Model building of thermoelectric generator exposed to dynamic transient sources

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Abstract. This paper presents the modeling of thermal and power generation behavior of a thermoelectric generator (TEG) exposed to transient sources. Most of the previous research concerned the analysis for steady-state behavior which only involves constant temperature value. However, in practice, the temperature of the TEG input fluctuates with time. Therefore this research will look into a focal point on transient heat sources that is being supplied to the hot junction with natural convection cooling process at the cold junction for single and multiple configuration of TEG. The model obtained the data from existing experiments with predicted various conditions of temperature, heat gradient, internal resistance and current attribute of TEG. Transient analysis on single TEG has shown that the value of Seebeck coefficient, thermal conductivity and figure-of-merit vary with the value of cold side temperature. When the ratio between the load and the internal resistance increases, the voltage increases. By considering the multiple TEGs, the matched voltage shows different values when the number of cascaded TEGs is varied. The simulation results have proven that the variation in the number of cascaded TEGs can be used to determine the output power characteristics of a TEG.

1. Introduction
The pressure to reduce our dependence on fossil fuel in producing electricity is getting greater day by day. Thus, the need for alternative power generation has attracted wide research interest. In the present days, there are many solutions to alternative power generation; for example solar energy, hydro energy, nuclear energy and wind energy. Each of these types of energy has its own inadequacy. Although solar energy is the most commonly used type of renewable energy, it needs extra effort on designing a method of storing energy for later use since its limitation is due to the sunlight availability. Nuclear sources are able to supply sufficient amount of energy to produce electricity but its hazardous waste is very harmful to the environment. This paper will discuss the use of thermoelectric device to overcome the limitations of current alternative energy sources.

Thermoelectric generator (TEG) is a solid state device which transforms thermal energy into electrical energy when there is thermal gradient between its two legs. Due to the absence of moving parts when converting thermal energy into electrical energy, such device can operate for a long period of time with free maintenance. Recently, this device has become a favorable solution in energy conversion since it produces no waste matter during the conversion process. Nuwayhid et.al has used

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TEG with domestic woodstove to convert the waste heat of the woodstove to beneficial power to be used in rural places where electric power is subjected to long-drawn-out interruptions [1].

This paper is aimed to conduct a transient and steady state analysis for a single TEG configuration. Previous studies have shown that when it comes to multiple TEGs, researches are mainly focused on the steady state analysis. In [2] the author converts some of the condenser wasted energy to electricity by using Bi$_2$Te$_3$ as thermoelectric material and also focuses on the steady state analysis. According to Nguyen and Pochiraju in [3], although there are a number of papers discussing TEG modules, including analytical and numerical steady state models, fully coupled and complete transient analyses of TEG are often not been discussed. Crane [4] also discussed on the transient operating model for the application of segmented thermoelectric elements. An examination on the behavior of a TEG has been studied by Carmo et.al [5] and Hsu et.al [6] but still solitude on single TEG.

To ensure a reliable model, equivalent circuit model of the TEG had been developed using PSPICE software [7]-[10]. TCAD software has been used in [11] to model the TEG using its three dimensional properties. For the design controller, MATLAB/SIMULINK software is a choice because of its ability to model the controller using control principle theory. In addition, the control strategy can be built by using built-in control blocks combined with the use of SimPowerSystem tools for the Maximum Power Point Tracking (MPPT) circuit development. Tsai and Lin [12] has used MATLAB for modeling the thermoelectric module which focused on the modeling of both thermoelectric cooler (TEC) and TEG.

2. Thermoelectric module principle
The basic unit of TEG consists of an array of p-type and n-type thermocouples which is connected electrically in series and thermally in parallel. This structure can be used to convert thermal energy into electricity when heat is applied to one side of the TEG. At this time, electrons in the n-type semiconductor and the holes in the p-type semiconductor will move away from the heating source. This will increase the electrical current produced by the movement of the electrons and holes. From figure 1 it can be seen when the heat flows across the junction, electrical current will be created. A TEG can be connected either in series to increase the output voltage or in parallel to increase the output current.

