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# Performance analysis of thermoelectric generator using dc-dc converter with incremental conductance based maximum power point tracking

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ABSTRACT

Thermoelectric generators (TEGs) are used for converting heat into electricity. One of the challenges behind TEG is that the power generated is unstable and therefore needs proper power conditioning mechanism before it is supplied to the load. Moreover, it is necessary to track the maximum power point (MPP) so that maximum power is always extracted from TEG devices. The objective of this work is to analyse the performance of dc-dc converter with maximum power point tracking (MPPT) enabled by incremental conductance (IC) method. The results of the IC based MPPT approach have been compared with those of perturb and observe (P&O) based MPPT from a previous researcher. The results indicate that the IC based MPPT approach is able to track the MPP but with relatively lower efficiencies than the P&O based MPPT method. The matching efficiency within a temperature range of 200 °C–300 °C is in the range of 99.92%–99.95% for P&O and 99.46%–99.97% for IC method. However IC based MPPT method has higher voltage gain and converter efficiency than the P&O based MPPT method. Therefore, dc-dc converters are able to improve the steady state performance of TEG system as well as boosting the voltage to the desired level, hence improving the overall performance of TEG system.


## Introduction

The growth of industrialisation along with increased population has increased the world energy demand. The indigenous fossil fuels besides being near their exhaustion have resulted into disastrous climatic changes such as greenhouse gas, especially due to industrial and transportation pollutions (Ramli et al., 2017a). A considerable amount of heat energy is wasted mainly in industrial and transportation sector. In the French industry, 75% of the final energy is used for thermal purposes such as furnaces, reactors, boilers and dryers. However, around 30% of this heat is assumed to be wasted in form of discharged hot exhaust gas, cooling water and heated product (Haddad et al., 2014). Thus, the recovery of waste heat is capable of contributing a considerable amount of energy for daily needs especially in the transportation sector. The rapid development of power electronics technologies has enabled the realization of high energy-efficient systems such as electric vehicles and thermoelectric (TE) technology (Tie & Tan, 2013). Therefore, the waste heat can be recovered using a thermoelectric generator (TEG) which is a device invented through thermoelectric technology to convert heat into electric energy (Zheng et al., 2014). TEG modules offer low cost electricity, and green energy technology without the use of moving parts or production of environmentally deleterious wastes (Seetawan et al., 2014).

In recent years, there has been a remarkable advancement of TE devices and therefore their efficiencies are increasing greatly especially due to TE material and device geometrical improvements (Liu et al., 2015a). However, the efficiency of TEG is still low, being a subject of further research to improve the performance of TEG system. In addition to the research for new and advanced TE materials, the interdependency between TEG device and heat exchanger for heat recovery from exhaust gas and heat removal from coolant has been investigated to improve the performance of the devices (Zhang, 2016).

Since low efficiency is the major challenge for TEG system, in a combined effort to improve the performance of TEG device, it is necessary to extract the maximum power so that the TEG device is operated near its full capacity. Hence, in addition to the application of methods related to the development of TEG devices such as TE material improvement and geometrical enhancement, power conditioning methods can also be applied to ensure that the maximum power is extracted from TEG system. Power conditioning method includes impedance matching and application of dc-dc converters. The impedance matching involves striking the balance between the total internal resistance of the TEG system and external load resistance connected to the TEG system. For proper impedance matching, the optimal electrical load should be equal to the internal resistance of the TEG module in order to ensure

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that the maximum power is transferred to the load (Remeli et al., 2015). However, it is extremely difficult to achieve the balance between the internal resistance of TEG and load without using special electronic devices. In this case it is hard to harvest the maximum power from TEG device. Hence, a dc-dc converter with maximum power point tracker (MPPT) is employed to achieve a stable voltage as well as the maximum power output (Mamur & Ahiska, 2015). MPPT techniques have been classified into conventional and intelligent techniques. The conventional methods include incremental conductance (IC), perturb and observe (P&O), and hill climbing methods (Ishaque & Salam, 2013). The variant of these three methods has also been used in literature for MPPT of solar PV systems. Intelligent techniques are sometimes referred to as soft computing (SC) techniques and are known to have the ability and flexibility to solve non-linear tasks and are suitable for handling different challenges arising out of adverse environmental conditions like rapid changes in irradiance and temperature (Ramli et al., 2017b). Although both conventional and intelligent techniques have greatly been applied to photovoltaic (PV) systems, few of them have been applied to TEG devices.

