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RESEARCH ARTICLE

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A new maximum power point tracking algorithm based on power differentials method for thermoelectric generators

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Summary

This study uses a new maximum power point tracking (MPPT) algorithm for Thermoelectric Generator (TEG) devices. The MPPT algorithm appears as an essential solution due to the nature and the variation characteristics of the TEG devices under certain conditions. In this paper, the power differentials-maximum power point tracking (PD-MPPT) algorithm is proposed to control the boost converter by measuring the output power of TEG devices at both the start and finishing points of the power curve along with making a comparison of these two measured power points. The priority is given to the highest power point until the maximum power point is achieved, and Kalman Filter has been applied to eliminate the oscillation generated from the TEG system. This algorithm does not require any extra circuit to measure the short-circuit current or the open-circuit voltage because there is no disconnection between the TEG and the load. The hardware implementation of the power differentials algorithm is demonstrated under steady-state conditions. Moreover, the PD-MPPT is an effective and applicable algorithm applied to grab the maximum power point from the Photovoltaics PVs and TEGs systems. The practical experiment is conducted using the "STM32f429" microcontroller to implement the algorithm. During the experiments, the change in the duty cycles is observed. The experimental results show that the PD-MPPT algorithm performs better under a steady-state and has the ability to track the maximum power point accurately.

KEYWORDS

boost converter, energy management, maximum power point tracking (MPPT), thermoelectric energy conversion

1 | INTRODUCTION

Thermoelectric generator (TEG) devices have attracted the attention of researchers for several energetic, economic, and environmental reasons. An essential focus has been discerning a method to obtain the most benefits of the waste heat taken from different applications such as vehicles, wherein the fuel combustion engines, 40% of the energy is breakdown due to the wasted heat in the exhaust gas.[1] Other applications that required a low level of energy in different fields such as medical, communication, and robotic field, TEG devices are highly recommended.[2-4] A TEG is one of the most capable devices in the energy-harvesting systems, and it has the features of converting the heat energy into electric energy based on the temperature difference that applies on its surface.

The level of the TEG's produced energy is proportional to the used material for manufacture and the

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temperature difference. There are different methods to increase the level of TEG energy by using either boost converters or making different TEG array construction; series/parallel/series-parallel connections depends on the desired energy. The ideal equivalent circuit of TEG devices electrically can be modeled as a Thevenin equivalent circuit by a DC source linked to internal resistance in series, as shown in Figure 1. When the internal resistance of a TEG device is equal to the load resistance, the maximum power can be extracted. On the other hand, when the TEG device is operating under various operation conditions, that is, a dynamic state, the internal resistance is changing according to the change of temperature difference that causes a mismatch between the source and the load. This mismatch will not allow the maximum power to be obtained unless the maximum power point tracking (MPPT) algorithm would be applied to grab the maximum power point (MPP).

The research efforts focus on improving the performance of the harvesting system and operating the system in the optimal operation point to get the maximum power. MPPT is an algorithm that has reference variables (voltage, current) and according to variations of these variables, the algorithm will act to drive the converter through a generated pulse for tracking the maximum power point, that is, changing the internal impedance to have a matched load. Because of the linearity characteristic of the TEG devices, most of the researchers are shedding light on the MPPT algorithm. Based on an open-circuit voltage and a short circuit current,[5-9] where the optimum value of the generated power is half of the short-circuit current (I_{sc})/open-circuit voltage (V_{oc}) of TEG.

For mentioned algorithms, most of the techniques have disadvantages of disconnecting the TEG from the load to measure I_{sc} and V_{oc} or estimate these values which do not provide the accurate result.[10-12] From an economic point of view, these techniques need extra equipment to be implemented, which increases the system cost and make it more complicated.

