International Journal of Smart Grid and Clean Energy

Experimental modelling of grid-tied thermoelectric generator from incinerator waste heat

Miftah Y Fauzan [a], S. M. Muyeen[b], Syed Islam[c]

[a] *Dept. of Electrical Engineering, Curtin University, Perth 6102, Australia*
[b] *Dept. of Electrical Engineering, Curtin University, Perth 6102, Australia*
[c] *School of Science Engineering and Information Technology, Federation University, Melbourne 3000, Australia*

Abstract

This paper presents an experimental investigation of nano power generation, less than 1 kW size, using Thermoelectric Generator (TEG). The heat source is harvested from the waste temperature of the incinerator, but in the laboratory experiment, it was generated from an electric heater and controlled by an electronic thermostat. A prototype of 0.02 kW system, consisting of 24 modules of bismuth telluride TEG connected in series, was built. The system is attached to cooling and temperature controller to investigate the characteristics. Preliminary experiments and analytical models of electric output power as function of specific temperature were presented. An optimum output power could be set at a certain condition.

Keywords: Thermoelectric Generator (TEG), incinerator, waste heat, optimum power, experimental modeling

1. Introduction

Nano power generation refers to a small size, less than 1 kW power generation. Thermoelectric Generator (TEG) is commonly used as the main component of nano power generation for harnessing the energy. TEG converts heat energy into electric power directly, without passing through intermediate energy conversion such as mechanical or electromagnetic. It is based on three effects, the Seebeck Effect, the Peltier Effect and the Thomson Effect [1]. Seebeck effect occurred when a circuit is made of two different materials, and a temperature difference is applied between the junction of the materials, then it generates an electromotive force. The Peltier effect is the opposite effect of Seebeck. When a current is supplied to two dissimilar materials connected in a closed circuit, heat is rejected and absorbed at the junction. Thomson effect is similar to Peltier effect, but the material of heat rejected and absorbed depends on the direction of the current in the circuit [1].

The heat for power generation using TEG could be from many sources, such as low temperature geothermal, thermal disk collector, incinerator exhaust etc. A 1 kW system was built by Changwei Liu et al, to be used in the geothermal site with low temperature. It employs 120°C temperature difference, presenting lower cost compared to PV in term of energy generated [2]. Parabolic reflector for collecting thermal sunlight was proposed by A. S. Wardhana et al [3] – [4]. This uses 2 reflectors, so that the thermal harvesting module (Stirling engine, TEG generators etc) can be placed on a static platform, instead of moving with the parabolic disk. Incinerator, a burner system for rubbish, can also be used as the heat source of TEG generator. The temperature in the exhaust pipe of a small-medium incinerator with a capacity of 10 meter cubic rubbish per day, may vary up to 300°C. This type of incinerator is commonly applied in such community or residentials. Figure 1 shows a typical incinerator in Bandung, Indonesia.

* Manuscript received April 6, 2019; revised February 17, 2020.
doi: 10.12720/sgce.9.2.304-313

Fig. 1. A typical small-medium incinerator.

Applications of thermoelectric generator have a huge opportunity in small to medium size of power systems. It may be combined with hybrid power system involving diesel generator, PV system, wind power etc. That has already been published by other researchers [7-9]. It requires power electronic device similar to dc-to-dc converter, voltage source inverter for PV, wind or other renewable energy sources systems [10-14].

This paper investigates an experimental model of the thermoelectric generator for nano power generation that the heat source is planned to be from an incinerator exhaust. A prototype of 0.02 kW was built for investigation. Characteristics of electric output power as a function of controlled temperature were presented. An optimum power point could be set at a certain condition.

2. Prototype of 0,02KW Thermoelectric Generator

A prototype of 0.02 kW TEG was built as shown in Figure 2. It consists of 24 modules of TEG from bismuth telluride type. All modules are connected in series producing 80 volts in open circuit and 2 amperes in short circuit at a typical condition. The device consists of a heat exchanger that are sandwiched between 12 thermoelectric generators on one side and 12 on the other side. Solid aluminium plate is then attached on the outer side of the thermoelectric generator to maximize the heat distribution. The thermoelectric generators are connected in series to maintain a sufficient voltage. Water is used as a medium to transfer the heat from the heat exchanger to the radiator. A heater element equiped with electronic temperature monitoring and controlling was also put in the system. This is able to maintain the temperature difference between the two surfaces to be in a constant rate.

