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THE EFFECT OF FOUR FLAT PLATE REFLECTORS ON LIGHT ENERGY-HARVESTING SYSTEM CHARACTERISTICS†

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Abstract. *In this paper, the effect of four flat panel reflectors (bottom, top, left and right side reflectors) on the total light radiation on a small-size photovoltaic cell is analyzed. An analytical model for the determination of the optimum inclination angle of the reflectors with respect to the cell's horizontal surface is presented. The optimal angle was calculated to be 66°. The calculated value was experimentally verified by measuring the short-circuit current of the cell. It was shown that the increase in the short-circuit current of the cell with reflectors in the optimal position was about 60% for the illumination levels between 10 lx and 1000 lx. The cell with reflectors was used to charge the primary capacitor in the energy harvesting circuitry of the wireless sensor node and it was demonstrated that the time needed for the cell to charge the primary capacitor could be reduced 35-40%.*

Key words: *photovoltaic cell, flat plate reflectors, optimal angle, wireless sensor node*

1. INTRODUCTION

Flat plate reflectors are used in the solar systems with thermal, photovoltaic (PV) or PV/thermal collectors in order to increase solar irradiation on the collector's surface. Their simple geometry and low-cost implementation are primary beneficial in the design of many solar systems. The use of planar reflectors for increasing the energy yield of flat-plate collectors has been widely analyzed (Arata and Geddes, 1986; Bollentin and Wilk, 1995; Dang, 1986; Garg et al., 1991; Grassie and Sheridan, 1977; Hussein et al., 2000; Kostić and Pavlović, 2012; Kumar et al., 1995; Pancotti, 2007; Pavlović and Kostić, 2015; Ronnelid and Karlsson, 1999; Tanaka, 2011.). Theoretical models have been proposed for various geometries and configurations of the reflectors in order to accurately predict an enhancement in solar energy collection of a tilted flat plate solar collector augmented by a plane reflector.

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Flat plate reflectors may be also applied on solar cells used in small-scale energy harvesting systems. These systems typically incorporate a single solar cell which is used to power-up telemetric circuitries. Values of the measured parameters are transmitted wirelessly, so the complete system may be seen as a wireless sensor node (WSN). Since there is no line or battery power, the systems are commonly referred to as energy harvesting WSNs. Applications are related to both outdoor and indoor environments. For the indoor use, the node should be as compact as possible, so it can be conveniently placed in various positions within the environment. This implies usage of a single small solar cell, which may not be able to provide enough power for the WSN in such environments, especially under low illumination levels (Carvalho and Paulino, 2013; EnerChip™ Smart Solid State Batteries, Cymbet Corporation, 2014; Hamilton, 2012; Kasemann et al., 2013; Pandharipande and Li, 2013; Paradiso and Starner, 2005; Randall and Jacot, 2003; Shigeta et al., 2013; Vullers et al., 2010; Wang et al., 2010; Weddell et al., 2011; Weddell et al., 2012). Under such conditions, it is significant to increase the amount of the harvested energy as much as possible (Prijic et al., 2015).

The objective of this paper is to present the impact of four flat plate reflectors on the light energy harvesting system characteristics for use in WSN. First, an analytical model for determination of the optimal position of flat plate reflectors for a given tilt angle of the PV cell will be presented. Then, the validation of the proposed model will be performed using the measured values of the short-circuit current I_{sc} of the PV cell and charging time of the primary capacitor.

2. Analytical Model

In order to get more light radiation, the PV cell is surrounded by four flat plate reflectors, as illustrated in Figs. 1 and 2. The PV cell collects direct light radiation, reflected radiation from top, bottom, left and right side reflectors, and total diffuse radiation. Note that the light source may be either natural (the Sun) or artificial, as used in indoor environments.

