Investigation of novel thermoelectric sensor array configurations operating under non-uniform temperature distribution conditions for the measurement of maximum output power in an energy harvesting system

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Abstract
This research work proposes a configuration study of thermoelectric module (TEM) sensor array operating under uniform and non-uniform temperature distribution (NUTD) conditions. The four different (10 × 10) TEM array configurations, which are electrically connected in series-parallel (SP), all-tied (AT), bridge-joint (BJ), and bee-hive (BH), are considered to evaluate its performance under six cases of NUTD conditions. The electrical characteristics of the various sensor array configurations have been analysed and tested under both temperature distribution conditions using MATLAB-Simulink. A comparison of results of the various configurations is carried out in terms of maximum output power, voltage and current corresponding to maximum power, utilization factor, losses, relative error, standard deviation, and root mean square error. The maximum output power obtained from various cases of NUTD conditions confirm that the performance of bridge-joint configuration is best than all other configurations in the field of thermoelectric energy harvesting systems.

1 | INTRODUCTION

In the world, the demand for energy is rising every day because of the growth of the human population. Fossil fuels fulfill almost the energy necessity of humans. However, fossil resources are being exhausted [1, 2], and their environmental damage [3] is growing day by day. Hence, research is increased dramatically in the production of clean electrical energy. A significant amount of waste heat energy is released directly into the environment from various sources include industries [4], vehicles [5–8], stoves [9–11], and helicopter [12]. Recovery of waste heat is, therefore, remarkable because it can save significant energy and reduce emissions [13]. The thermoelectric generator (TEG) is the most frequently used waste heat recovery technology. It is a solid-state device providing direct conversion of the waste heat energy into electrical energy that uses the Seebeck effect. Also, it has the advantages of quiet operation, no environmental pollution, less maintenance [14], and highly reliable. However, low conversion performance and high cost for manufacturing limit the development of TEGs. Therefore, enormous research works on thermoelectric materials have been effectively carried out to obtain high conversion performance [15]. Until now, bismuth telluride (Bi₂Te₃) alloy is commonly used thermoelectric materials with relatively high commercial value when compared to other materials, and therefore the conversion efficiency seems to be around 5% [16].

In actual applications, the performance of TEG depends on the boundary conditions of thermal transfer and their configuration [17, 18]. By decreasing the thermal resistance between thermoelectric modules (TEMs) helps to enhance the conversion efficiency and the output power [19]. Furthermore, the TEMs can produce a maximum output power with the use of maximum power point tracking (MPPT) controllers [20–22]. The concept of maximum power transfer theory says that, when the whole source internal resistance is equal to the load resistance, the TEMs delivers maximum power to the load. When
the difference in temperature between the cold and hot sides of the TEM remains constant, the output performance curve of the module follows the theory described above. However, it is a challenging task to sustain a constant $\Delta T$ across the TEM in practical applications [23].

The performance of the TEGs also depends on the conditions of temperature distribution. An analysis of the effect of the non-uniformity temperature on TEG is carried out by using a heat spreader [24]. With the use of simulation and experiments, an analysis is carried out under uniform and non-uniform distribution of temperature conditions on TEG in terms of output power. From the simulation and experimental results, the authors found that the uniform distribution of temperature on the heat spreader has enhanced performance. Moreover, a numerical and experimental study has performed in terms of power under non-uniform heat flux conditions [25] to analyse the performance of TEGs that are associated in series and parallel. The results proved that the output power is mainly affected in a parallel configuration under the above condition. Two TEMs are associated in parallel under various varying temperature conditions [26]. In this work, the authors analysed the energy harvesting system by performing simulation and experimental studies. The effect of electrical and thermal configurations on three TEMs has been investigated [27]. It concentrated mainly on TEMs that are associated with thermally and electrically in different forms. This work stated that TEMs linked thermally and electrically in parallel are optimal for acquiring maximum power. A series and parallel connection of three TEMs in temperature mismatch effect under different temperature conditions were analysed [28]. This work recommended that the series connection of TEMs provide enormous power than that of parallel connection.

To overcome the drawbacks of the NUTD conditions and hardware implementation of MPPT, such as slow speed of convergence, low convergence efficiency, complex coding, a larger number of sensors required in TEG systems and high cost. Hence, a configuration study on TEM array has been proposed for enhancing the output power of the system. Also, this research work proposes analytical modelling and simulation of (10 × 10) TEM array connected in SP, AL, BJ, and BH configurations. It analyses the performance of the configurations, as mentioned above, under uniform temperature distribution (UTD) and six different cases of NUTD conditions. Moreover, it compares the various configurations in terms of output power, voltage and current corresponding to maximum power, utilization factor, losses, relative error, standard deviation, and root mean square error to determine a suitable configuration for the energy harvesting applications.

