Performance Enhancement of Building Integrated Photovoltaic Module using Thermoelectric Cooling

Arati Kane*‡, Dr.Vishal Verma**

*Bharati Vidyapeeth College of Engineering

**Delhi Technological University

sanikakane@rediffmail.com, vishalverma@dce.ac.in

‡ Corresponding Author; Arati Kane, Bharati Vidyapeeth College of Engineering, Delhi, India, sanikakane@rediffmail.com

Received: 05.02.2013 Accepted: 04.04.2013

Abstract- Performance of solar panel decreases with increase in the temperature of the panel. Output power of PV module drops by 0.45% per ^{o}C rise in temperature if heat is not removed. In Building Integrated Photovoltaic System (BIPV) temperature rise is more as heat transfer due to convection is not possible from rear side of the panel. Cooling of the modules would enhance the performance of the module. In order to cool this system thermoelectric system is developed. Thermoelectric module is attached at the back of PV module and it is operated in cooling mode. This paper discusses about the development of BIPV/Thermoelectric system. Initially mathematical modeling of individual systems is carried out. Later on the dynamic model of BIPV/Thermoelectric system with consideration of temperature of PV panel temperature has been developed. This paper presents performance improvement of BIPV system with Thermoelectric cooling.

Keywords-

1. Introduction

As the world is facing critical problem of energy deficit, global warming and detoriation of environment and energy sources, renewable energy sources are getting more attention. Solar energy is one of the comparable candidates. Solar energy is widely available and it is free of cost. Solar energy can be converted into direct current electricity by

PV effect. PV system is static, noiseless and free of moving parts which reduces operation and maintenance cost of the system. Being clean and pollution free source of energy PV system has gained much importance. It is a relatively expensive means of producing electricity due to its high fabrication cost and less conversion efficiency. Output power of PV system depends on solar irradiance, temperature of solar cell and operating voltage. Building integrated photovoltaic system (BIPV) can be considered as economical system by taking advantage of PV technology and providing benefits in addition to energy production like weatherproofing, insulation, and even structural strength to the building.

Electrical energy is one of the components of solar energy conversion process. A typical PV module has ideal conversion efficiency in the range of 15% [2]. The remaining energy is converted into heat and this heat increases operating temperature of PV system which affects electrical power production of PV modules. The main problem with BIPV system is heat built up under PV modules. As the heat transfer process due to convection from rear side of PV module is stopped in BIPV system as the module is mounted on wall directly. Temperature of the module can rise upto 70^{o}C, this can cause structural damage of PV modules shorting its life span and lowering conversion efficiency [7]. Output power of PV module drops by 0.45% per ^{o}C rise in temperature if heat is not removed. Aim of this paper is to remove excess heat generated by PV modules to increase the performance of PV modules and to utilize the excess heat appropriately.

Thermoelectric technology provides alternative to traditional methods of power generation, heating/cooling and generation from waste heat. Thermoelectric module can convert heat energy into electrical energy directly. Thermoelectric phenomenon was observed by Seebeck. A small amount of power is generated by TEM if temperature difference is maintained between two terminals as shown in Fig.1 or it can operated as a heat pump based on Seebeck/Peltier effects. TEM possess salient features of being compact, light weighted, noiseless in operation, highly reliable, maintenance free and no moving or complex parts. TEM is composed of p-type and n-type thermo elements electrical connected in series and thermally parallel with electrical insulation is provided by two ceramic plates which serves as foundation for the module as shown in Fig.1. As TEM is bi-directional device which can be operated in Heating/Cooling mode [5] or Power generation mode, this working portability is used in BIPV system for cooling PV module and to generate additional electrical energy [9]. To develop efficient and cost effective system BIPV and Thermoelectric system are to be combined and hybrid model of BIPV/TE system needs to be developed.