![Figure 1. TEG electrical current production [13].](image-url)
There are several effects that are taken into account in order to obtain the heat modelling of the TEG including thermal conduction, Joule, Peltier, Seebeck and Thomson effects. This research will only focus on thermal conduction, Joule, Peltier and Seebeck effect to encounter the extrinsic temperature of the TEG which includes hot temperature, $T_h$, and cold temperature, $T_c$. In this TEG modelling, the additional Thomson effect which is described by the derivative of the Seebeck effect in time function is neglected since the value is too small.

TEG has high thermal conductivity to ensure the heat will be distributed equally at both end of the leg. The thermal conductivity follows the Fourier process with its heat transfer, $Q_{tc}$ described by

$$Q_{tc} = -\Delta T \kappa_{tc}$$

(1)

where $\kappa_{tc}$ is the thermal conductivity and $\Delta T$ is the difference between the hot side and cold side temperature. Joule effect is generated internally when electrical current, $I$ is flowing through thermoelectric leg. This effect is on both hot side and cold side with the same amount of energy as

$$Q_{joule} = I^2 R$$

(2)

where $R$ is the electrical resistance. The Peltier effect is the heating effect when electrical current is flowing through two dissimilar junctions and the total heat transfer is represented by

$$Q_{peltier} = \alpha \Delta T I$$

(3)

Where $\alpha$ is the Seebeck coefficient of the TEG. A phenomenon in which a temperature difference between two dissimilar electrical conductors or semiconductors produces a voltage difference between its two junctions is known as Seebeck effect. Seebeck coefficient is also defined as

$$\alpha = \frac{V}{\Delta T}$$

(4)

When designing the TEG for a certain condition of thermal flow and temperature, it is possible to obtain the maximum output power. This will happen when load resistance equals to the internal resistance of the TEG. Equation (5) and (6) shows energy balance equations for steady state analysis at the hot and cold junction of the TEG.

$$Q_h = \alpha T_h I - \kappa_{tc} \Delta T - 0.5 I^2 R$$

(5)

$$Q_c = \alpha T_c I - \kappa_{tc} \Delta T + 0.5 I^2 R$$

(6)

A good TEG must have a large Seebeck coefficient together with low electrical resistance and low thermal conductivity. The term that relates these three parameters is known as figure-of-merit, $Z$, and is expressed as

$$Z = \frac{\alpha^2}{R \kappa_{tc}}$$

(7)

3. TEG’s electrical parameter determination
The following parameters are used to specify TEG characteristics: $T_h$, the hot side temperature; $T_c$, the cold side temperatures; $W_m$, the power at the load resistance, $R_L$ matched to the internal resistance, $R$ where $(R_L=R)$ and $V_m$, the matched load voltage. The electrical resistance and Seebeck coefficient value is defined as

$$R = R_L = \frac{V_m^2}{W_m}$$

(8)

and

$$\alpha = \frac{2V_m}{\Delta T}$$

(9)
The load resistance can be varied in proportion to its internal resistance with the following relationship

\[ R_L = mR \]  

where \( m \) is the ratio between the load resistance and internal resistance. From equation (4), the current expression can be defined as

\[ I = \frac{\alpha \Delta T}{(1 + m)R} \]  

The equation will reflect onto the relationship between the internal and the load resistance. As the current varies with the value of \( m \), voltage also varies.