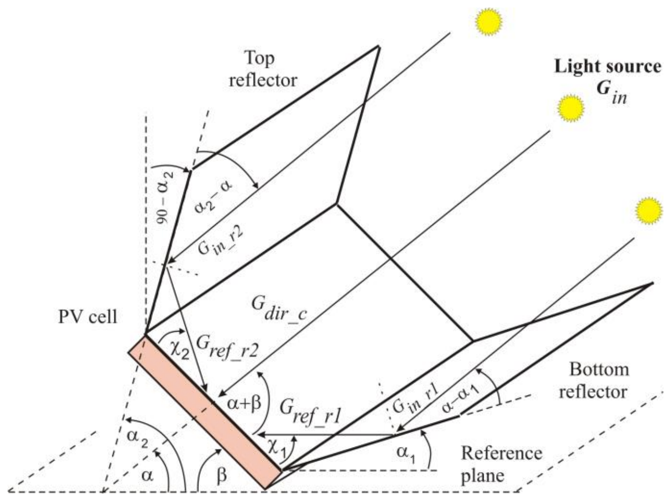

Fig. 1 Schematic diagram of the PV cell with top and bottom flat plate reflectors

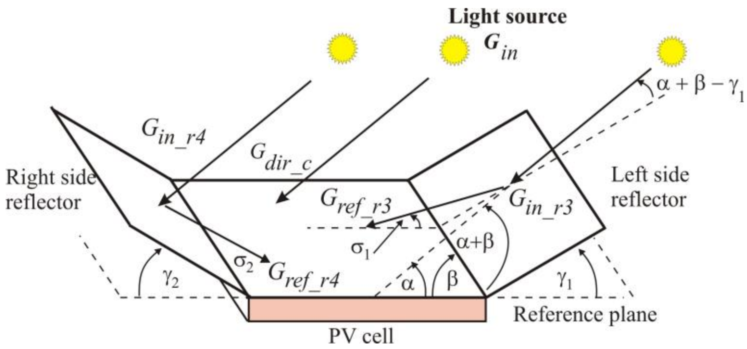

Fig. 2 Schematic diagram of the PV cell with left and right side flat plate reflectors

The following simplifying assumptions are made: (a) the PV cell does not reflect radiation back to the reflectors; (b) there are no mutual reflections between the reflectors; (c) only the diffuse component of radiation falls directly on the cell.

Total light radiation G_{tot_c} on the PV cell surface is the sum of direct light radiation on the PV cell's surface G_{dir_c}, reflected radiation from the bottom reflector which reached the PV cell's surface G_{ref_r1} at the tilted plane angle α_1 to the horizontal plane, reflected radiation from the top reflector which reached the cell's surface G_{ref_r2} at the tilted plane angle α_2 to the horizontal plane, reflected radiation from the left-side reflector which reached the cell's surface G_{ref_r3} at the tilted plane angle γ_1 to the horizontal plane, reflected radiation from the right-side reflector which reached the cell's surface G_{ref_r4} at the tilted plane angle γ_2 to the horizontal plane, and total diffuse radiation G_{dif_c}:

$$G_{tot\_c} = G_{dir\_c} + \sum_{i=1}^{4} G_{ref\_ri} + G_{dif\_c} \ , \tag{1}$$

Direct radiation from the light source on the cell's surface is given by (Duffie and Beckman, 2006.):

$$G_{dir\_c} = G_{in} \cdot \sin(\alpha + \beta) \, , \tag{2}$$

where G_{in} is incident radiation from the light source, α is the incident angle of radiation from the light source, and β is the tilted plane angle of the PV cell. Total diffuse radiation on the PV cell G_{dif_c} is the sum of the reflected radiation from the surrounding objects and it is neglected.

Reflected radiation from the bottom reflector falls on the cell's surface at the angle χ_1, and reflected radiation from the top reflector falls on the cell's surface at the angle χ_2 (Fig. 1). These angles of incidence may be expressed as: $\chi_1 = 2\cdot\alpha_1 - \alpha + \beta$ and $\chi_2 = 180 - (2\cdot\alpha_2 - \alpha + \beta)$.

