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Chapter

A Thermoelectric Energy Harvesting System

*Khalid Yahya, Mohammed Salem, Nassim Iqteit and Sajjad Ahmad Khan*

Abstract

Thermoelectric generators (TEGs) and their applications have gained momentum for their ability to use waste thermal energy. More contemporary technology must offer more exceptional energy-efficient applications at a lower cost. New technology must also have an ability to generate electric power through the conversion of wasted heat. The TEG has demonstrated its efficiency and how it can offer increased potential by adding an MPPT algorithm to increase the power flow while decreasing the cost of operation. The limitations can be offset by the use of lower cost manufacturing materials and automated systems in the TEG units. It is also important to note the cost per watt found in using a thermoelectric generator is estimated to be $1/W for an installed device. To achieve this goal, the optimum operating point should be monitored by DC to DC converters. The DC to DC converters should also be driven through a generated pulse using an MPPT algorithm.

Keywords: DC to DC converter, maximum power point tracking (MPPT) algorithm, thermoelectric generator (TEG)

1. Introduction

By increasing the demand for electric energy and a greater societal sensitivity to environmental consequences, renewable energy sources attract attention. Examples of renewable sources of energy include geothermal, hydraulic, sun, and wind energy. Moreover, the production of renewable energy is quickly becoming one of the best ways for energy production (7.6% p.a.) and is currently an estimated two-thirds of the total global generation of power. This amount is expected to double by 2040 (as shown in **Figure 1**). This increase is keenly taken as a goal to cover a minimum of 30% out of the total consumed energy [1].

Due to the rapid artificial growth of the market, there is a huge rise in the amount of energy consumption and the necessity of alternative low-cost renewable energy becomes a must. Typically, producing electrical power energy necessitates both a chemical energy combustion process and usage of a generator. The cost and the efficiency of conversion systems have to be essentially taken into consideration in terms of investment and evaluation. Furthermore, the implementation of combined gas-steam cycles could increase the conversion efficiency, but this still collides with the limits imposed by the increasing installation costs. Also, increasing the overall plant efficiency without the conversion burden may be possible from the implementation of exhaust gases of the combustion process.
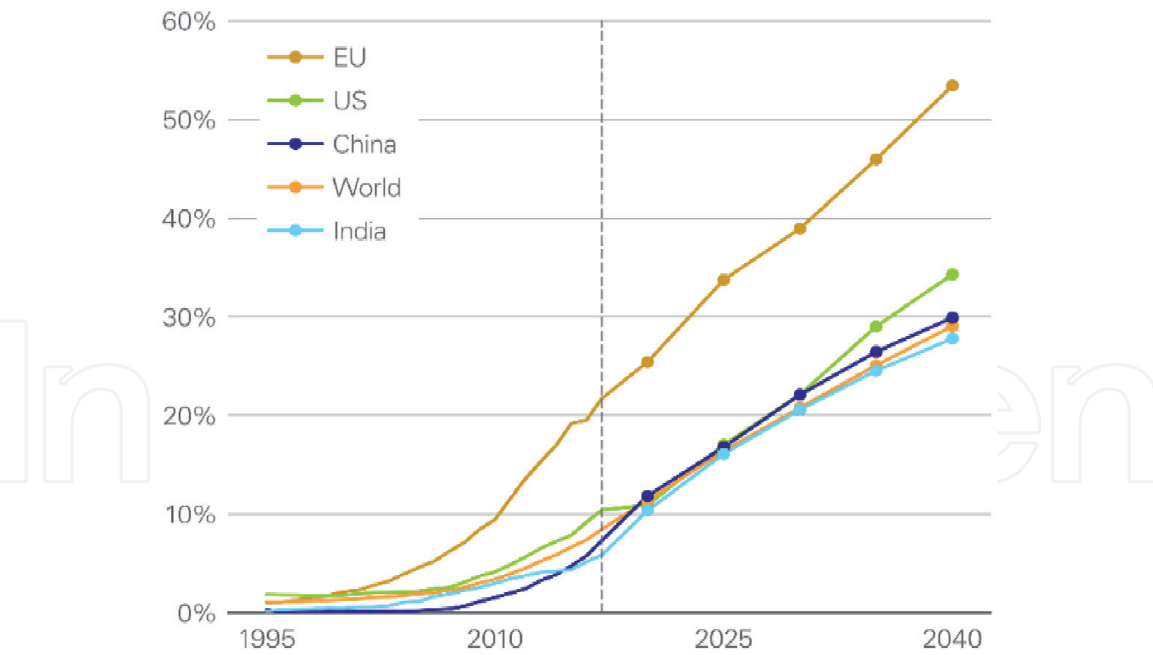
Figure 1.
Glimpses of energy future.

One of the noncostly renewable energy sources is the conversion of heat (a waste energy) where the thermal-electric energy can be automatically converted to electrical power without relying on the use of chemicals. This sort of energy is generated through a device called a thermoelectric generator (TEG).

TEG devices are cutting-edge technology, especially with recent applications such as cars exhaust, factories exhaust, and thermal panels each with a role in converting waste heat energy to applicable energy. Typically, the thermal energy production of the exhaust fumes utilized in the industries allows the insertion of a fumes/water heat exchanger to produce hot water for multi-industrial purposes. The application of such solutions go in contrast with the actual accessibility and then with investment sustainability.

Although marketing the heat for district heating is useful and attractive particularly in regard to economic values and the individual utilities' losses, but it is hard to be applied in undeveloped and urban areas where the classical energy sources appear strongly and occupy the people's priority and interest.

Another aspect has to be taken into account is the produced energy quality level; here, the heat is considered as a type of degraded energy and this thermodynamic point interprets the rational for less attraction for the market.

The sector of heat conversion attracts the huge interest of research, particularly the directly converting waste heat to electrical power. However, practical implementation is still being observed. The application of thermoelectric generators (TEG) in the field of large power generation introduces a unique step concerning the efficiency of the production system from fossil sources [2].

Feeding the power consumers through supplying a direct heat conversion is a favorable choice and attracts the global interest, especially in the realm of optimizing the production and enhancing the investment in new storage systems.

2. Thermoelectric generator (TEG)

TEG is a device for thermoelectric generation that uses semiconductors that provide an efficient system. This device is able to convert heat into electric power.

The construction of this device consists of N- and P-doped semiconductor pellets that are connected electrically through a series and further connected thermally parallel, to gain higher voltage. Also, mechanical substrate and electrical isolation are served by a ceramic layer. This device is able to operate in two different modes: an electrical power generating mode and in heating pumping mode.

In the power generation mode, the TEG can create voltage at different temperatures (ΔT). This is because the TEG is exposed on its sides according to the Seebeck effect. When the TEG is under a load, the terminals receive a current flow to the semiconductor couples while producing heat in Joules. The effect can be observed as heating while supplying more heat from the hot side to the cold side, as shown in the Peltier effect. The Peltier effect refers to the parasitic activity observed in generating power. The Peltier effect has shown the ability to increase the total thermal device conductivity.

