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Modelling and Simulation of a Thermoelectric Generator for Waste Heat Energy Recovery in Low Carbon Vehicles

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***Abstract*—This paper details the development of a thermoelectric generator (TEG) model undertaken within the Low Carbon Vehicle Technology Project (LCVTP*). The model has been developed as a tool for investigating the application of using a TEG for waste energy recovery from an automotive engine exhaust and converting it to electrical energy to offset the electrical demand on the 12V battery. The model features three main subsystems that make up the TEG system; these are the heat exchanger, the thermoelectric material and the power conditioning unit. Particular attention has been given to the power conditioning unit where two different DC-DC converter topologies namely; buck-boost and single ended primary inductor capacitor (SEPIC) have been compared for best performance. In addition, the Perturb and Observe maximum power point tracking algorithm has also been implemented and compared with a standard fixed duty cycle pulse width modulator (PWM) control. The process of developing the subsystems are briefly explained and the advantages of using the maximum power point system is demonstrated. The simulation results demonstrate that a power conditioning unit with a buck-boost converter and Perturb and Observe control is suitable for TEG systems. MATLAB/Simulink has been used for modelling and simulation of the system as well as implementation of the control strategy.**

I. Introduction

The increasing need to improve fuel economy and overall efficiency of automobiles has led to research and development into various technologies for reducing fuel consumption by means of waste energy recovery. Among the many forms of energy, the two prominent modes available for capture on the vehicle are kinetic and heat energy by using systems such as regenerative braking [1] and turbo compounding [2].

One such system that has recently been considered for waste heat energy recovery in particular is the Thermoelectric Generator (TEG) [3-5]. With about one-third of the combusted fuel energy being wasted in the exhaust [5]; thermoelectric power generation is an attractive option to improve fuel economy. TEGs, which use the thermoelectric or Seebeck effect of semiconductors to convert heat energy to electrical energy, have existed for many years with the initial discovery of the thermoelectric effect being made in 1821 by Thomas J. Seebeck. Due to the relatively low efficiency and high costs associated with the technology it has been limited in its use in industrial, military and aerospace applications [6-8]. However, with increasing advancements in thermoelectric materials and TEG system design and modelling [9-13] the scope for automotive applications has become apparent. In this application the primary target source for heat to electrical energy conversion is the exhaust with the converted electrical energy being used to offset the 12 V electrical demand.

One of the key factors in designing TEG devices is to match the impedance between the TEG and the load [14]. The mismatch power loss of TEG devices is due to the transient nature of the power output caused by the variance in the temperature distribution of the heat source input. To ensure maximum efficiency during transient conditions, emphasis is given to investigating the appropriate combination of DC-DC converter topology and a maximum power point algorithm for power conditioning. This paper presents a TEG model that has been developed in MATLAB/Simulink to evaluate the potential gains of the system and to optimise the power conditioning unit design.

II. Thermoelectric Generator (TEG) System Integration

The thermoelectric generator model developed consists of three main subsystems. These are the heat exchanger (HX), thermoelectric material/module (TEM) and power conditioning unit (PCU). The gas to liquid HX transfers the heat to and from the TEM, taking heat from the exhaust to provide a hot side and taking heat away via the coolant loop to provide the cold side. Given a hot and cold side, the thermoelectric module is able to generate electrical energy. The principle of operation is based on the Seebeck effect where, as in the case of thermocouples, when two dissimilar metals are joined in a junction and subjected to a hot or cold environment compared to ambient, a small amount of electrical power is generated when connected to a resistive load. Other material properties which are important to consider for thermoelectric generators are electrical resistivity and thermal conductivity.

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Consider

$$zT = \frac{\alpha^2 T}{\rho\kappa} \quad (1)$$

where α denotes the Seebeck coefficient (V/K), ρ denotes the electrical resistivity (m) and κ denotes the thermal conductivity (W/Km).
Equation 1 defines the dimensionless variable zT known as the 'figure-of-merit' which is a factor used to combine thermoelectric properties for evaluating the performance of a thermoelectric material.