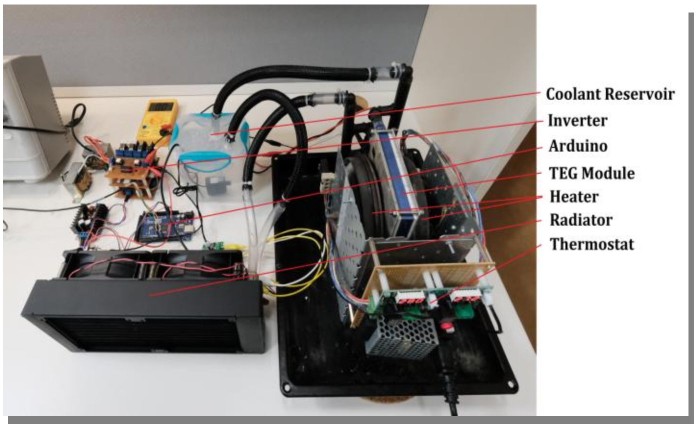

Fig. 2. TEG 0.02 kW with cooling system and temperature monitoring

The TEG module, as part of the entire system in Fig.ure 2, is shown in Fig. 3. The heat exchanger is colored in blue, and they are connected together by black PVC pipings. While the white colored plates are the thermoelectric modules. The aluminium plate on the outer side ensures the heat distribution is even on each thermoelectric module. It comprises many pairs of P-N junctions below the surface plate. These cells are connected in series in order to get higher output voltage.

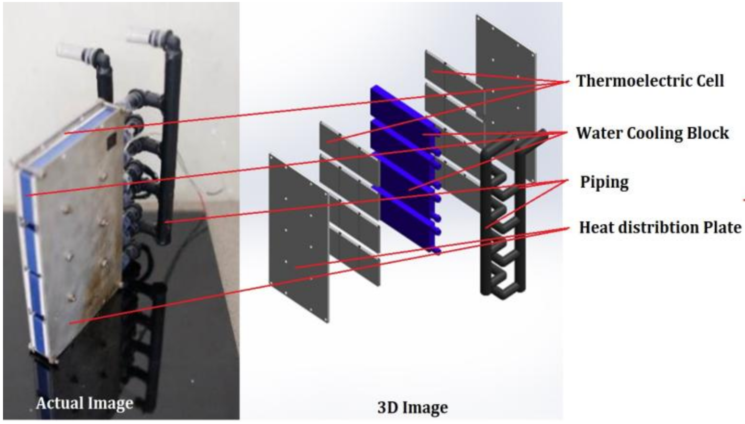

Fig. 3. TEG module.

The principles of a single cell TEG is shown in Figure 4. A heat source is applied to the left hand side of the picture, called hot surface. The heat is then distributed to the junction of P and N material. The other surface, the right hand side, is maintained cold by the heat exchanger acting as a cooling device. The temperature difference forces electrons to move, resulting in current flow through both P and N junction [5]. Semiconductor-based commercial thermoelectric is divided into three temperature levels: Low temperature (<177°C) using bismuth base mixed with antimony, tellurium, and selenium, this thermoelectric is the most common thermoelectric on the market. While the medium temperature (577°C) using telluride lead material, and high temperature (≤1027°C) using silicon and germanium based materials [6]. Generally, the thermoelectric module contains hundreds of thermocouples connected in series and sandwiched between thermal conductor plates. The thermocouples must be connected in series because an individual thermocouple produces a very small voltage (hundreds of microvolts per degree). Each thermocouple consists of n type and p type semiconductors.