Commercially, TEGs' come in a wide variety of sizes (a few millimeters to centimeters in size). Furthermore, the internal resistance and the current-voltage rating of the device are essentially affected by the cross-sectional area of the pellets. The wide pellets module can bear a limited number of pellets and provides a high output current, but it has small output voltage and internal resistance.

To meet the needed power level and to achieve a higher output voltage, various modules have to be connected either in series or parallel.

TEGs can be operated by utilizing different thermal energy sources. These devices possess extra advantages that other energy conversion methods lack such as light in weight, reliability, robust and have no mechanical moving parts, nonvibration, and muted operation.

In a steady-state condition, the equivalent circuit of TEG is presented as a voltage source connected to a resistance (internal resistance of TEG) in series as shown in **Figure 2**. Practically, the power generated by TEG is based on the temperature difference that imposes on its sides and the amount of the current which is drawn by the load. According to Thevenin's theorem, the maximum power can be harvested from the TEG device at any settled temperature difference, while the internal resistance of the source (TEG) should be matched with the load resistance. Characterizing the TEG and studying its performance under various temperature difference has a role in designing an efficient energy harvesting system. For the commercial TEG, the datasheet, in general, describes the operation performance under different conditions. On the other hand, it is hard to assign an optimal method of testing thermoelectric devices because of the datasheet record of the performance which is differing from the actual one.

## 2.1 Physical phenomena of thermos electrics

The three fundamental physical phenomena are related to a TEG's operation. The effect of Seebeck is the generated voltage when the change in temperature is sustained between two sides. The effect of Thomson is heating or the impact of cooling in the conductor that is homogeneous and it is observed at the time when the electric current is going through the electric current in the same gradient temperature direction. The effect of Joule is the heating effect that is observed in the conductor like the electric current that is passed by a conductor [3, 4].

2.1.1 Seebeck effect

It indicates that when any two dissimilar materials that are thermoelectric are connected in a single loop as shown in **Figure 3** with the help of two junctions that has the potential to maintain different temperature. In these, temperature has the
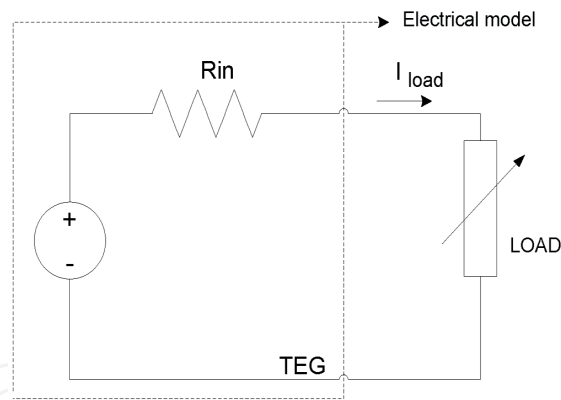
Figure 2.
Electrical model of a thermoelectric generator.
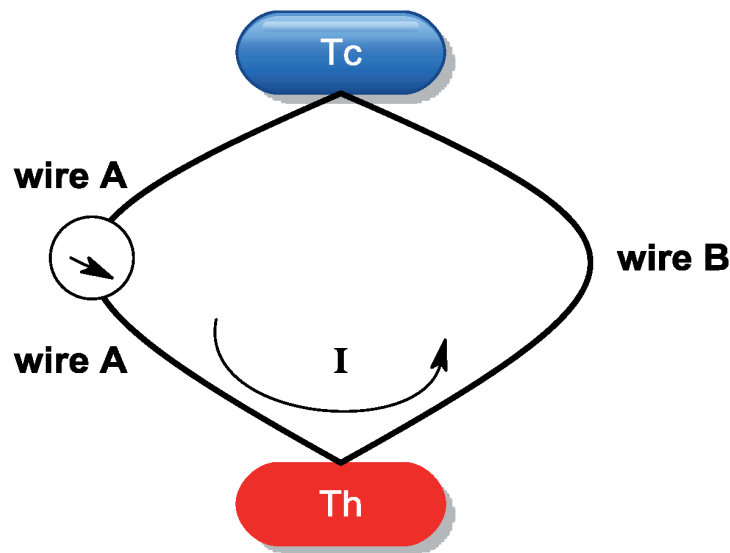
Figure 3.
*Schematic of the Seebeck effect.*

ability to induce the electrical current that is also known as electromotive forces is generated. These generated forces explain the voltage Seekbeck Voc and are recognized as Eq. (1) as shown below:

$$V_{oc} = \alpha_{ab}(T_H - T_C) \qquad (1)$$

Here, α is the representation of the two coefficient that is not the similar conductor, and (TH-TC) represent the different temperatures between the stated junction. In the open circuit, the voltage is proportional to a difference in temperature and it depends on the material of conduction type with the fact that it is not the temperature function along with the distribution of conductor.

Usually, a semiconductor is used as a material that is thermoelectric. This is because such a material can show right properties that make them able to show the desired properties that also make them able to convert thermal energy in the form of electric and vice versa. Usually, impurities make the part of semiconductor, which is a phenomenon that is called doping that has the objective to increase the charge. Usually, doping is found in different two types. These are positive, p-type, and negative, n-type, as observed in **Figure 4**.

In the first type, the valance electron is removed, and in the second type of doping electrons, valence is made as the part of valence electrons. When there is a
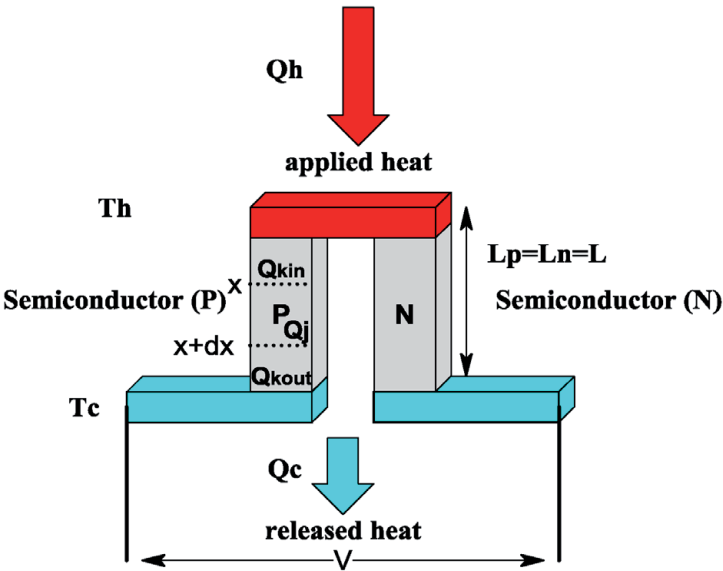
Figure 4.
Schematic of the thermocouple.

potential that semiconductor is related to two temperatures by which the flow of heat passes the pellets, then in the same direction, the charge flow carries, from the side that is the warm to the cold side. In the n-semiconductor, the tendency of electrons move to the cold side, while in the leg of p-semiconductor, the whole has the tendency to move the cold side.

