

# Highly Efficient Low Power Consumption Tracking Solar Cells for White LED-Based Lighting System

Theerawut Jinayim, Somchai Arunrungrasmi, Tanes Tanitteerapan, and Narong Mungkung

**Abstract**—Although White LED lighting systems powered by solar cells have presented for many years, they are not widely used in today application because of their cost and low energy conversion efficiency. The proposed system use the dc power generated by fixed solar cells module to energize White LED light sources that are operated by directly connected White LED with current limitation resistors, resulting in much more power consumption. This paper presents the use of white LED as a general lighting application powered by tracking solar cells module and using pulse to apply the electrical power to the White LED. These systems resulted in high efficiency power conversion, low power consumption, and long light of the white LED.

**Keywords**—Efficiency, lighting, light-emitting diode, pulse, Solar, white LED.

## I. INTRODUCTION

SOLAR cells or photovoltaic cells are in fact large area semiconductor diodes that convert sunlight into electrical current to produce usable power. They have long been used in situations where electrical power from power station is unavailable, such as in remote area power systems. The power output of a solar array is given in watts. In order to calculate the energy needs of the application, a measurement in watt-hours per day is often used. The output power of the solar cell depends on multiple factors, such as sunlight intensity and direction of the cells. In order to reach the maximum power, the solar tracker has been added to this system to avoid time limit of the fixed systems.

White Light Emitting Diode (WLED) is a device that emits white light when an electrical current passes through it in

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forward direction. The interest of WLED for lighting applications has been growing over the past few years and will replace the incandescent systems in the next few years due to their very long life, low voltage operation needs and high efficiency. This WLED based solar cells system for lighting application aims to provide solar energy for operating WLED lights for maximum hours of operation. To optimize the low power consumption of this system, the Pulse Width Modulation (PWM) has been used. This method is widely used in wireless optical communication system [1]-[3]. The method of driving a WLED is to switch it on and off between the maximum and zero current and use a MOSFET in switching regime with a low power consumption required. The light illumination is determined by duty cycle changing of the driving pulse signal at the gate of MOSFET. If the frequency pulse is high enough, the human eyes will not follow the changes of the light and will response only to the average level of light. WLED lamp emits high illumination intensity. Of course, for your eyes safety please do not look directly to the WLED lamp.

## II. SYSTEM DESCRIPTION

### A. Solar Cell Characteristics

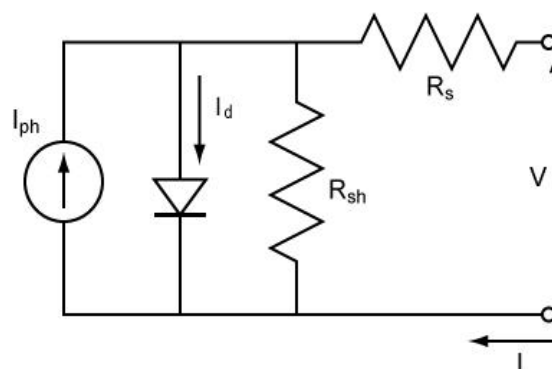


Fig. 1 Solar cell equivalent circuit

Fig. 1 shows the simplest solar cell equivalent model consists of diode and current source connected in parallel. Current source current is directly proportional to the solar radiation. Diode represents PN junction of a solar cell. Equation of ideal solar cell, which represents the ideal solar cell model, is

$$I = I_{ph} - I_s \left( e^{\frac{V}{mV_T}} - 1 \right) \quad (1)$$

where  $I_{ph}$  is photo current in ampere,  $I_s$  is reverse saturation current in ampere (approximately  $10^{-8}$ /square meter),  $V$  is diode voltage in volt, and  $m$  is diode ideality factor ( $m = 1$  for ideal diode).

Thermal voltage can be calculated with the following equation:

$$V_T = \frac{kT}{q} \quad (2)$$

where  $V_T$  is thermal voltage; its value about 25mV at 25°C  $k$  is Boltzmann's constant. The value of Boltzmann's constant is approximately  $1.3807 \times 10^{-23}$  joules per kelvin ( $J \cdot K^{-1}$ ).  $T$  is temperature in kelvin and  $q$  is charge of electron which value is  $1.6 \times 10^{-19}$  coulombs.

