IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676,p-ISSN: 2320-3331, Volume 10, Issue 3 Ver. III (May – Jun. 2015), PP 71-76
www.iosrjournals.org

Modelling and Simulation of Solar Thermoelectric Generator

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Abstract:*Thermoelectric generators (TEGs) are energy conversion devices, which unlike conventional heat engines are entirely solidstate;extremely reliable, safe, simple, compact andenvironmentally friendly.This paper presents implementations and verification of models of thermoelectric generator modules using Matlab/Simulink. Mathematical models of thermoelectric module for thermoelectric generators have been well developed to simulate their corresponding behaviours and analyse their performance. The TEG models proposed herein are compatible with Matlab/Simulink libraries for further DC and AC electronic circuit simulation.*

1. Introduction

The global energy crisis has motivated researchers to explore alternative means of generating power.One approach to providing electrical energy is by direct conversion of heat to electricity using thermoelectric generators (TEGs). It is attractive to use TEGs because they have no mechanical parts, resulting in a power system that is silent, virtually unlimited lifetime,reliable, and environment-friendly [1].

In the early 1800s,thermoelectricity was initially discovered. A voltage is generated when a junction of two dissimilar materials is held at a temperature gradient. Due to the prevalence of semiconductor materialsthermoelectric materials began to be made with n-type and p-type structure in the middle of the 1900s. Through control of the carrier concentration, the optimization of the bandgap can be achieved for the thermoelectric couple. Most of the thermocouples are then interconnected electrically in series to increase the operating voltage and thermally in parallel to increase the thermal conductivity, forminga thermoelectric module (TEM) [2].

A major challenge in the design of TEGs is its limited efficiency. A typical thermoelectric device exhibits only 5-10% conversion efficiency depending on the materials used and the temperature difference involved [3]. At the same time, the best solar cell at present is 3-5 times more efficient than thermoelectric devices [4]. The most effective way to increase the conversion efficiency of a TEG is by increasing the temperature difference across the thermoelement's surface which can be realized by using a high input heat flux such as that coming from the sun [5]. Hence, we propose to improve the efficiency of TEGs by utilizing a solar concentrator to focus solar radiation onto the hot junction of the TEG. It results; the temperature gradient across the device can be increased; subsequently improving the TEG's efficiency.

2. Basic Principle Of Thermoelectric Generator

In 1822, Seebeck observed that when two electrically conducting materials are connected in a closed loop and a temperature difference at the two junctions T1 and T2 is appliedas shown in Figure 1, then there was a deflection of the magnetic needle in his measurement apparatus [6, 7]. The deflection was dependent on the temperature difference between junctions and the materials used for the conductors.After some time of this, Oersted discovered the interaction between an electric current and a magnetic needle. After this, many scientists subsequently researched the relationship between electric currents and magnetic fields including Ampère, Biot, Savart, Laplace and others.

Through these studies it was discovered that the observation by Seebeck was not caused by a magnetic polarization, it was caused by electrical current flowing in the closed loop circuit. The electromotive force or induced voltage which is driving this electric current can be measured by breaking the closed loop of Figure 1. The open circuit voltage is represented as ΔVwhich is given by

$$\Delta V = S_{AB}\,(T_2 - T_1)$$

Here $S_{AB}$is the Seebeck coefficient for the two conductors which is defined as being positive when a positive voltage is measured for $T_1 < T_2$. The voltage is measured across terminals maintained at a constant temperature T_0 as shown in Figure 2.

