ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 3, Issue 9 , September 2016

A Solar Irradiance Prediction Method for the Development of Highly-Efficient and Low-Cost Supporting Structure System for Photovoltaic Generator

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ABSTRACT:Recently, there has been an acute demand for the development of a new commercial model combining the construction technology and the latest ICT technology in the domain of photovoltaics exploiting the available space like road and railroad. However, most of the available space is limited in area and requires the development of supporting structures increasing further the photovoltaic power production efficiency. Accordingly, the present study proposes a supporting structural system with a uniaxial tracker combined with a manually-operated axis that can achieve power generation comparable to the dual-axis tracker while demanding lower installation and maintenance costs. In addition, the technique predicting the power generation efficiency of the proposed supporting structure is developed and used to compare it with those of the fixed system and dual-tracking system. The comparison shows that the proposed supporting structure system achieves power generation efficiency larger by more than 19% than the fixed system and lower by less than 3% than the dual-axis tracker.

KEYWORDS:Solar irradiance, photovoltaics, supporting system,

I. INTRODUCTION

The amount of electric power generated by photovoltaics depends on the type of the structure supporting the photovoltaic (PV) panels. This supporting structure can be classified into the fixed-type and the tracking-type. The tracking system itself can be subdivided into the uniaxial system tracking the sun in south-north or east-west direction only and the dual-axis system tracking the sun simultaneously in two directions. The fixed system requires less installation and maintenance costs than the tracking system but generates less power. Besides, the tracking system generates larger power than the fixed system but requires higher installation and maintenance costs.

The present study proposes a supporting structural system with a uniaxial tracker combined with a manually-operated axis that can achieve power generation superior to the fixed system and requiring lower installation and maintenance costs than the dual-axis tracker. The proposed system tracks automatically the sun in the east-west direction and tracks seasonally the sun in the south-north direction by manual operation. The optimal direction of the PV panel revolving with respect to the south-north axis inclined by an arbitrary angle shall be determined to predict the amount of energy produced by the proposed system. Here, since the generated amount of solar power depends on the irradiance at the PV panel, the direction of the PV panel shall be determined adequately to maximize the irradiance so as to predict the maximum power generation.

The methods determining the direction of the PV panel can be divided into the program type and the sensor type. The program type calculates the direction of the PV panel maximizing the direct irradiance at the PV panel, and the sensor type adjusts the direction of the PV panel so as to maximize the total irradiance at the PV panel. The choice of the method depends on the size of the direct irradiance or diffuse irradiance compared to the total irradiance. In general, the sensor type is known to be advantageous in areas where the diffuse irradiance is significantly larger than the direct irradiance. The present study develops a program type method predicting the solar irradiance for the proposed supporting structure combining the uniaxial tracker and the manually-operated axis. This method is used to predict the maximum irradiance, which is then compared to those of the fixed system, the south-north uniaxial tracker, and the dual-axis tracker.

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II. DETERMINATION OF OPTIMAL DIRECTION OF PV PANEL

A.Total Irradiance of PV Panel

As shown in Eq. (1), the total irradianceat the PV panel is expressed as the sum of the direct normal irradiance (Eq. (2)) at the panel, the diffuse irradiance (Eq. (3)) and the reflected solar radiation (Eq. (4)). This total irradiance atthe PV panel is determined by means of the combination of the diffuse irradiance and the direct normal irradiance with respect to the horizontal.

$$I_T = I_{T,b} + I_{T,d} + I_{T,re} \tag{1}$$

$$I_{T,b} = I_b R_b \tag{2}$$

$$I_{T,b} = \begin{cases} \text{Isotropic model: } I_d \left(\frac{1+\cos\beta}{2}\right) \\ \text{HDKR model: } I_d \left\{(1-A_i)\left(\frac{1+\cos\beta}{2}\right)\left[1+f\sin\frac{3\beta}{2}\right]+A_i R_b\right\} \\ \text{Perez model: } I_d \left[(1-F_1)\left(\frac{1+\cos\beta}{2}\right)+F_1\frac{a}{b}+F_2\sin\beta\right] \end{cases} \tag{3}$$

