International Conference on Renewable Energies and Power Quality (ICREPQ'14)
Cordoba (Spain), 8th to 10th April, 2014
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, No.12, April 2014

Modelling and simulation of Λ-ridge concentrator system using commercial PV modules

J. Mroczka, K. Plachta

Chair of Electronic and Photonic Metrology
Wroclaw University of Technology
Boleslawa Prusa 53/55; 50-317 Wroclaw (Poland)
Phone/Fax number:+0048 71 320 62 32, e-mail: **janusz.mroczka@pwr.wroc.pl**, **kamil.plachta@pwr.wroc.pl**

Abstract. This paper presents the Λ-ridge and V-trough concentrator system with low concentration ratio applicable in independent power supply systems (e.g. chalets, road signs, traffic lights, street lamps, industrial cameras, CCTV), of an outpower not exceeding 500W. Actual area of photovoltaic modules, which doesn't exceed 3m^2 constitutes important parameter in this kind of construction. Small external dimensions and relatively light weight are the crucial principles of constructing Λ-ridge concentrator system. The performance of the system and the amount of energy produced constitute key factors for such restrictions. A series of simulations was conducted enabling evaluation of the efficiency of the presented systems depending on their technical parameters and weather conditions.

Key words

Low concentration photovoltaic systems, Λ-ridge concentrators, tracking system, temperature controls, mirrors

1. Introduction

The presented autonomous photovoltaic systems can be used to power the chalets, road signs, traffic lights, street lights, industrial cameras, CCTV and many other devices. Currently, monocrystalline photovoltaic panels reach efficiency of 13% to 17%. One of the solutions enabling improved efficiency is the application of Λ-ridge or V-trough concentrator system that direct additional reflected sun radiation onto the surface of the photovoltaic panel.

These systems apply a tracker system, according to several studies [1-6], increases the energy production of approximately 40%. The difference between the systems is based on the location and arrangement of mirrors. In the Λ-ridge concentrator (fig. 1a) mirrors are arranged in the shape of Λ-ridge, whereas photovoltaic panels are placed along their longer sides. As far as the V-trough (fig. 1b) solution is concerned, its cross section is of V-trough shape, with foundation in photovoltaic cells, and the walls made of mirrors [7-12].

a b

Fig. 1. The Λ-ridge (a) and V-trough (b) concentrator system with low CR.

Concentration systems can be divided on the basis of the value of the concentration ratio (CR - Concentration Ratio): low CR < 10X, medium CR < 100X and high CR > 100X [13], where *X* is the concentration ratio defined as the ratio of concentration solar radiation falling onto the surface of the photovoltaic module to the total solar radiation.

The value of CR coefficient affects: the amount of solar radiation incidenting on the surface of the photovoltaic, solar cell operating temperature, the viability of photovoltaic panels, the size and weight of the system hub. All these factors affect the efficiency of these systems.

System tracking the apparent position of the Sun on the celestial sphere constitutes an intrinsic part of the presented solution. The value of the concentration ratio is tightly linked to the tracking step system. Concentrator systems with medium and high CR require a very high resolution tracking step (less than 10 min) to ensure concentration of solar radiation on the small optical devices such as Fresnel lenses or Fly-eye. For systems with a low coefficient of CR, tracking step system may have a value of up to 2 hours.

2. The geometric model of the Λ-ridge concentrator with low concentration ratio

This paper presents a simulation, which aim was to determine the best parameters of the Λ-ridge concentrator system: opening angle (θ), total width (W_T) and tracking step system (k_M) depending on the latitude (ω). Simulations were performed in a dedicated program, created by the author of this article, based on a geometric model of Λ-ridge concentrator (fig. 1). Appropriate selection of these parameters allowed to increase system efficiency retaining its small size (<3m^2).

The article presents two models of concentrator system: Λ-ridge and V-trough that apply system tracking the apparent position of the Sun on the celestial sphere. Change of the position of the tracking system alter the angle inclination of the photovoltaic panel to the incident solar radiation. Time between rotations of the tracking system is bound up with the angle incidence of solar radiation on the surface of the photovoltaic panel (fig. 2).

