Aalborg Universitet

AALBORG UNIVERSITY

Transient Model of Hybrid Concentrated Photovoltaic with Thermoelectric Generator

Mahmoudi Nezhad, Sajjad; Qing, Shaowei; Rezaniakolaei, Alireza; Rosendahl, Lasse Aistrup

Link to publication from Aalborg University

9th International Conference on Applied Energy, ICAE2017, 21-24 August 2017, Cardiff, UK

Transient Model of Hybrid Concentrated Photovoltaic with Thermoelectric Generator

Sajjad Mahmoudinezhad[a], Shaowei Qing[b,c], Alireza Rezaniakolaei[a, *], Lasse Aistrup Rosendahl[a]

[a]*Department of Energy Technology, Aalborg university, Pontoppidanstræde 101, Aalborg DK-9220, Denmark*
[b]*Key Laboratory of Low-grade Energy Utilization Technologies and Systems, Chongqing University, Ministry of Education, China*
[c]*College of Power Engineering, Chongqing University, Chongqing 400044, China*

Abstract

Transient performance of a concentrated photovoltaic thermoelectric (CPV-TEG) hybrid system is modeled and investigated. A heat sink with water, as the working fluid has been implemented as the cold reservoir of the hybrid system to harvest the heat loss from CPV cell and to increase the efficiency and performance of the hybrid module. This investigation is carried out by using a numerical simulation approach with MATLAB software. The governing equations for CPV-TEG hybrid system in transient state is derived and discretized. The results are consisting of the variation of the temperatures, power generation and efficiency of the CPV and TEG with the time in the transient condition.

Keywords: Concentrated Photovoltaic Cell; Thermoelectric Generator; Hybrid Syesystem; Solar Energy; Transient Model.

1. Introduction

The use of solar energy is an important method to reduce the global greenhouse crisis. Due to better utilization of this source of energy it is important to improve the efficiency of photovoltaic (PV) cell. Even while using high efficiency concentrating multi junction (CMJ) cells, more than half of the solar irradiance is not converted into electricity and is dissipated by heat. Harvesting of this heat for increasing the system's efficiency even more can be

* Corresponding author. Tel.: +4521370284; fax: +4598151411.
  E-mail address: alr@et.aau.dk

approached by applying thermoelectric devices. CPV-TE hybrid system could be a prospective way to improve the utilization efficiency of solar energy. Several researches have been carried out focusing on improving efficiency of the hybrid CPV–TE [1-4]. Due to the variation of weather condition, considering transient model in heat transfer is very useful and applicable. A TE module was placed thermally in series with a photovoltaic module by Dallan et al. [5]. It was shown that the PV module's power output within the configuration of the PV–TE hybrid system increases up to 39% under fixed thermal input conditions relative to the PV module's operation in absence of the TEM. Beeri et al. [6] have investigated a CPV–TE hybrid demonstrator experimentally and theoretically. They found that, including Peltier cooling effect, the total contribution of the TEG to the hybrid system's efficiency reached a value of almost 40% at a sun concentration level of 200. Energy conversion and heat transfer process of the spectrum splitting CPV-TE hybrid system was investigated by Ju et al. [7], and an energy based numerical model for CPV-TE hybrid systems was presented. Results show that in comparison with PV-only systems the spectrum splitting PV-TE hybrid systems are more appropriate for working under high concentration condition. The effects of a series of parameters on the PV-TE hybrid system of solar energy utilization have been analyzed by Zhang et al. [8]. They found that among these parameters, temperature is one of the dominant factors, which affects the conversion efficiency of such hybrid systems. They also found that a large convection heat transfer coefficient is beneficial to maintain a larger temperature gradient of the thermoelectric module. Kraemer et al. [9] presented a general optimization methodology for the hybrid systems consisting of (PV) and (TE) modules. They developed the optimization method for the hybrid systems operating at low temperature combined. A thermally coupled model of PV/TEG panel was presented to accurately calculate performance of the hybrid system under dissimilar weather conditions by Rezania et al [10]. They found that with current thermoelectric materials, the power generation by the TEG is insignificant in comparison with electrical output by the PV panel, and the TEG plays only a small role on power generation in the hybrid PV/TEG panel. The possibility of using of thermoelectric generators in solar hybrid systems has been investigated by Urbiola et al. [11]. It was found that the TEG's efficiency had almost linear dependence on the temperature difference ΔT between its plates, reaching 4% at $\Delta T = 155^{o}C$ (hot plate at $200^{o}C$) with 3W of power generated over the matched load. A thermodynamic model for analyzing the performance of a (CPV–TEG) hybrid system including Thomson effect in conjunction with Seebeck, Joule and Fourier heat conduction effects was developed by Lamba and Kaushik [12]. It was observed that by considering Thomson effect in TEG module, the power output of the PV, TE and hybrid PV–TEG systems decreases and at C = 1 and 5, it reduces the power output of hybrid system by 0.7% and 4.78% respectively.