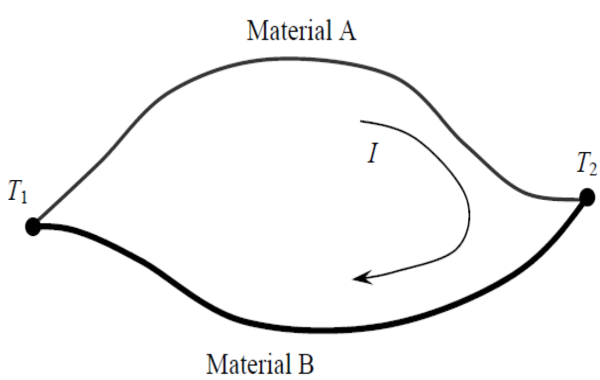

Fig 1- Closed circuit of Seebeck effect

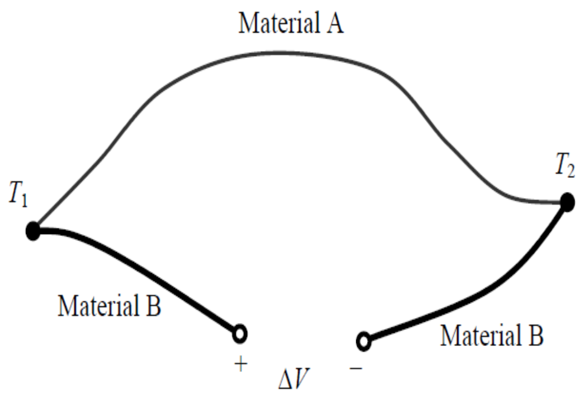

Fig 2- Open circuit Seebeck effect

While the Seebeck effect is associated with a couple formed by two materials, it was laterdiscovered through the Thompson effect that an absolute Seebeck coefficient could beassociated with each material individually asS_{AB}= S_A–S_B.

3. Solar TE Material Categories

Thermoelectric materials comprise a huge family, including various materials from semimetals and semiconductors to ceramics, containing various crystalline forms from monocrystals and polycrystals to Nano composites and covering varying dimensions from bulk, films and wires to clusters. Recently, certain polymers have also been shown to exhibit interesting thermoelectric material properties [8].

i. Metal-based thermoelectrics
ii. Ceramics
iii. Polymers
iv. Semiconductors

4. Governing Parameters For Thermoelectric Material Selection:

Governingparameters are based onintrinsic material propertieswhich are as follows [9]-

i. Energy gap and band structure in semiconductors
ii. Charge carrier concentration
iii. Mobility

5. Solar Thermo-Electric Generator Based On Design

For increasing the efficiency of thermoelectric generator different designs are taken as consideration [10].

i. U- shaped TE generator
a) U- shaped TE generator with external oven
b) U- shaped TE generator with catalytic combustion chamber
ii. Multipass TE generator

6. Design And Modelling Of Solar Thermoelectric Generators

The proposed system, illustrated in Fig 3, of using solar concentrators in conjunction with TEGs has already been demonstrated using commercially-available components [11]. At the micro scale, 7-8 times efficiency improvement by utilizing both solar and thermal concentration on a pair of vertically-oriented nanostructured bismuth telluride alloys has been established [12]. Although no implementation of solar TEGs employing lateral thermoelectric materials have been found at the micro scale, the concept of using a lens in conjunction with lateral TEGs to serve as on-chip supply to a microactuator have been presented [13]. This motivates further work on the design, modelling, andsimulation of lateral solar micro-TEGs.

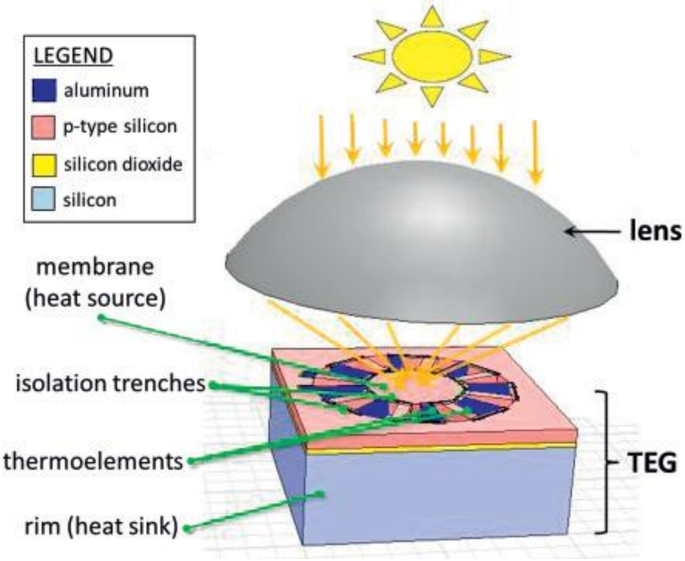

Fig 3- Solar TEG with a lens concentrating solar radiation onto the device [14]

Suppose the sun uniformly irradiates energy density qsonto the lens, then the heat power density qhof the incoming heat flux to the TEG membrane is given by:

$q_h = \gamma\, \zeta_{lens} \alpha_{mem} q_s$.. (1)

Whereγ is the concentration factor, ζ_{lens} is the lens transmittance, and α_{mem} is the membrane absorptance.