Several dc-dc converter topologies with MPPT have been proposed and analysed such as dc-dc conversion network (Li et al., 2011) and dc-dc converter with temperature sensor-based MPPT (Park et al., 2014). It is observed that dc-dc converters are able to provide more stable output voltages and improve the performance of TEG system. The purpose of this work is to analyse the performance of boost dc-dc converter with incremental conductance-based MPPT algorithm on TEG system and clarify the effects of TEG main design parameters. Unlike the indirect control MPPT methods that make use of proportional–integral (PI) controllers, there by complicating the MPPT control circuit, in the direct MPPT control methods such as P&O and IC, the duty cycle is computed directly in the MPPT algorithm. The direct control method is also advantageous because it simplifies the tracking structure and reduces the computation time, and less tuning effort is needed for the gain.

## The structure and modelling of TEG device

A TEG unit is primarily composed of n-type and p-type semiconductors. A number of TEG units are normally stacked to form a TEG module so as to produce the required power as illustrated in Fig. 1.

While choosing TEGs for application in varying conditions, it is necessary to select an appropriate semiconductor with acceptable performance in the temperature range of that condition [14]. The figure of merit (Z) is a parameter generally used to gauge the performance of a TE material:

$$Z = \frac{\alpha_{p,n}^2 \sigma_{p,n}}{\lambda_{p,n}} \quad (1)$$

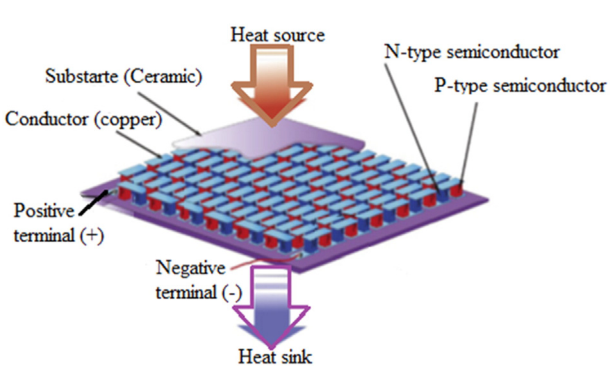


**Fig. 1.** Illustration of the TEG setting for power generation (Niu et al., 2015).

where $\alpha_{p,n}$ is the Seebeck coefficient of n-type or p-type material; $\sigma_{p,n}$ is the electrical conductivity of the material in p-type or n-type in Siemens per meter; $\lambda_{p,n}$ is the thermal conductivity.

With increased interest in TEG systems for different applications, research has been intensified, leading to the introduction of several advanced TEG models. This has been done through various modifications of the basic TEG module such as geometrical modifications, hybridizing of the materials used to form TEG, etc. As a result, tremendous improvements in the power output and efficiency have been achieved.

With the application of current through a thermoelectric element, thermal energy is generated or absorbed at the junction due to Peltier effect. The exchange of Peltier heat between the semiconductor and metal (both the n- and p-type) is demonstrated in Fig. 2(a). The Seebeck coefficient is proportional to the temperature and this effect is different at different places along the TE material (TECTEG MFR, n.d.). The thermoelectric element is a combination of a series of many small Peltier junctions [as shown in dotted lines in Fig. 2(a)], each of which separately produces or absorbs heat. This is the Thomson power developed per unit volume. In Thomson effect, the heat is evolved or absorbed when the current is passed through a TE element with a temperature gradient. Therefore, this effect is equally proportional to the temperature gradient and the electric current.

The Thomson coefficient $\tau$ is expressed as

$$\tau = T\frac{d\alpha}{dT} \quad (2)$$

where $\alpha$ is the Seebeck coefficient; T is the average temperature. This equation indicates that the Thomson coefficient must not be applied in situation where Seebeck coefficient is constant and calculated with the average temperature.

Two major categories of thermoelectric models are: the simplified and the complex models. The simplified models are based on a global balance of heat transfer and thermoelectric effects (macro approach) i.e. some of the TE effects are kept constant while others are neglected. For example the Seebeck effect is kept constant, leading to the Thomson effect to be zero or negligible (Fraisse et al., 2013). Unlike the simplified models, in complex models the thermoelectric element behaviour is described more precisely with the use of local energy balance equations because all thermoelectric effects are caused by coupling between charge transport and heat transport and therefore the quantification of these transports can be evaluated using the mass, energy and entropy equations, forming rigorous thermodynamic frameworks (Chakraborty et al., 2006). The simplest approach to model a TE element is to set up an overall thermal energy balance, assuming a symmetrical distribution of the Joule effect between the cold and hot sides of the TE element. The Seebeck coefficient $\alpha$, the thermal conductivity k, and the electrical conductivity $\sigma$ of the thermoelectric element are kept constant in the material and estimated from the mean temperature $\overline{T}$ of the hot and cold sides at $T_H$ and $T_C$, respectively.