For the intended automotive application, the heat source to provide the hot side is taken from the exhaust as shown in Figure 1. To ensure minimal degradation to engine performance and emissions, the TEG unit is positioned between the catalyst and muffler, which is also beneficial for packaging purposes. To provide the cold side, either the coolant circuit from the engine is used or in the case of hybrid-electric vehicles, the coolant loop for the power electronics and electric motors can also be used. The converted electrical energy that is generated, given a temperature difference, is used to charge the $12V$ battery. Due to transient unsteady heat flow, electrical output varies throughout the operation. However, the steady flow that is required is made possible by making use of a PCU which contains a DC-DC converter with a Maximum Power Point Tracking (MPPT) algorithm to regulate the required voltage and simultaneously output the maximum possible power for highest efficiency.

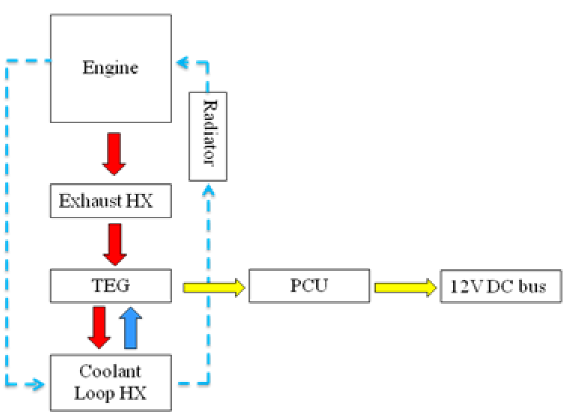

Fig. 1. Schematic Diagram of TEG system

III. TEG Subsystem and Model Description

Similar to the physical system, the model is set-up with multiples of the three subsystems with each multiple representing a section of the system in the stream of the exhaust as shown in Figure 2.

The TEG model requires the exhaust and coolant inlet temperature (T_{ai}, T_{wi}) and mass flow rate $(\dot{m}_a, \dot{m}_w)$ as inputs and outputs the voltage and current (V, I) generated by the TEG. The transient analysis capability of the model makes it possible to account for the initial warm up period and also

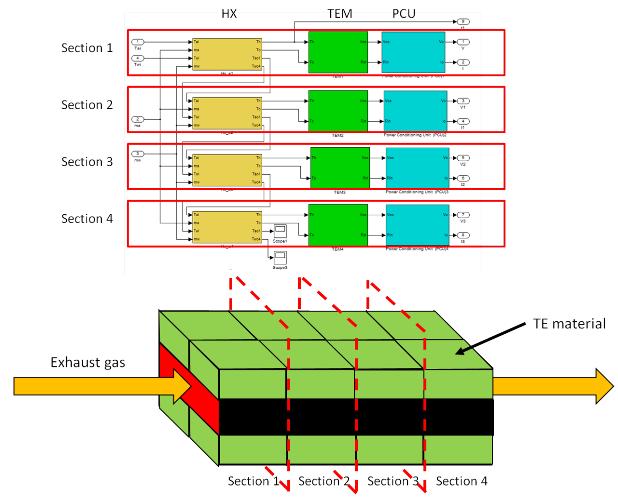

Fig. 2. TEG subsystem configuration in comparison to physical system

provides the capability to integrate with a vehicle model for fuel consumption analysis over defined drive cycles.

IV. Heat Exchanger (HX) Subsystem

The heat exchanger has been modelled using the following set of energy balance equations to effectively describe the heat transfer through the several layers present in the TEG system. Here the heat transfer section is assumed to behave as a 'perfectly stirred tank' [15].

$$\dot{Q}_a = \dot{m}_a c_a \left(T_{ai} - T_{ao}\right) \quad (2)$$

$$\dot{Q}_a = h_a A \left(T_{ai} - T_{ao}\right) \quad (3)$$

Equations 2 and 3 describe the heat transfer rate from the exhaust. If instantaneous heat exchange is assumed, combining Equation 2 and 3 gives:

$$T_{ao} = \frac{\dot{m}_a c_a T_{ai} + h_a A T_h}{\dot{m}_a c_a + h_a A T_h} \quad (4)$$

The energy balance equation for the HX hot side layer is given by:

$$m_h c_h \frac{\delta T_h}{\delta t} = h_a A \left(T_{ao} - T_h\right) - \frac{\kappa_t A}{L_t}\left(T_h - T_t\right) \quad (5)$$

The energy balance equation for the TEM layer is given by:

$$m_t c_t \frac{\delta T_t}{\delta t} = \frac{\kappa_h A}{L_h}\left(T_h - T_t\right) - \frac{\kappa_c A}{L_c}\left(T_t - T_c\right) \quad (6)$$

