# ANALYSIS ON SEE BECK EFFECT BASED TEC MODULES

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**Abstract- In order to develop sustainable, non-polluting electrical energy for meeting the increased global energy demand many different energy sources and conversion devices are being used in application. Recent developments in the field of thermo electric generators (TEG) have made them an attractive alternative in the field of renewable energy sources. Like solar PV modules TEGs can also be connected in series or parallel in order to achieve desired levels of voltage and current. Series and parallel connection of thermo electric modules may result in mismatch errors and this may lead to decrease in output power extraction. This paper is basically an analysis of thermo electric power generation using see beck effect based thermo electric cooler modules.**

**Index Terms— Mismatch errors, See beck effect, Thermo electric cooler, Thermo electric generator.**

## I. INTRODUCTION

Thermo electric generators convert heat energy in to electricity in a quantity dependent on the temperature difference across them and the electrical load applied based on see beck effect. Whereas, the Peltier effect can be considered as the back-action counterpart to the See beck effect.ie the presence of heating or cooling at an electrified junction of two different conductors. Even though the thermo electric power generation was invented 100's of years ago but the pace of progress has slowed due to limitations in the Figure of Merit of thermo electric materials. But recent developments in improving figure of merits of thermo electric materials like silicon Nano wires raised the scope of thermo electric power production as a promising alternative in direct conversion of waste heat energy in to electrical power.

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The magnitude of the TEG's open-circuit voltage is directly proportional to the temperature difference, and like with solar cells a convenient number of TEGs can be connected in series or parallel in order to achieve desired levels of voltage and current. Power electronic converters are very often used to interface TEGs to the required load. TEGs are often employed in dynamic environments with time-varying temperature differences therefore it is of great importance to quickly and precisely adjust the best electrical operating point in order to always maximize the harvested power. It is necessary to control the power electronic converters with a maximum power point tracking (MPPT) algorithm that matches the virtual load seen by the TEG to its actual internal resistance by changing the duty cycle of the converter. In the literature, the most used MPPT algorithms for TEGs are the Perturb & Observe (P&O) and the incremental conductance (INC). These MPPT algorithms have originally been developed for PV systems, in which the relationship between voltage and current is logarithmic. On the contrary, in TEGs, the electrical characteristic is linear:

$$V_{MPP} = \frac{V_{OC}}{2} \quad (1)$$

$$I_{MPP} = \frac{I_{SC}}{2} \quad (2)$$

Where, $V_{MP}$ and $I_{MP}$ are the voltage and current at the maximum power point, $V_{OC}$ is the open-circuit voltage and $I_{SC}$ is the short circuit current. MPPT algorithms that use this relationship either measure the open-circuit voltage or the short circuit current[12]. Thus open circuit voltage MPPT is the most suitable maximum power tracking method for thermo electric generators.

An experimental study is conducted in this paper for finding the characteristics of a see beck effect based thermo electric power source using Thermo electric cooler (TEC) modules. Current and Power v/s Voltage characteristics, series and parallel mismatch errors which can occur during the connection are shown in this paper.

## II. CASE STUDY

For developing hardware for 1800mAh rechargeable battery from see beck effect based thermo electric cooler modules (TEC) in cooperating OCV MPPT a case study was done on characteristics of TEC modules. TEC modules have been selected especially to reduce the experimental cost. For the experimental set up we used see beck effect based TEC 12706 Bismuth Telluride modules with a physical size of 40mm× 40mm×2.5mm. The device has 127 thermocouples in it. Its operating temperature is about $200^0$ C and having a life expectancy of 2, 00,000hours. The TEC modules used was sandwiched between 2 steel plates. .The module assembly was subjected to a temperature differences using Incandescent bulbs at the hot side and ice cubes are used at top to provide the heat sink.

### *A. I v/s V and P v/s V characteristics of the TEC modules*

Nine see beck effect based TEC1 12706 devices are connected in series and sandwiched between 2 steel plates. Hot side and cold side temperatures for the experimental set up was given by adjusting incandescent lamp at hot end and ice cubes at cold end. Current and Power v/s Voltage at temperature difference of $40^0$C and $50^0$C by varying load are tabulated as shown in Table 1.