The working point of the solar cell depends on load and solar insulation. The I-V characteristics at short circuit and open circuit conditions can be seen. Very important point in I-V characteristics is Maximal Power Point ( $V_{mp}$  &  $I_{mp}$ ). In practice we can seldom reach this point because at higher solar insulation even the cell temperature increases, and consequently decreasing the output power.

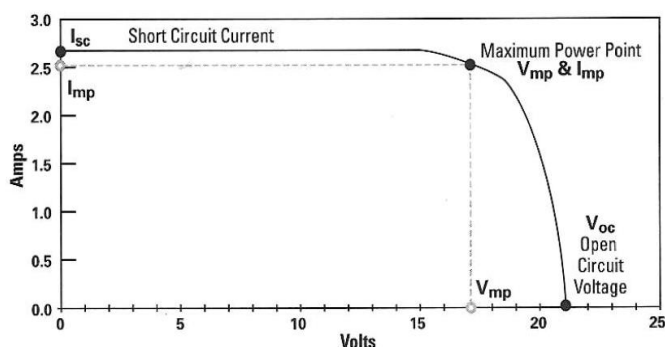


Fig. 2 The electrical characteristic of a solar cell

The maximum electrical power in watt of a solar cell is determined by

$$P_{mp} = I_{mp} \times V_{mp} \quad (3)$$

where  $P_{mp}$  is the maximum electrical power in watt,  $I_{mp}$  is the maximum current in amp, and  $V_{mp}$  is the maximum voltage in volt of a solar cell. Watts-hour is the power in watt of solar cell that is determined by

$$W = P \times t \quad (4)$$

where  $W$  is the electrical power energy in watts,  $P$  is the power generated by solar cell per hour in watt, and  $t$  is charging time in hour of a solar cell. In a solar cell system

design we have to know the amount of the average sunlight in place where the system will be installed.

TABLE I  
 SUN LIGHT INTENSITY PER DAY

Time	Watts/Square Meter	Watts-hour/Square Meter
5.00-6.00	0	0
6.00-7.00	25	25
7.00-8.00	25	25
8.00-9.00	50	50
9.00-10.00	300	300
10.00-11.00	1000	1000
11.00-12.00	1200	1200
12.00-13.00	1000	1000
13.00-14.00	300	300
14.00-15.00	50	50
15.00-16.00	25	25
16.00-17.00	25	25
17.00-18.00	0	0
<b>Total Watts-hour/Square Meter</b>		<b>4000</b>

Table I shows the intensity of the sunlight radiation changes with the hour of the day. To be able to make calculations in planning a system, the total amount of solar radiation energy is expressed in hours of full sunlight per square meter, or Peak Sun Hours (PSH). This term, Peak Sun Hours, represents the average amount of sun available per day throughout the year during 5.00 A.M. to 18.00 P.M. It is presumed that at the peak of sunlight, 1000 watts per square meter of power reaches the surface of the earth. Thus, for example, six PSH means that total daylight of energy received equals the energy that had the irradiance for six hours. Since the intensity of sunlight contacting the solar panel varies throughout the day, we use the term PSH as a method to smooth out the variations into a daily average. Early morning and late in the day sunlight produces less power than the mid-day sun. Naturally, cloudy days will produce less power than bright sunny days as well. When planning a system your geographical area is rated in average peak sun hours per day based on yearly sun data. In order to calculate the PSH value, the sum of sunlight all day is used and divided by 1000 watts per square meter.

$$PSH = \frac{\text{Watt - hour} / m^2 / \text{day}}{1000 \text{ Watt} / m^2} \quad (5)$$

For the best charging rate of the solar cell module, the factor that we have to concern is the direction of the solar cells module directed towards the sun. The tracking system has been added to mount for maximum solar efficiency or maximum power point. The solar tracker is a device used for orienting a solar cell module toward the sun to ensure that the concentrated sunlight is directed precisely to the solar cell module. This system uses a stepping motor to direct the solar cell module as commanded by PIC microcontroller responding to the sunlight direction. The design is based on the fact that the sun moves on accurate trajectories depending on the date and latitude. Note that the motor speed would need to be adjusted according to the date/latitude.