The energy balance equation for the HX cold side layer is given by:

$$m_c c_c \frac{\delta T_c}{\delta t} = \frac{\kappa_t A}{L_t}\left(T_t - T_c\right) - h_w A \left(T_c - T_{wo}\right) \quad (7)$$

The energy balance equation for the coolant channel is given by:

$$m_w c_w \frac{\delta T_{wo}}{\delta t} = \dot{m_w} c_w (T_{wi} - T_{wo}) - h_w A (T_c - T_{wo}) \quad (8)$$

Equations 4-8 describe the fact that only 1-dimensional heat transfer is taken into account. It is assumed that heat flows only from the exhaust layer to the coolant layer through the thermoelectric module layer without heat loss to ambient or parasitic effects in other directions. It is also assumed that the uniform heat transfer from hot to cold is calculated as a function of the mean temperature of each layer. Given the uncertainty of environmental effects to the system at this level of study, it has been assumed that the system exists within ideal insulation.

V. Thermoelectric Material/ Module (TEM) Subsystem

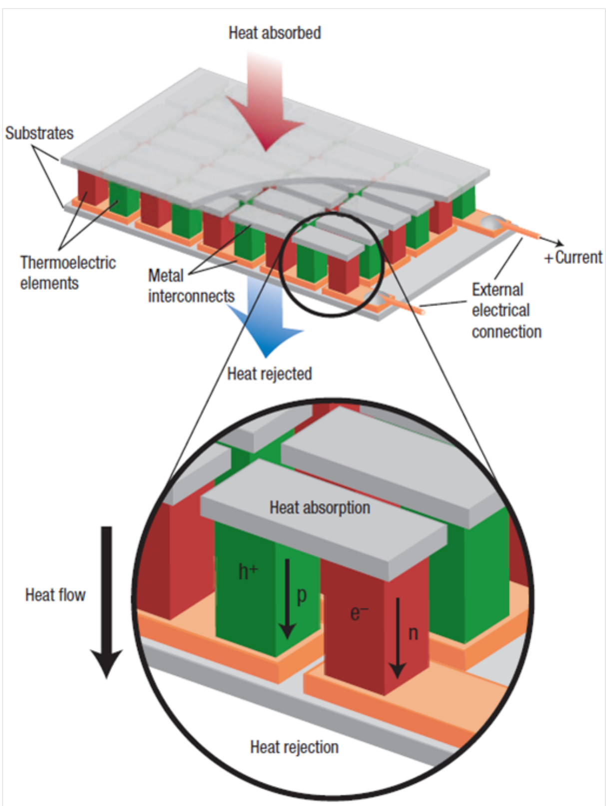

Fig. 3. Thermoelectric module [9]

As shown in Figure 3, the two dissimilar conductors are termed n-type and p-type legs or semiconductor ingots and together make a couple. Several couples connected together in turn make a module. Depending on the application scale, a thermoelectric generator uses a suitable number of modules to meet the power need. Similarly, material choice is also fundamental to the amount of thermoelectric material used and power generated. Figure 4 shows the variance in material performance where bismuth telluride (Bi_2Te_3) is the only currently commercially available material. While the figure-of-merit of Bi_2Te_3 is relatively acceptable, its operating temperature limitation of 250 ^oC makes the material unsuitable for high temperature applications

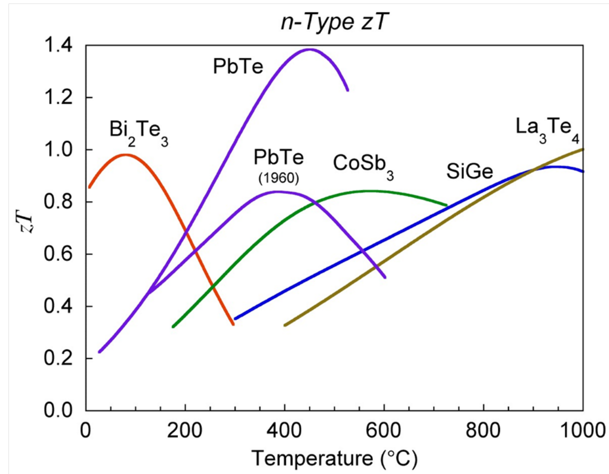

Fig. 4. Thermoelectric module [9]