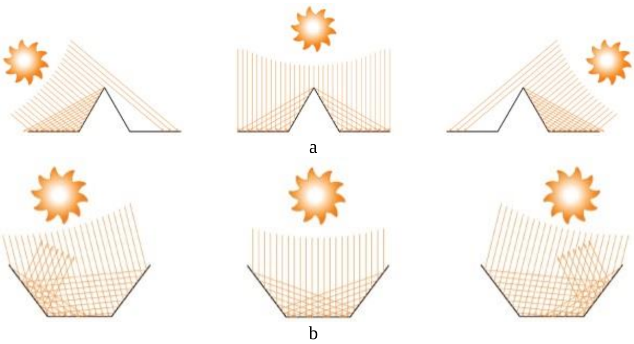

Fig. 2. Changing the direction of incidence of solar radiation depending on the value of the tracking step Λ-ridge (a) and V-trough (b) a concentrator system.

In both cases, dual-axis tracking system which provides a perpendicular angle of incidence solar radiation *($\pm k_M$)* on the surface of the photovoltaic panels constitutes an integral part of the concentrator system. Further analysis of this paper presents Λ-ridge concentrator system, which elements are: monocrystalline photovoltaic panels (PV1 and PV2), two symmetrically arranged mirrors (M1 and M2), and two-axis tracking system.

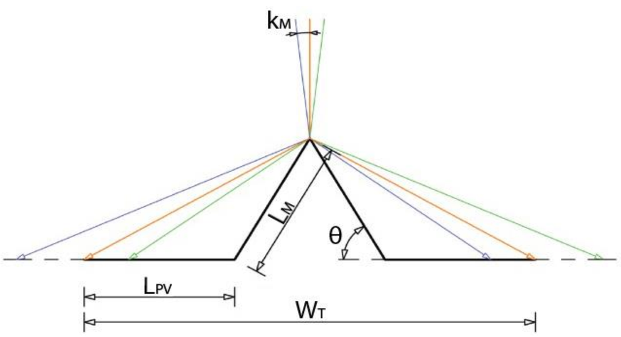

Fig. 3. The geometric model of Λ-ridge concentrator system with low concentration ratio.

Furthermore, the system parameters are: L - length, L_{PV} - width photovoltaic panel, L_M - the width of the mirror, W_T - the width of the concentrator system, θ - the opening angle between the surface of the photovoltaic module and mirrors, v - the angle of incidence solar radiation, β - the angle of the ridge concentrator, k_M – value of the tracking step. In order to determine the best parameters Λ-ridge concentrator system numerical simulations based on the geometric model were carried out (fig. 3).

Numerical simulations were performed in the program created by the author of this article. The interface is shown in the following figure.

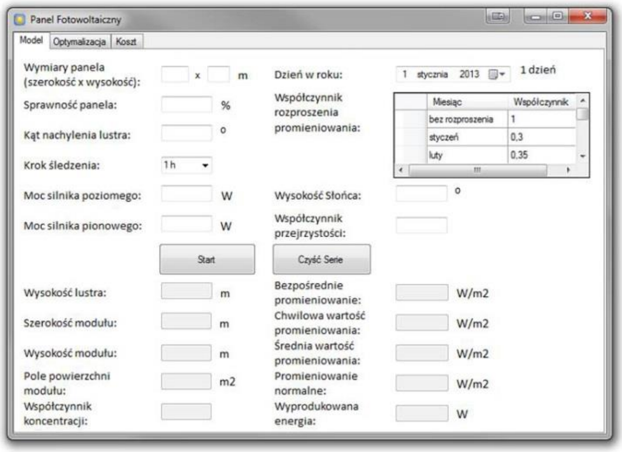

Fig. 4. The software interface applied in the simulations.

The software allows the selection of appropriate technical and atmospheric parameters. Technical parameters included: efficiency (η), dimension of the photovoltaic panel (W_T), opening angle (θ), the tracking step system (k_M), horizontal power motor (P_{MH}) and vertical power motor (P_{MV}). Subsequently, the atmospheric parameters embraced: diffuse radiation (DF), transparent ratio (T_R), day number of a year (N), height of the Sun (φ) and latitude (ω) of the place for which the simulation was performed.