According to previous investigations in the fields CPV-TEG hybrid systems, it can be found that hybrid systems are more efficient for harnessing solar energy. Hybrid systems could be optimized in different ways and also different combinations are exists. Due to variation of weather condition during a day for example in cloudy days, power generation and efficiency of hybrid system will changed with the time. Considering this variation can be very important and practical. The aim of this paper is the investigation of thermal behavior, power generation and also efficiency of CPV-TEG hybrid system in the transient condition for different solar radiations. Therefore, we propose a numerical model with considering some logical simplifying assumptions.

2. Numerical model

Fig.1 illustrates physical model of the CPV-TEG system including the heat sink. In order to verify the effect of the new TEG system with CPV cells, a corresponding numerical model algorithm is established. An unsteady-state heat transfer model with applicable simplifications is used to study the performance of the hybrid system. The main simplifying assumptions are as follows:

- The CPV and TEG modules are insulated thermally, therefor, thermal leakage from the modules to the surroundings is assumed to be zero except the hot surface of the CPV cell and heat dissipation from bottom surfaces of the cells, where are specified as heat source and heat sink, respectively.

- The N- and P- type thermoelements in the TEG are identical in dimensions and material properties.
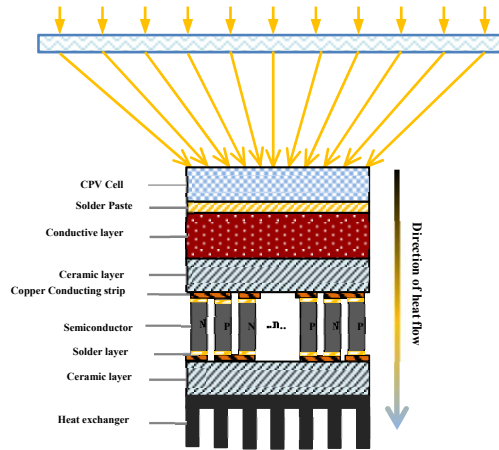

Fig. 1. The physical model of the CPV-TEG hybrid system

- For better consideration of the effect of the sun concentration, all the physical parameters are treated as constant values, except for the Seebeck coefficient, the Thomson coefficient, the electric conductivity and thermal conductivity which are depended on the temperature. And also the figure of the merit of the thermoelectric materials that varies as a key parameter in this study.
- The adjacent end-faces between the components of TEG system are well contacted, so the contact thermal resistance is not considered.

Then, we can construct a one-dimensional unsteady-state heat conduction model:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + q \tag{1}$$

Where ρ, c, x, k, q and T are the density, specific heat capacity, heat transfer direction, thermal conductivity, inner heat source and temperature of different materials, respectively and also t is the time. The inner heat sources of all the components are equal to zero.