Reflected radiations from the bottom and top reflector with the tilted plane angle α_1 and α_2, respectively, are defined as:

$$G_{ref\_r1} = \rho \cdot G_{in} \cdot \sin\chi_1 \cdot \sin(\alpha - \alpha_1) = \rho \cdot G_{in\_r1} \cdot \sin\chi_1 \, , \tag{3}$$

$$G_{ref\_r2} = \rho \cdot G_{in} \cdot \sin\chi_2 \cdot \cos(\alpha_2 - \alpha) = \rho \cdot G_{in\_r2} \cdot \sin\chi_2 \, , \tag{4}$$

where G_{in_r1} is incident radiation on the bottom reflector, G_{in_r2} is incident radiation on the top reflector and ρ is reflectance of the reflectors. Similarly, reflected radiation from the left and right side reflector with the tilted plane angle γ_1 and γ_2, respectively are defined as:

$$G_{ref\_r3} = \rho \cdot G_{in} \cdot \sin\sigma_1 \cdot \sin(\alpha + \beta - \gamma_1) = \rho \cdot G_{in\_r3} \cdot \sin\sigma_1 , \quad (5)$$

$$G_{ref\_r4} = \rho \cdot G_{in} \cdot \sin\sigma_2 \cdot \sin(\alpha + \beta + \gamma_2) = \rho \cdot G_{in\_r4} \cdot \sin\sigma_2 , \quad (6)$$

where G_{in_r3} is incident radiation on the left side reflector and G_{in_r4} is incident radiation on the right side reflector. Reflected radiation from the left side reflector falls on the cell's surface at the angle $\sigma_1 = 2\gamma_1 - (\alpha + \beta)$, and reflected radiation from the right side reflector falls on the cell's surface at the angle $\sigma_2 = 2\gamma_2 + (\alpha + \beta) - 180^o$ (Fig. 2).

By taking into account (2), (3), (4), (5), and (6), total radiation on the PV cell's surface given by (1) appears as an analytical function with the following parameters:

$$G_{tot\_c} = F(\alpha, \beta, \alpha_1, \alpha_2, \gamma_1, \gamma_2) . \quad (7)$$

In order to determine optimal inclination angles of the bottom (α_{1max}), top (α_{2max}), left side (γ_{1max}) and right side (γ_{2max}) reflectors, extrema of (7) should be found:

$$\frac{\partial G_{tot\_c}}{\partial \alpha_i} = 0 \quad \text{and} \quad \frac{\partial G_{tot\_c}}{\partial \gamma_i} = 0, \quad i = 1,2 \quad (8)$$

under the assumption that other parameters are constant. However, differentiation leads to cumbersome expressions, which generally do not have analytical solutions for optimal angles α_{1max}, α_{2max}, γ_{1max} and γ_{2max}. Instead, equations (8) are solved numerically. A computer program is developed to calculate total solar radiation using (7) as proposed by Pavlović and Kostić, 2015.

3. Experiments

The schematic block diagram of the photovoltaic energy harvesting WSN is shown in Figure 3. Note that WSN is not designed to operate continuously, but with a predetermined duty cycle. It is active only during data acquisition and transmission, spending the rest of the period in an idle state and harvesting energy for the next activity. Charging block circuitry principally consists of a PV cell and the primary capacitor.