Figure 1 shows the various topologies of TEM array configurations considered in this proposed research work under UTD and NUTD conditions and the performance parameters to evaluate the TEM array configurations.

![FIGURE 1 TEM array configurations considered under UTD and NUTD conditions and its performance parameters](image)

## 2. Mathematical Model of the Thermoelectric Module

A TEM consists of series-connected thermocouples with $P$-type and $N$-type semiconductor thermoelements. When the heat circulates through thermoelements, it excites the free electron to travel from one end to the other end. As a result, an open-circuit voltage $V_{oc}$ is created [29] which is directly proportional to the $\Delta T$ exist across the module that can be represented as:

$$V_{oc} = N\alpha_T (T_h - T_c) \quad (1)$$

where, $N$ signifies the overall quantity of thermocouples; $\alpha_T$ indicates the Seebeck coefficient, $T_h$ and $T_c$ are the TEM temperature at its hot and cold sides.
The $\alpha_T$ can be represented as:

$$\alpha_T = \frac{2 V_{\text{match}}}{\Delta T_m} \quad (2)$$

where, $\Delta T_m$ denotes the difference in temperature taken from the device datasheet; $V_{\text{match}}$ represents the matched voltage of the TEM.

The internal resistance $R_{\text{TEM}}$ can be indicated for the TEM as:

$$R_{\text{TEM}} = s_r \left[ \frac{T_h}{2} + T_c \right] + i_r \quad (3)$$

where, $i_r$ and $s_r$ stand for the intercept and slope of whole internal resistance versus maximum temperature, respectively.

The Matlab–Simulink model of TEM (GM250-127-28-10) is shown in Figure 2. Using this model, one can analyse the performance characteristics of TEM, such as power-current ($P-I$) and voltage-current ($V-I$).

The specifications for the TEM mentioned above are given in Table 1.

| Product Code | GM250-127-28-10 |
|--------------|-----------------|
| Size         | $62 \times 62 \times 4$ mm |
| Hot side temperature $[^{\circ}\text{C}]$ | 250 |
| Cold side temperature $[^{\circ}\text{C}]$ | 30 |
| Open circuit voltage [V] | 6.9 |
| Matched load resistance [$\Omega$] | 0.42 |
| Matched load output voltage [V] | 3.45 |
| Matched load output current [A] | 8.2 |
| Matched load output power [W] | 28.3 |
Figure 3(a,b) show the $P-I$ and $V-I$ performance characteristics of TEM at various $\Delta T$ such as 220, 200, 150, and 65 °C. From these characteristics, one can evaluate the electrical performance of TEM. From Figure 3(a), it can be noted that the power of TEM decreases with $\Delta T$ is due to the decrease in the open-circuit voltage.

### 3.1 | Series-parallel configuration

In this configuration, the TEMs are associated in series to obtain a required voltage and then in parallel to obtain a required current. It is the most frequently used configuration since it is inexpensive, simple structure, and easy to construct. Moreover, in this arrangement, the voltage and current simultaneously increases when increasing the TEMs. The power losses owing to mismatching are more in this configuration as more number of TEMs is connected in series.

The output voltage $V_{\text{TEM}}$ and output current $I_{\text{TEM}}$ of this topology can be signified as:

$$V_{\text{TEM}} = \sum_{j=1}^{10} V_j$$  \hspace{1cm} (4)  

$$I_{\text{TEM}} = \sum_{j=1}^{10} I_j$$  \hspace{1cm} (5)  

The open-circuit voltage $V_{oc}$ across each TEM can be expressed as

$$V_{oc} = \sum_{i=1}^{n} (V_i - I_i R_{\text{TEM}(i)})$$  \hspace{1cm} (7)  

### 3.2 | All-tied configuration

The topology of $(10 \times 10)$ array AT configuration is shown in Figure 5. In this topology, initially, multiple TEMs are associated in parallel, and then those parallel TEMs are connected in series. This topology has excess power losses because of more number of wiring connections, complex, and high cost due to electrical wiring. In this configuration, the voltage across the output is the addition of each module voltage in a row. The current through the load is computed by adding the currents in all TEMs of a row.