Table1: TEC characteristics at temperature differences of $40^0$C & $50^0$C

| ΔT of $40^0$C | | | ΔT of $50^0$C | | |
|---|---|---|---|---|---|
| Voltage (V) | Current (mA) | Power (mW) | Voltage (V) | Current (mA) | Power (mW) |
| 2.7 | 0 | 0 | 3.75 | 0 | 0 |
| 1.89 | 300 | 567 | 2.96 | 200 | 593 |
| 2.12 | 200 | 424 | 2.33 | 500 | 1165 |
| 1.35 | 500 | 675 | 1.87 | 700 | 1309 |
| 1.12 | 560 | 627 | 1.19 | 900 | 1071 |
| 0.6 | 750 | 450 | 0.4 | 120 | 480 |
| 0.16 | 900 | 144 | 0.18 | 1300 | 234 |
| 0 | 1200 | 0 | 0 | 1.5 | 0 |

Current v/s Voltage and Power v/s Voltage plots for the series connected TEC modules at temperature difference of $40^0$ C and $50^0$ C are shown in fig. 1 and 2 respectively. Here also we got a linear I v/s V characteristics and a parabolic P v/s V characteristics

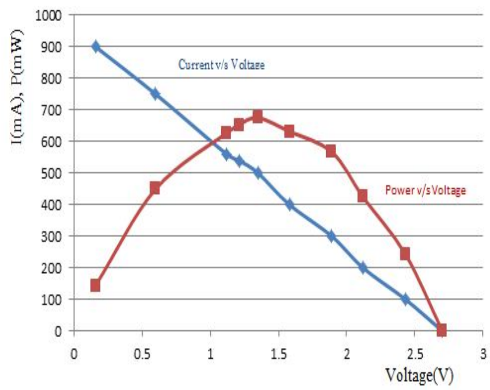


Fig.1: Power and Current v/s Voltage for TEC modules connected in series at ΔT of $40^0$C

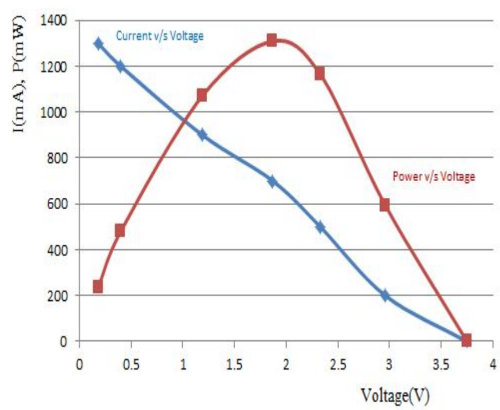


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Fig.2: Power and Current v/s Voltage for TEC modules connected in series at ΔT of $50^0$C

From these two graphs it's clear that at a constant temperature difference maximum power is obtained at half of its OCV in case of see beck effect based TEC modules also. So OCV MPPT method can be used for the power generation from this setup.

*B. Series and parallel mismatch*

Thermoelectric modules can be connected in series and/or parallel (forming an array) to provide the required voltage and/or current. The TEG can be electrically modeled as a voltage source in series with an internal resistance and as shown in Fig.3. The values of both the voltage produced and the internal resistance vary with temperature .Fig.8. Illustrates the series connection of three TEGs, each of them represented by a voltage source $V_{1,,3}$ in series with an internal resistance $R_{1,,3}$ . Under ideal operating conditions, each module within the array will experience an equal ΔT and therefore all modules will produce an equal output voltage $V_{OC}$ and the array will be in a balanced thermal condition. In this case the MPP is at $3V_{OC}/2$ and the overall array resistance is $3R_{int}$. However, actual thermal operating conditions in a practical system might be such that each TEG may experience a different ΔT and therefore their voltages and internal resistances will not be equal. In this case,
$V_{OC} = V1 + V2 + V3$ and the current flowing into the load is

$$I = \frac{V_{OC} - V_S}{R_1 + R_2 + R_3} \quad (8)$$

Where $V_S$ is the voltage at the arrays terminals.