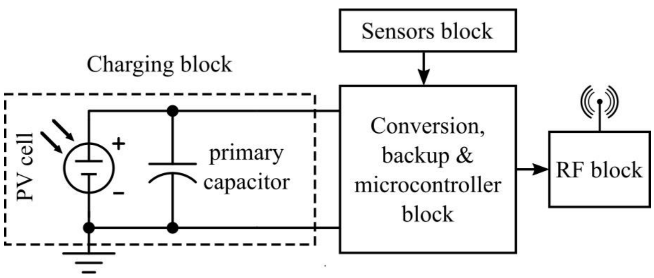

Fig. 3 Schematic block diagram of the photovoltaic energy harvesting WSN

Measurements were performed on a monocrystalline PV cell SLMD600H10 (IXOLAR High Efficiency SolarMD SLMD600H10, Data sheet, IXYS Corporation, 2011.) with and without flat plate reflectors. The cell is fixed at position angle $\beta = 0^o$ and its dimensions are 35 mm × 22 mm. In order to get more radiation on the PV cell surface, four flat plate reflectors made from 0.3mm thick sheets of fiberglass reinforced epoxy laminate (FR4) are added around the cell. The reflectors are about the same size as the cell (Fig. 4). They are cheap and easy to produce.

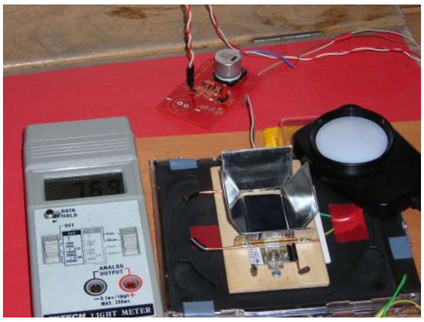

Fig. 4 Photography of the charging block used in the experiment

The bottom reflector was axially mounted at the bottom edge of the PV cell, so its inclination angle α_1 with respect to the horizontal plane can be changed (Fig. 1). Similarly, the top reflector was axially mounted at the top edge of the PV cell, so its inclination angle α_2 with respect to the vertical plane can be changed (Fig. 1). The left and right side reflectors, respectively, were axially mounted at the cell's left and right edges, so their inclination angles γ_1 and γ_2 can be changed with respect to the plane of cell's surface (Fig. 2).

An incandescent light bulb was used as a light source and incident angle of radiation was $\alpha = 90^o$. For the measurement of illuminance an Extech 450 lux meter was used, while currents and voltages were measured by using a digital multimeter Agilent 34410A.

4. RESULTS AND DISCUSSION

Optimal inclination angles of the reflectors for a given tilted plane angle of the PV cell $\beta = 0$ were determined by means of the model represented by equations (1)-(8). Note that the distribution of the total solar radiation on the solar cell surface is considered to be nearly uniform.

Calculated variations of incident and reflected radiation of the left/right side reflector with inclination angle γ_1 and γ_2, respectively, are shown in Figure 5. A maximum in the reflected radiation on the cell's surface corresponds to the optimal inclination angles of the left and right side reflectors ($\gamma_{1max} = \gamma_{2max} = \gamma_{max} = 66^o$).

In order to determine an optimal inclination angle experimentally, the short-circuit current I_{sc} of the PV cell was measured as a function of the inclination angle of the reflectors. Dependence of the short-circuit current I_{sc} on the inclination angle of the reflectors for the illuminance level $E_v = 100$ lx is shown in Figure 6. The reflectors do not contribute to the collected radiation as long as their inclination angles are lower than 44°. The short-circuit current exhibits a maximum when the reflectors are inclined at the angle of 65°, which is in a very good agreement with the value predicted by the model (Fig. 5). However, when the distance *d* between the light source and the PV cell's surface is reduced, experimental results deviate from theoretical predictions, because the model does not take into account divergency of the rays from the light source at short distances. Generally, the model may be considered to be reliable for $d > 0.5$m, which is the case regularly satisfied in practice in indoor environments.