By considering transient energy conservation law for the nodes of the CPV cell shown in Fig. 1, the electrical power generation by the cell and the heat flow through it can be calculated according to created set of nonlinear equations. On the top surface of the CPV cell:

$$\rho c V \frac{\partial T}{\partial t} = SC \times G \times A - Q_{rad} + KA \frac{\partial T}{\partial x} - P_{cpv} \tag{2}$$

Where SC, G, Q_{rad}, P_{cpv} are sun concentration, solar radiation, radiated heat loss from the CPV cell to the ambient and power generation of the CPV cell, respectively. Electrical conversion power of the CPV cell is defined based on the solar irradiation on the cell and its conversion efficiency:

$$P_{CPV} = SC \times G \times A_{CPV} \times \eta_{CPV} \tag{3}$$

Where, the efficiency of photovoltaic cells has been traditionally represented with linear expression [13]:

$$\eta_{CPV} = \eta_{T_{ref}}\big[1 - \beta_{ref}\big(T_{CPV} - T_{ref}\big)\big] \tag{4}$$

Where $\eta_{T_{ref}}$ is electrical conversion efficiency of the CPV cell at the reference temperature ($T_{ref} = 25\,°C$) and reference solar radiation ($G_{ref} = 1000\ W/m^2$) [14] and β_{ref} is CPV cell temperature coefficient at the reference temperature which normally given by the manufacturer. The absolute efficiency reduction is $-0.047\,\%/K$ [15].

Power generation and efficiency of CPV and TEG and can easily be calculated after obtaining the temperature of each contact surfaces. By considering the influence of Thomson effect, the electromotive force (EMF) of the TEG device with n_{mod} TE modules is:

$$E = n_{mod}n_{sc}\big[\alpha_{sc,h}T_{sc,h} - \alpha_{sc,c}T_{sc,c} - \textstyle\sum_{i=1}^{m-1}\tau_i(T_i - T_{i+1})\big] \tag{5}$$

Where α and τ are coefficient of Seebeck and Thomson; n_{sc} is the numbers of semiconductors; the subscripts h and c are referred to hot and cold side of semiconductors, respectively.

By taking into account the total internal resistance of the TEG system consists of copper conduction strip, solder layer and semiconductor, which can be expressed as:

$$R_i = n_{mod}\big(n_{ccs}r_{ccs} + n_{sl}r_{sl} + n_{sc}\textstyle\sum_{i=1}^{m}r_{sc,i}\big) \tag{6}$$

Where n_{sl} and n_{sc} and n_{ccs} are numbers of solder layer and semiconductor and copper conduction strip, respectively; r_{sl} and r_{sc} and r_{ccs} are electric resistances of solder layer and semiconductor copper conduction strip, respectively. Then the output power is:

$$P_{TEG} = (E/(R_i + R_L))^2 R_L$$
$$= \big[n_{mod}n_{sc}[\alpha_{sc,h}T_{sc,h} - \alpha_{sc,c}T_{sc,c} - \textstyle\sum_{i=1}^{m-1}\tau_i(T_i - T_{i+1})]\big]^2 R_L \big/ \big[n_{mod}(n_{ccs}r_{ccs} + n_{sl}r_{sl} + n_{sc}\textstyle\sum_{i=1}^{m}r_{sc,i}) + R_L\big]^2 \tag{7}$$

Also the efficiency of the TEG within a specified interval of Δt, is obtained by:

$$\eta_{TEG} = P_{TEG}\big/\big(SC \times G \times A - Q_{rad} - P_{cpv}\big) \tag{8}$$

3. Results and discussion

This study prepared a comprehensive method to predict the transient behavior of CPV-TE hybrid systems. The effect of the solar radiation during a typical period of time in wet season [16] on the efficiency of the hybrid module is considered. In the floating condition like cloudy weather, transient heat transfer will be more noticeable and power generation and efficiency of CPV-TEG system become more important. Variation of solar radiation in 15 minutes for a typical cloudy day is shown in Fig. 2(a).

In this investigation, sun concentration (SC) and heat transfer coefficient for the heat sink are considered 200 and $1000 W/m^2 . K$ respectively. The dynamic response of the temperatures of hot side and cold side of TEG and also on the surface of CPV cell in the CPV-TEG hybrid system is shown in Fig. 2(b). It can be seen that all the temperatures are directly influenced by the sharp fluctuations of the sun radiation.