This becomes the reason for the creation of gradient voltage between legs. It has not valued that the effect of Seebeck is the phenomena of contact by the connection of two nonsimilar material of thermoelectric.

2.1.2 Peltier effect

The effect of Peltier indicates that electrical current has the flows that are across from a junction between two materials that are not similar. That is why heat must continuously have subtracted or added to the junction for keeping the temperature constant. The heat rate absorbed at a junction because of the Peltier effect, which is proportional to the current flow, is presented as follows:

$$Q_{Pelter} = \pi_{ab} I \tag{2}$$

where π_{ab} (V) is the representation of relative coefficient of Peltier of two materials that are not similar, and it is a property that indicates the heating magnitude or cooling injunction that may occur in two material junctures. I (A) is the representation of electric current that uses thermocouple for flows. As the Seebeck effect, this effect is also the phenomena of contact that take place in the boundary of contact. It is essential that heating Peltier as reversible between electricity and heat that indicates heating may generate electricity that produces heat or cooling without the dissipation of energy.

2.1.3 Thomson effect

It states whenever in a wire, current flows with a gradient of temperature; then heat is absorbed across a wire that relay direction and material. The rate of heat absorbed along a length of wire is due to this effect. It can be explained as

$$Q_{Tho} = \tau I \tag{3}$$

where τ is the Thomson coefficient, while current is represented by I (A) and the temperature is by ΔT (K) which is the difference between the two ends' wire. The effect of Thomson heat can be altered and must not mix with Joule heating.

2.1.4 Joule heating

It is the effect that explains dissipated heat by the material that does not have resistance based on the availability of electric currents.

For high performance of TEGs devices, the materials should own a *significant Seebeck coefficients, high electrical conductivity, and low thermal conductivity.*

2.2 Structure of the TEG

The TEGs is constructed by various legs that are manufactured by n-type and p-type semiconductors that form thermocouples, and all these have the connection with the series as well as thermally electrically parallel. The legs of the semiconductor are linked with each other with the tabs copper and they are sandwiched
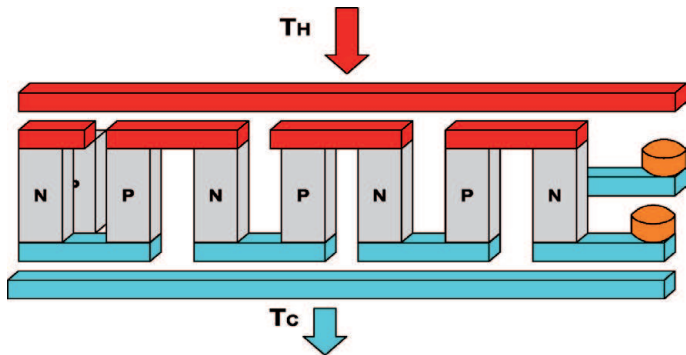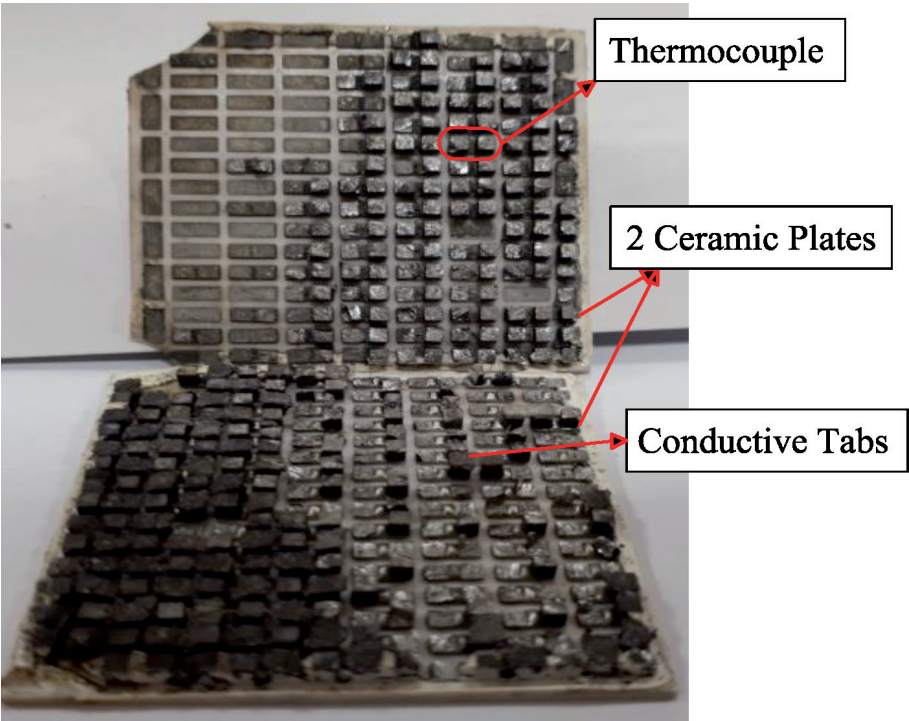

Figure 5.
TEG instructions.

Figure 6.
Internal structure of commercial TEG.

between ceramic plates. These plates may be able to conduct heat while creating an electrical current. The diagram of schematic three-dimensional (3-D) thermo-electric generator of multi-element is shown in **Figure 5**. The waste of the heat from different sources like automobile exhaust engines, infrastructure-heating and industry and activities can be supplied to TEG's top ceramic.

In **Figure 5**, the flow of heat by the plate of ceramic as well as the conductive copper tabs before the time when it reaches on the top surface of n-type and p-type legs that are made of semiconductors that can be explained as TEG's hot side are explained. The heat flow by both legs that are semiconductor and pass by tabs that are copper-conductive and a bottom plate of ceramic, as shown in **Figure 6**. With the sink of heat, the ceramic at the bottom plate is vital due to lower temperature as compared to the top for the production of high temperature that moves toward the high output.

It explains the temperature that is applied to the bottom and top ceramic plates that are related to p- and n-types materials. The n-type and p-type materials are included in the process of designing by semiconductors to maintain the difference observed in the temperature of a hot and cold TEG. The distribution is pictorial along with the TEG legs at the difference that is conditional on temperature between cold and hot sides [5].

3. Energy harvesting system

There are several ways to increase the produced electrical energy by TEG devices, one of the ways is by boosting the produced voltage boost converters and also modeling different TEG arrays such as series, parallel, and series-parallel connections based on the required energy. A TEG device operates under various operating conditions due to the change of the temperature difference which is not easy to control it. The resistance found inside the device changes because of the difference of temperature resulting in a mismatch between the load and the TEG device. This mismatching will not allow the conditions for maximum power operation without the Maximum Power Point Tracking (MPPT) algorithm [6]. The MPPT algorithm would be applied to grab the Maximum Power Point (MPP). **Figure 7** shows the block diagram of the energy harvesting system.