The calculations were performed for different values of the opening angle (θ), step tracking (k_M) and latitude (ω). The coefficient ε (eq. 1) was calculated on the basis of the geometrical model, i.e. it is the ratio of the mirror width (L_M) to the width of a photovoltaic panel (L_{PV}). The value of the parameter ε shows changes in the size of the concentrator system, which depends on the step of tracking system. Equations (1) and (2) are based on the angles incidence of extreme solar radiation (V_{M1}, V_{M2}), inclination of the mirror to the surface of photovoltaic panel (θ) and the tracking step system (k_M).

$$\varepsilon = \frac{L_M}{L_{PV}} = \frac{-\cos(2\cdot\theta + k_M)}{cos(\theta + k_M)} \tag{1}$$

The total width of the photovoltaic panel is expressed by the following equation:

$$W_T = 2 - \cos(2\theta + k_M) \tag{2}$$

On the basis of equation (5 and 6), plotted graphs (fig. 5), revealing the change of ratio ε and the total width of the concentrator system (W_T), depending on the opening angle between the surface of the mirror and photovoltaic panel (θ) and selected value of the tracking step k_M = 15° ⇔ 1 hour, k_M = 7.5° ⇔ 30min, k_M = 3.75° ⇔ 15 minutes and k_M = 1.875° ⇔ 7.5 min.

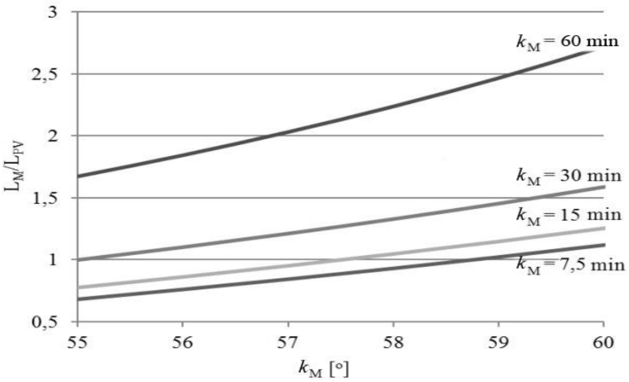

Fig. 5. Change in the value of ratio ε depending on opening angle (θ) and the tracking step (k_M).

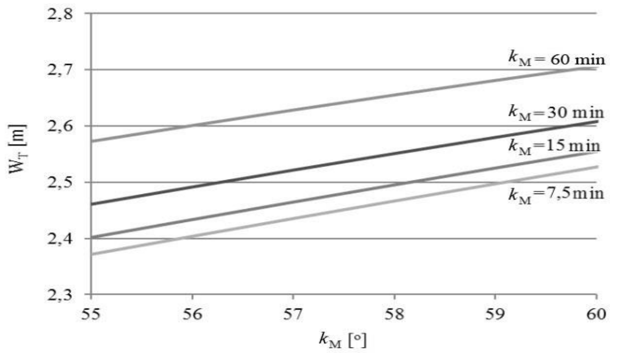

Fig. 6. Change of the width of Λ-ridge concentrator system, depending on the value of the opening angle θ and the tracking step k_M.

Correlation between the increase of step tracking system and the size of the concentrator system was observed on the basis of the obtained data (fig. 5). The width of the mirror *(L_M)* is greater than the width of the photovoltaic panel *(L_{PV})* for the values of parameter k_M=7.5, 15, 30 minutes and the opening angle θ smaller than 55°. In order to ensure the lowest overall size of the system, the tracking step with a resolution of 7.5, 15 or 30 minutes provides the best solution. The size of concentrator system is the smallest (fig. 6) for the first two values, whereas frequent rotation of the tracking system results in increased energy consumption. Therefore, in this case, the most reasonable approach is a step with a value of 30 minutes, which provides a compromise between the size and the consumption energy needed for the rotation of the system.

3. Analysis of geometrical parameters on the basis of numerical simulations.

Amount of incident solar radiation is calculated from the equation [14,15]:

$$B_S = B_0 \cdot \exp\left[\frac{-T_R}{0.9+9.7\cdot sin\alpha}\right] \qquad (3)$$

Where B_s is the direct solar radiation, T_R is the turbidity factor [14], α is the altitude angle and N – day number of a year.

The normal radiation falling onto the surface of the Λ-ridge concentrator system is reflected from the surface of the mirror. Is computed by means of the Lambert Law, as follows:

$$B_{M1,2} = \mu \cdot B_S \cdot cos\left(k_{M1,2}\right) \qquad (4)$$

where the coefficient μ was estimated using the equation (5):

$$\mu = \frac{L_M \cdot cos(\theta+k_M)}{-L_{PV}\cdot \cos(2\cdot\theta+k_M)} \qquad (5)$$

where L_M refers to the length mirror, L_{PV} is the length of the photovoltaic panel, and θ is opening angle.