$$\overline{T} = \frac{T_H + T_c}{2}. \quad (3)$$

This assumption is quite reliable in steady state as long as the Joule effect is not predominant. Other definitions can be considered from an evaluation of the temperature variation within the leg. It would allow calculating more precisely the average temperature. This is because the temperature variation is a posteriori known, i.e. the variations have to be justified through experimental observations. Based on

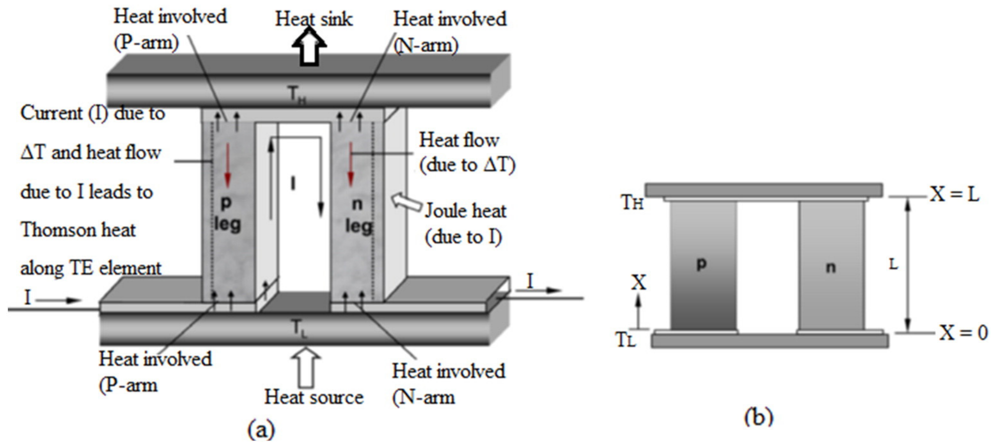


**Fig. 2.** The schematic view of a thermoelectric cooler (Chakraborty et al., 2006).

these assumptions, global energy balance in the whole leg produces the following expressions:

For TE Cooling (TEC)/TE Heating (TEH):

$$Q_H = \overline{\alpha} I T_H - \overline{K} \Delta T + \frac{1}{2} \overline{R} I^2 \quad (4)$$

$$Q_c = \overline{\alpha} I T_c - \overline{K} \Delta T - \frac{1}{2} \overline{R} I^2. \quad (5)$$

For TEG:

$$Q_H = \overline{\alpha} I T_H + \overline{K} \Delta T - \frac{1}{2} \overline{R} I^2 \quad (6)$$

$$Q_c = \overline{\alpha} I T_H + \overline{K} \Delta T + \frac{1}{2} \overline{R} I^2 \quad (7)$$

where

$$\overline{R} = \frac{L}{\overline{\sigma} A} \quad \text{: Electrical resistance} \quad (8)$$

$$\overline{K} = \frac{\overline{k} A}{L} \quad \text{: Thermal conductance.} \quad (9)$$

The electrical power is the difference between the hot and cold thermal fluxes:

$$P = Q_H - Q_C. \quad (10)$$

This gives:

$$P = \overline{\alpha} I \Delta T + \overline{R} I^2, \text{ for TEC/TEH} \quad (11)$$

$$P = \overline{\alpha} I \Delta T - \overline{R} I^2, \text{ for TEG.} \quad (12)$$

In TEC and TEH modes, the coefficients of performance (COPs) are respectively given by:

$$COP_c = \frac{Q_c}{P} \text{ and } COP_H = \frac{Q_H}{P}. \quad (13)$$

The electrical efficiency in TEG mode is given by;

$$\eta = \frac{P}{Q_H}. \quad (14)$$

In the above equations, the Thomson effect is zero as the Seebeck coefficient is assumed constant.