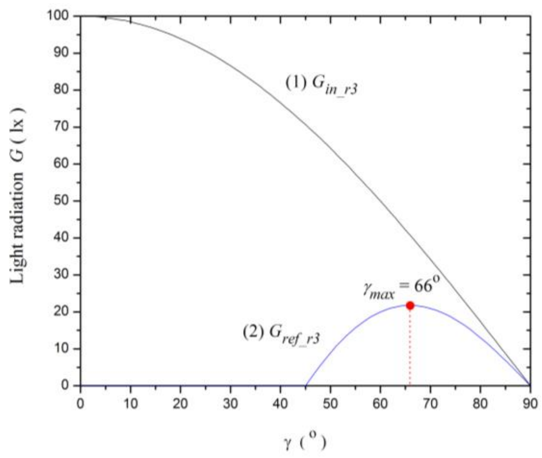

Fig. 5 Variation in the calculated values of radiation vs. inclination angle γ of the left side reflector: (1) G_{in_r3}, (2) G_{ref_r3} for fixed tilted plane angle of PV cell $\beta = 0$

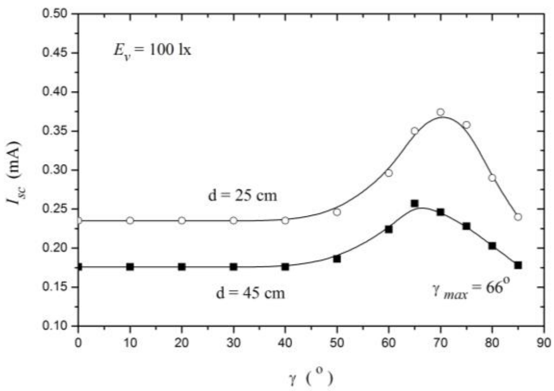

Fig. 6 Measured values of the short-circuit current I_{sc} vs. inclination angle γ of the reflectors at $E_v = 100$ lx; *d* is the distance between the light source and the PV cell's surface.

The short-circuit current I_{sc} of the PV cell was also measured as a function of the illuminance E_v, at optimal inclination angle of the reflectors. These results are shown in

Figure 7. It can be observed that the reflectors significantly contribute to I_{sc}, thus giving the possibility for the primary capacitor to be charged and recharged more quickly than without reflectors.

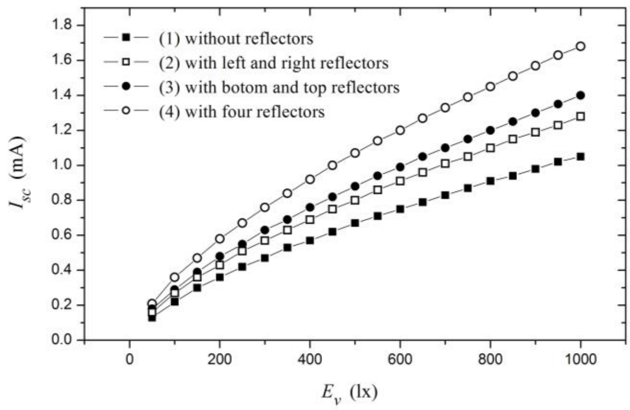

Fig. 7 Measured values of the short-circuit current I_{sc} vs. illuminance E_v: (1) without reflectors, (2) with left and right side reflectors, (3) with bottom end top reflectors and (4) with four reflectors at optimal inclination angle γ_{max}

Relative change in I_{sc} (calculated from the measured values shown in Figure 7) is shown in Figure 8, where: $I_{sc(4)}$ is the short-circuit current with four reflectors at optimal inclination angle γ_{max} and $I_{sc(1)}$ is the short-circuit current without reflectors. An average contribution of the four reflectors to the short-circuit current is about 60%.

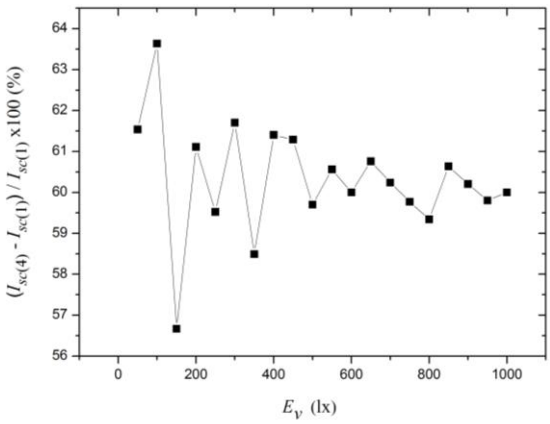

Fig. 8 Relative change in the short-circuit current I_{sc} vs. illuminance E_v

This is of special interest at low illumination levels (below 500 lx) because relying the operation of the WSN solely on the primary capacitor can lead to a significant spare of the backup supply, which is then used only when there is no illumination at all (i.e. in the dark).