On the basis of expression (3) the total amount of incident solar radiation on the photovoltaic module was determined depending on value of the tracking step (k_M) and opening angle (θ). The results of numerical simulation are shown in the charts below

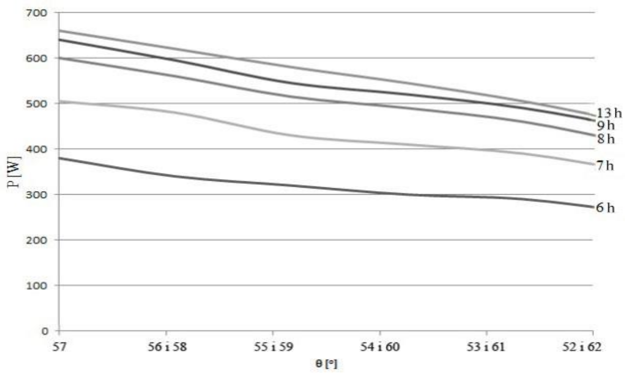

Fig. 7. The amount of energy produced by the Λ-dorsal system hub, depending on the opening angle between the surface and the surface of the photovoltaic panel.

Figure 7 shows a graph of the amount of produced energy depending on the opening angle (θ) for the parameters: N=156, δ=23.5°, TR=4, moderate zone. The system produces the greatest amount of energy for θ=57°, whereas for the opening angle θ equal to 55°, 56°, 58° or 59° the amount of power generated is reduced by 5-8% relative to θ=57°. In the case of an opening angle greater than 60°, the amount of energy produced is reduced by 40%.

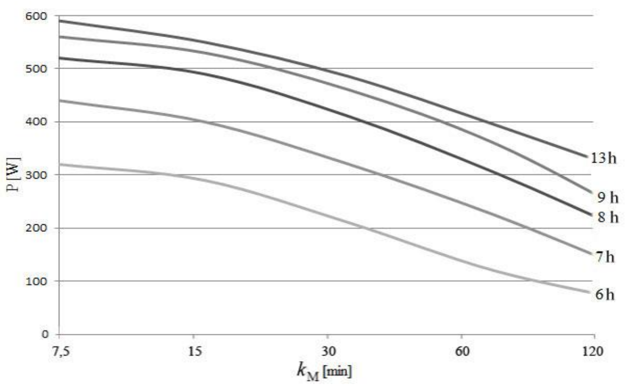

Fig 8. The amount of energy produced by the Λ-ridge concentrator system, depending on the tracking step.

Basing on the data from figure 8 a correlation between the amount of energy produced and the value of the tracking step system (k_M) was observed. The best result was obtained for step k_M=7.5min. For k_M=15min. 9%, were noticed while for k_M=30min 22% decrease in energy received was reported. The increase in the value of the parameter k_M to 2 hours brought about a 48% reduction in produced energy.

Simulations proved that the amount of produced energy highly depends on the opening angle (θ). In addition, inappropriate selection of its value may cause 40% reduction of the power of photovoltaic panel. Similar correlation can be observed taking into account incorrect selection of value tracking step system (k_M). Too frequent rotation of the tracking system results in excessive energy consumption by engines, while rare movement tracking system can cause a 48% reduction of produced energy.

The next step was to analyze the efficiency of Λ-ridge and V-trough concentrator system. It considered the effect of temperature on the efficiency of the solar cells as well as the ratio of the used space of photovoltaic cells to the produced energy.

4. Comparison of Λ-ridge and V-trough concentrator system.

The increase in temperature has a significant impact on the efficiency of photovoltaic panels. The temperature of the solar cell is estimated using the equation:

$$T_{PV} = T_{amb} + (NOCT - 20) \cdot \frac{E}{800} \qquad (6)$$

where T_{amb} is ambient temperature, NOCT is normal operation cell temperature, E is intensity of solar radiation [W/m^2].