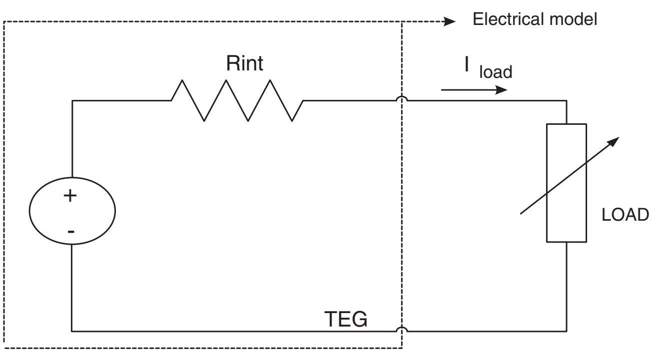

FIGURE 1 Electrical model of a thermoelectric generator

MPPT algorithms used in TEG energy harvesting systems are the same ones applied in PV systems, notably the P&O algorithm,[13-15] the incremental conductance (IC) algorithm,[15,16] for hybrid MPPT algorithms. Some researchers have made a Hybrid MPPT Algorithm Based on Fractional Short-Circuit Current Measurement with P&O algorithm which decides intelligently the disconnecting time of the photovoltaic array to measure the short-circuit current and improve the power ripples of the conventional technique and some other algorithm which is proposed for a constant heat flux.[17] Recently, research studies and algorithmic models have been presented to deal with the problems resulting from irridation of PV systems, and fluctuations in temperature in TEG energy harvesting systems. Each algorithm addressed specific factors, such as convergence speed, efficiency, and complexity.[18] However, many of these algorithms fall short on accuracy due to steady-state oscillation in the P&O algorithm. Application of Incremental Conductanceis is one way of preventing oscillations occurring at the MPP in P&O. Importantly, IC compares the generator conductance negative value's I-V curve line to the negative value of the conductance of the I-V slope.[19,20] At the points where the voltage is lower than the MPP on the I-V curve and where the conductance negative value > the I-V slope, the operational point moves to a higher voltage until MPP has been reached where the conductance negative value = the I-V slope. At the points where the I-V slope > the conductance negative value, the operational point is moved toward a lower voltage. Sampling stops at MPP, and it continues when the current changes as it moves to the new MPP. Extracting the MPP by measuring OCV[21,22] can be seen with the use of the fractional OCV method. The MPP voltage for a given condition is determined by periodically sampling the OCV. This is done by switching off the power source or shutting off the power converter. This method is useful for TEG systems because of the nature of TEG's linear voltage-current.[23] However, while the OCV-based methods do not require power measurement, the implementation process can be complex and cause temporary loss of power. Other research has looked at advanced and simple MPPT techniques that use a single-volt/current sensor.[9] The MPP is located and tracked by calculating the output power derivative from the instantaneous voltage.[24] Other system uses current measurement to calculate optimal impedance.[25,26]

For a small application such as femtocells and picocells,[27] authors proposed an algorithm to solve the disconnect problem for measuring the I_{sc}.[9] In this work, an alternative MPPT algorithm for the extensive power

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generation system is proposed to obtain the optimal operation point. The algorithm is operated based on two different power point, and the Kalman filter is used to estimate the output power curve of TEG in the dynamic conditions.

Moreover, the proposed energy harvesting system is employed as shown in Figure 2. The power differentials-maximum power point tracking (PD-MPPT) is proposed and used to keep the load matched with TEG to achieve the MPP. Due to the transient condition power variation appears in the TEG output and made the tracking of optimal operation power difficult. The author used the Kalman filter along with the use of STM32F429 and the selected microcontroller clarifies the possibility of observing the value of the duty cycles and the value of the MPP power.

The manuscript is organized as follow; Section 2 throws the light on the TEG devices behaviors. In addition, Section 3 is investigating the characteristics of the TEG array and for its experimental clarification. Section 4 discusses the converter, which is used to interface the TEG with the load sink. While Section 5 is presenting the usage of a Kalman filter in the energy harvesting system. Section 6 describes the PD-MPPT algorithm. Section 7 shows the implementation of the algorithm and its results. Finally, Section 8 concludes the work.

2 | THERMOELECTRIC POWER GENERATOR

The thermoelectric couples are thermally connected in parallel and sandwiched between two surfaces. As a result of two different temperature junctions (T_{hot} and T_{cold}), a potential voltage is produced on the terminal of thermoelectric couples, and this phenomenon is called the Seebeck effect. In addition, the level of this energy is relying on the electrical and thermal conductivity of the TEG materials and ΔT (the difference between the hot side and cold side temperature). When there is a load RL linked to the terminal of TEG device, generated power PTEG appeared and presented as in Equation (1). The open-circuit voltage based on the applied ΔT, Seebeck coefficient α concerning TEG's materials and electrical as well as thermal conductivity (best TEG which has high electrical conductivity (σ) and low thermal conductivity (K)). These faces would be set together and called Figure-of-merit (Z).[28]

$$P_{TEG}=\left(\frac{\alpha(T_H-T_C)}{R_L+R_{int}}\right)^2 R_L \tag{1}$$

where α is the Seebeck effect, T_{H} and T_{C} are the temperatures applied across the TEG device surface, and R_{int} is the internal resistance of the TEG device.

$$Z=\left(\frac{\alpha 2\sigma}{K}\right)T \tag{2}$$

To verify the characteristics of commercial TEG devices, Simulink of TEG module as shown in Figure 3 is implemented in Matlab, and by applying the given standard in TEP1-142T300 datasheet. Where, the operation temperatures are T_{cold} is 50°C and the T_{hot} is 150°C, the number of the couples is 128, the internal resistance 2.25 Ω, matched load out voltage 2.05 V, matched load out current 0.91A and the efficiency is 2.8%. The electric characteristics of commercial TEG were verified by comparing it with given datasheet.

In case if TEG devices are operating in the steady-state, the output voltage can be represented as a straight line function $f(x) = b + ax$ where $f(x)$ is the electric voltage, x is the temperature difference (ΔT) across TEG's surface. a,b are constants number and can be experimentally calculated by using Gaussian elimination method