Minimal voltage for a reliable operation of the WSN from Fig. 3 is 2.35V, and it is the value at which the primary capacitor, shown in Fig. 3, should be charged from the PV cell. The charging time is measured using an SMD aluminum electrolytic primary capacitor with the capacity of 3300 μF. The initial condition is that the capacitor is empty, corresponding to the cold-boot state (Chou and Kim, 2010.) of the WSN. A diagram of the charging time *t* vs. illuminance level without reflectors, and with four reflectors at optimal inclination angle γ_{max} is shown in Figure 9. An overall contribution to the reduction of the charging time is about 35% - 40% at all illuminance levels.

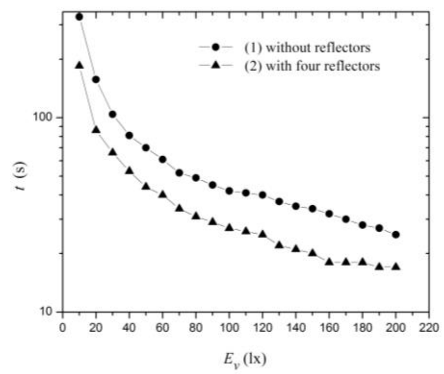

Fig. 9 Measured values of charging time *t* of the primary capacitor vs. illuminance E_v: (1) without reflectors, and (2) with four reflectors at optimal inclination angle γ_{max}.

Shorter recharge time for the primary capacitor means that WSN may be able to operate at higher duty cycles, i.e. to acquire and transmit data more frequently. Also, from the networking point of view, distribution of the nodes within the environment can be more flexible.

5. CONCLUSION

The problem of finding inclination angles of four flat plate reflectors is analyzed in order to get a maximum concentration of the solar radiation intensity on the small-size PV cell. The cell is used to harvest the energy necessary to supply the wireless sensor node. An analytical model for the calculation of optimum angles' values for the reflectors is developed. It is found that the optimal inclination angle of the reflectors with respect to the cell's plane was 66°. The calculated results are compared with the experimental data and a systematically good agreement is found. It is shown that the reflectors in the optimal position can increase the cell's short-circuit current up to 60%. Thus, the charging time needed for the cell to charge the primary capacitor is reduced from 35% to 40%. The benefit of using the reflectors is in improving the overall energy harvesting node's energy storage and management performance.

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UTICAJ ČETIRI RAVNA REFLEKTORA NA KARAKTERISTIKE SISTEMA KOJI SE AUTONOMNO NAPAJA ENERGIJOM SVETLOSTI

U radu je analiziran uticaj četiri ravna reflektora (donji, gornji, levi i desni bočni reflektor) na ukupno svetlosno zračenje koje dospeva na solarnu ćeliju malih dimenzija. Dat je analitički model za određivanje optimalnog nagibnog ugla reflektora u odnosu na horizontalnu ravan u kojoj se nalazi solarna ćelija. Izračunati optimalni ugao iznosi 66°. Izračunata vrednost je eksperimentalno proverena merenjem struje kratkog spoja solarne ćelije i pokazano je da povećanje struje kratkog spoja solarne ćelije sa reflektorima u optimalnom položaju iznosi oko 60% za nivo osvetljenosti između 10 lx i 1000 lx. Solarna ćelija je korišćena za punjenje primarnog kondenzatora samonapajajućeg senzora i pokazano je da vreme potrebno za punjenje primarnog kondenzatora može biti smanjeno od 35% do 40%.

Ključne reči: *solarna ćelija, ravni reflektori, optimalni ugao, samonapajajući senzor*