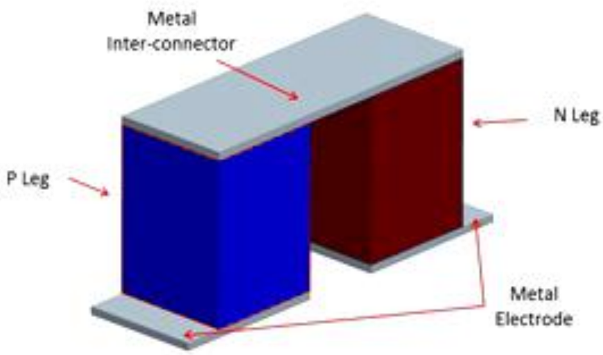

Fig. 4. Principles of single cell TEG.

Referring to Shripad Dhoopagunta [5], the characteristics of various TEG types are illustrated in Figure 5. This generally informs the current development of thermoelectric technology. It presents material types, temperature ranges and the capability to produce electric energy. The term ZT is called the dimensionless Figure of merit. The more the ZT value the better the device performs in producing electricity [5].

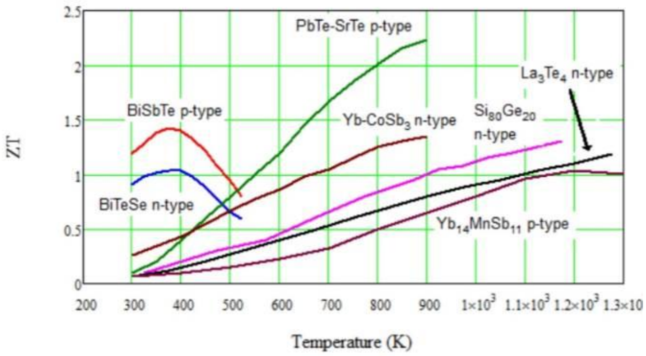

Fig. 5. Performances regarding the TEG material [5].

For defining the maximum efficiency (η_{max}) and the power output (P) of a thermoelectric generator, we used Eq. 1 and 2 [6] as follows:

$$\eta_{\max} = \frac{T_H - T_C}{T_H} \frac{\sqrt{1+\frac{Z(T_H+T_C)}{2}}-1}{\sqrt{1+\frac{Z(T_H+T_C)}{2}}+\frac{T_C}{T_H}} \tag{1}$$

$$P = \frac{\alpha^2 T_c^2 \left(\frac{T_H}{T_C}-1\right)^2 \left(\frac{R_L}{R}\right)}{R\left(1+\frac{R_L}{R}\right)^2} \tag{2}$$

where T represents temperature, subscript H indicates hot junction and C is a cold junction. Coefficient α is the Seebeck coefficient. R represents the internal resistance, while R_L is the resistance of the load.

Equation (3) is the ideal form of the Carnot equation multiplied by a factor, also called the "Figure of merit" Z, defined in the following equation:

$$Z = \frac{\alpha^2 \sigma}{k} \tag{3}$$

where α is the Seebeck coefficient, σ is the coefficient of electrical conductivity, and k is the coefficient of thermal conductivity. Some literature says that the Figure of merit, ZT, can also be defined in the form $Z = (T_L + T_H) / 2$. Thermoelectric development research focuses on increasing the value of the Figure of merit. These three coefficients are the main factors in determining thermoelectric compilers. The greater the value of the Figure of merit, the thermoelectric efficiency will be higher so that the power generated is also greater.

3. Energy Harvesting Using TEG

3.1. Model system

Fig. 6 shows the complete block diagram of the proposed system. The TEG is modelled as a voltage source with a resistance in series. The system consists of three important blocks: 1) MPPT Controller; 2) DC to DC Converter; 3) DC to AC Converter. The MPPT controller continuously measures the power output of the TEG, it ensures the TEG to generate the maximum power in any temperature difference variations. The DC to DC converter is a boost converter that steps up the TEG voltage from 40-50V to 311V. While the DC to AC converter converts the 311V DC to a $220V_{RMS}$ and transfers it to the grid.