The thermoelectric material subsystem uses the hot and cold side temperature inputs from the heat exchanger subsystem to give the electrical power generated using the following equations

$$V_{oc} = n_{couple} (-\alpha_n + \alpha_p) \Delta T \quad (9)$$

$$R_m = \frac{n_{couple} (\rho_n - \rho_p) L}{A} \quad (10)$$

$$K_m = \frac{n_{couple} (\kappa_n - \kappa_p) L}{A} \quad (11)$$

where V_{oc} denotes the open circuit voltage (V), R_m denotes the module internal resistance (Ω), K_m denotes the module thermal conductivity (W/Km), A denotes the cross-sectional area (m^2), n_{couple} denotes the number of couples, L denotes leg length (m), subscripts n and p refer to n-type and p-type legs.

VI. Power Conditioning Unit (PCU)

A power conditioning unit (PCU) is essential in a system which comprises of unstable heat sources and loads. Figure 5 illustrates the block diagram of the PCU considered in this paper. The output of a TEM is connected to the DC-DC converter and the output of the converter is connected to the 12 V load (battery). Voltage and current measurements taken from the TEM are applied to the MPPT controller as inputs and pulse width modulation (PWM) as an output. The power loss which is caused by the mismatch between internal resistances of the DC-DC converter and the TEG is one of the major problems in power output regulation. The idea is to develop an algorithm which will change the operating point of the DC-DC converter in order to reduce the mismatch, consequently the output power will be maximised.

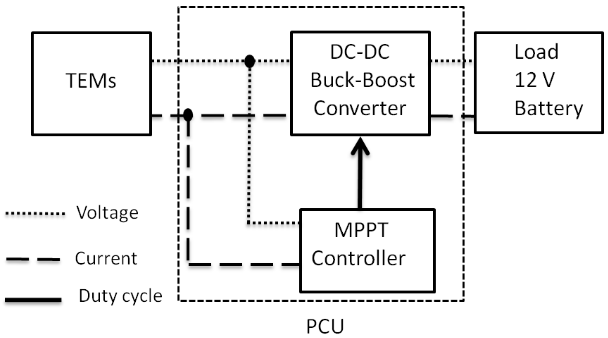

Fig. 5. Block diagram for the power conditioning unit (PCU)

A. DC-DC Converter

In this paper, DC-DC converter topologies known as buck-boost and SEPIC are considered. These converters provide a controllable and/or constant output DC voltage despite variation of the input voltage. Converter choice is based on the fact that the output voltage of the TEG can either be higher or lower than the battery voltage allowing for flexibility in design due to variability in system input and output.

1) Buck-Boost Converter: Buck-boost is an inverting DC-DC converter with the output voltage greater or lower than the input voltage. One of the drawbacks of this converter is that the switch does not connect to the ground; as a consequence, the driving circuitry is complex. As long as the power supply is isolated from the load circuit which acts as a supply, this will no longer be a drawback. Figure 6 illustrates a schematic diagram of the buck-boost converter. The buck-boost converter circuit comprises of two dynamic energy storage elements, denoted, L and C_{out}. In this paper the both converters are considered to work in continuous conduction mode (CCM). In this mode the output voltage of the buck-boost converter is given as:

$$V_o = -\frac{dV_{in}}{1-d} \tag{12}$$

where V_o denotes the output voltage, d denotes the duty cycle and V_{in} denotes the input voltage.

Changing the duty cycle d will change the output current I_o as the output voltage is regulated at a constant value of $14.4V$. The output current I_o is expressed as:

$$I_o = -\frac{(1-d)\,I_{in}}{d} \tag{13}$$

where I_o denotes the output current and I_{in} denotes the input current.

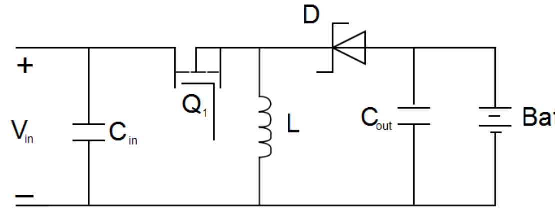

Fig. 6. Schematic diagram of a buck-boost converter

2) SEPIC Converter: SEPIC converter is a non inverting DC-DC converter with the output voltage higher or lower than the input voltage. A basic schematic of a SEPIC converter is illustrated in Figure 7. It is made of two inductors denoted L_1 and L_2, three capacitors denoted C_{in}, C_s and C_{out}, one diode denoted, D_1 and one switch denoted, Q_1.