With this approach, we can generate an input heat flux in the order of hundreds of kW/m^2. The general heat transfer equation shows that an increase in the input heat flux would translate to a corresponding increase in the temperature difference across the thermoelements; also resulting in an effective increase in its output voltage. The amount of input power on the TEG membrane is the product of the input heat flux (qh) and the heated membrane area, Ah.

6.1 Thermal and electrical model

To investigate effects of variations in several design parameters, an analytical model of the solar TEG system is developed. The thermal and electrical equivalent circuits are shown in Fig 4.

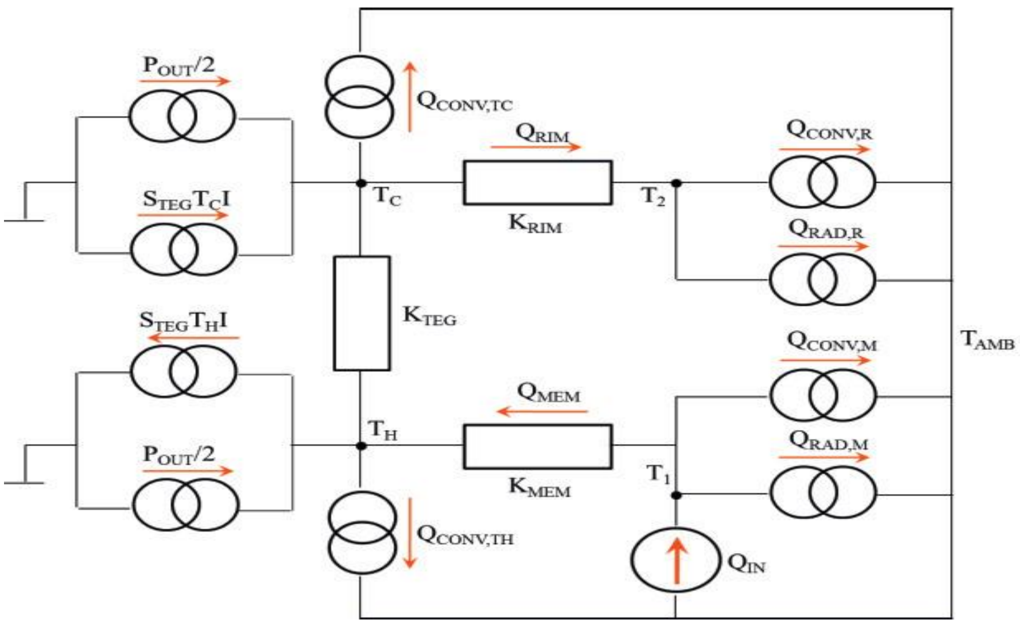

Fig 4(a)- Thermal equivalent circuit [14]

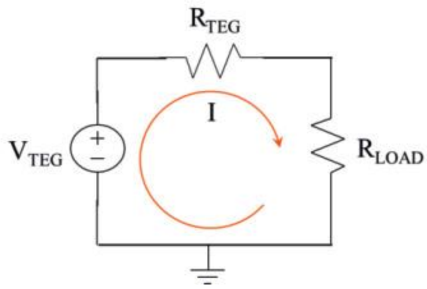

Fig 4(b) -Thevenin equivalent circuit of solar TEG [14]

6.2 Mathematical analyses

$Q_{MEM} = Q_{IN} - Q_{RAD,M} - Q_{CONV,M}$
$= qh\ Ah - \varepsilon\ \sigma\ A_{MEM}(T_1^4 - T_{AMB}^4) - hc\ A_{MEM}(T1 - T_{AMB})$ ....(2)

$Q_{MEM} = Q_{CONV,TH} + K_{TEG}(T_H - T_C) + S_{TEG}T_HI - 1/2\ P_{OUT}$
$= hcA_{TEG}(T_H - T_{AMB}) + K_{TEG}\Delta T + S_{TEG}\ (T1 - (Q_{MEM} / K_{MEM})) - 1/2\ P_{OUT}$ ....(3)