$$I_{T,re} = I\rho_g \left(\frac{1+\cos\beta}{2}\right) \tag{4}$$

where I_T = global irradiance at PV panel; I_b = horizontal direct irradiance; I_d = horizontal diffuse irradiance; $I_{T,b}$ = direct normal irradiance at PV panel; $I_{T,d}$ = diffuse irradiance at PV panel; $I_{T,re}$ = reflected solar radiation at PV panel; R_b = geometric coefficient; β = surface tilt angle of PV panel from horizon; A_i = anisotropic index; f = adjusting factor in HDKR model; F_i = brightness coefficient in Perez model; and, ρ_g = reflectance.

B. Direction Vectors of the Sun and PV Panel

Assuming α_s as the solar altitude angle or elevation angleof the sun measured from the horizontal and γ_s as the azimuthal angle facing due south (Fig. 1), the direction vector of the sun can be expressed by Eq. (5).

$$\vec{v}_{sun} = (\cos\alpha_s \sin\gamma_s, \cos\alpha_s \cos\gamma_s, \sin\alpha_s) \tag{5}$$

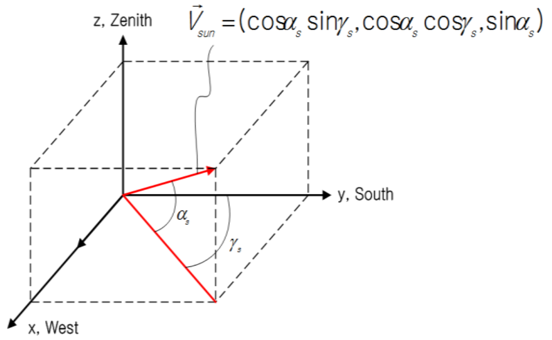

Fig.1Direction vector of the sun

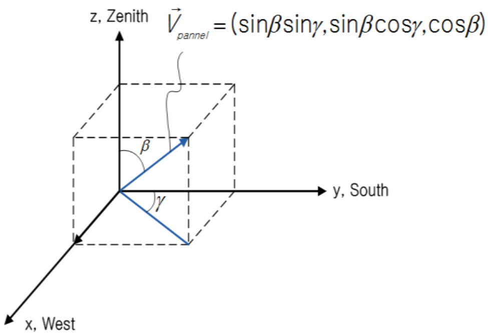

Fig.2Direction vector of PV panel

The solar altitude angle, α_s, and the azimuthal angle, γ_s, of the sun in Eq. (5) are determined with respect to the latitude (ϕ) and the hour angle (ω) of the area at which the PV panel is installed and the declination between the sun and the earth.

$$\alpha_s = \sin^{-1}(\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta) \tag{6}$$

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 3, Issue 9 , September 2016

$$\gamma_s = \text{sign}(\omega)\left|\cos^{-1}\left(\frac{\sin\alpha_s \sin\phi - \sin\delta}{\cos\alpha_s \cos\phi}\right)\right| \quad (7)$$

$$\omega = (\text{hour} - 12) \times 15° \quad (8)$$

Assuming β as the angle formed by the direction vector of the PV panel and the zenith of the celestial sphere, and γ as the azimuthal angle facing due south (Fig. 2), the direction vector of the PV panel can be expressed as follows:

$$\vec{v}_{\text{panel}} = (\sin\beta \sin\gamma , \sin\beta \cos\gamma , \cos\beta) \quad (9)$$