The output voltage $V_{\text{TEM}}$ and output current $I_{\text{TEM}}$ of this topology can be signified as

$$V_{\text{TEM}} = \sum_{j=1}^{10} V_j$$  \hspace{1cm} (8)  

$$I_{\text{TEM}} = \sum_{j=1}^{10} I_j$$  \hspace{1cm} (9)  

### 3.3 | Bridge-joint configuration

Figure 6 shows the topology of $(10 \times 10)$ array BJ configuration. This configuration makes use of bridge architecture. In
In this bridge structure, two TEMs are in series, and then the series modules are connected in parallel. The series connection of BJ configuration is more than the AT configuration and less than SP configuration. This topology overcomes the drawback of SP configuration and has fewer power losses due to mismatching. By adding the voltage of the series modules and the currents in the parallel modules, a required amount of output voltage and output current are obtained. The output voltage $V_{TEM}$ and output current $I_{TEM}$ of this topology can be signified as:

$$V_{TEM} = \sum_{i=1}^{10} V_i$$  \hspace{1cm} (10)

$$I_{TEM} = I_1 + I_6 + I_{16} + I_{26} + I_{36} + I_{46} + I_{56} + I_{66} + I_{76} + I_{86}$$  \hspace{1cm} (11)
3.4 | Bee-hive configuration

The topology of \((10 \times 10)\) array BH configuration is shown in Figure 7. In this topology, every six TEMs are group together in a hexagonal shape like a honey bee architecture. The series connection of BH configuration is more than the BJ and AT configuration and less than SP configuration. Therefore, the power losses owing to mismatching are more than AT and BJ configurations. The voltage of the series modules and the current in the parallel modules are added, to acquire the required output voltage and output current.

The output voltage \(V_{\text{TEM}}\) and output current \(I_{\text{TEM}}\) of this topology can be signified as:

\[
V_{\text{TEM}} = \sum_{j=1}^{10} V_j \tag{12}
\]
\[ I_{\text{TEM}} = I_1 + I_7 + I_{17} + I_{27} + I_{37} + I_{47} + I_{57} + I_{67} + I_{77} \]  

\[(13)\]

### 4.1 ANALYSIS OF NUTD CONDITIONS

The different cases of NUTD conditions are shown in Figures 8(a–d) and Figure 9(a,b).

**Case 1**: The \( \Delta T \) values of the first and second column of the TEM array are 65 °C, the third, fourth and fifth column are 150 °C and other columns of TEMs are 200 °C. Figure 8(a) shows the case 1.

**Case 2**: The \( \Delta T \) values of the left upper half of the first, second, third and fourth column of the TEM array are 65 °C, the lower half of the seventh, eighth, ninth and tenth column are 150 °C, and other TEMs are 200 °C. Figure 8(b) shows the case 2.
Case 3: The $\Delta T$ values of the TEMs in diagonal of the TEM array are $65 \, ^\circ C$, the neighbourhood modules of the diagonal are $150 \, ^\circ C$, and other TEMs are $200 \, ^\circ C$. Figure 8(c) shows the case 3.

Case 4: The $\Delta T$ values of the middle four TEMs of the array are $65 \, ^\circ C$, the two neighbourhood modules are $150 \, ^\circ C$, and the other TEMs are $200 \, ^\circ C$. Figure 8(d) shows the case 4.

Case 5: The $\Delta T$ values of the TEMs at the corner of the array are $65 \, ^\circ C$, the neighbourhood modules of the corner are $150 \, ^\circ C$ and other TEMs are $200 \, ^\circ C$. Figure 9(a) shows the case 5.

Case 6: The three $\Delta T$ values are distributed randomly in the TEM array. Figure 9(b) shows the case 6.

5 | RESULTS AND DISCUSSION

Figure 10(a,b) shows the $P-I$ and $V-I$ characteristics of TEM array configurations at UTD conditions. The performance of TEM array configurations is analysed by operating all TEMs with the same $\Delta T$ of $200 \, ^\circ C$.

Table 2 shows the maximum power of the TEM array $P_{\text{TEM(max)}}$ in all configurations at the UTD conditions. From Table 2, one can examine that the same maximum power of 2360.92 W is acquired from all configurations. Moreover, the voltage $V_{\text{TEM(max)}}$ and current $I_{\text{TEM(max)}}$ corresponding to maximum power are given in Table 2.