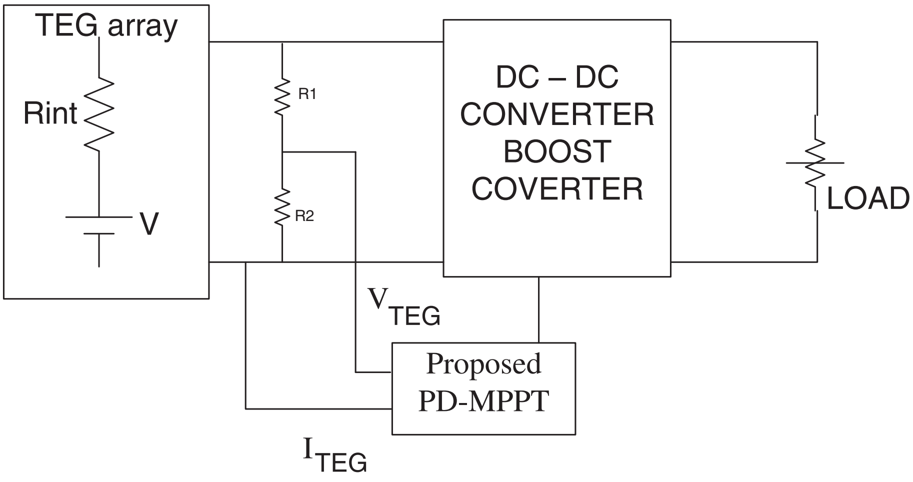

FIGURE 2 Proposed harvesting energy for TEG

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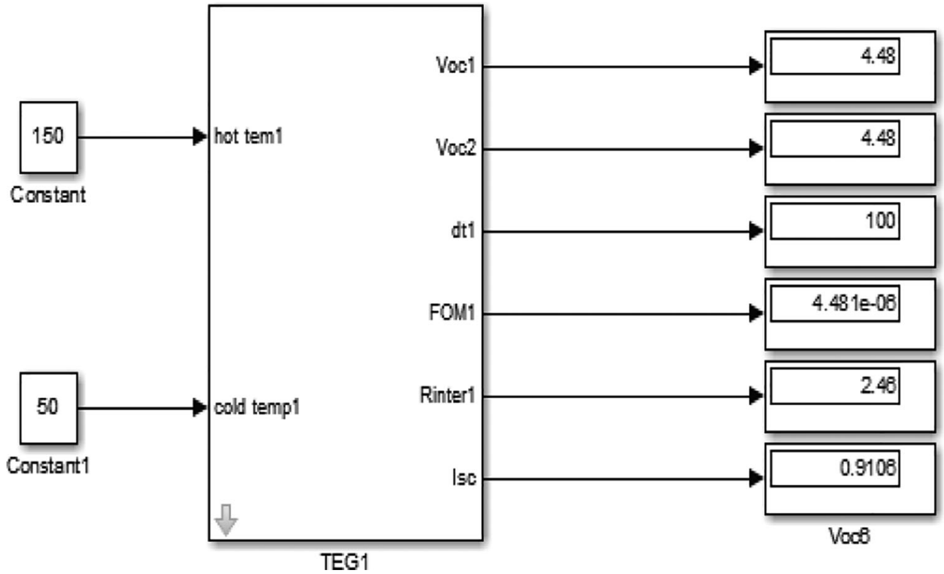

FIGURE 3 The simulink of TEG model

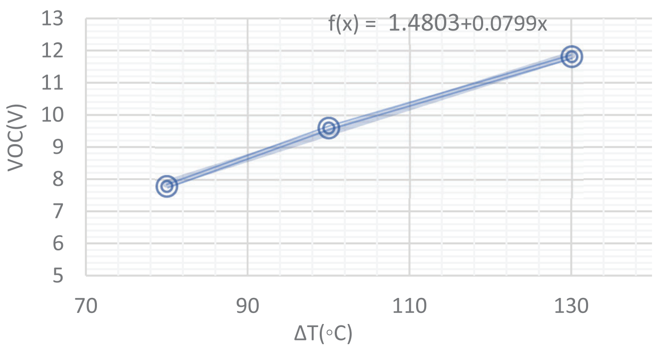

FIGURE 4 The open-circuit voltage (V_{oc}) and temperature difference (ΔT) characteristics [Colour figure can be viewed at wileyonlinelibrary.com]

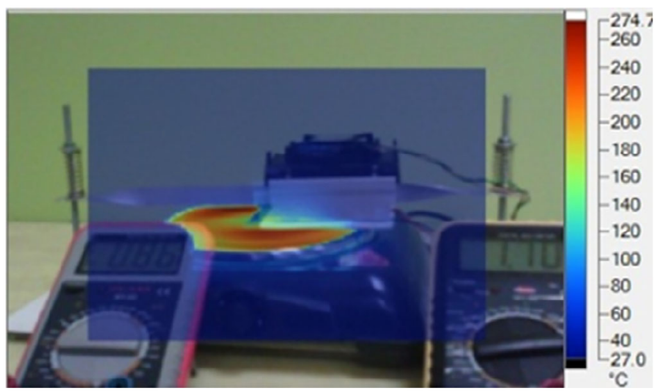

FIGURE 5 The experimental test for TEG [Colour figure can be viewed at wileyonlinelibrary.com]

from the variation of open-circuit voltage with ΔT as shown in Figure 4. The dynamic condition of TEG operation system happens when there is an increase or a decrease of the temperature difference across its surfaces at the starting or ending of the operating period that causes variation in the output power.

In this work, a commercial TEG device is used for the rig test; three of TEP1-142T300 are connected in series and characterized under two study cases. The first case includes three different ΔT different ΔT: 80°C, 100°C, and 130°C. And this case counted as a steady-state. While the second case is the transient case which ΔT changes in a specific period from 80°C to 130°C.

3 | CONFIGURATION TEST

This experiment studies the TEG devices performance and its ability to generating power. Correspondingly it investigates TEG characteristics along with the internal resistance changes comparing to the temperature differences. The experiment has been applied through three TEG devices (TEP1-142T300) connected in series (array) which are inserted between two blocks (hot block and cold block). The hot surface represents the adjustable stove while the cold surface considers as a heat sink linked with a cooling fan. The platform test is shown in Figure 5.

The terminal of TEG array is joined to the variable resistive load and its reaches to the characterized by employing three different temperature degrees (ΔT: 80°C, 100°C, and 130°C). In the interval of operation, it has been observed an essential change in the electrical characteristic of TEG array, as shown in Figure 6. Concerning TEG materials, the output power increases whenever the differential temperature rises and that causes an incensement of TEG's internal resistance

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which results in a system mismatch. In addition, the experiment has been stated that the optimal power point centralizes the short-circuit current and/or open-circuit voltage.