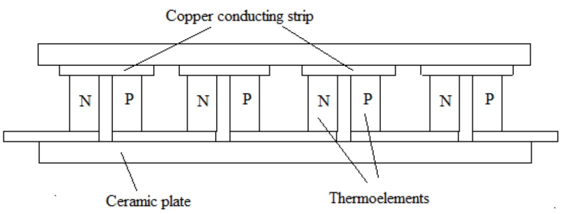

Fig. 1. Basic single stage thermoelectric module

When a temperature difference is maintained across two junctions of the module, electrical power will be delivered to an external load and the device operates in generation mode as shown in Fig.2

2. Thermoelectric Module

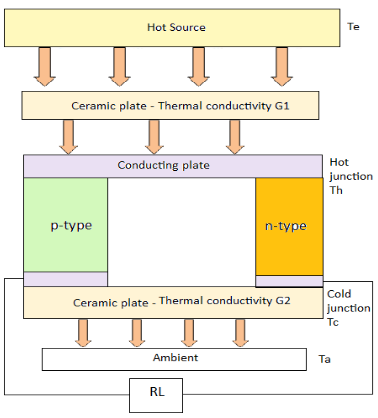

Fig. 2. A single thermoelectric couple used as Generator

The Seebeck voltage V_s (EMF) of the TEM is given by

$$V_s = \alpha(T_h - T_c) \quad (1)$$

where T_h and T_c are hot and cold junction temperatures and α is Seebeck coefficient. By applying energy balance equations for steady state conditions and introducing Joule heat equally distributed throughout the volume of TEM, Peltier terms αITh and αITc at the two boundary points heat at hot junction q_h and at the cold junction q_c can be computed.

$$q_h = \alpha\, IT_h + G(T_h - T_c) - I^2\, R/2 \quad (2)$$

$$q_c = \alpha IT_c + G(T_h - T_c) - I^2\, R/2 \quad (3)$$

where G and R are total thermal conductance and internal resistance of TEM.

The rate of heat flow from the high temperature heat source to TEM and from TEM to heat sink are considered as two externally irreversible heat transfer process then we can get

$$q_h = G_1(T_e - T_h) \quad (4)$$

$$q_c = G_2(T_c - T_a) \quad (5)$$

where G_1 and G_2 are the interface thermal conductance between the generator and the heat source and sink in the hot and cold sides, respectively.

The expression of current in the generator supplied by the built-in Seebeck voltage is given as:

$$I = \frac{\alpha_m(T_h - T_c)}{R_m + R_L} \quad (6)$$

Output voltage V across the load R_L is expressed as

$$V = \alpha(T_h - T_c) - IR \quad (7)$$

Maximum power can be calculated using equation (8) as shown below

$$P_m = \alpha_m[(T_h)_m - (T_c)_m] I_m - (I_m)^2 R \quad (8)$$

2.1. Mathematical Modeling of TEM

Mathematical model of TEM for heating/cooling mode have been well developed to simulate their corresponding behavior and analyze the performance and to optimize it. MATLAB SIMULINK offer gives the advantage of writing programs in user defined S-function. S-Function can compute a set of program and interface with simulink model to enable dynamic changes through passing of parameters. In this model 'Tcold' S-Function is developed to calculate temperature at the cold junction. The inputs to this function are T_h, and I respectively. Equations (1)-(8) are used to build a model [9]. Ambient temperature is input variable for the model. In addition the load resistance is selected to equal the effective internal resistance of the thermoelectric module for maximum power purpose. Output parameters are stored in .mat file for comparison and further analysis.

TEM is supplied with DC current source with one junction kept at known temperature and depending on the direction of current flows through TEM other junction will become hot or cold. In this paper TEM is used in cooling mode where hot side of TEM is exposed to atmosphere and cold side is attached to the object to be cooled. Mathematical model of TEC is shown in Fig.3.

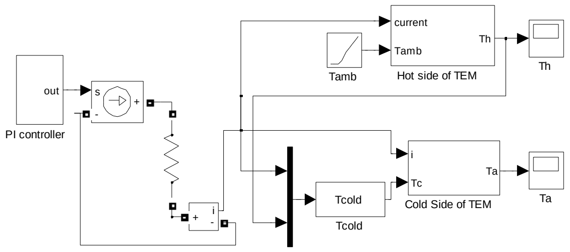

Fig. 3. Mathematical model of TEM developed for cooling mode

3. Photovoltaic Module-

Solar cell converts electromagnetic radiation into electricity by PV effect. When cells are exposed to appropriate wavelengths, electrons in p-type region will be excited from valence band to conduction band and they contribute to a current. The equivalent circuit of solar cell represented by connecting current source in parallel with a diode is shown in Fig. 4

