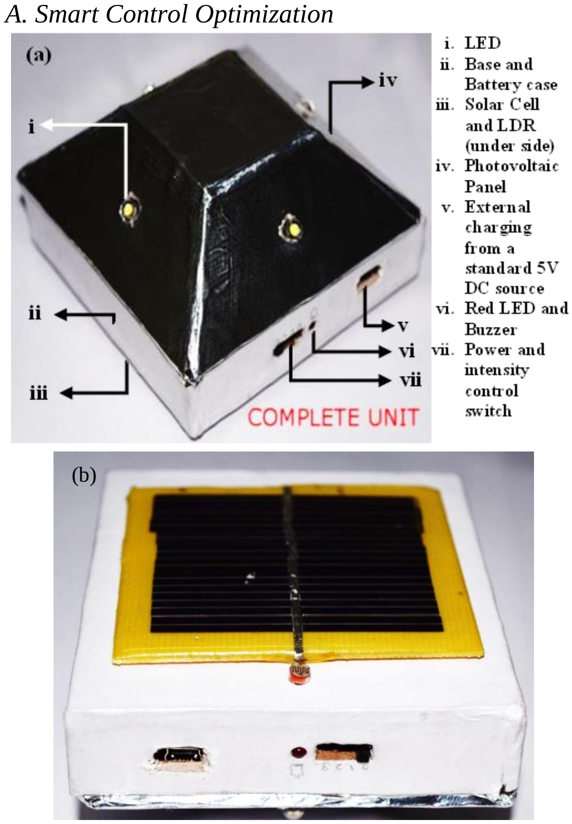

Fig.3. (a): Solar LED bulb module designed in present study, (b) Top view (Solar panel & Light dependent resistor (LDR))

At first, the smart control module that comprised of the microcontroller application workbench along with other breakout out boards was designed and tested for performance. The complete prebuilt application workbench for microcontroller was then replaced by a smaller and customized PCB for the fabrication of the anticipated module, which in turn reduces its cost drastically. The final version of prototype unit is showcased in Fig.3 as well labelled snapshots. The Fig.3 (a) showcases the LED bulb arrangement with silver coated sheet for light reflective purpose and thus better illumination from a non-focused source. Fig.3 (b) shows solar panel arrangement.

Fig.4 shows the performance of the designed prototype under real conditions. The bulb shows remarkable output performance and was aptly illuminating the room like a normal incandescent bulb of 40W. The prototype bulb was found fit for study table purposes. With the dimensions of the room specified, the bulb designed can be used for general lighting purpose in remote areas.

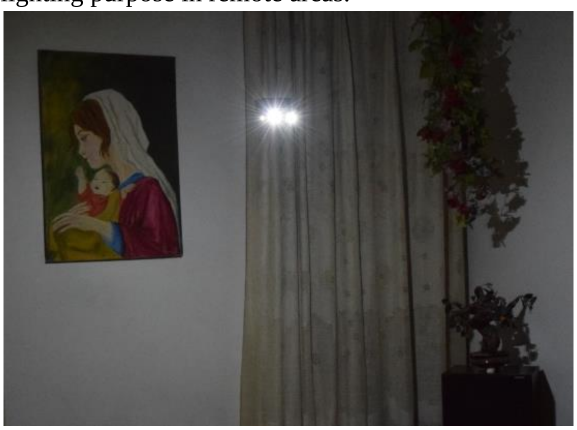

Fig.4 Illumination in 15’ x12’ room, image captured at a distance of 8’ from solar LED bulb prototype.

The batteries available at the time of design of prototype were compared to best fit with the requirements (shown in Table I). Lithium ion was found to be most promising option due to its all-round performance. Initially, Lithium polymer type battery was tested with a capacity of 450mAh, later the battery was changed to a Lithium-ion type due to its higher current capacity of 2600mAh, with a marginal increase in cost. The Nickel Cadmium (Ni-Cd) cell was a good candidate in comparison to Lithium-ion battery but lacks in several factors i.e. lower cell voltage, self-discharge property, longer charge time. The lead acid (Pb based) cell also doesn’t fit an optimized input because of low capacity and low cell voltage. Also, if we choose Ni-Cd cell or Pb based cell than a series of cells were required and thus, comprised the packing density of the prototype unit. The Solar panel selected was apt for charging all type of cells. The prototype developed at first used a 5V reference generator source (boost reference source) to power the microcontroller, which added to the cost and also reduced the battery backup as a part of the battery power was used by the 5V reference source. On close study of the microcontroller operation characteristics from its datasheet, it was observed that, the microcontroller could be operated from a voltage of 2V to 5V and the battery operating range is 3V to 4.2V so the circuit was redesigned to operate without the 5V reference voltage source, thus saving on cost and battery power.

