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# Battery charging considerations in small scale electricity generation from a thermoelectric module

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## HIGHLIGHTS

- Small amounts of electrical power are generated using the thermoelectric effect.
- The electricity produced is used to charge a rechargeable 3.3 V $LiFePo_4$ battery.
- The study investigates methods of delivering maximum power to the battery.
- For low temperature gradients (<100 °C) a DC–DC convertor is recommended.
- Above this temperature gradient more power was delivered to the battery by direct charging.

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## ABSTRACT

This project involves the development of a prototype electrical generator for delivering and storing small amounts of electricity. Power is generated using the thermoelectric effect. A single thermoelectric generator (TEG) is utilised to convert a small portion of the heat flowing through it to electricity. The electricity produced is used to charge a single rechargeable 3.3 V lithium–iron phosphate battery. This study investigates methods of delivering maximum power to the battery for a range of temperature gradients across the thermoelectric module. The paper explores load matching and maximum power point tracking techniques. It was found that, for the TEG tested, a SEPIC DC–DC converter was only beneficial for temperature gradients less than 100 °C across the TEG. At a temperature gradient of 150 °C, the effective resistance of the battery was close to the internal resistance of the TEG. For temperature gradients in excess of 100 °C a DC–DC converter is not suggested and a simple charge protection circuit is sufficient.


## 1. Introduction

Thermoelectric generators (TEGs) are solid state devices that convert heat directly to electricity. Although TEGs are commercially available, they are low in efficiency, typically of the order of 3–5%. This being the case, they are generally used in niche applications that require power in the range of 1 μW to 100 W [1].

The low efficiency of TEGs is compounded by the fact that for a given temperature differential the power generated by a TEG generator system is a function of the load resistance. Since there is a peak maximum power at a critical load resistance, the real life efficiency could be much less than the maximum possible efficiency if the load resistance is greater or less than this critical value. This is the case for both single TEG technologies, such as that reported in O'Shaughnessy et al. [2] as well as generators with multiple TEGs, such as that reported by Lesage and Pagé-Potvin [3]. Thus, a complete TEG generator design requires that not only the heat source, the TEG and the heat sink be modelled, but also the effective impedance of the electrical load to which the TEG is supplying electricity.

Recent work with regard to testing and modelling thermoelectric modules aims to provide the theoretical framework to predict the electrical output characteristics given the thermal boundary conditions on the hot and cold faces of the TEG. Based on the works of Sandoz-Rosado and Stevens [4], Rodríguez et al. [5], Hodes [6] and Hsu et al. [7], it can be said that theoretical modelling of thermoelectric generators is mature. On the other hand, there has been less attention paid to technologies which ensure that the maximum power is being drawn from the TEG for the given thermal loading condition.

Eakburanawat and Boonyaroonate [8] developed a SEPIC DC–DC converter that was controlled by a microcontroller to optimally charge a battery from thermoelectric modules. Maximum power was transferred to the battery when the input impedance of the DC–DC converter matched the impedance of the battery. The input

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**Nomenclature**

| | |
|---|---|
| $A$ | cross-sectional area of a single thermo-element, $m^2$ |
| $I$ | current, A |
| $I_m$ | current at matched load, A |
| $L$ | length of thermo-element, m |
| $L_c$ | contact layer thickness, m |
| $N$ | number of thermo-elements |
| $P_{elec}$ | electrical power, W |
| $Q_H$ | heat delivered to TEG hot side, W |
| $Q_C$ | heat dissipated from TEG cold side |
| $R_L$ | load resistance, Ω |
| $R_{TEG}$ | TEG internal resistance, Ω |
| $T_h$ | module hot side temperature, K |
| $T_c$ | module cold side temperature, K |
| $\Delta T_{TEG}$ | module temperature difference, K |
| $V$ | voltage, V |
| $V_m$ | voltage at matched load, V |
| $V_{oc}$ | open circuit voltage, V |
| $Z$ | figure of merit, 1/K |
| $\alpha$ | seebeck coefficient, V/K |
| $\alpha_{eff}$ | effective seebeck coefficient, V/K |
| $\alpha_{p,n}$ | seebeck coefficient of p/n element, V/K |
| $\lambda$ | thermal conductivity, W/m K |
| $\lambda_c$ | contact thermal conductivity, W/m K |
| $\lambda_{p,n}$ | thermal conductivity of p/n element, W/m K |
| $\rho$ | electrical resistivity, Ω m |
| $\rho_c$ | electrical contact resistivity, Ω m |