Increase of the solar cell temperature results in decrease of its power, power loss reaching 0.47% per 1°C taking into consideration monocrystalline panels. For Λ-ridge and V-trough concentrator system of concentration the value of ratio is respectively 1.6 and 2.4 CR. On a sunny day (T_{amb}=25°C, E=1000W/m^2) the temperature of photovoltaic panel Λ-ridge ($T_{\Lambda PV}$) concentrator system is lower by more than 25°C compared to the temperature of the V-trough (T_{VPV}) system. The temperature difference $T_{\Lambda PV}$ and T_{VPV} brings about a 13% decrease in the efficiency of the V-trough solution compared to solutions for Λ-ridge. Such difference in the efficiency of both systems is reflected in the increase of the required space of the surface of photovoltaic V-trough concentrator in order to obtain an equal amount of energy produced by both systems.

Total size of the discussed systems makes up another criterion for the assessment of such systems. The following graph (fig. 9) shows the ratio of the width the V-trough to Λ-ridge concentrator system, depending on the value of the opening angle of the mirror (θ) and tracking step system (k_M).

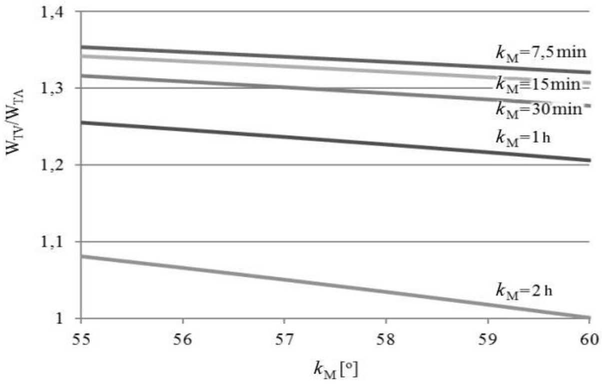

Fig 9. Changing the ratio of the total width the V-trough to the Λ-ridge concentrator system depending on the values of opening angle θ and tracking step k_M.

The increase of the value of the opening angle θ results in a decrease of the overall size of the two concentrator systems. Moreover, ratio of the width $W_{TV}/W_{T\Lambda}$ affects parameter k_M. For the tracking step equal to 7.5, 15 and 30 min. the total surface area of the Λ-ridge concentrator system constitutes ca. 75% of the V-trough area.

Taking into account the above criterion, the coefficient ζ was calculated, i.e. it is the ratio of the amount of produced energy to the total area of the concentrator system. Diagram (fig. 10) shows the value of the coefficient ζ depending on the geographical area.

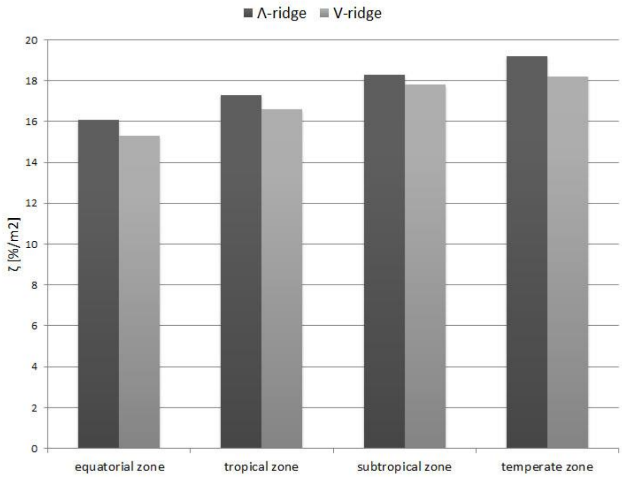

Fig. 10. Change of the value of the coefficient ζ depending on the geographical area

Considering the results of simulation, the evidence clearly shows that the solution of Λ-ridge concentrator system is the best. Nonetheless, taking into account equal, total area of the two systems for the different latitude, efficiency of Λ-ridge concentrator system is about 1.5% higher than the V-trough.

5. Conclusions

In summary, the efficiency of Λ-ridge concentrator system works is influenced by the following parameters: efficiency (η), dimension of the photovoltaic panel (W_T), opening angle (θ), the tracking step system (k_M), horizontal power motor (P_{MH}) and vertical power motor

(P_{MV}). In order to obtain the best performance of the system it is necessary to accept a compromise between the amount of produced energy, the tracking step and the size of the photovoltaic module.