B. White LED Characteristics

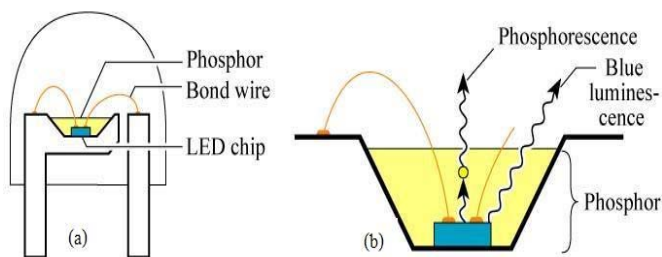


Fig. 3 (a) Structure of WLED consisting of a GaInN blue LED chip and a phosphor encapsulating the die. (b) Wavelength converting phosphorescence and blue luminescence (after Nakamura and Fasol, 1997)

White light is composed of various colors of the whole range of visible spectrum. The first commercial WLED based on Phosphors was produced by Nichia in Japan. The structure of WLED is shown in Fig. 3 which was also the first to manage to make the blue LED. Nichia used a blue light emitting Gallium Indium Nitride and coated the chip with yellow fluorescent phosphor.

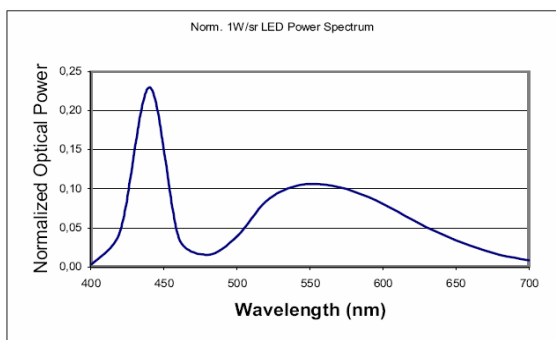


Fig. 4 Spectrum characteristic of White LED [1]

Fig. 4 shows the WLED spectrum, the color of WLED is determined by the band gap of the semiconductor used to make them. White light contains all colors and cannot be directly created by a single LED. The most common form of WLED really is not white. It is a Gallium Nitride blue LED coated with a phosphor that, when excited by the blue LED light, emits a broad range spectrum that in addition to the blue emission, makes a fairly white light. The actual light has a blue cast and is similar in color to a mercury vapor street lamp. On the curve of Fig. 4 shows that the peak at the left side is the shortest wavelength blue light from the LED. The lump of emission to the right side is the longer wavelength emission of the phosphor. There are other types of WLED that are made from several different LED chips of different colors assembled into one package. These have not been particularly successful as they tend to change color depending on viewing angle and their color balance is not really good at best.

The LED generates light when current passes through it in the forward direction and produces a tight bright beam that goes further down the track than most incandescent lamps. The viewing angle and the brightness of LED usually vary inversely. A wider angle will result in lower brightness in any given direction as the total light output of the LED is spread over a larger area. For lighting system applications, a 20° viewing angle is appropriate. This is the tightest angle typically available and produces the most intense beam. Intensity is rated in candlepower, a typical tight beam LED runs 4000 to 5600 micro candle (mcd). The size of the diode package determines the minimum beam width; a larger package with a larger lens can focus a tighter beam. For most large scale lighting system applications, a 5 mm diode package is adequate and it is used in this system.

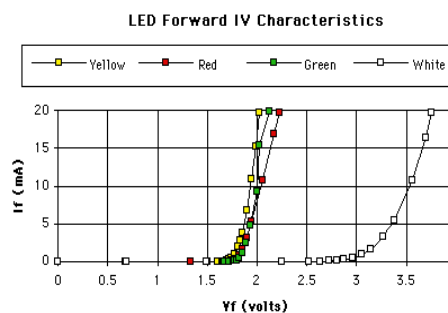


Fig. 5 Forward characteristics of White LED

Fig. 5 shows the forward I-V characteristics of various types of LED. The important thing to note that is the red, green and yellow LED are made from Gallium Arsenide and they all have about the same forward voltage required. The WLED is made from Gallium Nitride semiconductor and has a higher forward voltage drop. All other WLED of the same technology will be about the same [4]-[6]. When operating as a reversing lighting directly from power source, diode is said to be reversed biased and no current should flow. However all diodes have an avalanche or breakdown voltage. This is the highest voltage that the diode can stand before it starts to conduct in the reverse direction. Reverse conduction is very hard on any diode not designed for it. Whatever current that does flow will do so with high voltage impressed across the diode and the dissipation will be very high and could result in rapid thermal destruction of the diode. In general the characteristics of WLED can be defined by