For the used TEG module, Figure 7 shows the changes of the out power according to the changes of ΔT. Wherein Figure 7A the red curve illustrates the increment of temperature on the hot side of the TEG while the blue curve is showing the cold side temperature and the incensement of ΔT under dynamic states at 4 Ω. Figure 7B clarifies the relation between TEG output power and temperature difference ΔT.

For a high-performance energy harvesting system, A DC-DC converter is needed to interface between TEG device and the load sink. The interfacing process can be implemented by adjusting the load resistance based on the TEG's internal resistance variation. The later adjustment leads to extracting the maximum and optimal point of TEG devices.

In meanwhile, the energy harvesting systems use three standard DC-DC converters (Boost, Buck, Buck-Boost).[29] The required energy and operating conditions of the applications control the employed converter type. The Buck-Boost converter is typically used for high range power applications which can be operated as buck or boost. Furthermore, the ability of multi-output power is provided by the isolated model of Buck-Boost transformer. In terms of enhancing the generation efficiency of the low power harvesting system, a Boost converter is selected to implement the proposed algorithm.

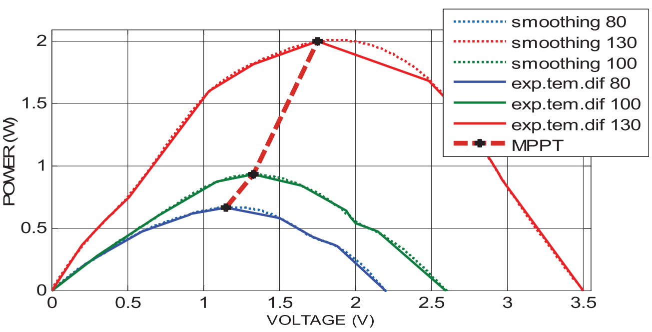

FIGURE 6 P-I characterization of TEG mode (TEP1-142T300) [Colour figure can be viewed at wileyonlinelibrary.com]

4 | MPPT CONVERTER

Under various thermal conditions, Boost converter is commonly used to track the Maximum Power Point due to the ability to operate under different power ranges (low/middle level). The Boost converter conversion factor can be smoothly and accurately dominated.[29] These aspects grant a high-performance system for multi-level power applications. It is constructed in two different modes, continuous conduction operation (CCO) and discontinuous conduction operation (DCO). The former mode presented clearly in the inductor of the boost converter, where the inductance current in the discharging period never goes to zero, as shown in Figure 8.

This mode picked for high-efficiency usage of switches. In a discontinuous mode, the inductance current goes to zero, and it is not perfect because of the reduction in the dynamic condition. In this paper, the power generation system is practically designed for applying the Proposed MPPT which consists of the mentioned rig test (TEG array) linked to the boost converter in order to meet the required power of DC load. For implementing the MPPT algorithm, a current sensor and a voltage divider are used periodically to measure the current and voltage under different operation conditions.

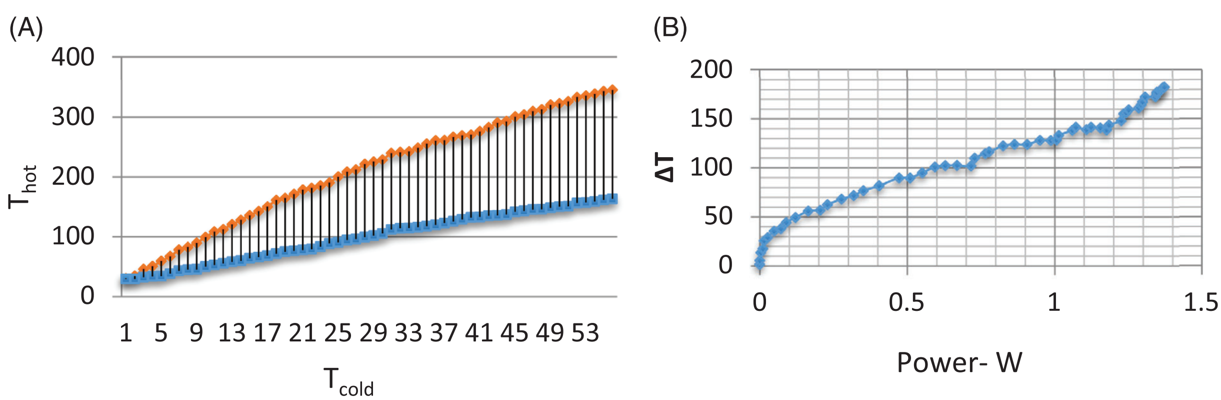

FIGURE 7 (A) The increment of temperature difference on TEG Surfaces and (B) the relation between TEG output power and temperature difference ΔT [Colour figure can be viewed at wileyonlinelibrary.com]