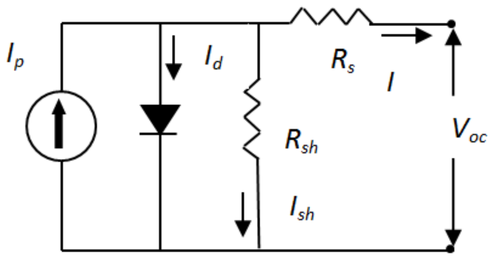

Fig. 4. Equivalent circuit of solar cell

In ideal solar cell series and parallel resistance are not present but in practical case these resistance are included due to ohmic resistances and leakage current. If solar cell is not exposed to solar irradiation, it behaves as p-n junction diode and if connected to external supply it generates a current I_D, diode current. Characteristic equation of solar cell is given as [1]-[4]

$$I = I_L - I_0\left[\exp\left(\frac{qv}{nkT}\right) - 1\right] - \frac{v+IR_s}{R_{sh}} \tag{9}$$

where

I_L-Light generated current
I_0- Diode saturation current
k- Boltzmann's constant (1.38×10^{-23}J/K)
q- Electric charge (1.69×10^{-19}C)
n- Ideal factor
R_s-Series resistance
R_{sh}-Parallel resistance
T- Absolute temperature
The open circuit voltage V_{oc} is given as

$$V_{oc} = \frac{kT}{q}\ln\left[\frac{I_L}{I_0}+1\right] \cong \frac{kT}{q}\ln\left[\frac{I_L}{I_0}\right] \tag{10}$$

When temperature increases amount of saturation current will increase more than amount of photocurrent and therefore makes V_{oc} decreased rapidly. The effect of temperature is shown in Fig. 5

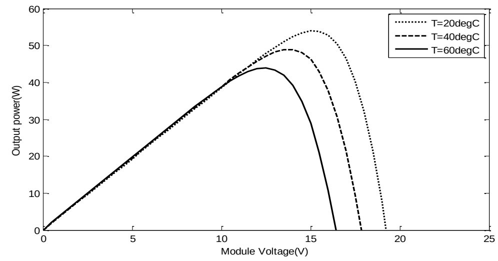

Fig. 5. Effect of PV module temperature on the output power

Efficiency of PV module based on manufacturer data is given as

$$\eta_{pv} = \eta_{ref}\left[1 - \beta(T_{mod} - T_{ref}) + \gamma log\left(\frac{G}{G_{ref}}\right)\right] \tag{11}$$

with η_{ref} is reference module efficiency at reference temperature T_{ref} for reference solar irradiation . γ and β are the solar irradiance and temperature coefficients provided by manufacturer. Fig.6 shows the effect of solar irradiance on the efficiency at various module temperatures.

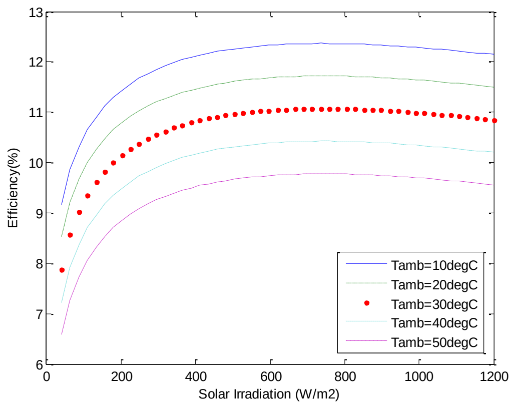

Fig. 6. Variation in Efficiency with solar irradiation

Efficiency begins to increase with increasing solar irradiation then decreases because at high solar irradiance PV module temperature is high and temperature influence counterbalances solar irradiation effect. Fig.6. depicts decrease in efficiency at low and high irradiation levels.

Cooling of the PV panel will lower the PV module temperature and hence enhance the efficiency.

3.1. Mathematical Model of PV Cell

Mathematical model of PV cell is developed with consideration of the influence of ambient radiation G and cell temperature T on the cell characteristics as shown in Fig.2 Solar cell temperature can be computed by considering atmospheric temperature, solar irradiation and heat transfer due to conduction, convection and radiation [10]. In BIPV system convection from rear surface is negligible. Equations (1) and (2) are used for model development. The effects of changing temperature and solar irradiation are modeled inside the 'PV' S-Function.