TABLE I Different rechargeable batteries under consideration

Battery type	Capacity	Charging time	Cost	Nominal Voltage
Lithium polymer	450mAh	2 hours	Rs. 100	3.7V
Lithium ion	2600mAh	5-6 hours	Rs. 150	3.7V
Nickel Cadmium	2700mAh	10-12 hours	Rs. 70	1.2V
Lead Acid	1000mAh	4-5 hours	Rs. 40	2V

It was observed that even though if the average current through the LED is comparatively higher in the high PWM ratios, there is no major detectable change in the intensity (very small change measured by the power meter, which is virtually undetectable by the human eye). Using the lowest detectable PWM range in the three intensity modes allowed to obtain the optimal intensity which led to maximum utilization of the current thus saving on battery power which added to the backup time.

To provide for a reference for the ambient light sensor, a low cost commercially available programmable source was used. The cost of the programmable source is just a fraction of the 5V reference voltage source initially used. The microcontroller internal reference source was used for the Analog to Digital converter (ADC). The low voltage operation benefitted the proposed design but also emphasized the need to operate the LEDs through a metal oxide semiconductor field effect transistor (MOSFET) as the microcontroller output current was limited which was not enough to operate power LEDs. The MOSFET provided isolation between the microcontroller output and the LEDs and was easily able to handle the current required by the LEDs which was directly sourced from the Li-ion battery.

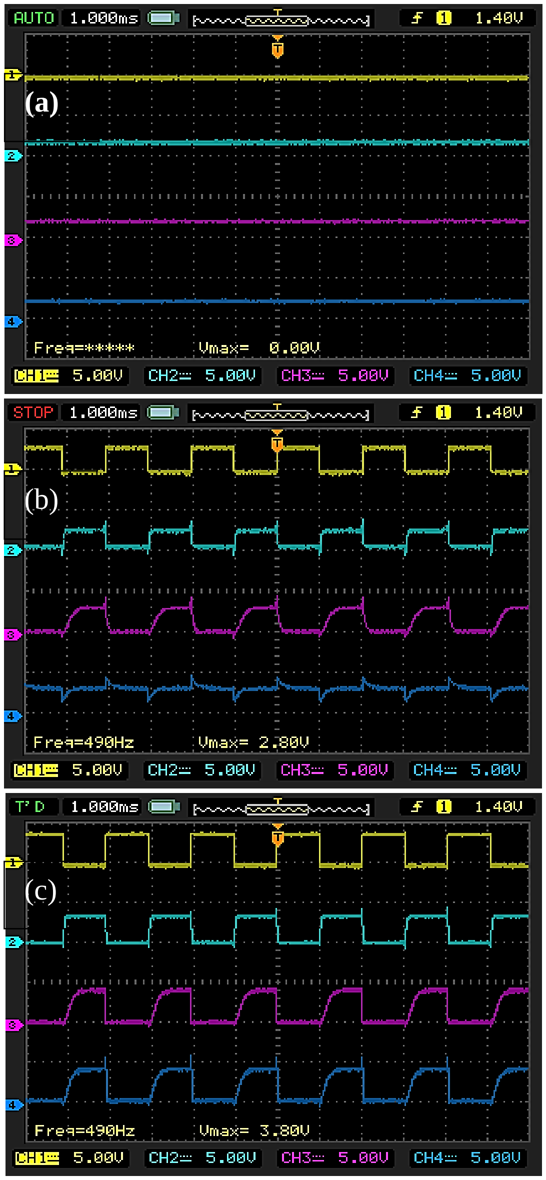

Fig. 5 Microcontroller PWM output (Yellow), low power logic MOSFET output (Cyan), high power logic MOSFET output (Magenta) and high-power standard MOSFET output (Blue) operated at (a): 2V supply voltage. (b) 3V supply voltage, (c) 4V supply voltage.

Initially a commercial grade generic MOSFETs were used, which had a higher threshold value in the range from 3V-4V, which meant that at low voltages the MOSFETs failed to switch on. Therefore, the design of the prototype switched to the use of generic logic MOSFETs with threshold voltages of 1V. The usage of both low power and high power commercially available generic logic MOSFETs was explored. The high power MOSFET was found to be optimum as it provides greater flexibility to support variable loads (no need to change the circuit to drive high wattage LEDs, instead one needs to increase the battery capacity to enhance the operation time), lower cost, and ease of availability.