Moreover, the performance of TEM array configurations has examined under the NUTD conditions by simulating the six different cases of it. Table 3 shows the comparison of the simulation results of all TEM array configurations under different cases of NUTD conditions.

Under case 1 of NUTD conditions, the maximum power provided by all configurations is the same, which is $1483.98 \, W$ with an associated voltage and current of $24.5848 \, V$ and $60.3618 \, A$, respectively.

Under case 2 of NUTD conditions, Bj configuration provides the highest maximum output power of $1605.44 \, W$. The corresponding maximum voltage and current are $25.6196 \, V$ and $62.6644 \, A$, respectively. The next highest maximum output power ($1596.97 \, W$) is provided by the BH configuration, whereas the AT configuration gives the least maximum output power ($1577.06 \, W$).

Under case 3 of NUTD conditions, Bj configuration offers an excellent performance than the other configurations with the highest maximum output power ($1893.76 \, W$), and a related maximum voltage and current are $27.9432 \, V$ and $67.7719 \, A$, respectively. The next comes the SP configuration with a second highest maximum output power of $1888.26 \, W$. The AT configuration supplies the lowest maximum output power ($1863.39 \, W$).
Under case 4 of NUTD conditions, BJ configuration supplies the highest maximum power (1910.06 W) with an associated voltage of 28.0696 V and current of 68.0473 A. The SP configuration provides the next highest maximum power (1907.85 W), and the AT configuration gives the least maximum power (1903.39 W).

Under case 5 of NUTD conditions, BJ configuration presents an outstanding performance with the highest maximum output power (1823.33 W), and a related maximum voltage and current are 27.3912 V and 66.5663 A, respectively. The next comes the BH configuration with a second highest maximum output power of 1819.86 W. The AT configuration supplies the lowest maximum output power (1813.28 W).

Under case 6 of NUTD conditions, BJ configuration generates the highest maximum output power (1196.03 W) with a corresponding voltage and current of 21.5186 V and 55.5809 A, respectively. The next highest maximum output power (1184.33 W) is provided by the SP configuration, while the AT configuration gives the least maximum output power (1157.35 W).

Figures 11(a–d) and 12(a,b) show a comparison of $P-I$ characteristics for the cases (1)–(4) and cases (5) and (6), respectively under NUTD conditions.

Table 4 shows a sum of maximum power from individual TEMs in various cases of NUTD conditions. For each case, the maximum power $P_{\text{TEM(max),i}}$ is the same for all TEM array configurations.
FIGURE 11  Comparison of $P$–$I$ characteristics under NUTD conditions (a) case 1 (b) case 2 (c) case 3 (d) case 4

FIGURE 12  Comparison of $P$–$I$ characteristics under NUTD conditions (a) case 5 (b) case 6
The maximum power and its corresponding voltage and current for various cases under NUTD and UTD conditions are compared. Consequently, the maximum power from SP, AT, BJ, and BH configuration is the same for UTD conditions and Case 1. For all other cases, the BJ configuration has provided the highest maximum output power. Moreover, the results obtained from the UTD and various cases of NUTD conditions are compared in terms of utilization factor, losses, relative error, standard deviation, and root mean square error. The above parameters can be computed by using the expressions that are given below:

The utilization factor is investigated and compared among all configurations under both conditions. The obtained results are shown in Table 5.

From Table 5, it is seen that the array utilization is the same for all configurations under case 1 and UTD conditions. The BJ configuration provides a higher array utilization in all other cases of NUTD conditions. Moreover, it is observed that the array utilization is less in cases 1 and 6, whereas it is almost above 90% in all other cases. However, the array utilization is higher in case 4 among the different cases of NUTD conditions. The comparison of the utilization factor under UTD and various cases of NUTD conditions is shown in Figure 13.

\[
\text{Utilization factor (\%)} = \frac{P_{\text{TEM(max)}}}{\sum P_{\text{TEM(max)/modules}}} \times 100 \quad (14)
\]

\[
\text{Mismatch power losses (\%)} = \frac{P_{\text{TEM(max)/j}} - P_{\text{TEM(max)/i}}}{P_{\text{TEM(max)/j}}} \times 100 \quad (15)
\]

The mismatch power losses of all configurations are compared, and the values are given in Table 6. From Table 6, it is noticed that the losses in an array are more in cases 1 and 6. The losses taking place in the BJ array configuration is less than that of other configurations. As a result, the efficiency is higher. Moreover, the losses are less in all configurations of case 4, among the other cases. Figure 14 shows the comparison of mismatch power losses among the various configurations under UTD and various cases of NUTD conditions.