MPPT algorithm improves the performance of the harvesting system and operates the system in the optimal operation point to generate the maximum power. MPPT is an algorithm which 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, i.e., changing the internal impedance to have 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 [7–9], the optimum value of the generated power is half of the short-circuit current (I_{sc})/open-circuit voltage (V_{oc}) of TEG.

A simple test on TEG's performance is normally made to provide accurate repeatable measurements and to get the TEG's electrical characteristic.

3.1 TEG characterization

A TEG device is found between the hot and cold blocks. The device contains high temperatures that are heated through the use of an electric stove. The cold block is kept cool by the use of a fan system. The TEG output is shown as a variable resistive load –-142T300 and can be identified by three separate gradients of temperature as ΔT: 80, 100, and 145°C. The test platform can be observed in **Figure 8**
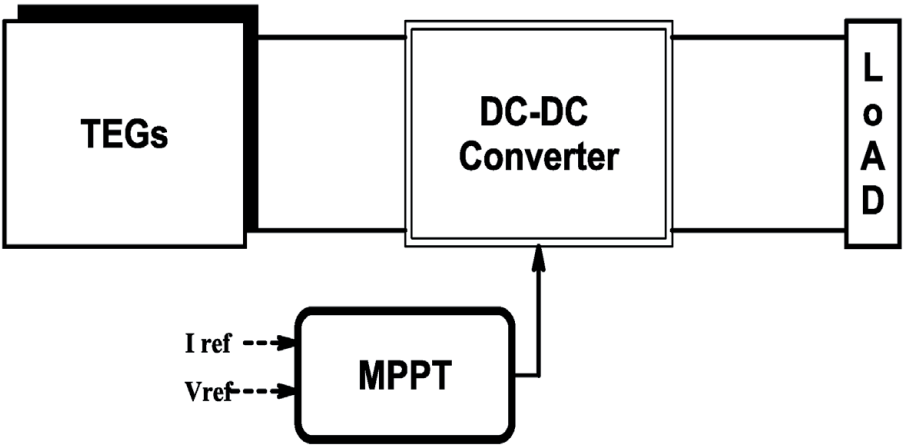
Figure 7.
*The block diagram of the energy harvesting system.*
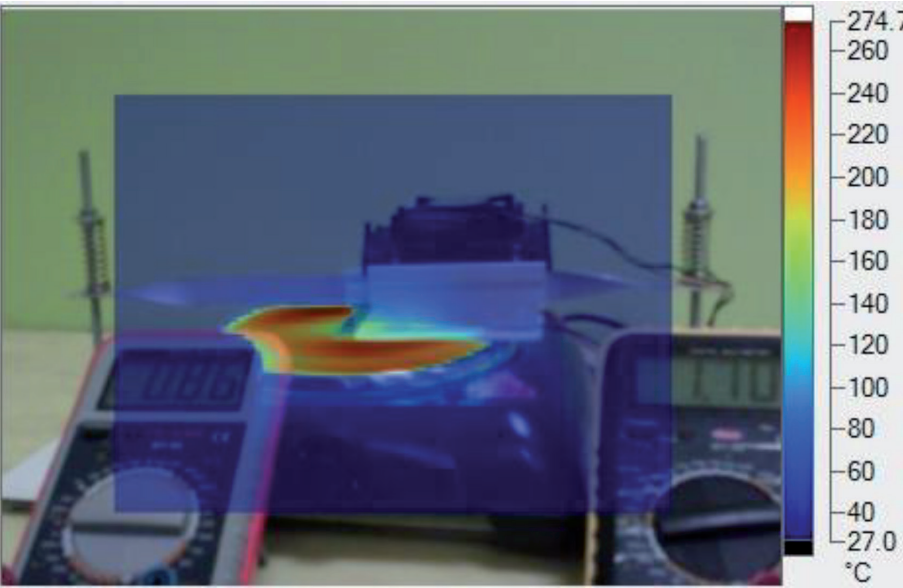
Figure 8.
The experimental test for TEG.

as it shows true measurements under different temperatures on the TEG's terminal while performing under a number of resistive loads.

In **Figure 9**, the power curve (P–I) for the device can be observed. In **Figure 10**, a straight line is shown to represent voltage versus current (V–I). The short-circuit current I_{SC} is the amount of the current when the resister of the load is equal to zero, i.e., TEG's terminals are connected together, while VOC (open-circuit voltage). Is where the voltage at the maximum and there is no load connected on the terminals. The MPP is at the medal of the curve on the peak point and that MPP can be tracked by knowing the V_{OC} or I_{SC} since the maximum power of TEG = $V_{oc}/2$ or $I_{SC}/2$ and is made when an equal amount of electrical load resistance of external circuits that are connected to the TEG equals that of the internal electrical resistance R_{int} of the TEG. The inverse slope (Rint) of the V–I line and the absolute value depends upon the temperature of the TEG while it is operating and is without a fixed value.

3.1.1 Series and parallel array configurations

T modules of thermoelectric are developed in different studies by connecting in parallel and/in series based on the required voltage and current.
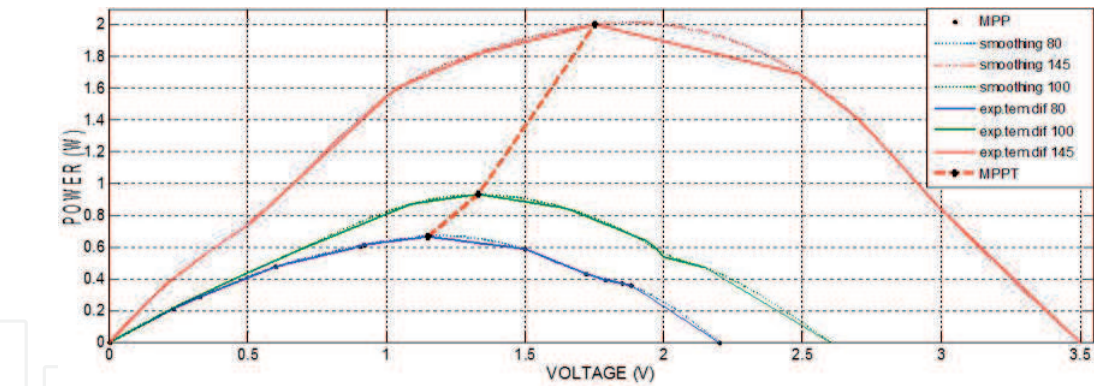
Figure 9.
P-I characterization of TEG mode (TEP1-142T300) for three different ΔT.
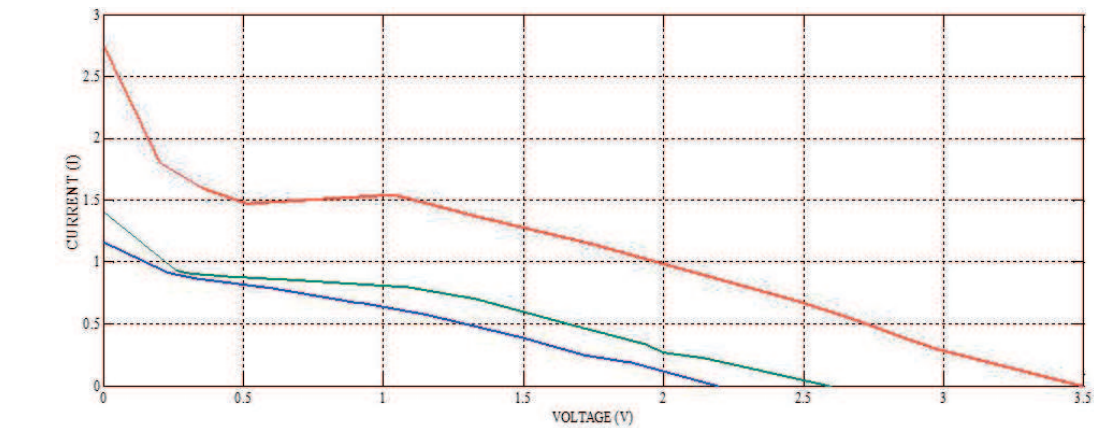
Figure 10.
V-I characterization of TEG mode (TEP1-142T300) for three different ΔT.