C. Optimal Direction of PV Panel for Uniaxial (South-North) Tracking System

Since the direction vector of the south-north tracker must lie in the $y - z$ plane as shown in Fig. 3, this vector can be expressed as follows:

$$\vec{v}_{\text{panel}} = (0, \sin\beta, \cos\beta) \quad (10)$$

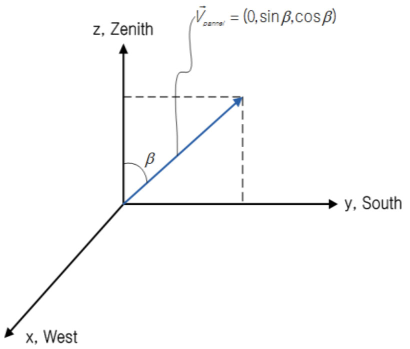

Fig.3Direction vector of south-north tracking panel

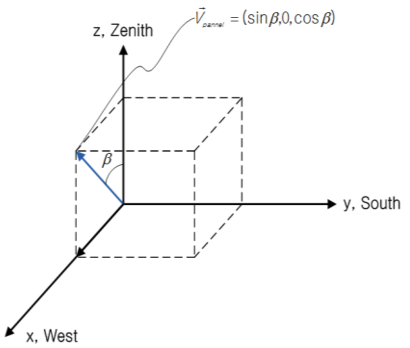

Fig.4Direction vector of dual-axis tracking panel

The direction vector of the PV panel shall be determined by Eq. (11) to minimize the angle between the sun and the panel.

$$\beta = \tan^{-1}\left(\frac{\cos\gamma_s}{\tan\alpha_s}\right) \quad (11)$$

D.Optimal Direction of PV Panel for Uniaxial (East-West) Tracking System

Since the direction vector of the east-west tracker must lie in the $x - z$ plane as shown in Fig. 4, this vector can be expressed as follows:

$$\vec{v}_{\text{panel}} = (\sin\beta, 0, \cos\beta) \quad (12)$$

The direction vector of the PV panel shall be determined by Eq. (13) to minimize the angle between the sun and the panel.

$$\beta = \tan^{-1}\left(\frac{\sin\gamma_s}{\tan\alpha_s}\right) \quad (13)$$

E.Optimal Direction of PV Panel for Supporting Structure with Uniaxial Tracker and Manually-Operated Axis

The direction vector of the system tracking in the east-west direction and of which central axis of the PV panel forms an angle Σ with the horizontal (Fig. 5) shall be determined by means of Eqs. (14) and (15).

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 3, Issue 9 , September 2016

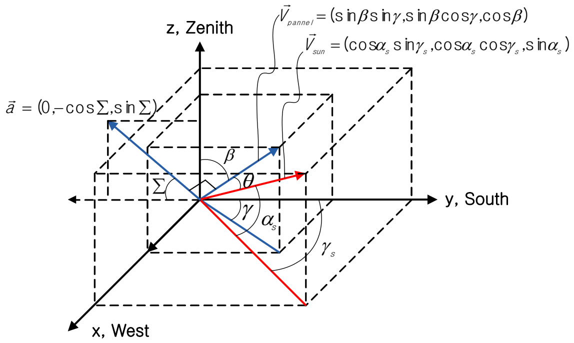

Fig.5Direction vector of panel with uniaxial tracker and manually-operated axis

$$\beta = \tan^{-1}\left(\frac{\tan\Sigma}{\cos\gamma}\right) \tag{14}$$

$$F(\gamma) = \left|1 - \left(v_{s,x}\sin\beta\sin\gamma + v_{s,y}\sin\beta\cos\gamma + v_{s,z}\cos\beta\right)\right| \tag{15}$$

where $\vec{v}_{\text{panel}}$ = direction vector of panel; $\vec{v}_{\text{sun}}$ = direction vector of the sun; $\vec{a}$ = gradient vector of panel; β = surface tilt angle of panel from horizon; γ = azimuthal angle of panel; α_s = solar altitude angle; γ_s = azimuthal angle of the sun; and, Σ = inclination of the panel axis from the surface of the earth.
In Fig. 5, the direction vector of the panel, $\vec{v}_{\text{panel}}$, is perpendicular to the gradient vector $\vec{a}$ of the panel and it can be seen that the angle θ formed with the direction vector of the sun, $\vec{v}_{\text{sun}}$, shall be minimum. Accordingly, the value of γ (azimuthal angle of panel) is computed by minimizing Eq. (15) in which Eq. (14) is substituted, and the direction vector of the PV panel can then be determined by computing the value of β by substituting the obtained value of γ in Eq. (14).