The error analysis, such as relative error, standard deviation, and root mean square error, are investigated for all configurations.
TABLE 7  Values of relative error for all configurations

| Configurations | UTD conditions | Under NUTD conditions |
|----------------|----------------|-----------------------|
|                |                | Case 1   | Case 2   | Case 3   | Case 4   | Case 5   | Case 6   |
| BJ             | 0.0002         | 0.1016   | 0.0824   | 0.0423   | 0.0281   | 0.0454   | 0.1153   |
| AT             | 0.0002         | 0.1016   | 0.0986   | 0.0576   | 0.0315   | 0.0507   | 0.1439   |
| SP             | 0.0002         | 0.1016   | 0.0905   | 0.0451   | 0.0292   | 0.0479   | 0.124    |
| BH             | 0.0002         | 0.1016   | 0.0872   | 0.0483   | 0.0294   | 0.0473   | 0.1269   |

TABLE 8  Values of standard deviation for all configurations

| Configurations | UTD conditions | Under NUTD conditions |
|----------------|----------------|-----------------------|
|                |                | Case 1   | Case 2   | Case 3   | Case 4   | Case 5   | Case 6   |
| BJ             | 0.0492         | 16.8714  | 14.8844  | 8.3965   | 5.5468   | 8.7247   | 15.6675  |
| AT             | 0.0492         | 16.8714  | 17.3407  | 11.4488  | 6.2172   | 9.7348   | 19.5550  |
| SP             | 0.0492         | 16.8714  | 15.9116  | 8.9493   | 5.7689   | 9.1871   | 16.8434  |
| BH             | 0.0492         | 16.8714  | 15.3397  | 9.5895   | 5.8001   | 9.0735   | 17.2414  |

configurations under both conditions. The results are computed and reported in Tables 7–9.

From Tables 7–9, it is observed that the relative error, standard deviation, and root mean square error are highest in AT configuration. Moreover, it is found that all the above errors are lowest in BJ configuration when compared with all other configurations. Hence, we recommend that the BJ configuration is suitable to generate higher power in the field of thermoelectric energy harvesting systems. The comparison of relative error, standard deviation, and root mean square error are shown in Figures 15–17, respectively.

6 | CONCLUSION

This research work analysed the performance of electrical connections of (10 × 10) TEM sensor array configurations such as SP, AT, BJ, and BH configurations that influences the maximum output power under UTD and different cases of NUTD conditions. The P-I performance characteristic of all the above configurations is investigated under both conditions. The performance of the TEM array configurations is examined in terms of maximum output power, voltage and current related to maximum power, utilization factor, mismatch power losses, relative error, standard deviation, and root mean square error. From the simulation results, it is seen that the maximum power is the same in all configurations under UTD and the first case of NUTD conditions. However, under NUTD conditions, it is different for all configurations and depends mainly on various cases of NUTD conditions. It is observed that the bridge-joint TEM configuration has provided the highest maximum output power when compared to other configurations for the cases (2–6) under NUTD conditions is due to the minimal mismatch power loss. The minimal mismatch power loss is due to the advantage of fewer series connections than that of series-parallel and Bee-hive configuration. Also, it has a higher

TABLE 9  Values of root mean square error for all configurations

| Configurations | UTD conditions | Under NUTD conditions |
|----------------|----------------|-----------------------|
|                |                | Case 1   | Case 2   | Case 3   | Case 4   | Case 5   | Case 6   |
| BJ             | 0.002075       | 1.1312   | 0.8979   | 0.4412   | 0.2889   | 0.4761   | 1.3034   |
| AT             | 0.002075       | 1.1312   | 1.0940   | 0.6113   | 0.3249   | 0.5342   | 1.6812   |
| SP             | 0.002075       | 1.1312   | 0.9949   | 0.4716   | 0.3009   | 0.5026   | 1.4151   |
| BH             | 0.002075       | 1.1312   | 0.9557   | 0.5070   | 0.3025   | 0.4961   | 1.4534   |

FIGURE 15  The relative error for four different configurations

FIGURE 16  The standard deviation for four different configurations

FIGURE 17  Root mean square error for four different configurations
open-circuit voltage than that of the All-tied configuration. Therefore, it is recommended to prefer a bridge-joint configuration for the applications of thermoelectric energy harvesting systems.

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Compliance with ethical standards

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