Basing on the obtained results, the following has been found:

1. For constant width photovoltaic panel (L_{PV}), the width of mirrors (L_M) increases proportionally to opening angle (θ) between the surface of the mirror and photovoltaic panel and tracking step (k_M).
2. The increase of resolution tracking step (k_M) causes reduced width of mirror (L_M).
3. Amount of energy produced by the system is tightly linked to opening angle (θ) and the resolution tracking step (k_M).
4. Efficiency of Λ-ridge concentrator system is about 1.5% higher compared to the V-trough solution.

Taking into consideration the insolation at a latitude of 50°, one of the most optimal and reasonable solutions, accompanying good efficiency and acknowledged total size, is to use Λ-ridge concentrator system with the following parameters: opening angle (θ) equal to 57°, the tracking step equal 15 minutes, as well as application of tracking system equipped in two motors with an engine power of 30W (P_{MH}) and 50W (P_{MV}).

6. References

[1] F.R. Rubio et al., *Application of new control strategy for sun tracking*, Energy Conversion and Management 48 (2007) 2174–2184.

[2] V. Poulek, M. Libra, *New solar tracker*, Solar Energy Materials and Solar Cells 51 (1998), 113-120.

[3] P. Roth et al., *Cheap two axis sun following device*, EnergyConversion and Management 46 (2005) 1179–1192.

[4] T. Tomson, *Discrete two-positional tracking of solar collectors*, Renewable Energy 33 (2008), 400–405.

[5] H. Mousazadeh et al., *A review of principle and sun-tracking methods for maximizing solar system output,* Renewable and Sustainable Energy Reviews 13 (2009)

[6] M.J. Clifford, D. Eastwood, *Design of a novel passive solar tracker*, Solar Energy 77 (2004) 269–280.

[7] N. Fraidenraich, *Applications design procedure of V-trough cavities for photovoltaic systems*, Prog. Photovoltaics: Res. Appl. 6 (1998) 43–54.

[8] K.G.T. Hollands, *Concentrator for thin-film solar cells*, Sol. Energy 13 (1971) 149–163.

[9] N. Fraidenraich, G.J. Almeida, *Optical properties of V-trough concentrators*, Sol. Energy 47 (1991) 147–155.

[10] H. Tabor, *Stationary mirror systems for solar collectors*, Solar Energy 2 (1958) 27–33.

[11] A. Rabl, *Comparison of solar concentrators*, Solar Energy 18 (1976) 93–111.

[12] Reis, F., et al., *Power Generation and Energy Yield using Doublesun Photovoltaic Solar Concentration*. In: Proc. 24th EU PVSEC, Hamburg, Germany, September 2009, pp. 803-806.

[13] Luque, A.L., Andreev, V.M., *Concentrator Photovoltaics*. Berlin Heidelberg. Springer-Verlag, 2007.

[14] Meliss, M., *Regenerative Energiequellen.* Berlin. Springer, 1997, pp. 5-7.

[15] I.S. Hermenean, I. Visa, A. Duta, D.V. Diaconescu, *Modelling and optimization a CPV system with equatorial tracking.* Bulletin of the Transilvania University of Brasov, Vol. 3 (52) – 2010.

Janusz Mroczka is a professor of electronic and photonic metrology at Wroclaw University of Technology. He was born in Poland in 1952. In 1991, he received the higher doctor’s degree (habilitation) for a thesis in metrological problems of scattered light application on particle size distribution investigation in dispersed solutions, from the same university. Since 1998, he has been the head of the Chair of Electronic and Photonic Metrology at Wroclaw University of Technology.

His research interests are concentrated on physical and mathematical modeling in complex measurements, inverse problem, intelligent measuring devices, scattering radiation spectral and polarization analysis, and multisensor data fusion and time-frequency representations in data processing. Professor Mroczka is a member of SPIE, a member of the Polish Physical Society, and President of the Committee for Metrology and Instrumentation at the Polish Academy of Science. Since 2010, he has been a Corresponding Member of the Polish Academy of Science.

Kamil Plachta is a PhD student in the Chair of Electronic and Photonic Metrology at Wroclaw University of Technology. He was born in Poland in 1988. He graduated with honors in 2011. He works on the project Λ-ridge concentrator system as part of his PhD thesis. Its objective is to improve the efficiency of commercial photovoltaic panels. His research interests are concentrated on renewable energy. His main interests are electronics and computer science.