F. Optimal Direction of Dual-axis Tracking PV Panel

Since the direction vector of the dual-axis tracker shall be identical to the direction vector of the sun, this vector can be determined by Eqs. (16) and (17).

$$\beta = 90° - \alpha_s \tag{16}$$

$$\gamma = \gamma_s \tag{17}$$

III. PREDICTION OF IRRADIANCE

The analysis of the irradiance of Seoul located nearest to the site where the supporting structure developed in this study is installed revealed that the horizontal direct normal irradiance and diffuse irradiance showed similar sizes (Tables 1 and 2). Consequently, the direction of the PV panel is determined so as to maximize the direct normal irradiance at the panel and predict the irradiance. Here, the isotropic, HDRK and Perez models (Eq. (3)) are applied to predict the diffuse irradiance.

Table1.Horizontal direct normal irradiance (Seoul) in kW/m^2/day

Mo.	5am-6am	6am-7am	7am-8am	8am-9am	9am-10am	10am-11am	11am-12am	12am-1pm	1pm-2pm	2pm-3pm	3pm-4pm	4pm-5pm	5pm-6pm	6pm-7pm	Total
1	0	0	0.01	0.07	0.13	0.18	0.22	0.22	0.18	0.13	0.07	0.01	0	0	1.21
2	0	0	0.04	0.1	0.17	0.23	0.27	0.27	0.23	0.17	0.1	0.04	0	0	1.64
3	0	0.01	0.06	0.13	0.2	0.26	0.3	0.3	0.26	0.2	0.13	0.06	0.01	0	1.94
4	0	0.03	0.09	0.16	0.23	0.29	0.32	0.32	0.29	0.23	0.16	0.09	0.03	0	2.27
5	0.01	0.05	0.1	0.16	0.22	0.27	0.3	0.3	0.27	0.22	0.16	0.1	0.05	0.01	2.21
6	0.01	0.04	0.08	0.13	0.18	0.22	0.24	0.24	0.22	0.18	0.13	0.08	0.04	0.01	1.8
7	0	0.02	0.04	0.07	0.11	0.13	0.15	0.15	0.13	0.11	0.07	0.04	0.02	0	1.05
8	0	0.02	0.06	0.1	0.15	0.19	0.21	0.21	0.19	0.15	0.1	0.06	0.02	0	1.49
9	0	0.02	0.06	0.12	0.19	0.24	0.27	0.27	0.24	0.19	0.12	0.06	0.02	0	1.83

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 3, Issue 9 , September 2016

10	0	0	0.05	0.11	0.19	0.25	0.29	0.29	0.25	0.19	0.11	0.05	0	0	1.8
11	0	0	0.02	0.07	0.13	0.18	0.21	0.21	0.18	0.13	0.07	0.02	0	0	1.2
12	0	0	0.01	0.05	0.11	0.16	0.19	0.19	0.16	0.11	0.05	0.01	0	0	1.03

Table2.Horizontal diffuse irradiance (Seoul) in kW/m^2/day

Mo.	5am-6am	6am-7am	7am-8am	8am-9am	9am-10am	10am-11am	11am-12am	12am-1pm	1pm-2pm	2pm-3pm	3pm-4pm	4pm-5pm	5pm-6pm	6pm-7pm	Total
1	0	0	0.02	0.06	0.09	0.12	0.13	0.13	0.12	0.09	0.06	0.02	0	0	0.82
2	0	0	0.04	0.09	0.12	0.15	0.17	0.17	0.15	0.12	0.09	0.04	0	0	1.14
3	0	0.02	0.08	0.13	0.17	0.2	0.21	0.21	0.2	0.17	0.13	0.08	0.02	0	1.59
4	0	0.06	0.12	0.17	0.21	0.24	0.26	0.26	0.24	0.21	0.17	0.12	0.06	0	2.12
5	0.03	0.09	0.15	0.2	0.24	0.27	0.29	0.29	0.27	0.24	0.2	0.15	0.09	0.03	2.51
6	0.04	0.1	0.16	0.2	0.24	0.27	0.29	0.29	0.27	0.24	0.2	0.16	0.1	0.04	2.61
7	0.03	0.08	0.13	0.18	0.21	0.24	0.25	0.25	0.24	0.21	0.18	0.13	0.08	0.03	2.24
8	0.01	0.07	0.12	0.17	0.21	0.23	0.25	0.25	0.23	0.21	0.17	0.12	0.07	0.01	2.11
9	0	0.03	0.09	0.14	0.18	0.21	0.22	0.22	0.21	0.18	0.14	0.09	0.03	0	1.74
10	0	0	0.05	0.1	0.14	0.16	0.18	0.18	0.16	0.14	0.1	0.05	0	0	1.28
11	0	0	0.02	0.06	0.1	0.12	0.14	0.14	0.12	0.1	0.06	0.02	0	0	0.87
12	0	0	0.01	0.05	0.08	0.1	0.12	0.12	0.1	0.08	0.05	0.01	0	0	0.72