As it can be seen the temperatures of the hot side of TEG and surface of CPV are almost the same and the temperature of the cold side of TEG is also varied in a same manner but by a time delay. This delay is because of the time which heat passes through the CPV and the components of TEG. All of the temperatures are changed by variation of sun radiation which presented in fig. 2(a). Obviously by increasing the sun radiation during the time, all temperatures are increased and vice versa. One another important point in the fig. 2(b) is related to the low sun

radiations. As it can be seen, in the small sun radiations, all the temperatures are very close to each other. It is clearly due to low amount of heat transfer through the hybrid system.
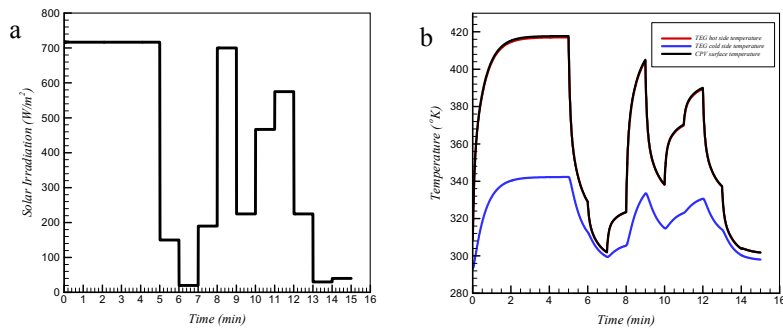

Fig. 2. (a) Variation of solar radiation by the time; (b) Variation of the temperatures of hot side and cold side of TEG and surface of CPV cell

Fig. 3(a) shows the power generation by the CPV during the time. By comparing fig. 2(a) and fig. 3(a) it is very clear that in high sun radiations, there is more power generation and due to dependency of CPV power (P_{CPV}) to the sun radiation it was predictable. Temperature difference between the hot side and cold side of the TEG has the most important effect in the power generation by the TEG. Power output by the TEG is presented in fig. 3(b). By comparing results in the fig. 2(b) and fig. 3(b), the importance of this effect will be approved. As it can be seen, everywhere that temperature difference is high, more power will produced and vice versa.
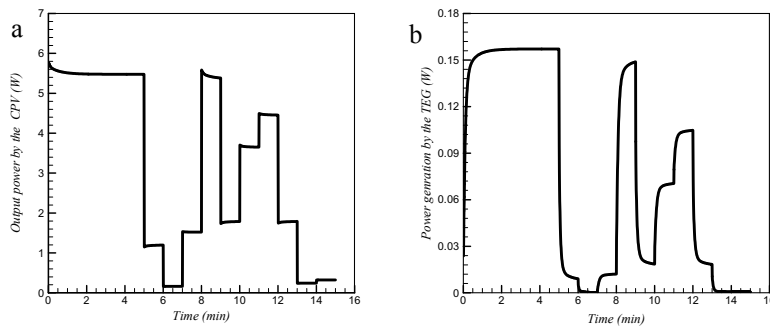

Fig. 3. (a) Power generation by the CPV; (b) Power generation by the TEG
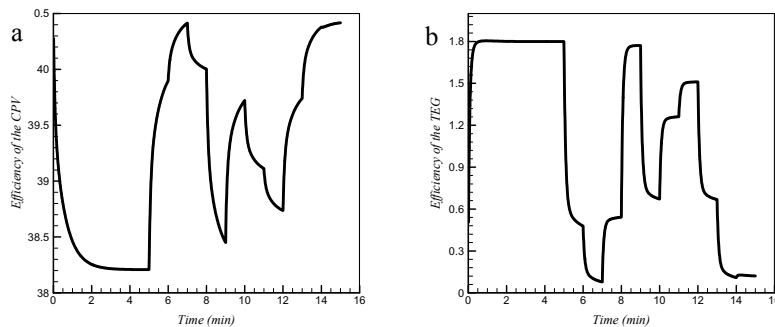

Fig. 4. (a) Efficiency of the CPV; (b) Efficiency of the TEG

Fig. 4(a) illustrates the variation of the efficiency of the CPV as a function of time. By taking into account the variation of the temperature of the CPV cell in the fig. 2(b), by increasing the temperature of the CPV cell, the efficiency will be decreased and vice versa. It is completely compatible with the equation of the efficiency of the CPV. Fig. 4(b) shows the efficiency of the TEG. As it can be observed, due to the low power generation and also small temperature difference between the hot side and cold side of the TEG the amount of the efficiency is not very significant. Although in the higher solar concentrations and temperature differences and also with using materials with higher ZT, the efficiency and power generation by TEG will be increased.

