

Power conditioning of thermoelectric generated power using dc-dc converters: A case study of a boost converter

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Abstract: The near exhaustion of non-renewable energy resources such as fossil fuels followed by disastrous climatic changes have alerted the world to invest in alternative energy sources. Thermoelectric (TE) technology is responsible for innovating TE devices such as thermoelectric generators (TEGs) which are used to generate electrical energy from heat in an environmentally friendly manner. One of the challenges behind TEG is that they have low efficiency due to low figure of merit. Moreover the power generated is unstable and therefore needs proper power conditioning mechanism before it is connected to the load. The objective of this work is to analyze the performance of a boost dc-dc converter connected on TEG system. The simplified models have been used as the basis of TEG design. Results indicate that the converter is able to stabilize and boost the voltage and higher converter efficiencies are achieved at different hot side temperatures.

Keywords: Thermoelectric effect; TEG device; dc-dc converter.

1 Introduction

The rapid development of power electronics technologies has enabled the realization of high energy-efficient systems such as electric vehicles¹. In the French industry, 75% of the final energy is used for thermal purposes such as furnaces, reactors, boilers and dryers. However, around 30% of this heat is assumed to be wasted in form of discharged hot exhaust gas, cooling water and heated product². Thus, the recovery of the waste heat is believed to contribute considerable amount to the daily energy needs especially in transportation sector. The waste heat can be recovered using thermoelectric generators (TEG). Thermoelectric (TE) effect is the direct conversion of temperature difference into electric voltage and vice versa. TE modules offer low cost electricity, and green energy technology without the use of moving parts or production of environmentally deleterious wastes³. TE technology has seen increasing applications in recent years due to increase in TE research. Although TEG devices were primarily being used for waste heat recovery, they are now applied for harvesting energy from biomass, geothermal, solar and others. In recent years, the efficiency of TE devices has improved greatly due to TE material and device geometrical improvements. However, TEG/TEC efficiency is still low, being a subject of further research to improve TE devices performance.

Particularly, to improve the performance of the overall TEG system, several power conditioning methods have been proposed and analyzed^{4 5 6}. It can be observed that dc-dc converters are able to provide a more stable power output and improve the efficiency of TEG system. The purpose of this work is to analyze the boost dc-dc converter performance on TEG system.

2 The structure of TEG device

A TEG unit is primarily composed of an n-type and a p-type semiconductor. A number of

TEG units are normally stacked to form a TEG module so as to produce the required power as illustrated in Figure 1.

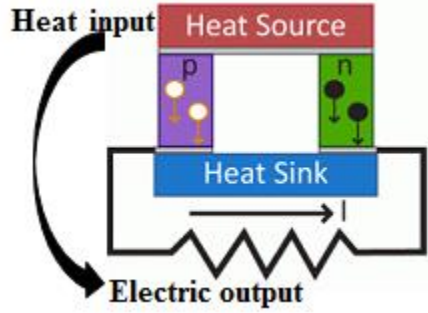


Figure 1. TEG module ⁷.

While choosing TEGs for application in varying conditions, it is necessary to select an appropriate semiconductor with acceptable performance in the temperature range of that condition ⁷. The figure of merit (Z) is a parameter generally used to gauge the performance of a TE material:

$$Z = \frac{\alpha_{p,n}^2 \sigma_{p,n}}{\lambda_{p,n}} \quad (1)$$

Where $\alpha_{p,n}$ is the Seebeck coefficient of n-type or p-type material; $\sigma_{p,n}$ is the electrical conductivity of the material in p-type or n-type, Siemens per meter; $\lambda_{p,n}$ is the thermal conductivity.

In general, to obtain maximum TEG efficiency, the important characteristic for thermoelectric material is the dimensionless figure of merit ZT ⁸.

2.1 TEG modelling

The thermoelectric element is a combination of a series of many small Peltier junctions each of which separately produces or absorbs heat⁹. This is the Thomson power developed per unit volume.

The Thomson coefficient τ is expressed as

$$\tau = T \frac{d\alpha}{dT} \quad (2)$$

This equation indicates that the Thomson coefficient must not be applied in situations where Seebeck coefficient is constant and calculated with the average temperature. Because of the existence of such thermoelectric effects in a sole TE element which affect its performance, it is necessary to consider these effects in the modelling process to achieve a more accurate prediction of performance of TE devices. Several TE models have been proposed including the standard simplified models in which the Seebeck coefficient is held constant and hence the Thomson effect is zero ¹⁰. The simplified TEG model can generate the voltage and internal resistance parameters as the output. Therefore, in this paper, the simplified model is used as the basis for designing the TEG in Simulink.