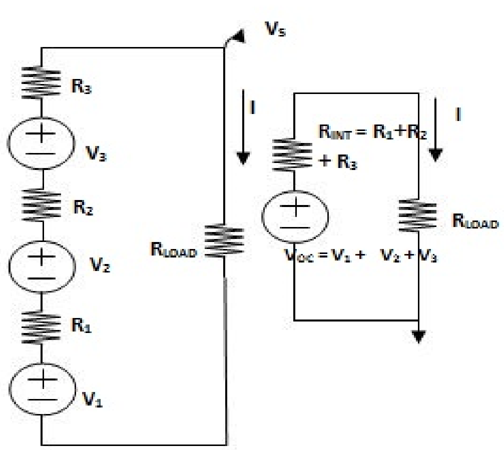


Fig.3: Series array configuration

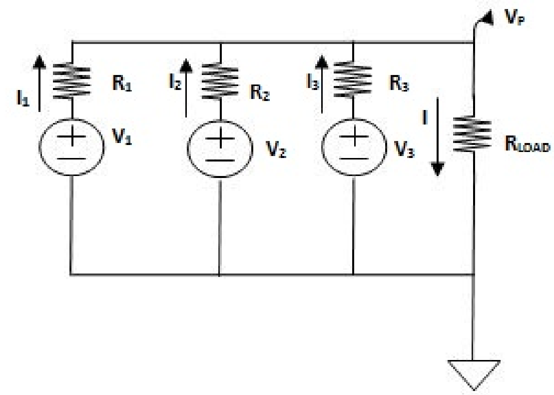


Fig.4: Parallel array configuration

Fig.4 shows three TEGs in a parallel configuration. For ideal operating conditions, the TEG modules in the array operate at the same ΔT. Hence each TEG produces the same voltage and operates at maximum power, with $I_1 = I_2 = I_3$. Under non-ideal thermal conditions the different temperature gradient across each TEG unit will lead to a mismatch voltage at the arrays in the currents magnitude. In most TEG systems the individual thermoelectric modules are subject to temperature mismatch due to operating conditions. Variability of the electro-thermal performance and mechanical clamping pressure of individual TEG modules are also sufficient to cause a significant mismatch. Consequently, when in operation each TEG in the array will have a different electrical operating point at which maximum energy can be extracted and problems of decreased power output arise.

Impedance matching between TEG and load is a basic concept in the design of TEG systems. When the TEG system is composed of single TEM with stable heat source and the load, the system design is simple. However, almost heat sources have temperature distribution, causing mismatch power loss of TEG systems. In large TEG systems, thermoelectric modules are connected in series to obtain required output voltage of the load, composing the string. Each string is connected in parallel to obtain required output power. The mismatch power loss increases with temperature distribution of heat source, much depending on the connection topology of TEMs.

An experiment has been conducted with the 3 See beck effect-based thermoelectric power source using TEC modules, to find the characteristics in series and parallel connection. In this experiment the modules are tested at an average temperature difference of $28^0$ C, $44^0$ C and $56^0$ C respectively. Individual, series and parallel connection with the modules had been done at this temperature differences and the corresponding voltages, current has measured and tabulated as shown in table2-4. Corresponding power and internal resistance are also calculated.

Table 2: TEG characteristics at an average temperature difference $28^0$ C

| Temperature difference $(\Delta T)^0$C | Parameters | TEG 1 | TEG 2 | TEG 3 | Series | Parallel |
|---|---|---|---|---|---|---|
| $28^0$ C | $V_{OC}$ (mV) | 130 | 140 | 120 | 380 | 120 |
| | I (mA) | 39 | 47 | 38 | 37.5 | 98 |
| | Power(mW) | 5.07 | 6.58 | 4.56 | 14.25 | 11.76 |
| | $R_{INT}$ (Ω) | 3.3 | 2.97 | 3.1 | | |

Table 3: TEG characteristics at an average temperature difference $44^0$ C

| Temperature difference $(\Delta T)^0$C | Parameters | TEG 1 | TEG 2 | TEG 3 | Series | Parallel |
|---|---|---|---|---|---|---|
| $44^0$ C | $V_{OC}$ (mV) | 330 | 390 | 320 | 1010 | 320 |
| | I (mA) | 95 | 130 | 90 | 91 | 240 |
| | Power (mW) | 31.35 | 50.7 | 28.8 | 91.9 | 76.8 |
| | $R_{INT}$ (Ω) | 3.4 | 3 | 3.5 | | |