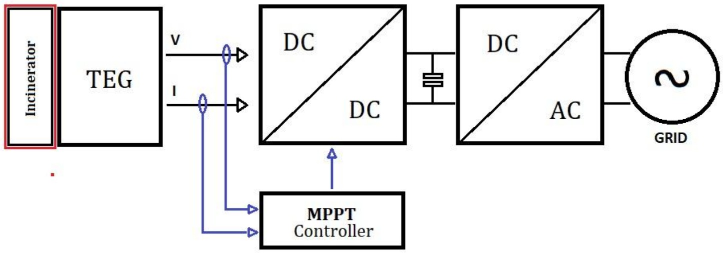

Fig. 6. Block diagram of the TEG Harvesting system.

3.2. MPPT controller

The fluctuations of ΔT on TEG hot side and cold side results in internal resistance variations. This internal resistance variations causes variations of the maximum power point (MPP) generated by the TEG. Which according to the Thevenin's Equivalent Circuit, MPP will be achieved when the load resistance and the internal resistance of the TEG is equal (R_L=R_{int}). To achieve MPP on various ΔT, the MPPT has to be implemented between the load and the TEG. A Perturb and Observe (P&O) algorithm is chosen because its efficiency, simplicity, and low cost.

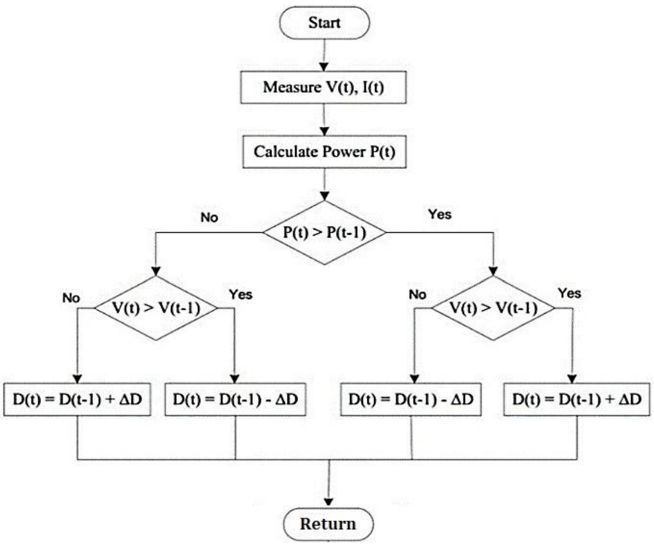

Fig. 7. Flow chart of perturb and observation method.

3.3. DC to DC converter

The proposed harvesting system utilizes a TEG array that can generate voltage up to 100V, while the output of the system is connected to the grid. In order to match the grid voltage, a boost converter is necessary. In this case, this boost converter boosts the output of the TEG which is 100V to be 311V. While stepping up the voltage, this boost converter also maintains the TEG to generate MPP. All of these functions are driven by an Arduino UNO microcontroller. The R load on the right hand side illustrated on Fig. 8 would be the DC to AC converter which will be explained in point D.

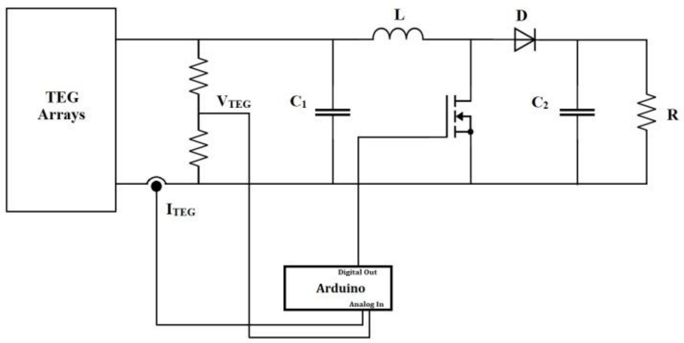

Fig. 8. Design of the DC to DC Converter.