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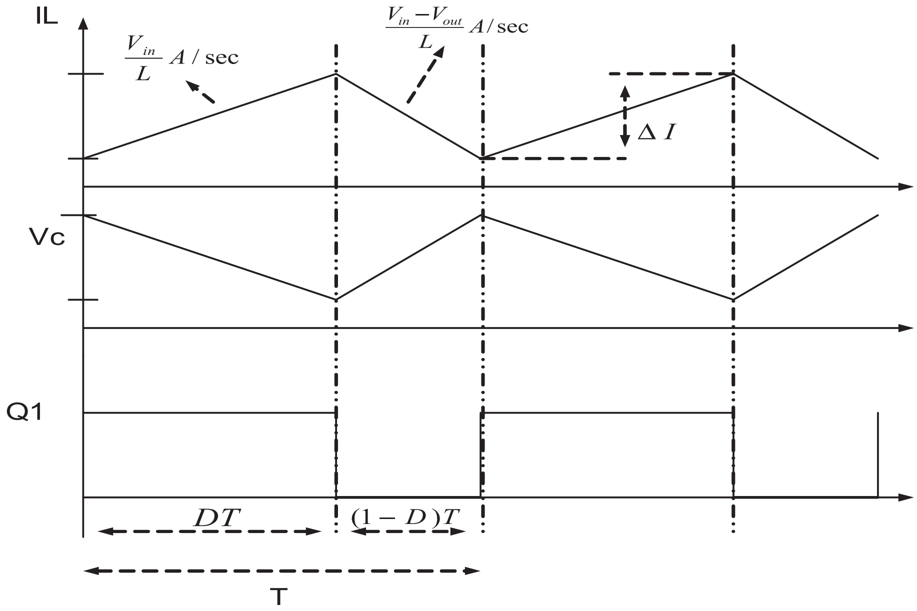

FIGURE 8 The schematic diagram of the proposed system

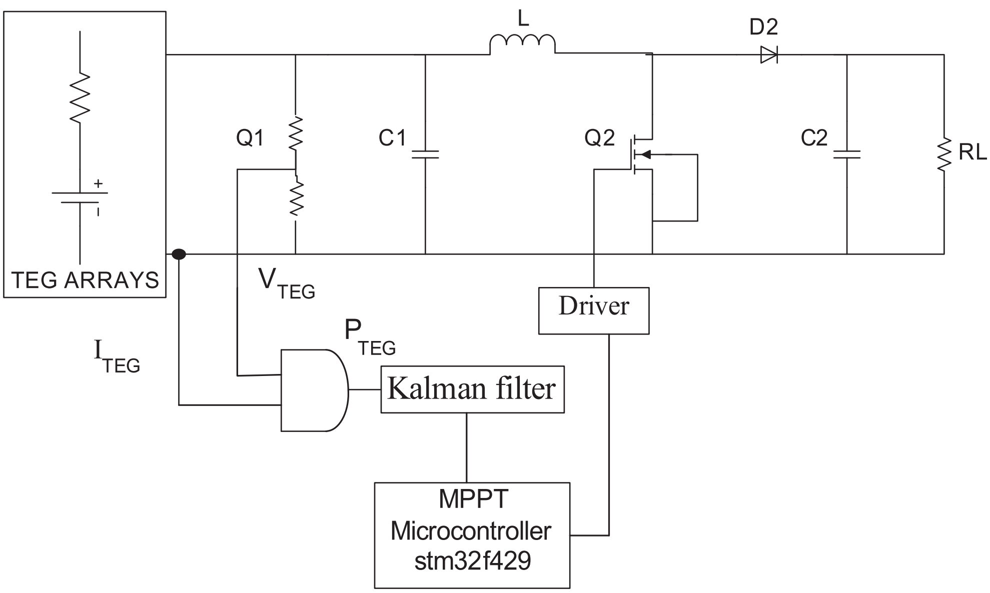

FIGURE 9 Continuous conduction mode of the boost converter

Figure 9 reveals the constructed diagram of the proposed power generation system.

5 | KALMAN FILTER

A Kalman filter is an estimator which provides an optimal stochastic estimation in a noisy environment.[30,31] The mechanism of Kalman filter relies on two core stages; time updating and measurement updating. From a practical review, the energy harvesting system has a mix of disturbances that appears on the output power of the TEG array. In addition, the system disturbances which caused by thermal noise, switching noise, electromagnetic interference (EMI), etc. have a significant impact on the MPPT work nature and its quality performance. To overcome these disturbances, the Kalman filter is regarded as the ideal option because of recursively behaving the noise effect. It estimates the power curve and gives the ability to track the MPP smoothly without confusion. Kalman filter is applied in the microcontroller as shown in the Block diagram in Figure 10.

Three main iterative calculations should be completed to achieve the actual correct values. In each iteration, there is a calculation made for Kalman filter gain, current estimate and new error in the estimated value. For Kalman gain (K_g) has the value between zero and 1, and it is calculated by Equation (3).

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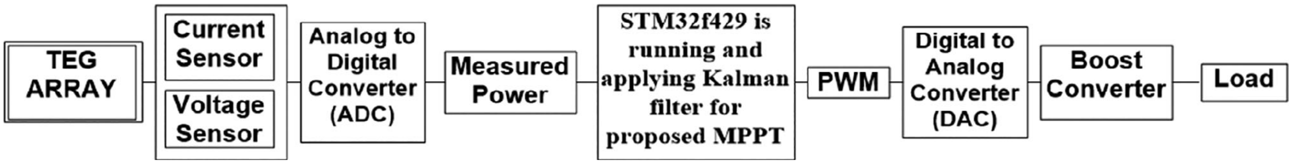

FIGURE 10 Block diagram of the proposed system

$$K_g = \left(\frac{E_{est}}{E_{est} - E_{mea}}\right) \tag{3}$$

The current estimate for each time EST_t can be calculated as shown in Equation (4)

$$EST_t = EST_{t-1} + K_g(MEA - EST_{t-1}) \tag{4}$$

While the new error in the estimated value NEEST_t is calculated as shown in Equation (5).

$$NE_{EST_t} = \left(\frac{(E_{mea})(E_{est-1})}{(E_{mea}) + (E_{est-1})}\right) \tag{5}$$

where E_{est} is the error in the estimate, Emea is the error in the measurement, MEA is the measurement values, and $\text{EST}_{t\text{-}1}$ is the previous estimate. By applying the iteration for the mentioned equations, the estimation processes are set in the measurement update that functions as a corrector for the estimated value and facilitator for optimal power tracking operation.