$$I_D = I_s \left( e^{\frac{qV_D}{KT}} - 1 \right) \quad (6)$$

where  $I_s$  and  $n$  are parameters of the geometry and material,  $I_D$  is the WLED current,  $V_D$  is the source applied potential,  $q$  is the charge of electron which value is  $1.6 \times 10^{-19}$  coulombs,  $T$  is the temperature in Kelvin, and  $K$  is a Boltzmann's constant.

The value of Boltzmann's constant is approximately  $1.3807 \times 10^{-23}$  joules per kelvin ( $J \cdot K^{-1}$ ).

To design lamp system, we have to concern about the heat at the PN junction of the WLED because it is one of the main factor that can effect the life of the WLED [3]. To avoid this effect we have to design WLED to meet maximum requirement of forward voltage and forward current. In general application, the WLED is running at 20 mA of forward current and 3.6V of forward voltage drop.

### C. System Design

A photovoltaic module is the basic element of each photovoltaic array. It consists of many jointly connected solar cells. Polycrystalline photovoltaic module is used in this system and it is designed to track the maximum sunlight by stepping motor that is commanded by PIC microcontroller as shown in Fig. 6.

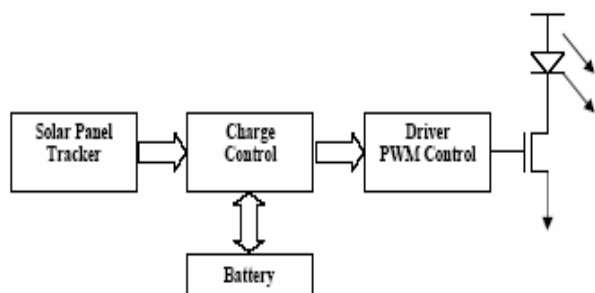


Fig. 6 System block diagram

Phototransistor is the light sensing device that uses to track the maximum sunlight; it is put in the black box with small hole on the top to allow the sunlight pass through it. When the phototransistor detects the maximum illumination of sunlight, state one will command PIC microcontroller to move stepping motor and stop it. In the same time if the phototransistor cannot detect the sunlight, state zero will command PIC microcontroller to move stepping motor until it can detect the state one again and the process repeat.

A WLED driver circuit that uses a current limitation series resistor is an extremely simple, but it can minimize overall design and production costs. However, the disadvantages include minimal efficiency and the need for various resistors values based on forward voltage of each WLED. Increasing the number of series WLEDs per resistors resulted in greater efficiency and sensitivity to varying source voltages. Decreasing the total number of series WLEDs per resistors tend to decrease efficiency, but can provide a benefit by decreasing sensitivity to varying source voltages. The main disadvantage of this system is the heat at each current limitation resistors. To avoid this problem; the Pulse Width Modulation (PWM) technique has been used. PWM control works by switching power supplied to the WLED on and off rapidly. The DC input voltage is converted to square wave signal with duty cycle. Duty cycle is the proportional of on time to total cycle time and it is used not only to determine the acceptable lighting illumination level of the WLED lamp but

also to limit the maximum current so as to not exceed. The duty cycle ( $D$ ) is determined by

$$D = \frac{T_{on}}{T_{on} + T_{off}} \times 100\% \quad (7)$$

where  $T_{on}$  and  $T_{off}$  are on time and off time respectively. If the switching frequency is high enough, we will response only to the average value. The switching frequency is determined by

$$f = \frac{1}{T} \quad (8)$$

where  $f$  is the switching frequency in hertz and  $T = T_{on} + T_{off}$  is the time in second. The output MOSFET is either on or off, so small power is wasted as heat and smaller heat sink can be used, resulting in low power consumption.