*Abbreviations*

| | |
|---|---|
| TEG | thermoelectric generator |
| TEM | thermoelectric module |
| PWM | pulse width modulated |
| MPPT | maximum power point tracking |
| MOSFET | metal oxide semiconductor field effect transistor |
| SEPIC | single ended primary inductor converter |

impedance of the DC–DC converter was changed by varying the duty cycle of the pulse width modulated (PWM) signal applied to the gate of the MOSFET. Six Taihuaxing TEGs (TEP-1264-1.5) were connected in series to give a combined internal resistance of 17.8 Ω at 140 °C. These were then used to charge a 6 V battery with internal resistance of 0.1 Ω. Three experiments were set up: in the first experiment, the TEGs were directly connected to the battery. The maximum power transferred to the battery was 6.35 W. In the second experiment, a SEPIC converter was introduced with the duty cycle fixed at 35%. In this case the power transferred to the battery was 7.63 W. In the third experiment, the duty cycle of the MOSFET was varied throughout the experiment in order to deliver maximum power to the battery. This was implemented by measuring the current into the battery and varying the duty cycle until maximum current flowed into the battery. The Perturb and Observe maximum power point tracking (MPPT) technique was used, however only the current was measured as it was assumed that the battery voltage remained relatively constant. In this scenario 7.99 W was transferred to the battery and the SEPIC was found to be 95.11% efficient. The maximum power point tracking circuit was determined to be 15% more efficient than direct charging. It was also observed that during direct charging, if there was no temperature difference across the TEG, the TEG acted as a load and discharged the battery. This did not happen when the SEPIC was inserted.

In 2006, Nagayoshi and Kajikawa [9] developed a buck-boost based maximum power point tracker to reduce the impedance mismatch between an array of thermoelectric modules and the load. The resistance of the load was varied from 3 Ω to 40 Ω. The MPPT algorithm operated by increasing the duty cycle until the conductance of the load matched the internal conductance of the TEG array. If the effective conductance of the load was lower than that of the TEG array, boost mode was employed. Conversely, if the effective conductance of the load was higher than the internal conductance of the TEGs, buck mode was employed. The circuit was 80% efficient.

Nagayoshi et al. [10] later compared the output power with and without the maximum power point trackers. Two experimental rigs were set up. The first rig consisted of four strings of TEGs held at different temperature gradients: 40 °C, 70 °C, 100 °C and 130 °C. Within each string, the temperature was held constant. In the second rig, maximum power point trackers were placed on each string of TEGs. Nagayoshi et al. [10] compared the output power of each system with a range of load resistances. When a load of 5 Ω was applied, direct charging delivered more power than the MPPT method for the string of TEGs held at 70 °C and 100 °C. This highlights that while the internal resistance of the TEGs is temperature dependent, the resistance changes only slightly with temperature and thus if the load is matched at a given temperature, direct charging can be optimal even if this temperature fluctuates within a certain range.

Lihua et al. [11] investigated power conditioning for thermoelectric modules. Ten TEGs were connected in series and a 40 Ω load was attached, which was close to the total internal resistance of the TEGs. At a temperature gradient of 119 °C, the output power of the TEGs was calculated to be 50.6 W. The 40 Ω load was then replaced by a light bulb and the TEG output power dropped to 23 W. A maximum power point tracker was then developed using a boost DC–DC converter with synchronous rectification and the Perturb & Observe method. Efficiencies of 95.3% were achieved. The maximum power transferred to the light bulb was 47 W. This increase in power was due to load matching.

Vieira and Mota [12] designed and built a maximum power point tracker to optimally charge a lead acid battery using a thermoelectric module. The MPPT was based on a SEPIC circuit working in continuous conduction mode and the Perturb and Observe method was employed to find the maximum power point. In the algorithm, charge protection was also implemented to protect the lead acid battery from over-charging. The experimental results showed that if the 12 V battery was directly connected to the TEG, the TEG generated 19 W, whereas if the MPPT was inserted between the TEG and the battery, the TEG produced 28.5 W. The MPPT circuit produced 33% more power from the TEG than direct charging.

This paper focuses on charging a rechargeable battery using only one thermoelectric generator. The context of the research is for developing world applications, such as that reported by O'Shaughnessy et al. [2], where small amounts of electricity can be used to charge LED lanterns and low power demand mobile phones. Within this context, the specific objectives of this study are to:

- Select a thermoelectric module and fully characterise it at different temperature gradients and with different load resistances.
- Select a battery and consider different methods of charging the battery.