6 | POWER DIFFERENTIALS ALGORITHM

The proposed algorithm is sensing the output current and voltage of the TEG system to trace the variation of temperature. The main PD-MPPT algorithm is directly depending on the calculated operation power for two different locations. The first location of the operation power point starts when the duty cycle of the converter is close to zero while the second ower point is starting when the duty cycle of the converter is close to 1. From a Practical angle, Bubble Sort algorithm is used to obtain only the optimum power point. In other words, with the use of this algorithm a PD-MPPT algorithm compares the measured power values of the characteristic curve and chooses the largest value. Since the highest power point is updated as power reference Pref and the low-point side directed to a new power point. A particular step in every iteration leads the system to reach the largest power point that represents the MPP. In addition, the control strategy is set the duty cycle of the converter to have two power operating point positions (as shown in Figure 11 the design algorithm mechanism).

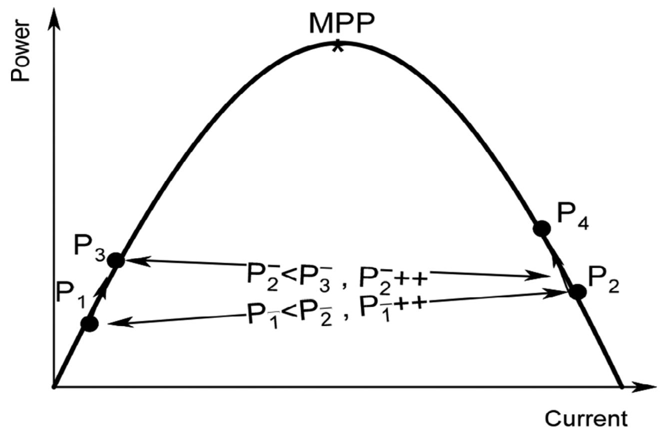

FIGURE 11 The mechanism of the PD-MPPT algorithm

P_1 is considered as the starting point of the power curve, and P_2 is considered as the power value at the end of the power curve. For the sake of points differentiation, a comparison is drawing between P_1 and P_2 in order to move the un-optimum point P_1 by certain step (++) to a new position P_3 with the ability of transfer P_2 to P_4 till achieving a unique MPP.

The essential principles of the algorithm are communication and learning. Hence by the maximum power transfer theorem, maximum power is eliciting from the TEG when one of the points raised to the highest point. The flowchart of the proposed algorithm is presented in Figure 12.

7 | EXPERIMENTAL RESULTS

The current work presented practically an implementation of the power generation system and proposed a PD-MPPT algorithm for harvesting energy. The algorithm tracks successfully the optimum maximum power of commercial TEG (TEP1-142T300) module as an array. Figure 13 shows the experimental elements of the proposed harvesting system circuit.

It consists of a boost converter that used to implement the mentioned PD-MPPT algorithm due to its high performance under wide power range operation. Furthermore, the system contains a microcontroller which is

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STM32f429 discovery kit with high features. It observes the value of the two duty cycle in the operation time under different operation conditions of the proposed algorithm. INA250 high sensitivity is used for sensing the current and a voltage divider to measure the voltage.

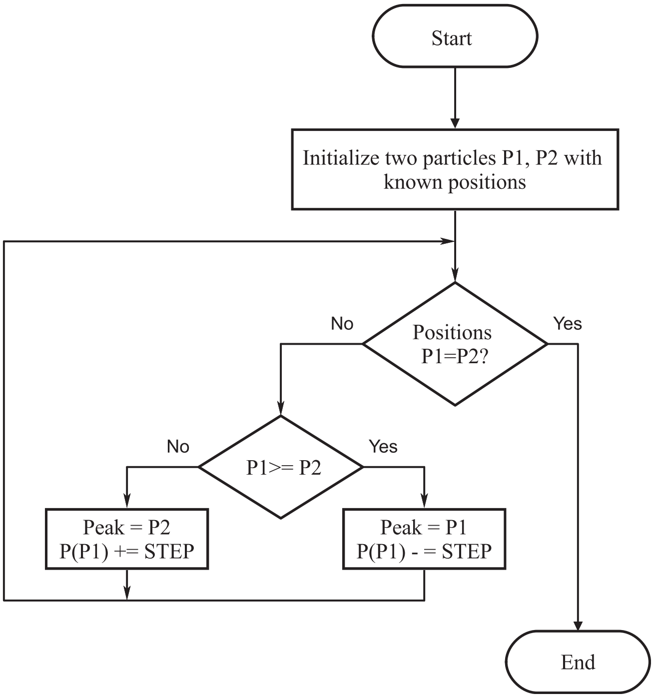

FIGURE 12 The flowchart of PD-MPPT algorithm

PD-MPPT algorithm was evaluated under three different temperatures differentials ΔTs which are: 80°C, 100°C, and 130°C. The PD-MPPT algorithm grabs the optimum power point and reduces the steady-state error that appeared in the output power of TEG. Furthermore, the algorithm has been evaluated under steady-state conditions which presented in three temperatures differentials. Due to the measuring of two different power points, the algorithm proceeds a slow settling time which is suitable for the change of temperatures differentials on the TEG energy harvesting system based on the environmental changes.