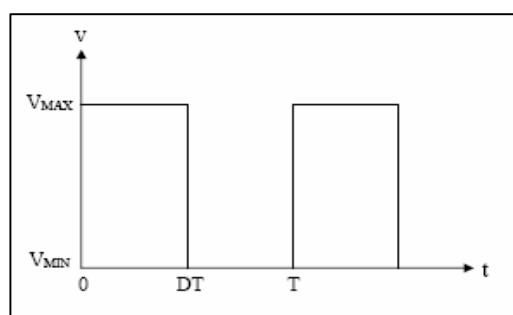


Fig. 7 Pulse wave form

Adjusting the duty cycle of the signal resulted in variation of the average output value. If we consider the pulse waveform  $f(t)$  with the value  $V_{min}$  and  $V_{max}$  in Fig. 7 with a duty cycle  $D$ , the average output value is given by

$$\langle \hat{v} \rangle = \frac{1}{T} \int_0^T f(t) dt \quad (9)$$

where  $f(t)$  is a pulse wave form function, its value is  $V_{max}$  for  $0 < t < DT$  and  $V_{min}$  for  $DT < t < T$ , then the above expression will be

$$\langle \hat{v} \rangle = \frac{1}{T} \left( \int_0^{DT} f(t) dt + \int_{DT}^T f(t) dt \right) \quad (10)$$

$$\langle \hat{v} \rangle = DV_{max} + (1 - D)V_{min} \quad (11)$$

where  $D$  is duty cycle. If  $V_{max}$  and  $V_{min}$  switch between power supply and zero respectively, it means that the average value  $\langle \hat{v} \rangle$  depends only on the duty cycle  $D$ .

### III. EXPERIMENTAL RESULTS

The relationship between the average solar radiation over a day and the power generated by the panels is largely linear, although the fluctuations are large, due to the different actual solar radiation levels across a day. The experimental result in Fig. 8 compares the power generated by fixed and tracking solar cell module. The fixed module produces the maximum power only when there is direct sunlight to the module as shown in the graph. What this means is that charging time interval is limited due to sunlight direction. Total charging

time is about 4 hours per day, but the greatest charge current is not more than 2 hours per day. Compared to tracking system, charging time interval is wider than fixed system, and therefore greater charge current increase. This is because the solar cells module always direct to the sunlight. But, nothing is 100% efficient and actual charge current will be somewhat lower as some power is lost due to solar cell temperature.

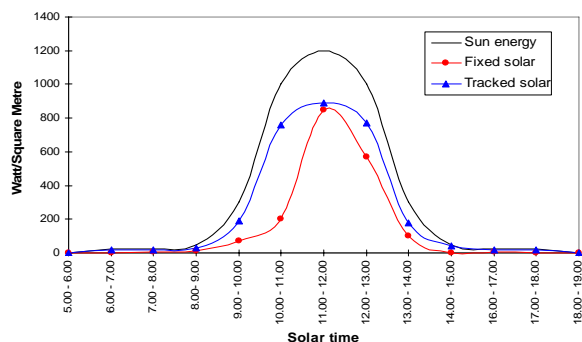


Fig. 8 Fixed and Tracking solar power energy

Lumen is the unit of total light output from a light source. If a WLED lamp were surrounded by a transparent bubble, the total rate of light flow through the bubble is measured in lumens. Lumens indicate a rate of energy flow. Note that lumen output is not related to the light distribution pattern of the WLED lamp. A large fraction of a WLED lamp's lumen output may be useless if it goes in the wrong directions.

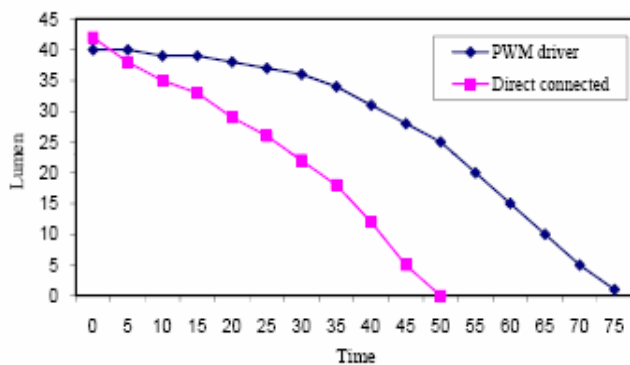


Fig. 9 Comparisons of Directed connected and PWM driver

The WLED brightness between directly connected with current limitation resistors and PWM driver almost the same. In addition to operation for long light brightness, PWM driver is used. The brightness of WLED depends on amount of current pass through it. The graph in Fig. 9 shows that the brightness of WLED that is driven by PWM is slightly decreased in proportion with the time. The energy losses at the current limitation resistors are the main factor that decreases the efficiency of the system. Note that the lumens per watt figures in this paper are lumens of light produced per watt of current delivered to the WLED.