A. Prediction of Irradiance per Type of Supporting Structure

The yearly irradiance was predicted for the fixed system (Fig. 6), the south-north tracker (Fig. 7), the uniaxial and manually-operated axis tracker (Fig. 8) and the dual-axis tracker (Fig. 9). For the supporting structure with the uniaxial and manually-operated axis tracker, it was assumed that the direction of the panel was adjusted seasonally in the south-north direction that is 4 times per year.

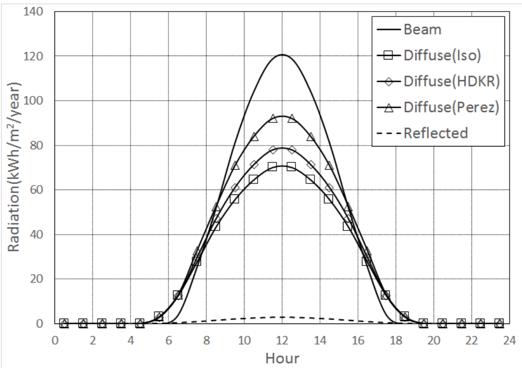

Fig.6Irradiance for fixed supporting structure

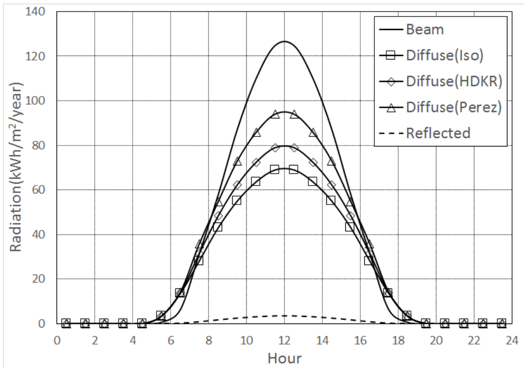

Fig.7Irradiance for supporting structure with south-north tracker

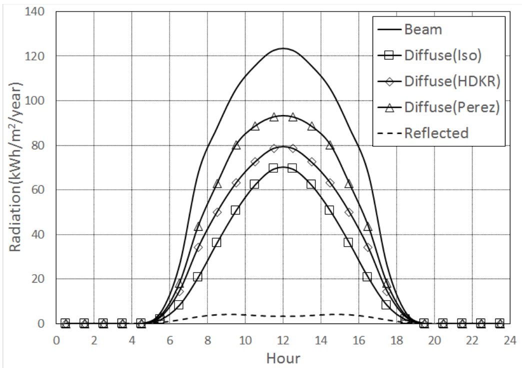

Fig.8Irradiance for supporting structure with uniaxial tracker and manually-operated axis

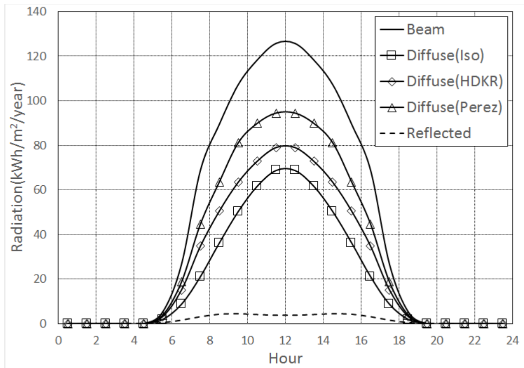

Fig.9Irradiance for supporting structure with dual-axis tracker

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 3, Issue 9 , September 2016