From the measured operating data points, the TEG characteristic curves are extracted to achieve the accurate MPP for the suggested temperature conditions. The previous processes pass through a sort of comparison between the obtain MPP from the characteristic data and the result obtained from the proposed energy harvesting system. The implemented energy harvesting system hardware includes low-cost, high-performance aspects. On the other hand, the use of Kalman filter overcomes the disturbance appeared in the output power of the system.

It is necessary to investigate TEG modules under different operating conditions and to construct an analytical TEG sequence model with varying methods of connection (serial, parallel). The output performance of the serial TEG sequence and the output performance of the parallel TEG sequence were examined separately in this study. This made the PD-MPPT algorithm guaranteed

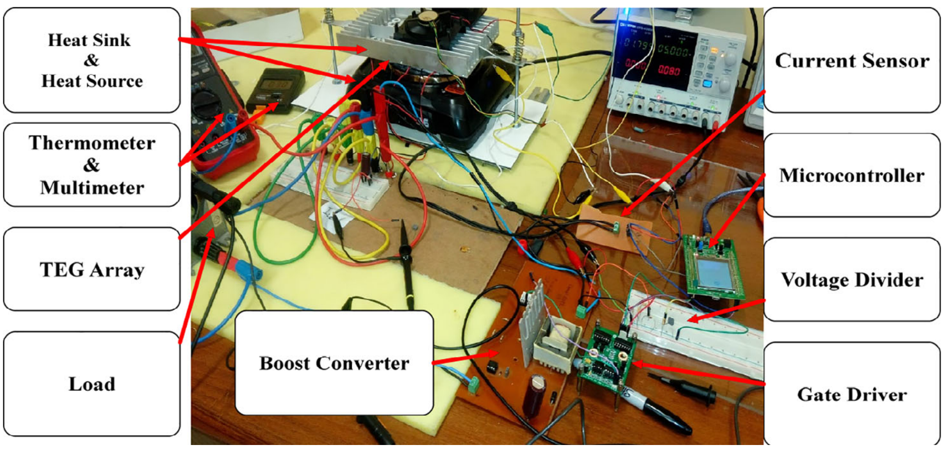

FIGURE 13 The used elements of the energy harvesting system [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Results of PD-MPPT Algorithm for Single TEG

	MPP at the rig test			MPP at proposed PD-MPPT		
ΔT (°C)	V (v)	I (amp)	MPP (w)	V_{MPP} (v)	I_{MPP} (amp)	MPPT (w)
80	1.15	0.58	0.667	1.14	0.56	0.660
100	1.41	0.7	0.987	1.40	0.69	0.987
130	1.96	1.03	2.018	1.96	0.99	1.9404

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TABLE 2 Results of PD-MPPT algorithm for three series TEG

	MPP at the rig test			MPP at proposed PD-MPPT		
ΔT (°C)	V (v)	I (amp)	MPP (w)	V_{MPP} (v)	I_{MPP} (amp)	MPPT (w)
80	3.45	0.58	2.001	3.4	0.57	1.938
100	3.99	0.7	2.793	3.87	0.703	2.72061
130	5.25	1.142	6	5.12	1.132	5.79584

TABLE 3 Results of PD-MPPT algorithm for three parallel TEGs

	MPP at the rig test			MPP at proposed PD-MPPT		
ΔT (°C)	V (v)	I (amp)	MPP (w)	V_{MPP} (v)	I_{MPP} (amp)	MPPT (w)
80	1.15	1.74	2.001	1.12	1.72	1.9264
100	1.33	2.1	2.793	1.3	2.1	2.73
130	1.75	3.428	5.999	1.9	3.06	5.814

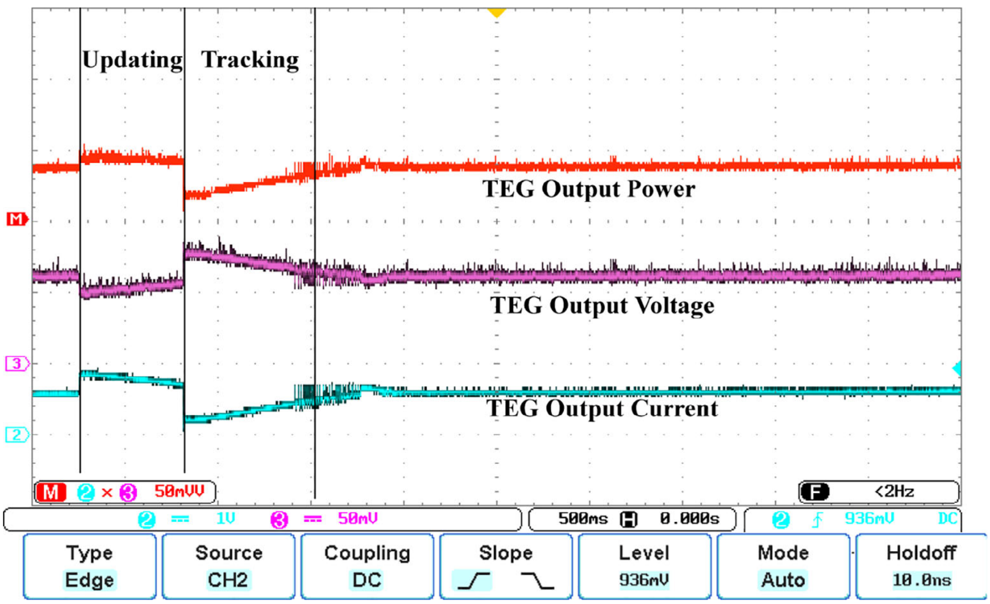

FIGURE 14 The output power, current and voltage of three series TEP1-142T300 with STM32F429 microcontroller [Colour figure can be viewed at wileyonlinelibrary.com]