$Q_{RIM} = K_{TEG}\ (TH - TC) + S_{TEG}T_CI - Q_{CONV,TC} + 1/2\ P_{OUT}$
$= K_{TEG}\Delta T + S_{TEG}\ (T2 + (Q_{RIM} / K_{RIM})) - hcA_{TEG}(T_C - T_{AMB}) + 1/2\ P_{OUT}$ ....(4)

$Q_{RIM} = Q_{RAD,R} + Q_{CONV,R}$
$= \varepsilon\ \sigma\ A_{RIM}(T_2^4 - T_{AMB}^4) + hcA_{RIM}(T_2 - T_{AMB})$ ....(5)

$T_1 - T_2 = Q_{MEM} / K_{MEM} + \Delta T + Q_{RIM} / K_{RIM}$... (6)

$P_{OUT} = V_{TEG}^2 / (4\cdot R_{TEG}) = (S_{TEG}\cdot\Delta T)^2 / (4\cdot R_{TEG})$ -- under matched load conditions

WhereK $_{MEM}$, k $_{RIM}$, and $K_{TEG}$are the lumped thermal conductance of the membrane, rim, and thermocouples, respectively; A_{MEM}, A_{RIM}, and $A_{TEG}$are the surface area of the membrane, rim, and thermocouples, respectively; ε is the surface emissivity; σ is the Stefan-Boltzmann constant; hcis the convective heat transfer coefficient; and $S_{TEG}$is the Seebeck coefficient of the TEG [14].

6.3Thermoelectric module using MATLAB/SIMULINK

Mathematical models of TEM for TEGs have been well developed to simulate their corresponding behaviours and analyse their performance. Modelling and simulation allows for design, optimization of TEMs andanalysis to cut down the design cycle. In recent era, equivalent circuit models of TEMs have been built using SPICE software for easy module analysis and for further extraction of model parameters from specifications in commercial datasheets.

Basically, equivalent-circuit models implemented using SPICE are suitable for simulation of power-electronics applications. Now for the control purpose, it is better to build a TEM model using the Matlab/Simulink package and further to use its SimPowerSystem tool, especially for the development of temperature control and maximum power point tracking (MPPT) technologies for TEG applications.

7. Simulation Results

Taking an HZ-20 module for example, the manufacturer's datasheets show that $T_H = 230^0$C, $T_C = 30^0$C, Wm = 19 W, Vm = 2.38 V, and $n_{max} = 4.5\%$.
Through the TEG module block, one can calculate the model parameters: S = 0.0238 V/K; R = 0.2981X; K_{th} = 1.6985 W/K, and Z = 0.0011 K^{-1}; as shown in output results.
Here T_H andT_C are the temperature of hot and cold surface respectively. Similarly Wm, Vm, n_{max}arethe maximum power, maximum voltage and maximum efficiency.