#### A. Other Recommendations

The solar tracking used in this system is one axis; it can only track the sunlight only one direction. To improve the system efficiency, the researchers recommend using the dual axis for solar cell tracking. Most of energies loss in stepping motor is much more than light source so the researchers also recommend not using tracking system for small solar panel.

For WLED lamp, it generates cool white light with limitation angle about 20-30 degree. Although WLED has a high illumination, but in order to replace fluorescent lamp with WLED lamp, you have to think twice. For example, 20W fluorescent lamp, compared to WLED lamp, hundreds of WLED are used. How much does it cost? This system is only the choice for situation where electrical power line is unavailable and energy saving is the main factor to consider for long lighting application.

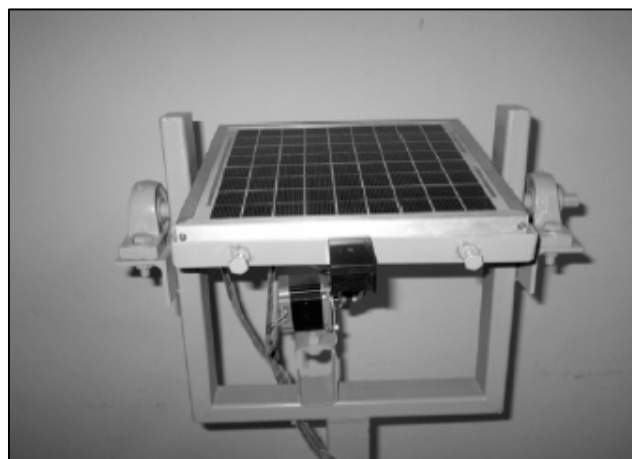


Fig. 10 Tracking system for solar module

#### IV. CONCLUSION

In this paper, we considered the solar tracking system and apply for lighting application based on WLED that use Pulse Width Modulation (PWM) technique for WLED circuit driver. The results of this study shows that maximum charging time for tracking system is more than fixed module, so the utilization efficiency of solar cell module will be considerably increased. The concept and control principle of directly connected White LED circuit driver with current limitation resistors has low efficiency because most of energy lost as heat at each resistor. Compared to Pulse Width Modulation (PWM), the average output value is controlled by duty cycle of input pulse. The output MOSFET that is directly connected to the WLED is either on or off, so small power is wasted as heat resulting in low power consumption and long lighting system. As for future study, for more energy conversion we can improve the system by using dual axis for solar module and include maximum power point tracking.

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#### REFERENCES

- [1] F. J. Lopez\_Hernandez, E. Poves, R.Perez-Jimenez and J. Rabadan, "Low-Cost Diffuse Wireless Optical Communication System based on White LED," *ISCE '06. 2006 IEEE Tenth International Symposium on Consumer Electronics, 2006*, June 2006.
- [2] T. Komine, M. Nakagawa. "Fundamental Analysis for Visible-Light Communication System using LED Lights". *IEEE Trans. Cons. Elect.* vol 50 Feb, 2004.
- [3] T. Komine. M. Nakagawa. "Integrated System of White LED Visible-Light Communication and Power-Line Communication". *IEEE Trans. Cons. Elect.* vol. 49, Feb 2003.
- [4] Nadarajah Narendran and Yimin Gu, "Life of LED-Based White Light Sources," *IEEE/OSA Journal of Display Technology*, vol. 1, pp. 167-171, September 2005.
- [5] M. S. Rea, *The IESNA Lighting Handbook*, ninth ed. New York: Illum.Eng. Soc. of North America, 2000.
- [6] N. Narendran, L. Deng, R. M. Pysar, Y. Gu, and H. Yu, "Performance characteristics of high-power light-emitting diodes," in *Proc. SPIE Third Int. Conf. on Solid State Lighting*, vol. 5187, San Diego, CA, 2003, pp.267-275.1997.

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