The most important part before designing any controller or MPPT circuit, is to maximize the output power at matched load, \( R_L = R \). The maximum current of TEG is the short-circuit current at zero load voltage, \( V_L = 0 \) which referred as

\[ I_{\text{short-ckt}} = 2I_m = \frac{2W_m}{V_m} \]  

Based on Ohm's Law and the resulting equations of (11) and (12), the TEG voltage can be obtained as

\[ V = -R(I - I_{\text{short-ckt}}) \]  

### 4. Model building and simulation analysis

The steady-state analysis is done to verify the electrical parameters of the TEG model. The specifications of the TEG module (TEP1-12656-0.6) are listed in table 1. By applying equations (1) to (7), one may obtain the model parameters for steady state condition of the followings; \( \alpha = 0.031 \text{ V/K} \), \( R = 1.2 \text{ \Omega} \), \( \kappa_c = 20.85 \text{ W/K} \) and \( Z = 3.869 \times 10^{-5} \text{ K}^{-1} \).

| Specifications                  | Values   |
|---------------------------------|----------|
| Hot side temperature (°C)       | 300      |
| Cold side temperature (°C)      | 30       |
| Open circuit voltage (V)        | 8.4      |
| Matched load resistance (Ω)     | 1.2      |
| Matched load output voltage (V) | 4.2      |
| Matched load output current (A) | 3.4      |
| Matched load output power (W)   | 14.6     |
| Heat flow across the module (W) | ≈365     |
| Heat flow density (Wcm\(^{-2}\)) | ≈11.6    |

#### 4.1. Transient analysis of a single TEG

Cold side temperature data from [3] is used for the transient analysis of both single TEG and multiple TEGs arrangement. The hot side temperature is fixed at 115 °C. Figure 2 shows the variation of the temperature on its cold side. The cold side temperature is gradually increased from 25 °C to 75 °C and is maintain at that value until the end of the simulation time.
The TEG model is implemented using MATLAB/SIMULINK as shown in figure 3. The inputs of the model are the cold side temperature and the hot side temperature. For the transient analysis, the value of $\alpha$, $\kappa_c$, and $Z$ vary with the value of $T_c$ in which the effect is shown in figure 4, 5 and 6.

From the figure, the waveform behaviour of $\alpha$, $\kappa_c$, and $Z$ follows the nature of the cold side temperature. As the cold side temperature increase, the value of $\alpha$, $\kappa_c$, and $Z$ will also increase since all these values are proportional to the temperature gradient of the TEG.
The PI and VI characteristics of the single TEG with transient sources is shown in figure 7. This result reveals that the maximum power is 14.6 W at matched load current of 3.4 A and matched load voltage of 4.2 V. The PI and VI characteristics of the TEG are still the same even when the hot side temperature varies. This results show that the converter of the MPPT circuit must follow the voltage, current and power attribute of the selected TEG.
An analysis has been carried out to see the effect of the voltage when the ratio between the load and internal resistance is varied. Figure 8 shows the voltage at four load resistance values: $m_2=m$, $m_2=2m$, $m_2=1.5m$ and $m_2=0.5m$ where $m$ is the actual ratio and $m_2$ is the new ratio. Simulation result shows that the voltage increases as the ratio increases.

In terms of current attributes, when the ratio between load and internal resistance increases, the current decreases. This fact can be clearly seen in figure 9 where the analysis is done at four load resistance values: $m_2=m$, $m_2=2m$, $m_2=1.5m$ and $m_2=0.5m$ where $m$ is the actual ratio and $m_2$ is the new ratio.
4.2 Transient analysis of a multiple TEG

This section will describe the characteristics of the multiple TEGs where three and six TEGs are connected in series. The matched voltage depicted from figure 10 shows a diverse value when different numbers of TEGs are connected electrically in series and thermally in parallel. In contrast, the matched current in figure 11 gives the same value as the single TEG. When the TEGs are cascaded, it will sum up all the single TEG voltage that can be expressed as

$$V_i = i \times V$$  \hspace{1cm} (14)

where $i$ is the number of cascaded TEGs. Since power is directly proportional to the voltage, the total power will be the maximum power of the single TEG multiplies by the factor of $i$. For TEG (TEP1-12656-0.6), the total power will be 43.8 W and if there are six TEGs cascaded together the total power can be increased up to 87.6 W. These results are shown in figure 10.