3.1.1.1 Series array configuration

In the series array configuration, TEGS that are three in number are represented in such a way that all are connected in series as shown in **Figure 11**. In this configuration style, voltage is kept in series as V_1, V_2, V_3,..., and V_n equal to the resistance; it is also placed in the series as R_1, R_2, R_3,..., and R_n.

In the ideal condition of the module, the performance and the outcome vary with the nonideal condition of the modules; here in ideal condition, the outcome will be equal to the ΔT. In the normal condition of the thermal balance, the equal voltage will be generated. However, on the other hand, in the normal and actual thermal condition, voltage and resistance will project different unequal values. For instance, MPP is considered as $nV_{oc}/2$.

In the nonideal thermal condition, the voltages will be in flow as $V_{oc} = V1 + V2 + V3$. Eq. (4) elaborates further:

$$I_L = \left(\frac{V_{OC} - V_S}{R_1 + R_2 + R_3 + ... + R_n} \right) R_L \tag{4}$$

3.1.1.2 Parallel configuration

Three parallel configuration TEGs models are projected in **Figure 12**. To achieve the ideal conditions of operations TEG Models must be operate at same ΔT. The voltage and maximum power of the operations of these models are kept the same

that is $I_1 = I_2 = I_3$, while TEG units will mismatch if the conditions are changed and rearranged in such a way that generates the condition of nonideal thermal conditions.

$$I_1 = \left(\frac{V_1 - V_L}{R_1}\right), I_2 = \left(\frac{V_2 - V_L}{R_2}\right), I_3 = \left(\frac{V_3 - V_L}{R_3}\right) \tag{5}$$

In the array terminals, the voltage is presented through the V_L.

3.2 MPPT converters

The design DC to DC converter connects between the TEG models and enables it to optimize the maximum power at all the time for voltage and current. Boost converters made up from the four elements are shown in **Figure 13**; it includes the inductor, MOSFET, diode, and capacitors. In DC to DC converters, it is attempted to control the output voltage to high or low values. This is accomplished through a control switch that feeds the load by a pulse voltage of different widths. The method is referred to as the pulse-width modulation (PWM). The PWM control method is one of the most commonly used applications. The method is also used in the case study of controlled DC to DC converter. To provide further explanations of this method, circuits observed in **Figure 13** are studied with the ideal switches and loads.
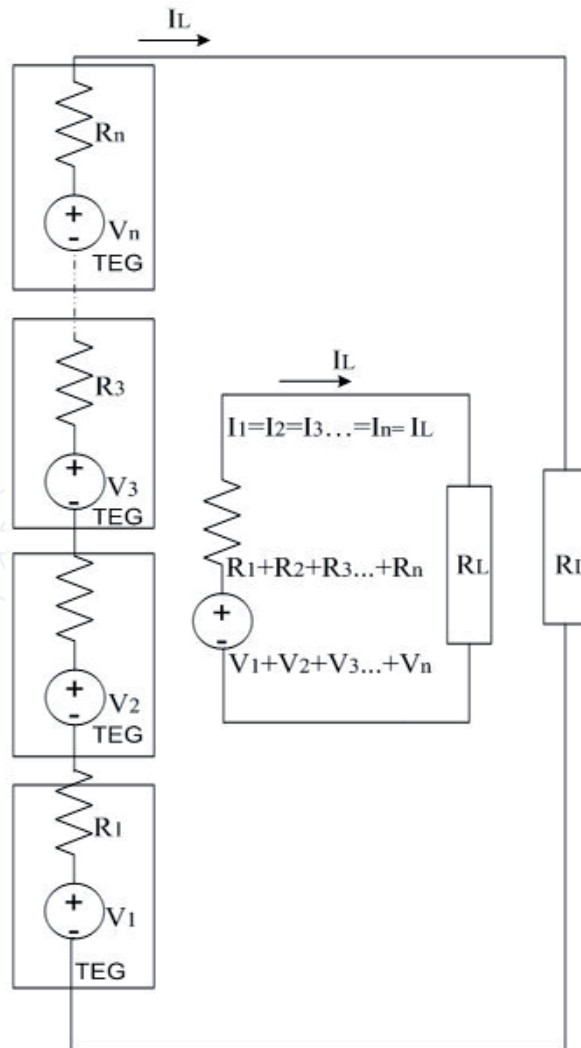
Figure 11.
TEG modules electrical schematic of the series array.
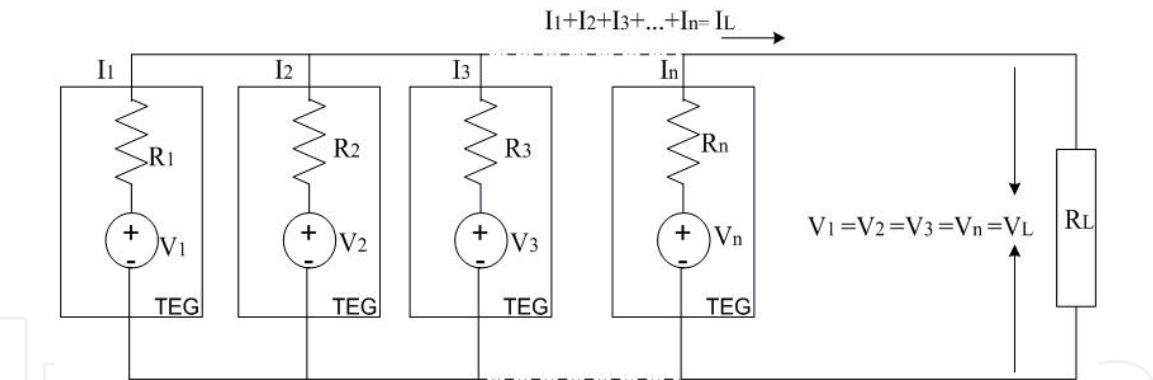
Figure 12.
Electrical schematic of parallel array of TEG modules.
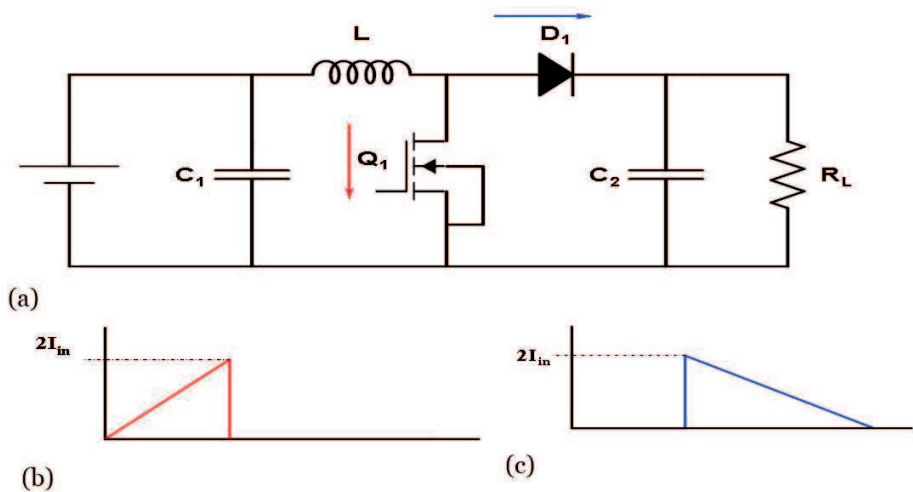
Figure 13.
(a) The schematic diagram for required components; (b) MOSFET currents; and (c) diode currents.