In this study, TEG1-12611-6.0 TEG Module specifications have been utilised in the simulation model. The module specifications are shown in Table 1.

Table 1. Specifications of the TEG module

Parameters	Values
Hot side temperature/ $^{\circ}\text{C}$	300
Cold side temperature/ $^{\circ}\text{C}$	30
Matched load output voltage/V	4.2
Matched load output current/A	3.4
Matched load resistance/ Ω	1.2
Matched load output/W	14.6

3 The proposed TEG power conditioning system

The voltage-current characteristics as well as power of a TEG are non-linear and therefore it is quite necessary to recondition the power output of the TEG before it is supplied to the load. Several methods are reported which can be applied to stabilize the voltage generated from the TEG to improve the overall performance of the system¹¹⁴. The choice of a dc-dc converter affects the optimum performance of the whole system and therefore a proper criterion has to be followed to choose the best converter. The available converter topologies include the boost, buck, buck-boost, push-pull, Cu'k, fly-back and converters. The proposed TEG power condition circuit consists of three (3) main components; the TEG, the dc-dc converter and the PWM signal generator. Figure 2 shows a block diagram of the proposed circuit and the boost converter circuit implemented in this work is shown in Figure 3.

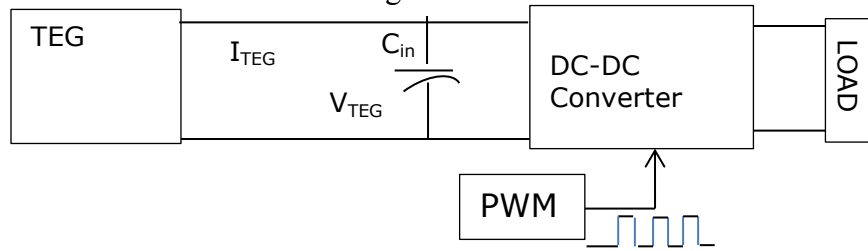


Figure 2. Block diagram of the proposed TEG Power conditioning system

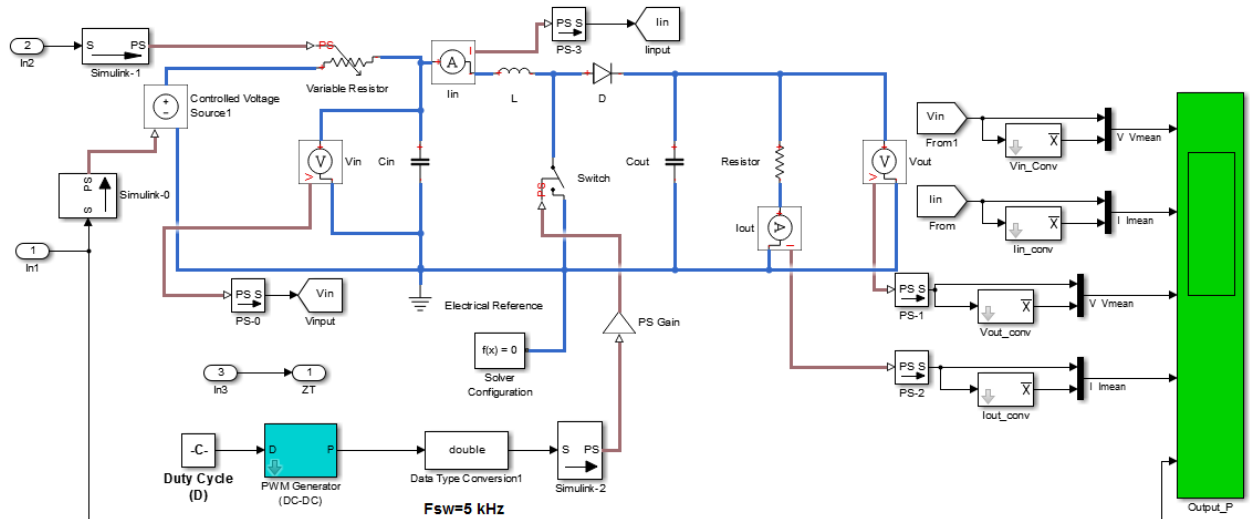


Figure 3. Boost converter circuit implemented in Simulink

4. Results and discussion

As indicated earlier, the modelling is performed in Simulink. So, Figure 4 shows the modelled circuit in Simulink from which the results are obtained for analysis. The cold side temperature is set as 30 °C whereas hot side temperatures is set at 200 °C, 225 °C, 250 °C, 275 °C and 300 °C in order to test the performance of the converter system at those temperatures. The results are presented with steady state values of Voltage and power.