The prediction of the irradiance at the PV panel for all the types of supporting structure showed that the size of irradiance followed the descending sequence: direct normal irradiance > diffuse irradiance > reflected solar radiation. In concern with the diffuse irradiance, the prediction revealed that the Perez model resulted in the largest size followed successively by the HDKR model and the isotropic model.

B. Yearly Irradiance Prediction for Supporting Structure with Uniaxial Tracker and Manually-operated Axis

Figs. 10 to 12 compare the yearly total irradiance by type of supporting structure with respect to the diffuse irradiance model. It appears that the supporting structure with uniaxial tracker and manually-operated axis developed in this study is predicted to achieve efficiency improved by 19% to 27% compared to the fixed structure and to show a difference in efficiency within 2% to 3% compared to the dual-axis tracking system.

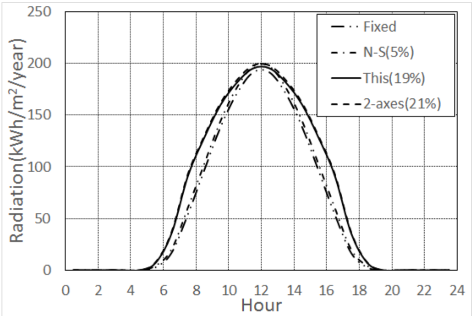

Fig.10Irradiance by isotropic model

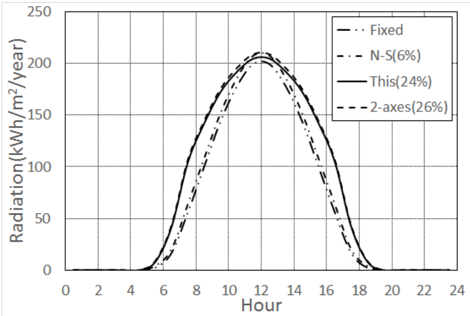

Fig.11Irradiance by HDKR model

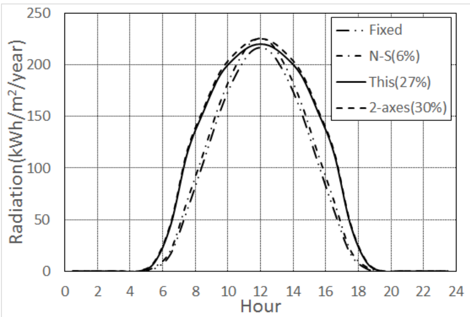

Fig.12Irradiance by Perez model

IV. CONCLUSIONS

This paper proposed a supporting structural system with uniaxial tracker and manually-operated axis requiring less installation and maintenance costs than the dual-axis tracker known to achieve superior solar power generation compared to the fixed system. The optimal direction of the photovoltaic (PV) panel revolving with respect to an axis (south-north axis) inclined by an arbitrary angle was determined to predict the maximum energy-generation efficiency of the proposed system. This enabled to predict the maximum irradiance and compare it with the irradiance of the fixed system, the south-north uniaxial tracker, and the dual-axis tracker. The results showed that the proposed system with uniaxial tracker and manually-operated axis could achieve efficiency improved by more than 19% compared to the fixed system and a difference in efficiency smaller than 3% compared to the dual-axis system. The proposed system with uniaxial tracker and manually-operated axis could realize outstanding efficiency by adjusting the direction of the PV panel only 4 times per year. Consequently, if applied on site, the proposed system is expected to be able to achieve efficiency comparable to the dual-axis tracker with significantly reduced cost.

ACKNOWLEDGEMENTS

This research was supported by a grant from a Strategic Research Project(Development of High Efficiency Solar Road Power Generation Technology) of the Korea Institute of Civil Engineering and Building Technology.

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