![Figure 10. PV characteristics of multiple TEGs.](image1)

By considering the same number of cascaded TEGs, the PI characteristics of both cases show the same manners as can be seen from figure 11. With this validation, it is proven that cascaded TEGs will not give any effect to the current value. The only parameter that can be adjusted is the output power since it reflects to the number of cascaded TEGs.

![Figure 11. PI characteristics of multiple TEGs.](image2)

5. Conclusion

A formulation of the TEG behavior which includes thermal behavior and electrical properties has been developed using MATLAB/SIMULINK. This model is used to determine the output power characteristics of both single and multiple TEGs. The output characteristics are mainly used for transient analysis where the cold side temperature is varied with the simulation time.

The analysis with various conditions of temperature, heat gradient, internal resistance and current attribute of TEG also has been discussed. Simulation model using available TEG parameters has been proven to be the same as the provided parameters by the manufacturer. The results show that the prediction with various input parameters was able to determine the output power characteristics of a TEG.

For power condition, the steady state voltage is half of the peak voltage of the TEG. The hot side temperature of the TEG must be controlled to hold the temperature gradient at this optimal point. In
this case, a suitable controller need to be accurately designed to maintain the output power behavior as outlined in this paper.

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References
[1] Nuwayhid R Y, Shihadeh A and Ghaddar N 2005 Development and testing of a domestic woodstove thermoelectric generator with natural convection cooling J. Energy Conversion and Management 46 1631-43
[2] Rafiee M, Siadatan A, Afjei E and Abadi E Z A 2012 Improving the efficiency of thermal power plant using thermoelectric material 4th Int. Conf. on Intelligent and Advanced Systems
[3] Nguyen N Q and Pochiraju K V 2013 Behavior of thermoelectric generators exposed to transient heat sources J. Applied Thermal Engineering 51 1-9
[4] Crane D T 2011 An introduction to system-level, steady-state and transient modeling and optimization of high-power-density thermoelectric generator devices made of segmented thermoelectric elements J. Elec Materi 40 561-9
[5] Carmo J P, Antunes J, Silva M F, Ribeiro J F, Goncalves L M and Correia J H 2011 Characterization of thermoelectric generators by measuring the load-dependence behavior J. Measurement 44 2194-9
[6] Hsu C T, Huang G Y, Chu H S, Yu B and Yao D J 2011 An effective Seebeck coefficient obtained by experimental results of a thermoelectric generator module J. Applied Energy 88 5173-9
[7] Chavez J A, Ortega J A, Salazar J, Turo A and Garcia M J 2000 SPICE model of thermoelectric elements including thermal effects. Proc. Conf. on Instrumentation and Measurement Technology Conference
[8] Mitrani D, Tome J A, Salazar J, Turo A, Garcia M J and Chavez J A 2005 Methodology for extracting thermoelectric module parameters Instrumentation and Measurement IEEE Transactions 54 1548-52
[9] Lineykin S and Ben-Yaakov S 2007 Modeling and analysis of thermoelectric modules Industry applications IEEE Transactions 43 505-12
[10] Mitrani D, Salazar J, Turo A, Garcia M J and Chavez J A 2007 Lumped and distributed parameter SPICE models of TE devices considering temperature dependent material properties 13th Int. Workshop on Thermal Investigation of ICs and Systems (17-19 September 2007)
[11] Gould C A, Shammas N Y A, Grainger S and Taylor I 2011 Thermoelectric power generation: Properties, application and novel TCAD simulation Proc. of Power Electronics and Applications (30 August 2011-1 September 2011)
[12] Tsai H L and Lin J M 2010 Model building and simulation of thermoelectric module using Matlab/Simulink J. Elec Materi 39 2105-11
[13] Silva M F. 2010 Thin-films for thermoelectric application Msc Thesis on Micro/Nanotechnologies University of Minho
[14] Liang G, Zhou J and Huang X 2011 Analytical model of parallel thermoelectric generator J. Applied Energy 88 5193-9
[15] Kim S 2013 Analysis and modeling of effective temperature differences and electrical parameters of thermoelectric generators J. Applied Energy 102 1458-63