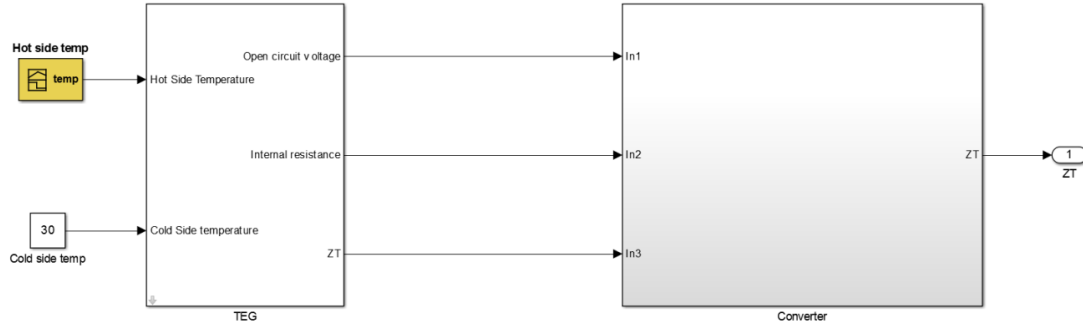


Figure 4. The proposed TEG Power conditioning system

4.1 Steady state model performance

At steady state, the values of voltages, currents and power as well as resistance of the systems are recorded by computing the average values at each hot side temperature level. Figure 5 shows the average open-circuit voltage of TEG, input and output voltage of the converter at different temperature for a single TEG module. The average input and output power of the converter and TEG output power at different temperatures for a single TEG module are shown in Figure 6.

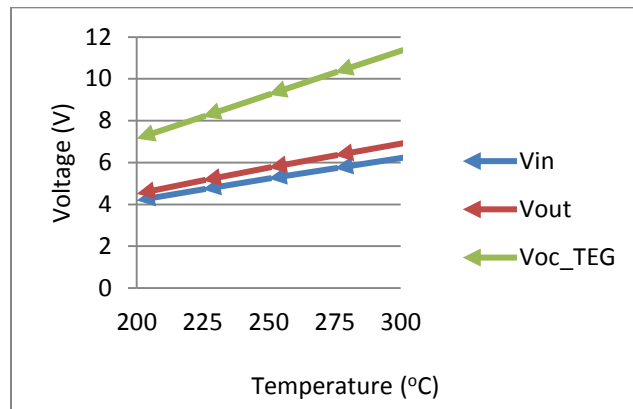


Figure 5. Average input, output voltage of the converter and open circuit voltage of TEG at different temperature for a single TEG module.

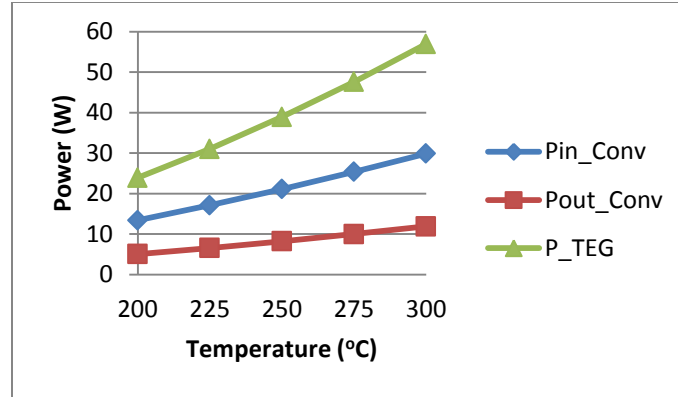


Figure 6. Average input, output power of the converter and TEG output power at different temperatures for a single TEG module.

4.2 Verification of simulation results

The results of this study are compared with the results presented in ¹². In ¹², the author studied a similar TEG/boost converter model with the same TEG specifications as in the present study. It can be observed from Figure 7a that the matched power output from the converter at a temperature of 200°C is 14.1W for a single TEG module in previous work whereas it is 13.9 W at the same temperature in this study (Figure 7b) which is approximately the same value. The relationship between the hot side temperature and the matched power is the same in both cases whereby the matched power output increases as the hot side temperature increases.