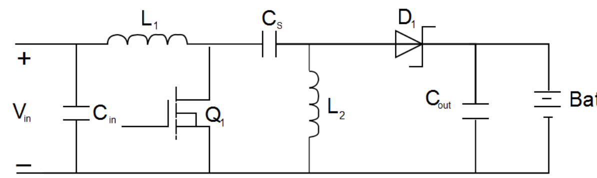

Fig. 7. Basic schematic of a SEPIC converter

For a SEPIC converter working in CCM, duty cycle is given as:

$$d = \frac{(V_o + V_D)}{(V_{in} + V_o + V_D)} \tag{14}$$

where V_D denotes the voltage across the diode.

B. Maximum Power Point Tracking

MPPT is an iterative approach which varies the electrical output of a TEG to deliver maximum available power. Maximum power is achieved by matching the internal resistances of the TEG and the DC-DC converter. The implementation of a MPPT algorithm in a TEG offers:

- extra power due to reduction of mismatch between the TEG internal resistance, and the DC-DC converter internal resistance,
- detecting the variations in TEG current and voltage

1) Perturb and Observe: This is the method which perturbs the operating point of the TEG system and observes the output power to determine the direction of change for maximising the output power.

The P&O MPPT algorithm operates as follows:

Voltage and current are measured and used to calculate power at time instant k. Current power is then compared with the previous power. If the latter is greater than former and the flag is:

- set, then the duty cycle will be incremented
- clear, then the duty cycle will be decremented

Conversely if the latter power is smaller than the former the following actions will be preformed:

1) Based on flag state:

- if it is set then the duty cycle will be decremented
- if it is clear then the duty cycle will be incremented

2) The flag values are reversed (from 0 to 1 and from 1 to 0)

Figures 8 and 9 illustrate, respectively, the P&O algorithm flow chart and waveform

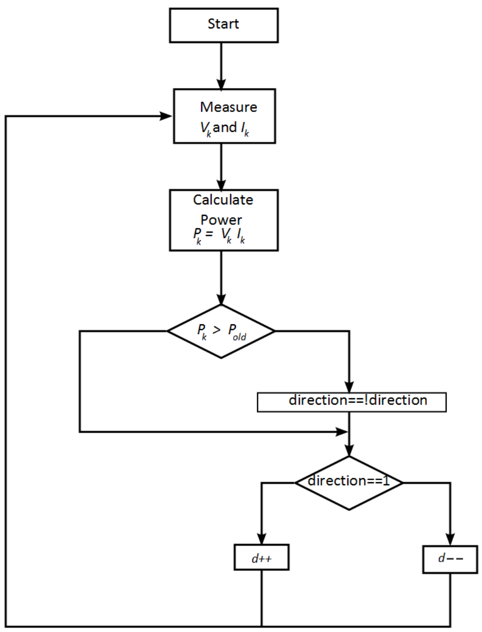

Fig. 8. A flow chart algorithm for P & O

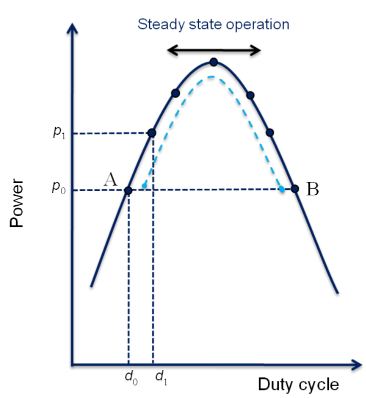

Fig. 9. Waveform for the P & O algorithm

VII. Simulation results

The requirement for a dual functionality step-up step-down DC-DC converter for TEG applications is shown in Figure 10. Given the transient behaviour of the system it is important that the DC-DC converter is able to maintain a stable output while the input is continuously varied. This is particularly the case with hybrid-electric vehicles where the engine start-stop functionality is always present. Whilst the