Fig.5 (a), (b) and (c) show the MOSFET switching for 2V, 3V, 4V supply voltages. Fig 5(a) shows that none of devices were operative at 2V. Fig 5(b) shows that at this voltage the Microcontroller, low power logic MOSFET and high power logic MOSFET were showing acceptable output stream. So, in order to have minimum losses and high-performance time the high power logic MOSFET was shortlisted for the final circuit. Also the high power logic MOSFET was comparatively cheaper in cost as compared to the low power logic MOSFET because of it higher availability in the market.

TABLE II Microcontroller power consumption for different clock frequencies at 3V, 4V, 5V operation

Microcontroller Clock freq. (MHz)	Microcontroller current (mA) for 3V operation	Microcontroller current (mA) for 4V operation	Microcontroller current (mA) for 5V operation
4	2.2	3.1	7.1
8	3.5	5.0	9.7
16	4.2	6.2	11.1

The operating frequency of microcontroller was further reduced from 16MHz to 4MHz to save on the idle and operating power (lower clock frequency meant lower current consumption of the microcontroller. The turn on time (boot loader + battery voltage check + ambient light sense + intensity selection) is approximately 2 seconds at 16MHz, which increased to about 6-8 seconds at 4MHz. This time delay can be compensated by the reduction in current consumption (microcontroller current consumption reduced nearly by half) which increased the backup time (Table II).

With these optimizations the authors were able to increase the operation time of the Solar LED bulb to a time exceeding 8 hrs and above. The use of Surface mounted device (SMD) LEDs mounted on a MCPCB (metal core PCB) along with optics to provide for Omni directional light was also explored. The compatibility with the MCPCB allows using commercially available LED bulb fixtures. The prototypes were tested with high efficiency LEDs, multi-chip LEDs, 1W high power LEDs and UV

LEDs. The structure used was more or less pyramidal geometry based which was easy to design and construct. This structure consumes less space with good mechanical stability and robustness.

The designed Solar LED bulb shown in Fig. 2 is fully compatible with high efficiency single chip, multi-chip LEDs. It can also be used with industry standard 3020, 3528, 5050, 5730 SMD LEDs with MCPCBs. It can also be interfaced with boost converters to drive high power LEDs (requires higher battery capacity).

Cost Analysis of the proposed LED bulb

TABLE II: Cost of Solar LED bulb designed in present study

Components used in the design	Cost (INR)
Solar panel	100
Battery	150
LED + LED mount	30
Lens	50
Microcontroller, crystal	160
LDR	10
Wires, switches, MOSFET etc	50
Total estimated cost	500

The cost of all the components used in the designing of solar LED bulb is present in Table II. The cost of the solar LED bulb with smart controls designed in the present work is much less than the earlier reported LED lamp [21].

The Solar LED Bulb features ambient light sensing; prevents LED activation in case the ambient light is above a preset threshold level (can be easily adjusted/customized as per surrounding by software or hardware), thereby reducing accidental battery discharge. The full automated battery charge control; prevents overcharging of battery and extends battery life. Supports external charging from a standard 5V DC source (e.g. a mobile charger) in case solar charging is not possible. Low battery cut off and indication; Disables the LEDs and provides an audio and visual low battery indication, prompting the user to switch off the device and set it for charging. Three level intensity control; LOW, MID, HIGH using digital techniques (PWM), control of high efficiency White LEDs via high channel conductance MOSFETs. The ambient light sensing is enabled for all the three intensity modes. The Solar LED bulb is capable of continuous operation in excess of 8 hrs. The LED unit design can be customized for different light illuminations; focused light for studying purposes or uniform illumination for general room illumination. The solar LED Bulb is easily customizable for different solid state light sources like: UV LEDs for medical and green house applications, IR LEDs for medical applications, Blue LEDs for lighting applications,

III. CONCLUSION

A low-cost eco-friendly lighting solution was possible by integrating different current technologies. The design promotes a healthy growth of knowledge and sharing of ideas and utilization of open-source environments. The designed Solar LED bulb is fully compatible for high efficiency single chip, multi-chip LEDs. It can also be used with industry standard 3020, 3528, 5050, 5730 SMD LEDs with MCPCBs. It can also be interfaced with boost converters to drive high power LEDs (requires higher battery capacity).The designed Solar LED bulb has ambient light sensing; prevents LED activation in case the ambient light is above a PRESET threshold level thereby reducing accidental battery discharge, full automated battery charge control, prevents overcharging of battery and extends battery life, supports (e.g. a mobile charger) in case solar charging is not possible, low battery cut off and indication, three level intensity control. The prototype designed in present study is capable of continuous operation for more than 8 hrs. The LED unit design can be customized (with add-ons) for different light illuminations; focused light for studying purposes or uniform illumination for general room illumination.

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