Developed model is dynamic as cell temperature varies with variation in solar radiation, ambient temperature and wind speed.

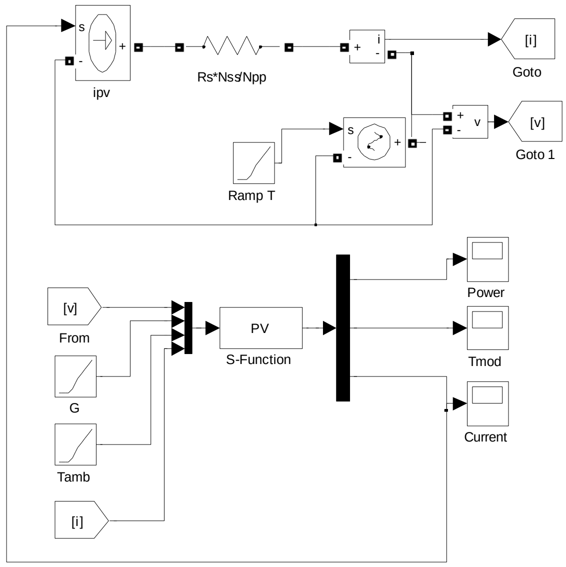

Fig. 7. Model of solar cell showing module temperature dependence on power output

4. BIPV/TEG Modeling

Heat sink is attached to the hot side of TEM to increase heat transfer process and this assembly is attached at the back side of PV module. Hot side of TEM is exposed to ambient temperature and cold side is attached to the PV module as shown in Fig.8. Under high solar irradiation conditions panel temperature generally reaches upto 60-80 ^{o}C.

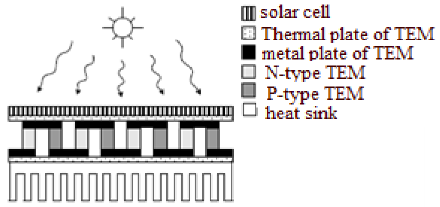

Fig. 8. PV cooling module with TEM attachment.

PI(Proportional Integral) controller has been used to control temperature of cold side of the module. Current calculator block calculates the current required to operate TEC for given temperature as depicted in Fig. 9.

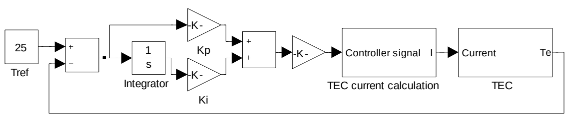

Fig. 9. PI controller for TEC system.

Fig.10. shows BIPV/TEG hybrid system with PI controller to control temperature of PV panel. In this model PV and TEC two S-Functions are developed for PV and TEC modeling with PV module temperature is feedback to PI controller.

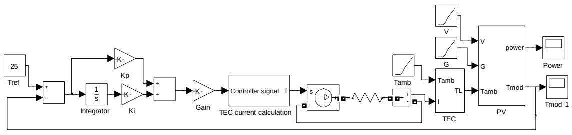

Fig. 10. Matlab model for PV/TEG system

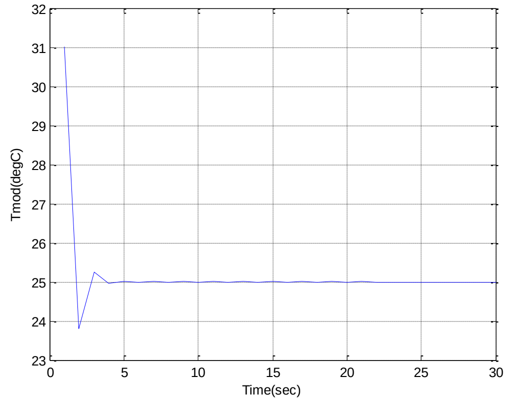

Fig. 11. Response of PI controller with reference temperature at 25^{o}C

Fig. 11. shows response of PI controller for G=1000W/m2, Tamb=35^{o}C and PV module temperature is controlled to 25^{o}C.