3.4. DC to AC converter

The DC to AC in this proposed harvesting system should be able to convert the 311V DC output from the DC/DC converter to a stable $220V_{RMS}$ while keeping synchronized to the grid. This converter consists of four MOSFETs that are arranged in a H-Bridge conFigureuration, a zero crossing detector, and Arduino UNO Microcontroller. The Microcontroller is programmed to work as a phase locked loop and a controller that generates sinusoidal-PWM to drive the four MOSFETs. In this particular setup, to maintain simplicity and efficiency, the MOSFETs on the top and the bottom are n-channel and p-channel. The gates are connected together and coupled to the Arduino via an optocoupler. Every time there is a signal, both the n-channel and p-channel MOSFETs are working in opposite. Fig. 9 presents the design of the DC to AC converter.

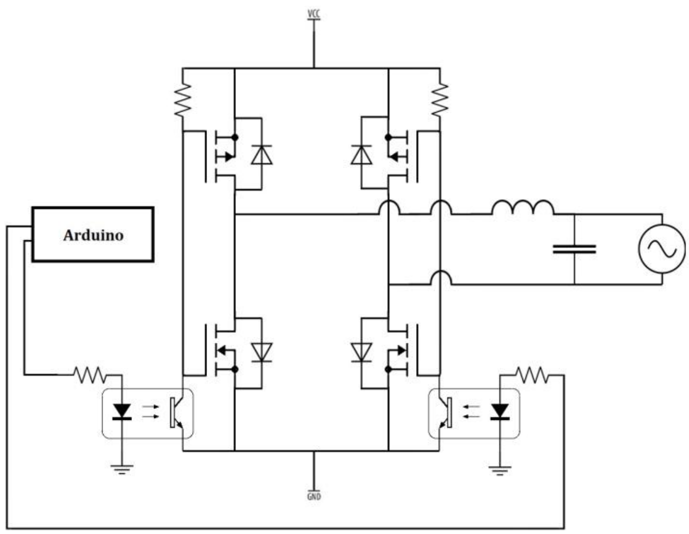

Fig. 9. Design of DC to AC Converter.

4. Preliminary Experiment and Analysis

Preliminary experiments were conducted to draw the output power using the prototype. There are 2 types of TEG used: single module and 24 pieces in a series connection of TEG modules. The single module is applied with 30°C temperature difference between hot surface and cold surface, while the 24 pieces TEG were applied with 58°C temperature difference. This temperature is maintained constant, while the load current is varied.

4.1. Test of single TEG module

Fig. 10 shows the curve of power versus current of a typical single TEG module. It is exposed to a temperature difference of 30°C. A variable resistor is met to vary the load current. The characteristic of power versus current represents a quadratic curve. The maximum power point curve is presented in Figure 6. On a particular condition, a single TEG module generates 0.45W of power on it's peak.

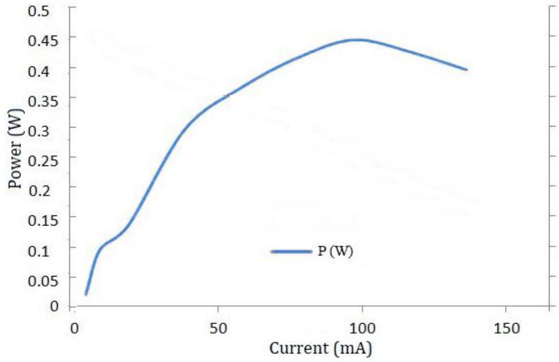

Fig. 10. Characteristics of a typical single TEG.

Using a simple quadratic equation, there are three positions already known from the data, then the characteristics of the power can be calculated. For a single TEG module, at a particular condition, the electric power generating is as follows:

$$P(Watt) = -3x10^{-4} I^2 + 75x10^{-4} I \tag{4}$$

where I is the load current in mA.

4.2. Test of 24 TEG modules in series

In this test, 24 TEG modules were connected in a series to increase the voltage and total power generation. On this particular test, the temperature difference was set to 58°C. Figure 7 shows the V-I characteristics. When the system was open circuit, the current was zero but the voltage is higher at 80 Volts. On the other hand, during short circuit, the current I was maximum at 1 Amperes while the voltage was zero.