Table 4: TEG characteristics at an average temperature difference $56^0$ C

| Temperature difference $(\Delta T)^0$C | Parameters | TEG 1 | TEG 2 | TEG 3 | Series | Parallel |
|---|---|---|---|---|---|---|
| $56^0$ C | $V_{OC}$ (mV) | 440 | 550 | 440 | 1400 | 440 |
| | I (mA) | 150 | 170 | 150 | 150 | 360 |
| | Power (mW) | 66 | 93.5 | 66 | 210 | 158.4 |
| | $R_{INT}$ (Ω) | 2.93 | 3.235 | 2.93 | | |

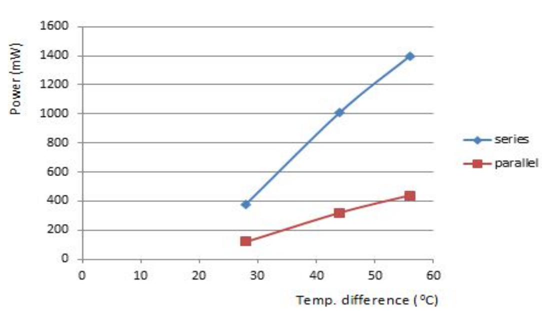


Fig.5: Power v/s temperature differences for series and parallel

The power v/s temperature curve for the series and parallel connection are plotted and are as shown in Fig.5. Series connection of the tested modules produces more power than parallel connection. Similarly voltage v/s temperature difference curve for series and parallel connection and individual see beck based TEC modules are plotted and are as shown in Fig.6 and 7 respectively. Analysis of Fig.7 shows the second module produced more power than the other two tested.

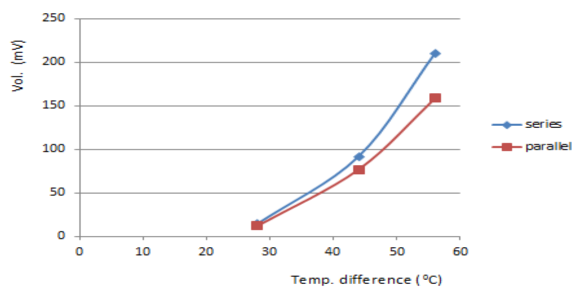


Fig.6: Voltage v/s temperature difference for series and parallel

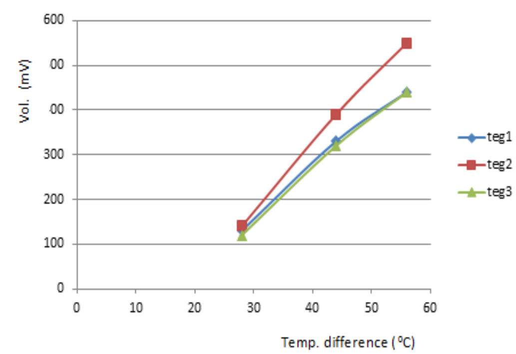


Fig.7: Voltage v/s temperature difference for 3 modules

Even though same modules are used for testing we can clearly understand slight variation in the outputs is mainly due to the non-uniformity in the temperature distribution. TEG2 produce more power than the other 2 modules. In our experimental set up steel plate is employed to provide bottom and top surfaces this may be the main reason for the non-uniformity in the temperature distribution. Materials with higher thermal conductivity should be used so that each plate will distribute heat well. In such materials copper(400W/mK) or aluminium(235W/mK ) can be choose while considering the cost of other high thermal conductive materials like gold, silver etc. It's also observed that more power is produced in series connection than the parallel connections of the three modules. The internal resistance also varies with temperature differences.