7.1 Current v/s voltage (I-V)characteristic of TEG

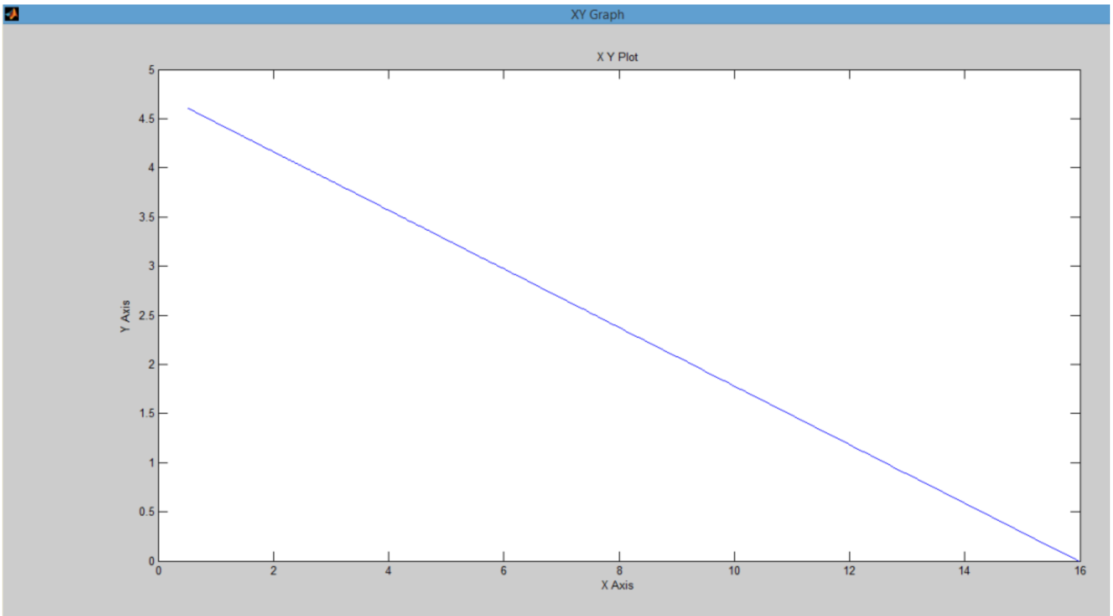

Fig 5(a) - Result of I-V characteristic.

7.2 Current v/s power (I-W)characteristic of TEG

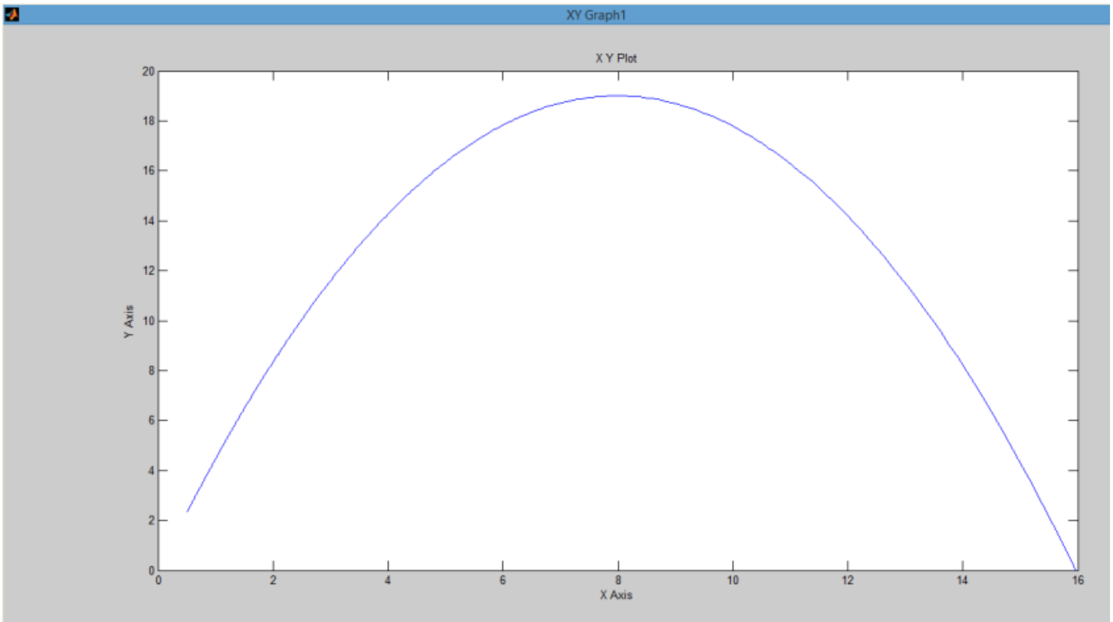

Fig 5(b) - Result of I-W characteristic

8. Conclusion

This study focuses on the simulation and design of a thermal concentrated solar TEG.The output characteristics of I–V and I–W for the TEG are shown in Fig-5(b). The TEG has maximum power output with the matched load of $R_L = R$. Taking the hot-side temperature as an input variable, the output characteristics of current, voltage, and power at the matched load are depicted. These results reveal that the maximum power is about 19 W at I = 7.9832 A and V = 2.38 V, and the maximal thermal efficiency is 4.5% as I approaches about 7.2 A. For the MPPT design of the TEG, the working voltage is controlled at 2.38 V for the DC–DC converter.

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