5. Result

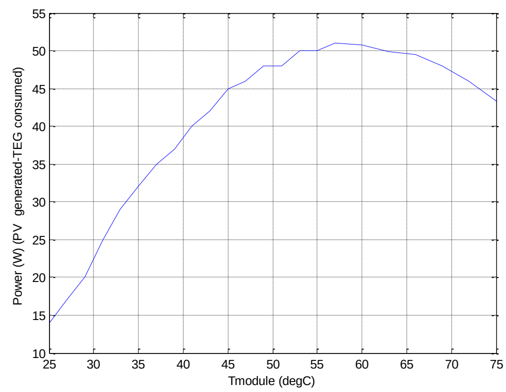

Fig. 12. Solar irradiation and temperature of PV

Fig.12 depicts that maximum power generated by PV module is 50W at 1000W/m^2 solar irradiation and at ambient temperature of 35 ^{o}C. Simulated temperature of PV model without cooling is 63.5 ^{o}C. Power generated with combined PV/TEC system with controlled PV panel temperature is plotted in Fig.12. More power can be drawn from a PV system by operating at lower temperature for the same solar irradiation. Operating power of Thermoelectric system also depends upon the PV module temperature at low PV module temperature TEC consumes more power. This power must be less than power gain from PV system. This simulation can provide a way to quantify the available power increase from cooling. The results show that PV/TEC combined system can be operated at 53 ^{o}C PV module temperature without loss of PV power thus module can be cooled down by 10 ^{o}C which will enhance life of PV module.

6. Conclusion

This paper proposes an application of Thermoelectric cooling system for PV module for the enhancement of efficiency and life time of module. Results of the simulation shows that proposed cooling method improves efficiency of PV module but at the cost of minimal power loss. The detailed analysis of the model indicates that performance and life enhancement of BIPV module could be achieved with 10^{o}C cooling without loss of power.

It is proposed to use TEM application as power generator utilizing heat generated at PV module and PV/TEG system with complimentary use of cooling and heating application for best efficiency improvement of PV system in next phase of research.

References

[1] Duffie, J.A. & Beckman, W.A. (1991), Solar Engineering of Thermal Processes, 2nd Edition, Wiley-Interscience, New York

[2] Stuart R. Wenham, Martin A. Green, “Applied photovoltaics”, ISBN:1844074013, Feb 2007

[3] R J. A. Gow, C. D. Manning “Development of a photovoltaic array model for use in power electronics simulation studies,” IEE Proceedings on Electric Power Applications, vol. 146, no. 2, pp. 193-200, March 1999.

[4] Notton G, Lazarov V, Stoyanov L., “Optimal sizing of a grid-connected PV system for various PV module technologies and inclinations, inverter efficiency characteristics and locations.” Renew Energ 2010.

[5] Jung-Sik Choi, Jae-Sub Ko, and Dong-Hwa Chung, “Development of a Thermoelectric Cooling System for a High Efficiency BIPV Module”, Journal of Power Electronics, Vol. 10, No. 2, March 2010, pp. 187-193.

[6] R.C.Chu, R.E. Simons, “Application of Thermoelectrics to Cooling Electronics : Review and Prospects”, International Conference on Thermoelectrics, 1999, pp. 270-279.

[7] Dajiang Yang, Huiming Yin, “Energy Conversion Efficiency of a Novel Hybrid Solar System for Photovoltaic, Thermoelectric, and Heat Utilization”, IEEE Transactions on Energy Conversion, Vol. 26, NO. 2, JUNE 2011, pp.662-670 used for generation.

[8] R.E. Simons, R. C. Chu, “Application of Thermoelectric Cooling to Electronic Equipment: A Review and Analysis”, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68-73.

[9] Chih Wu;“Analysis of waste-heat thermoelectric power generators,” Applied Thermal Engineering vol. 16, No. 1, pp. 63-69.

[10] Mark W. Davis, Brian P. Dougherty and A. Hunter Fanney, “Prediction of Building Integrated Photovoltaic Cell Temperatures”, Transactions of ASME, Journal of Solar Energy Engineering, Special Issued: Solar Thermochemical Processing, Vol. 123, No. 2, August 2001, pp. 200-210.