While it is switched "on," or the SW is closed, there is no conduction over the diode. The inductor pulls and gathers power from output of the TEG. The output of the converter as views at the load is gained through the energy inside the capacitor from previous cycles. In the "off" position, or when the SW is open, the diode is conducting energy. At this position, the inductor is load connected, and can show an output of power into the RC network. In the "off" setting, the power of the inductor is a combination of stored power and power supplied by the TEG. Part of the energy of the inductor is sent to the load and to charge the capacitor. As a result, the voltage of the output port may be observed as more than the input port.

The estimated resistance of the input of the converter is decided through the PWM signal duty cycle D and resistance of the load:

$$R_{in} \approx (1 - D)^2 R_L \tag{6}$$

3.3 Algorithm for maximum power point tracking (MPPT)

The main internal makeup of an MPPT's hardware is a DC to DC, switch-mode converter. It is more commonly found in DC supplies and DC motor drives for converting an unregulated DC input into controlled DC output, for a specified level of voltage. The MPPT converter is able to be used for a number of purposes. This includes the regulation of input voltage at PV MPP and can give a matching load during maximum power transfer.

A number of techniques have been offered for the MPPT, for the TEG in energy harvesting systems. There are a number of similarities in the methods that are found in PV systems and used in the TEG. One such algorithm is the Perturbation and Observation (P&O) MPPT technique. The P&O method is based upon two different power point observations of dynamic measurements and variables performed before and after a duty cycle of the converter that has been perturbed with both the short-circuit and the open-circuit-based algorithms. These are performed both before and after the duty cycle has been perturbed. The Incremental-Conductance (InC) algorithm has its basis in the principle in the MPP of TEG generators. There are less complicated maximum power point trackers found for thermoelectric generators [10]. A voltage-trend detection circuit is made [11], in which the gradient of the boost-converter output is drawn through the measurement of output voltage. This method allows a low-power application of the hill-climbing MPPT method. Circuit noise has been found to affect the MPPT efficiency in P&O and InC algorithms. It has also been discovered that it affects the accuracy in TEG output calculations or current gradient. As provided in [8, 9, 12, 13], increased perturbation steps will result in high steady-state oscillation around the MPP. This will reduce TEG power production. However, increased accuracy in the power or gradient measurements will also increase complexity and the consumption of power of the control unit in the MPPT. This characteristic of operation is important for low-power TEG processes for power production of the source of the TEG and power consumption of the control unit in the same order. Modern technology needs highly efficient devices with a low cost and the ability to convert waste heat into electric energy [14]. This deficiency can be covered by manufacturing low-cost materials and well-automated mechanisms for TEG units.

4. Case study: energy harvesting system

The performance of the thermoelectric campaign in different circuits configures with different temperatures. The measurement system can attach to the circuit in the experimental laboratory. This experiment is started to the test the actual environmental conditions and its effect on the real application, where the temperature is beyond the control.

As it can be seen in **Figure 14**, the TEG array ship is between a hot and cold block. In the experimenter, there are high temperature and high power provided by the direct current. The latter is air cooled by the attachment of the first device that is named in this experiment as TEG. TEG can attach to an electronic device or another desire component for the first circuit for one TEG device. A spring was used for load and weight over the TEG.

Moreover, a thermometer was used to sense the cold side (heat sink and fan unit) and the copper side as well (heat source) of the surface. The thermometer was used for obtaining the judgment of the temperature through the TEG device. The configuration of the thermoelectric array is connected to meet the required power with the different resistant load to get precise of different values according to the temperature range. The set consists in the determination of the ability of the system to operate in the MPP under different ΔTs. The need of graphing MPP under various conditions leads us to develop an MPPT algorithm.

4.1 MPPT technique development

The technique that has been developed in this case study to measure TEG's short-circuit current must be equipped with a capacitor in parallel, current sensor, switch,
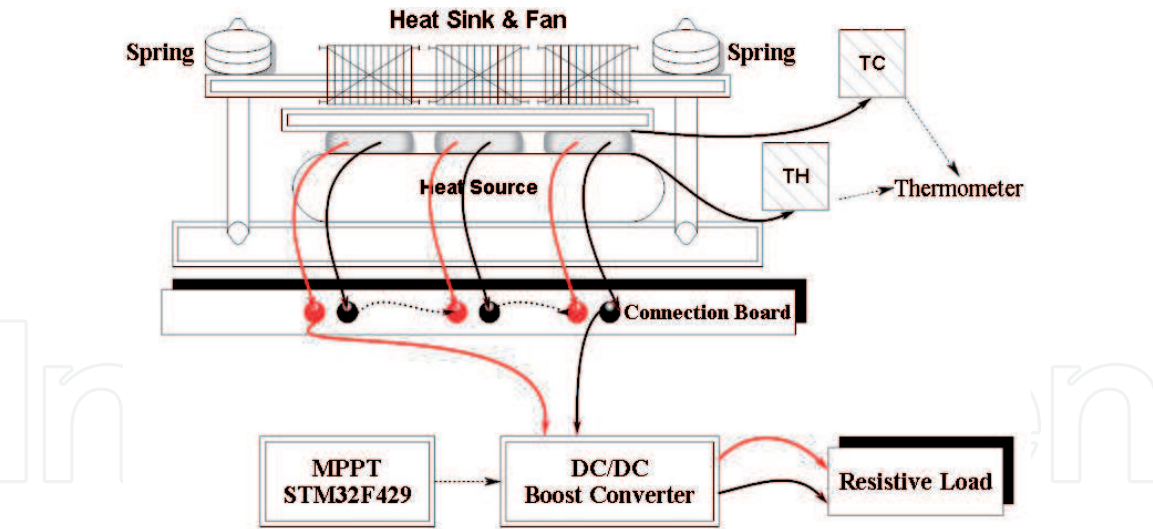
Figure 14.
The general schematic of the experiment.

and a diode in series provided with the output of TEG. This is equal to the time of input of the boost. The algorithm that was chosen for the case study was designed for smaller applications.