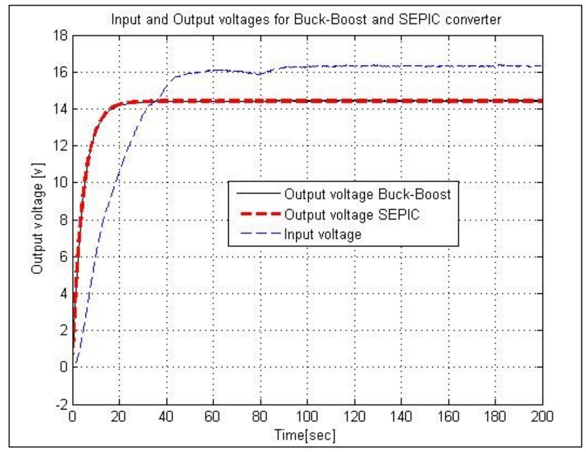

Fig. 10. Input voltage and output voltages for Buck-Boost and SEPIC converter

Buck-Boost and SEPIC converters are both able to regulate constant output voltage with varying input voltage, Figure 11 shows that the Buck-Boost converter is more efficient than the SEPIC converter. This is mainly attributed to the fact that SEPIC converters utilize two inductors in their circuit rather than the single inductor in the Buck-Boost. The advantage

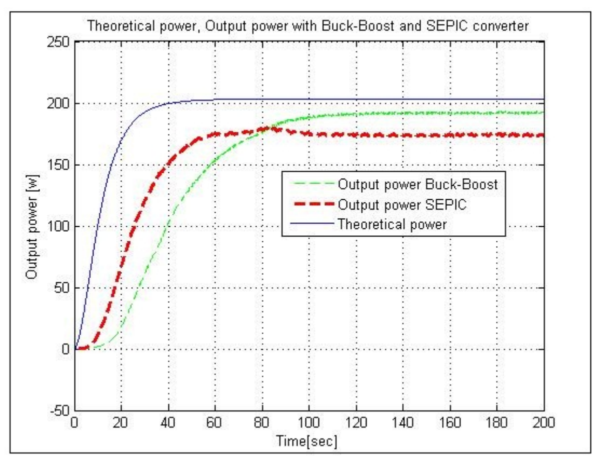

Fig. 11. Output power with Buck-Boost and SEPIC converter

of using a MPPT controller rather than a fixed duty cycle control is demonstrated in Figure 12 where the input hot side temperature to the TEG is increased in fixed steps ranging from $600K$ to $900K$. As can be seen, the P & O MPPT algorithm is able to adapt with increasing temperature with consistent efficiency values. Whereas the fixed duty cycle is only optimised for around $800K$ and is not able to perform as well as the P & O algorithm in other temperature ranges.

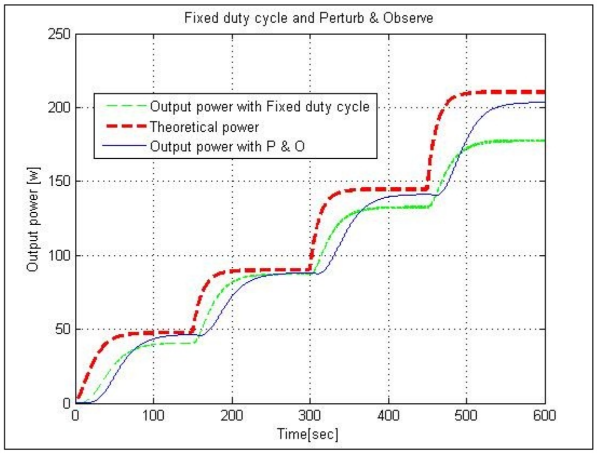

Fig. 12. Output power with fixed duty cycle and P&O

Temp (K)	Pmatch	Fixed	Fixed	P&O	P&O
	$P(w)$	$P(w)$	$\eta\%$	$P(w)$	$\eta\%$
600	47.61	40.8	85.69	46.50	97.67
700	90.00	87.4	97.11	88.14	97.93
800	144.72	132.6	91.23	141.20	97.58
900	210.50	177.6	84.37	203.45	96.67

TABLE I
TEG RESULTS WITH DIFFERENT MPPT ALGORITHMS

VIII. Conclusion

The thermoelectric generator model presented is a useful tool to aid in the design and development of a TEG system as well as for investigating the potential benefits of the system for automotive applications. With continuous advancement in thermoelectric technology new material data can be added to the model to aid the initial material selection process. In addition other DC-DC converter topologies and MPPT algorithms can also be investigated using this model.

It has been determined that a step-up step-down type converter and a MPPT algorithm combination is required for power conditioning in TEG systems due its transient nature. For the converters assessed, Buck-Boost converters are the preferable choice along with the P & O MPPT algorithm which demonstrates a favourable performance.

Acknowledgment

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