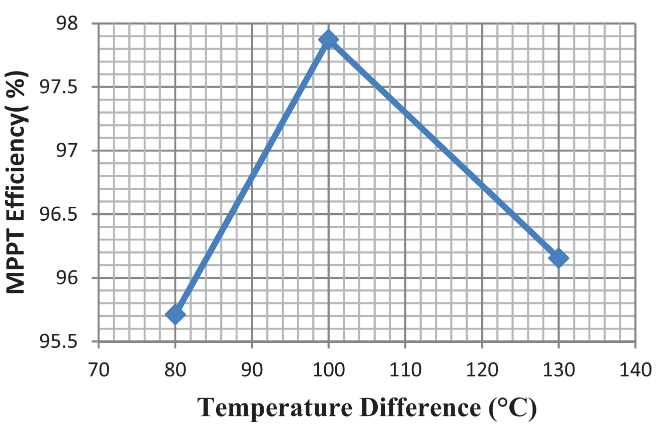

FIGURE 15 The efficiency of PD-MPPT algorithm under various ΔT for single TEG [Colour figure can be viewed at wileyonlinelibrary.com]

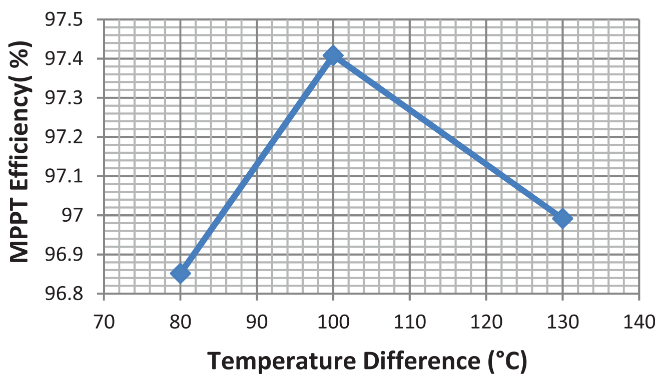

FIGURE 16 The efficiency of PD-MPPT algorithm under three different ΔT for three series connected TEGs [Colour figure can be viewed at wileyonlinelibrary.com]

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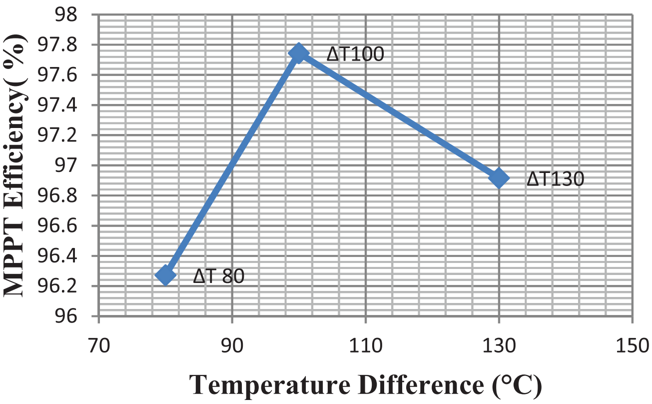

FIGURE 17 The efficiency of PD-MPPT algorithm under various ΔT for three parallel connected TEG [Colour figure can be viewed at wileyonlinelibrary.com]

successful tracking. Tables 1–3 show the obtained MPP under three different construction with the usage of the proposed algorithm in energy harvesting system.

Moreover, Figure 14 shows the TEG current, voltage and the output power during the functional operation of the algorithm, where the algorithm periodically updates and tracks the MPP according to the change of the system behaving.

The presented MPPT system was tested in the laboratory under stable and transient conditions. PD-MPPT algorithm in terms of efficiency; It exceeds 97.7%. Figures 15–17 show the efficiency of the algorithm for three different configurations. The PD-MPPT algorithm is capable of successfully monitoring MPP in the PV/TEG-PV hybrid system when there is more than one MPP at the output power.

8 | CONCLUSION

This paper presented an energy harvesting system for TEG arrays. To obtain the optimum operation power for the system, a PD-MPPT algorithm is proposed. This algorithm is not costly and less complexity. Moreover, it does not need any extra circuit such as a snubber circuit. The selected converter is a boost converter that can be operated under a vast range of temperatures differentials across the TEG array.

Furthermore, Kalman filter has been used for estimating the power curve to reduce the system disturbances. The presented MPPT system was laboratory tested in under steady-state condition in terms of the PD-MPPT algorithm efficiency; it has been exceeded to 97.7%. PD-MPPT algorithm can track the MPP successfully in the PV/ TEG-PV hybrid system when there is more than one MPP appears in the characteristics of the output power.

The results here within indicate that an appropriate temperature difference can make the system more efficient while reducing its consumption. The smaller the system temperature difference, the higher the system cost per watt, and the lower the tracking efficiency. In order to make these systems marketable and economically viable (the smaller ones in particular), consideration must be given to both power output and construction costs. Improvements to the energy harvesting system remain to be made, even though the PD-MPPT algorithm has been optimized. The convergence speed is significantly important in comparison to conventional algorithms. Nevertheless, the convergence speed of the PD-MPPT algorithm itself can be further analyzed. In the future, improvements could be made in an attempt to further reduce the examination period and better enhance the energy harvesting system's efficiency.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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