Short-Current Pulse (SCP) principal algorithms are dependent upon the relationship of optimum current I_m (current at maximum power point) and short-circuit current I_{SC}. This can be observed in section III as its fundamentals are seen in Eq. (7).

$$I_m = 0.5\,I_{sc} \qquad (7)$$

The fundamentals of the Short-Current Pulse algorithm are shown in **Figure 15**; it performs a measurement while comparing the current and short-circuit current. If the current is more than half of the short-circuit current, the operating point of TEG is on the left side of the optimum power point. However, if the current is less, the operating point is on the right of the optimum power point. Based on this information, it can be observed that the MPP location can be confirmed and tracked [15, 16]. This operation can be done periodically in order to keep the MPP in a steady and dynamic state.

The power that is generated from the TEG module is considered to be low. There are a number of processes which should be kept to maximize output power. This makes the TEG array with n-TEG modules using a boost converter in the input voltage comparable to the circuit design. For this research, the MPPT system configuration was designed in the lab from the TEG array (a series of three connected TEG modules). These connections included a Short-Current Pulse circuit and a boost converter which was controlled by the designed MPPT linked to a resistive load. The schematic of the system can be seen in **Figure 16**.

To boost the converter when switched "on," the switch Q2 is closed without a current passing through the diodes D2. The stored energy from the output capacitor C2 will supply the load. When the circuit is open, the circuit position will cross the diode D2, while the output power of the TEG stores power through the input capacitor and inductor. While in the "off" position, the switch Q2 will not have a current passing through the switch and the diode D2. The stored energy is gathered during the "on" period of the inductor and the energy from the TEG will flow in the direction of the load. The observation made according to the previous steps is the output voltage that was found to be greater than the input.
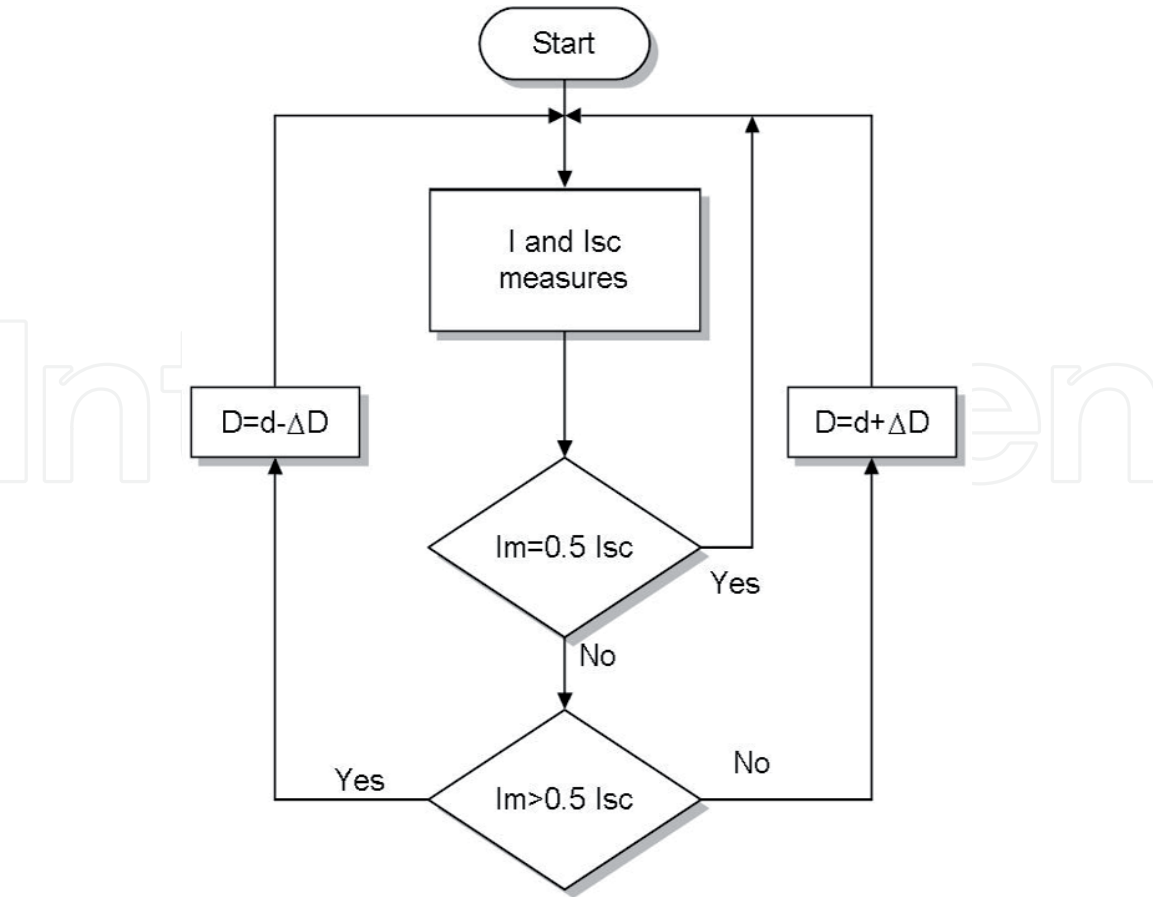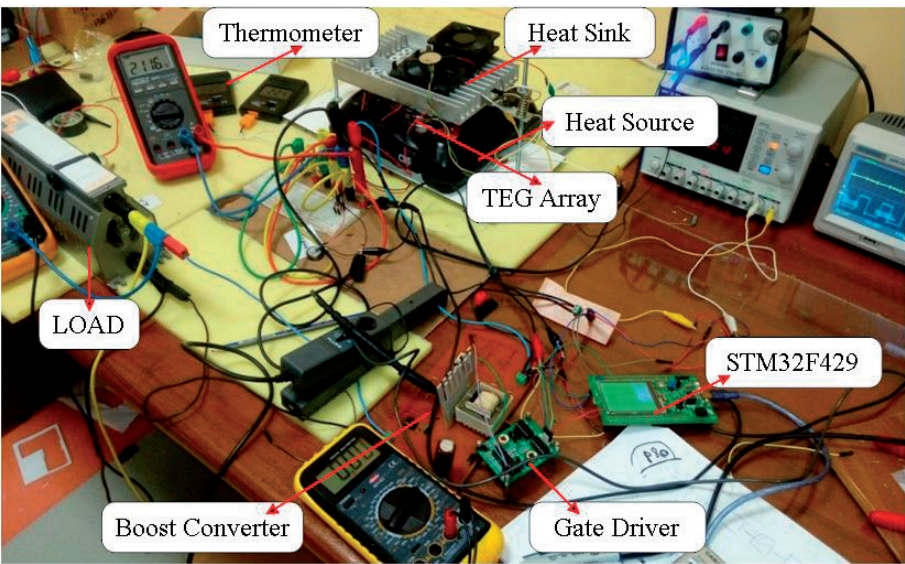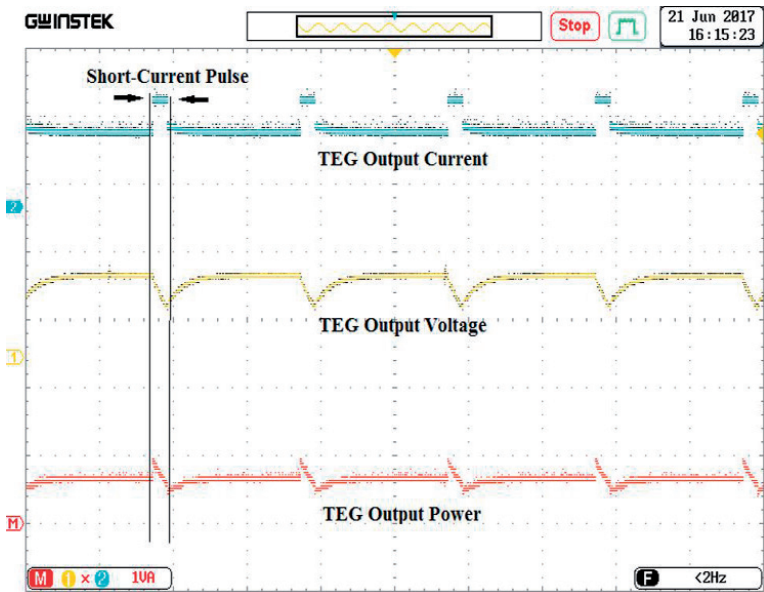
Figure 15.
Flow chart of SCP algorithm.
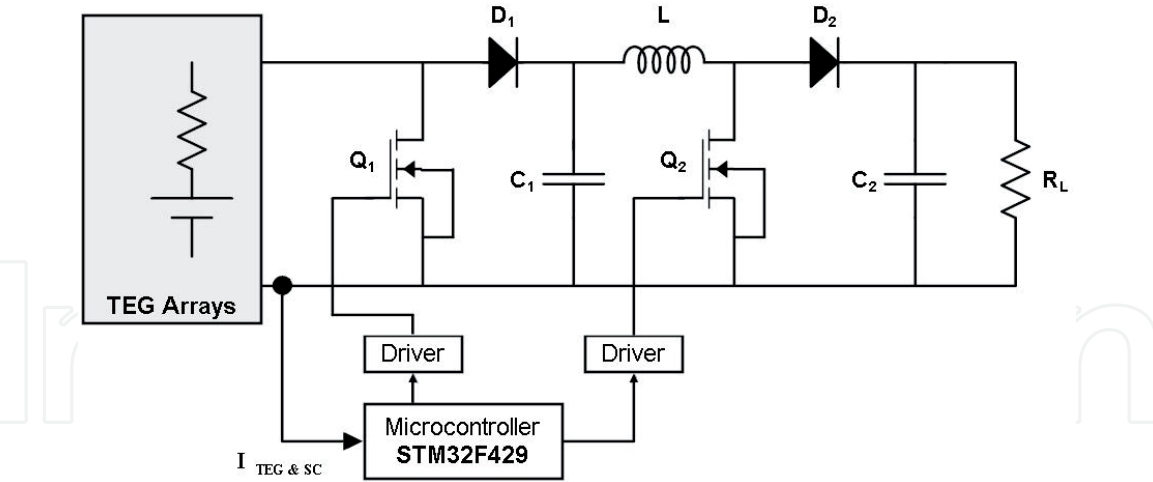
Figure 16.
The proposed energy harvesting system for TEG array.