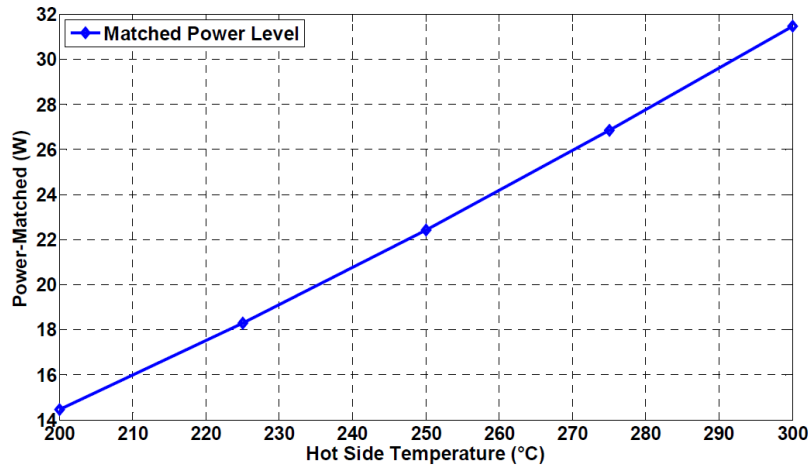


Figure 7a. Input power to the converter under the matching condition in previous work

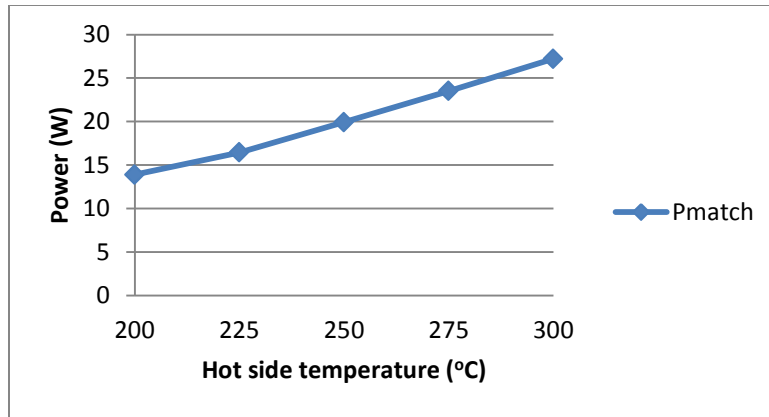


Figure 7b. Input power to the converter under the matching condition in present work

From Figure 8b, the highest conversion efficiency achieved in the previous study is about 81 % at a temperature of 300oC. However, in Figure 8b a higher conversion efficiency of 88.7% is recorded in the current study which confirms proper tuning of the converter circuit. In both cases the efficiency increases as the temperature increases which is expected since the matched power output has a similarly trend.

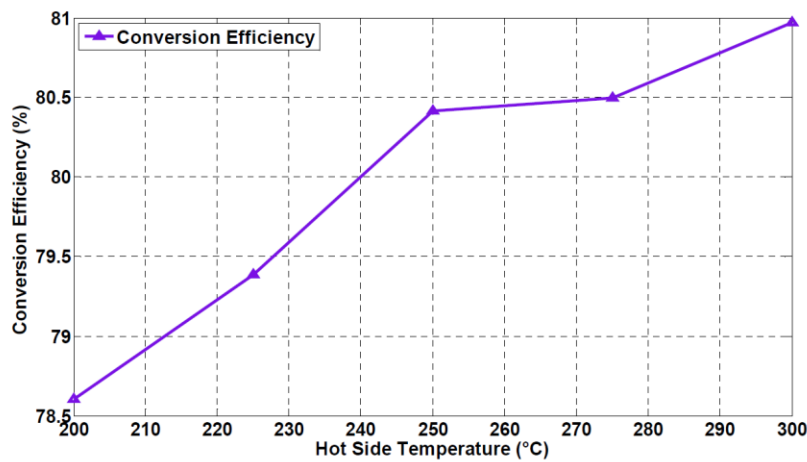


Figure 8a. Conversion efficiency of the converter at different hot side temperatures with previous work ¹²