Based on the experiment the mismatch errors are calculated as shown below:

The maximum power at TEG1 at $27^0$ C = 5.07mW

The maximum power at TEG 2 at $28^0$ C = 6.58mW

The maximum power at TEG3 at $26^0$ C = 4.56mW

When these three TEGs are connected in series the total power obtained is 14.25mW

Maximum power of TEG1 at $27^0$ C + Maximum power of TEG 2 at $28^0$ C + Maximum power of TEG3 at $26^0$ C =16.21mW

But the maximum power obtained in series= 14.25mW

Mismatch percentage = 100-(14.25/16.21)100 =12.09%

But maximum power when these are connected in parallel is found to be =11.76mW

Mismatch percentage in parallel connection

= 100-(11.76/14.25)*100=17.47%

The maximum power at TEG1 at $43^0$ C = 31.35mW

The maximum power at TEG 2 at $44^0$ C = 50.7mW

The maximum power at TEG3 at $41^0$ C = 28.8mW

When these three TEGs are connected in series the total power obtained is 91.91mW

Maximum power of TEG1 at $43^0$ C + Maximum power of TEG 2 at $44^0$ C + Maximum power of TEG3 at $41^0$ C =110.85Mw

But the maximum power obtained in series= 91.91mW

Mismatch percentage =100- (91.91/110.85)100 =17.08%

But maximum power when these are connected in parallel is found to be =76.800mW

Mismatch percentage in parallel connection

` =100-(76.8/110.85)*100=30.7%

The maximum power at TEG1 at $50^0$ C = 66mW

The maximum power at TEG 2 at $55^0$ C = 93.5mW

The maximum power at TEG3 at $50^0$ C = 66mW

When these three TEGs are connected in series the total power obtained is 210mW

Maximum power of TEG1 at $50^0$ C + Maximum power of TEG 2 at $55^0$ C + Maximum power of TEG3 at $50^0$ C =225.5mW

But the maximum power obtained in series= 210Mw

Mismatch percentage =100- (210/225.5)100 =6.8%

But maximum power when these are connected in parallel is found to be =158.4mW

Mismatch percentage in parallel connection =

100-(158.4/225.5)*100=29.7%

The calculated results convey that connecting thermoelectric generators in series produces better electrical system efficiency, provided that the temperature differences remain constant. The temperature-mismatch situation created in the experiment demonstrated a power production drop of 6.8% and 39%, for the series and parallel cases at an average temperature of $55^0$C respectively, from the maximum power that would be available in case each TEG was controlled individually. From the electrical connection point of view, the parallel-connected array has lower voltage and higher current, which leads to higher $I^2$ R losses (Joule heating) in the wiring, thus further decreasing the overall system electrical efficiency. System cost in parallel connection is adversely affected because of the need for high-current inductors in the Switch-Mode. Thus when thermo electric modules are connected a balance must be maintained between series and parallel in order to meet the requirement and cost.

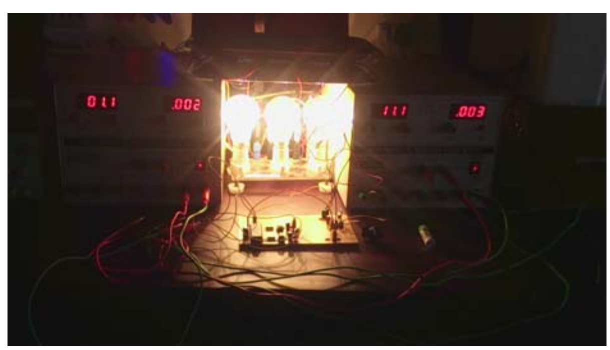

Fig.8: Experimental setup.

## lll. CONCLUSION

This paper shows the analysis done on thermo electric power production using see beck effect based TEC modules. From the analysis of see beck based thermoelectric modules it is clear that the I v/s V characteristics of modules are linear in nature and the P v/s V curve have a parabolic nature .The comparison of I v/s V an P v/s V curve shows that the maximum power is produced from a thermoelectric modules during half its open circuit voltage ant thus proves its only necessary to track the voltage to be half of its OCV in order to obtain maximum power thus this set up can be used with OCV MPPT for waste heat recovery. From the Series and parallel connection analysis of the modules it is clear that mismatch errors will occur which reduce the power extraction. So optimum connection should be provided so as meet the load and cost requirement. Proper moulding of modules are essential so as to extract maximum efficiency and the figure of merit of thermoelectric materials, temperature difference should be high and internal resistance should be low.

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