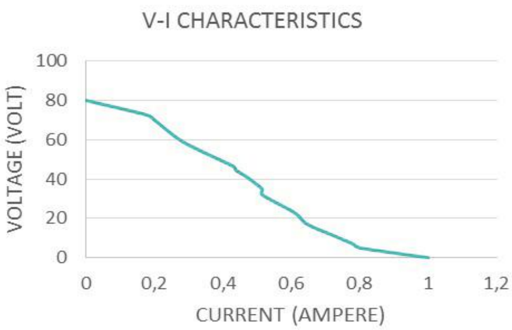

Fig. 11. V-I Characteristics of 24 pieces typical TEG modules.

The power curve as a function of current is shown in Fig. 12. The curve starts with open circuit, which is zero for both the current and power. The maximum power generated in this particular condition was achieved at 20 Watts with the current at 0.45 Ampere. The other side of the curve also showed ending at zero, where the modules were short circuited. During short circuit, the current is 1 Ampere, and the voltage is zero, thus the output power becomes zero.

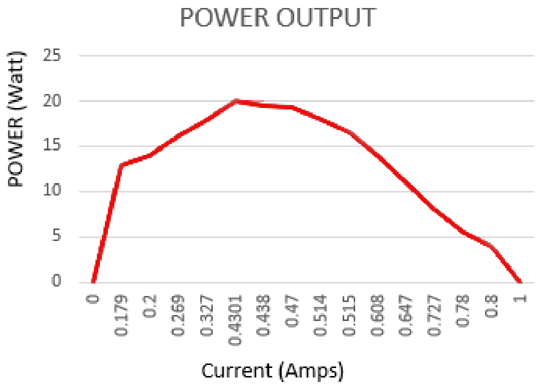

Fig. 12. Typical TEG output power as function of current.

Fig. 13 depicts the TEG output power as a function of voltage. This curve was initiated with a short circuit and completed with open circuit conditions.

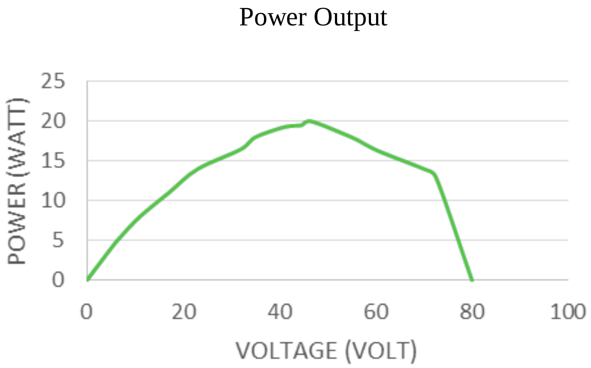

Fig. 13. Typical TEG output power as function of voltage.

From Fig. 12 and 13, it is found that the maximum point (mp) of power at P_{mp} = 20 Watt, current I_{mp} = 0.43 Amp, and voltage V_{mp} = 46.5 Volt. The maximum point was found when the internal resistance is equal to the load resistance. Thus, by using data set from the experiments, the Seebeck coefficient α, and the internal resistance R can be calculated. The power output from theoretical using plotting of Eq. 2 compared to experiments (redraw from Fig. 12) is shown in Fig. 14.

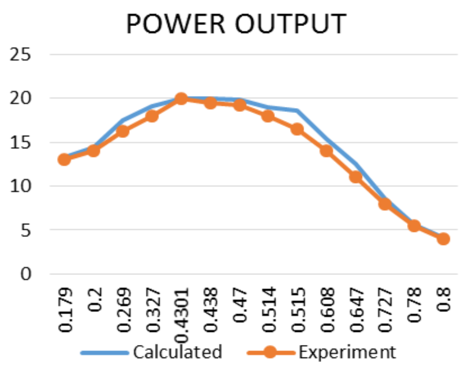

Fig. 14. Comparison of the calculated and experiment result.