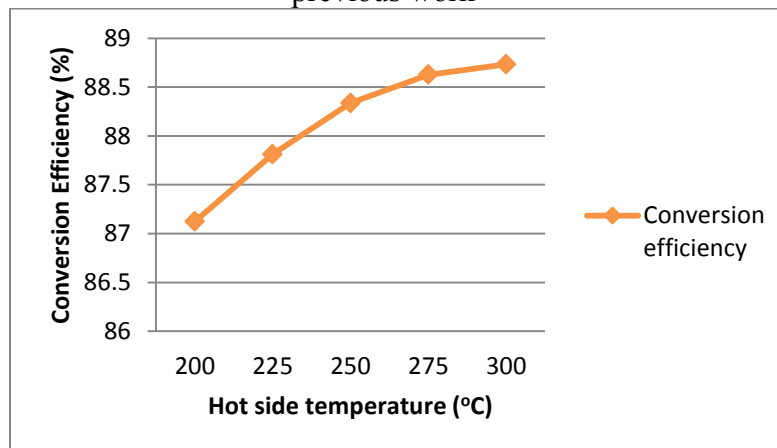


Figure 8b. Conversion efficiency at different hot side temperatures with present work

Figure 9 shows the output voltages of the converter at different values of D . it can be observed that at $D = 0$, the highest values of output voltages are obtained and hence the converter efficiency is computed at these values.

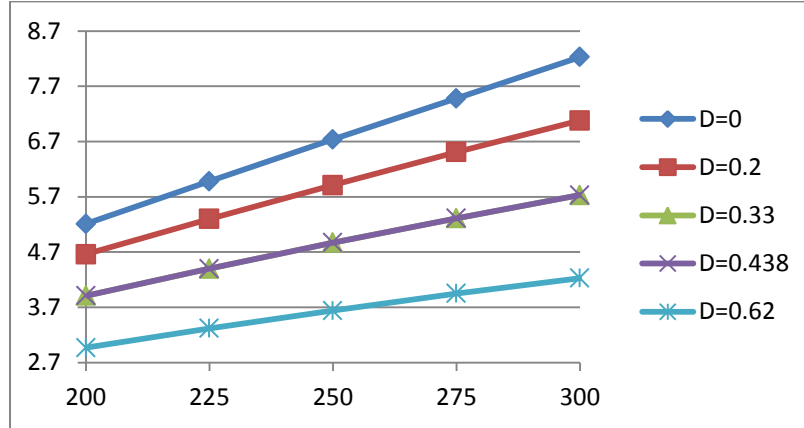


Figure 9. Output voltages of the converter at different values of D

4.3 Variation of voltage with TEG modules

A number of scenarios are considered with the number of TEG modules varied in order to investigate how the voltage from TEG and converter will respond to the increase in the number of TEG modules. It can be observed from Figure 10 that there is a linear relationship between the converter input voltage and the hot side temperature. Similarly, there is a direct relationship between converter input voltage and the number of TEG module i.e. as the number of number of TEG modules (TEG-Mn) is increased the voltage also increases.

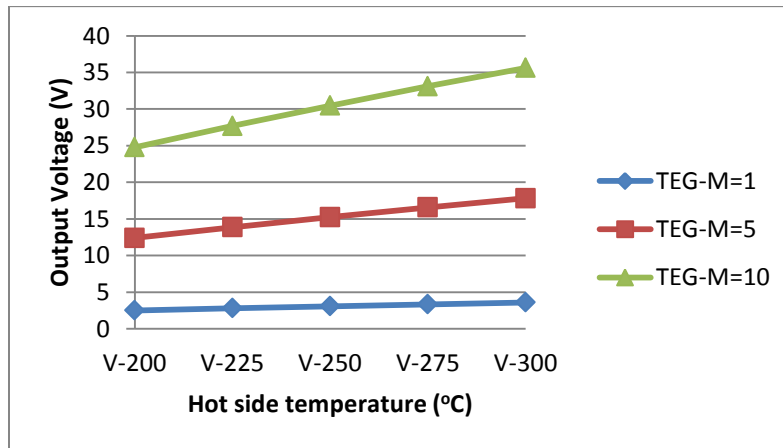


Figure 10. The relationship between the converter input voltage and the hot side temperature.

8. Conclusion

Thermoelectric (TE) technology is responsible for innovating TE devices such as TEGs which are used to generate electrical energy from heat in an environmentally friendly manner. In this paper the boost dc-dc converter performance with TEG system has been analyzed based on simplified model. The application of boost converter to TEG system is

observed to have better steady state performance, hence improving the TEG performance and the overall system efficiency. The use dc-dc converter with maximum power point tracking algorithms will be considered in future work.

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