4. Conclusion

Transient power generation and efficiency of a CPV-TEG hybrid system has been investigated. Temperature variation for the CPV and hot side and cold side of TEG also was presented. The results also showed that with increasing the sun radiation, the power generation by CPV and TEG increased. However, the efficiency of the CPV is reduced by increasing the sun radiation. The system could be optimized with optimization of the TEG geometries, thermoelectric materials properties and using a more efficient heat sink.

Acknowledgements

References

[1] Al-Nimr MA, Tashtoush BM, Jaradat AA. Modeling and simulation of thermoelectric device working as a heat pump and an electric generator under Mediterranean climate. Energy 2015;90(Part 2):1239–50.
[2] Wang N, Han L, He H, et al. A novel high performance photovoltaic– thermoelectric hybrid device. Energy Environ Sci 2011;4(9):3676–9.
[3] Rezania A, Rosendahl LA. Feasibility and parametric evaluation of hybrid concentrated photovoltaic-thermoelectric system. Appl Energy 2017;187:380–9.
[4] Wu YY, Wu SY, Xiao L. Performance analysis of photovoltaic–thermoelectric hybrid system with and without glass cover. Energy Convers. Manage 2015;93:151–9.
[5] Dallan BS, Schumann J, Frédéric JL. Performance evaluation of a photoelectric– thermoelectric cogeneration hybrid system. Sol. Energy 2015;118:276–85.
[6] Beeri O, Rotem O, Hazan E, Katz EA, Braun A, and Gelbstein Y. Hybrid photovoltaic-thermoelectric system for concentrated solar energy conversion: Experimental realization and modeling, J. Appl. Phys 2015; 118: 115104–1.
[7] Ju X, Wang Z, Flamant G, Li P, Zhao W. Numerical analysis and optimization of a spectrum splitting concentration photovoltaic-thermoelectric hybrid system. Sol. Energy 2012; 86:1941–54.
[8] Zhang J, Xuan Y, Yang L. Performance estimation of photovoltaic-thermoelectric hybrid Systems. Energy 2014;78:895-903.
[9] Kraemer D, Hu L, Muto A, Chen X, Chen G, Chiesa M. Photovoltaic-thermoelectric hybrid systems: A general optimization methodology. Appl. Phys. Lett 2008;92:243503–1.
[10] Rezania A, Sera D, Rosendahl LA. Coupled thermal model of photovoltaic-thermoelectric hybrid panel for sample cities in Europe. Renewable Energy 2016;99:127-135.
[11] Urbiola EAC, Vorobiev YV, Bulat LP. Solar hybrid systems with thermoelectric generators. Sol. Energy 2012;86: 369–78.
[12] Lamba R, Kaushik SC. Modeling and performance analysis of a concentrated photovoltaic– thermoelectric hybrid power generation system. Energy Convers. Manage 2016;115: 288–298.
[13] Notton G, Cristofari C, Mattei M, Poggi P. Modelling of a double-glass photovoltaic module using finite differences. Appl. Therm. Eng 2005;25:2854–77.
[14] Evans DL. Simplified method for predicting photovoltaic array output. Sol. Energy 1981;27: 555–60.
[15] AZUR SPACE Solar Power GmbH, Concentrator triple junction solar cell, Cell Type: 3C42-10 × 10 mm^2, Data Sheet (HNR 0003877-00-00), [Cited: June, 2016].
[16] Mi Z, Chen J, Chen N, Bai Y, Wu W, Fu R, Liu H. Performance Analysis of a Grid-connected High Concentrating Photovoltaic System under Practical Operation Conditions. Energies 2016, 9, 117; doi:10.3390/en9020117.