5. Conclusion

The preliminary experimental model was presented using a single module, as well as 24 TEG modules in series. Both experimental types present that the power generating has a maximum point, within a quadratic curve. It was also approved that thermoelectric characteristics from theoretical and laboratory experiments presenting very similar results. The average error was found as 5.6%. TEG modules have opportunities to be applied for power generating unit, due to direct conversion from heat into electricity. The heat source may use the waste heat from the incinerator. This system produces electricity, concurrently solving problems of domestic refusal in places all over the world.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Miftah Y. Fauzan developed the theoretical formalism, performed the analytical calculations and performed the simulation with experimental validation. Both S.M. Muyeen and Syed Islam contributed to the final version of the manuscript. All authors had approved the final version.

Acknowledgements

This work is conducted as part of Master Program in Curtin University - Australia, supported by LPDP scholarship, provided by the government of Republic Indonesia.

References

[1] H. J. Goldsmid, *Introduction to Thermoelectricity*, Heidelberg, New York: Springer, 2010.

[2] C. Liu, P. Chen, and K. Li, "A 1 kW thermoelectric generator for low-temperature geothermal resources," *Transactions - Geothermal Resources Council*, vol. 38, pp. 749-754, January 2014.

[3] A. S. Wardhana, H. Suryoatmojo, M. Ashari, "Optimization of heat flux distribution on dual parabolic dish for stirling engine applications," in *Proc. International Conference on Sustainable Energy Engineering and Application (ICSEEA)*, 2016.

[4] A. S. Wardhana, H. Suryoatmojo, M. Ashari, "Design of parabolic solar concentrator to improve the optical efficiency for thermal engine generator using dual reflector Gregorian method," in *Proc. International Seminar on Intelligent Technology and Its Applications* (ISITIA), pp. 457-464, 2016.

[5] S. Dhoopagunta, "Analytical modeling and numerical simulation of a thermoelectric generator including contact resistances," Master's Theses, Western Michigan University, December 2016.

[6] Y. David, "Modeling and application of a thermoelectric generator," MASc Thesis. 2011.

[7] F. A. Pamuji, Soedibyo, M. Ashari, "Grid quality hybrid power system control of microhydro, wind turbine and fuel cell using fuzzy logic," *Journal of International Review on Modelling and Simulations*, vol. 6, no. 4, 2013.

[8] Soedibyo, H Suryoatmojo, I Robandi, M Ashari, "Optimal design of hydrogen based wind-microhydro using genetic algorithm," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 10, no. 6, pp. 1309-1318, 2012.

[9] H Suryoatmojo, T Hiyama, A. A. Elbaset, M. Ashari, "Optimal design of wind-PV-diesel-battery system using genetic algorithm," *IEEJ Transactions on Power and Energy*, vol. 129, no. 3, pp. 413-420, 2009.

[10] B. Amri, M. Ashari, "The comparative study of Buck-boost, Cuk, Sepic and Zeta converters for maximum power point tracking photovoltaic using P&O method," in *Proc. International Conference on Information Technology, Computer, and Electrical Engineering (ICITACEE)*, 2015, pp 327-332, 2015.

[11] M Ashari, D. K. Setiawan, "Inverter control for phase balancing of diesel generator—battery hybrid power system using diagonal recurrent neural network," in *Proc. of 21st Australasian Universities Power Engineering Conference* (AUPEC), pp. 1-5, 2011.

[12] B. Sujanarko, M. Ashari, M. Hery Purnomo, "Universal algorithm control for asymmetric cascaded multilevel inverter," *International Journal of Computer Applications*, vol. 10, no. 6, 2010.

[13] M. Ashari, C. V. Nayar, S. Islam, "Steady-state performance of a grid interactive voltage source inverter," in *Proc. of IEEE Power Engineering Society Summer Meeting*, vol. 1, pp. 650-655, 2001.

[14] C. V. Nayar, M. Ashari, "Phase power balancing of a diesel generator using a bidirectional PWM inverter," *IEEE Power Engineering Review*, vol. 19, no. 11, pp. 46-46, 1999.