4.2 Experimental results and discussion

The harvesting system hardware has the benefit of a lower cost but a high-performance element. This includes a high sensitivity INA250 used to sense the current; a STM32f429 discovery kit with an ARM® Cortex®-M4 core. The kit is also equipped with a monitor which provides a means to check the algorithm's accuracy of an operation. The measured parameters can also be tested to include the short-circuit current, output current of TEG, and duty and operating duty cycle of the boost converter at the MPP. In the experiment, in order to match the "on" voltage (microcontroller output voltage capability) of the Mosfet, two gate drivers

Figure 17.
Energy harvesting system prototype.

Figure 18.
The output power, current, and voltage of three series TEP1-142T300 with STM32F429 microcontroller.

were created to drive the Mosfet of SCP while boosting the converter circuit. The prototype of the system implementation can be observed in **Figure 17**.

As shown in **Figure 18**, the TEG takes a period of time in order to become stable when compared to response time of the boost converter. The SCP algorithm is discovered to have a high tracking performance and an efficiency of nearly 100% in measuring the short-circuit current at three times per second in order to make adjustments to the operating point while controlled by a generated pulse of a maximum power point tracking algorithm. It has been observed that the short-circuit current pulses can increase and decrease per second through the change set into the values of the code implemented in STM32f429.

5. Conclusion

Thermoelectric generators (TEGs) has opened the way for many new researchers by improving the coverage of renewable energy sources. There is no negative

impact on the environment because TEGs have no pollution and are noiseless. It also has the advantages of low maintenance and the use of common waste heat energy. Temperature plays an important role in the TEG energy conversion process. In TEG performance, there are several other factors that have a significant effect, such as the effect of temperature difference ΔT between the two plates. To provide the desired voltage and/or current, the TEG device can be electrically connected in series and/or parallel form. TEGs can be applied at different temperature environments, different thermal forces, and different electrical loads. As a consequence of the operating conditions for each device in the TEG array, the changes of the temperature difference can affect on the system operation. For this reason, it is necessary to ensure that the energy conversion in the thermoelectric system is precisely monitored on a device basis and that maximum energy can be drawn from the system. For this operation, it is inevitable to use a power converter controlled by the Maximum Power Point Tracker (MPPT) algorithm between TEG and load.

Author details

Khalid Yahya[1*], Mohammed Salem[2], Nassim Iqteit[3] and Sajjad Ahmad Khan[4]

1 Faculty of Engineering and Architecture, Department of Mechatronic Engineering, Istanbul Gelisim University, Istanbul, Turkey

2 School of Electrical and Electronic Engineering, Universiti Sains Malaysia, Nibong Tebal, Malaysia

3 Department of Electrical Engineering, Palestine Polytechnic University, Hebron, Palestine

4 Faculty of Electrical and Electronics Engineering, Electronics and Communication Engineering Department, Istanbul Technological University, Istanbul, Turkey

*Address all correspondence to: khalid.omy@gmail.com

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