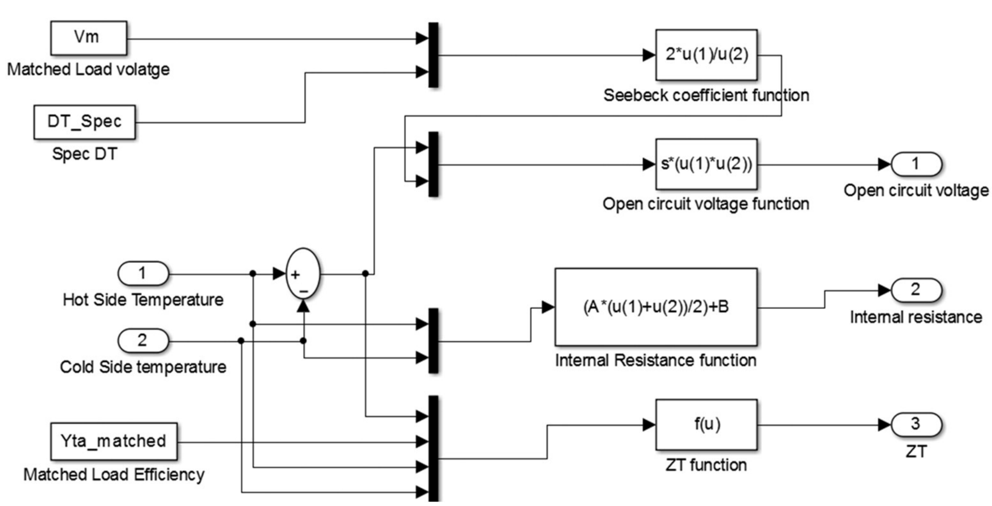


**Fig. 3.** The simplified model.

**Table 1**
Specifications of the TEG module.

| | |
|---|---|
| Hot side temperature (°C) | 300 |
| Cold side temperature (°C) | 30 |
| Matched load output voltage (V) | 4.2 |
| Matched load output current (A) | 3.4 |
| Matched load resistance (Ω) | 1.2 |
| Matched load output (W) | 14.6 |

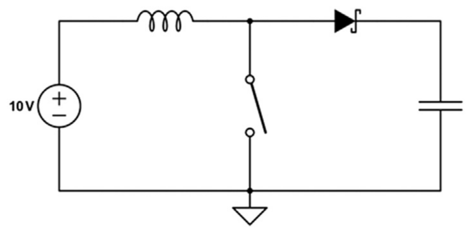


**Fig. 4.** A classical boost converter equivalent circuit.

In the improved simplified model, as compared to the standard simplified model, the Thomson effect is taken into account and assumed to be equitably distributed on both sides of the semiconductor.

The second improvement is relative to the evaluation of the thermoelectric coefficient as a function of temperature. The temperature used to evaluate each coefficient is defined by distinguishing the volume phenomena in the leg (conduction, Joule and Thomson effects) and the Seebeck effect taking place at the junction of two semiconductors. Thus the mean temperature $\overline{T}$ is used to evaluate the coefficients k, σ, and τ.

The simplified TEG model can generate the voltage and internal resistance parameters as the output. This is very important especially when modelling with dc-dc converters which require voltage and resistance as input parameters for analysis of their performance. Therefore, in this paper, the simplified model is used as the basis for designing the TEG. Fig. 3 shows the simplified model.

In this study, the parameters of a TEG device called TEG1-12611-6.0 have been utilized in the simulation model. The module specifications are shown in Table 1 (TECTEG MFR, n.d.).

## The dc-dc converter

A classical boost converter can take a low voltage for example 10 V, as input and step it up or boost it to high voltage say, to 15 V. Fig. 4 shows a classical boost converter with a 10 V source as its input voltage.

Fig. 5 shows how the boost converter operates to boost the voltage. When the switch is open, the output capacitor gets charged to 9.5 V. So far, the voltage has dropped due to the current flow across the diode since it has some internal resistance. When the switch is closed, the diode prevents the capacitor from discharging, so the output voltage stays at 9.5 V. But now there is a current path from the source through inductor and the switch to the ground.

The switch is closed for a fraction of a second just long enough to allow some current to flow through the inductor. This leads to the energy to be stored in the inductor in form of magnetic field. When the switch is opened and since the current in the inductor does not change instantly, the current has to flow through the inductor and the diode into the capacitor. So energy gets transferred from the inductor through the diode to the capacitor and the voltage increases. The boost converter has now boosted or stepped up the voltage. So, since the switch is not supposed to be closed for a very long time, it should be controlled with a high frequency PWM signal. Hence the use of PWM signal in dc-dc converters to control the switch.

### *Power conditioning and efficiency improvement of TEG*

The voltage–current characteristics as well as power of a TEG device are non-linear and therefore it is quite necessary to recondition the power output of the TEG before it is supplied to the load. Several

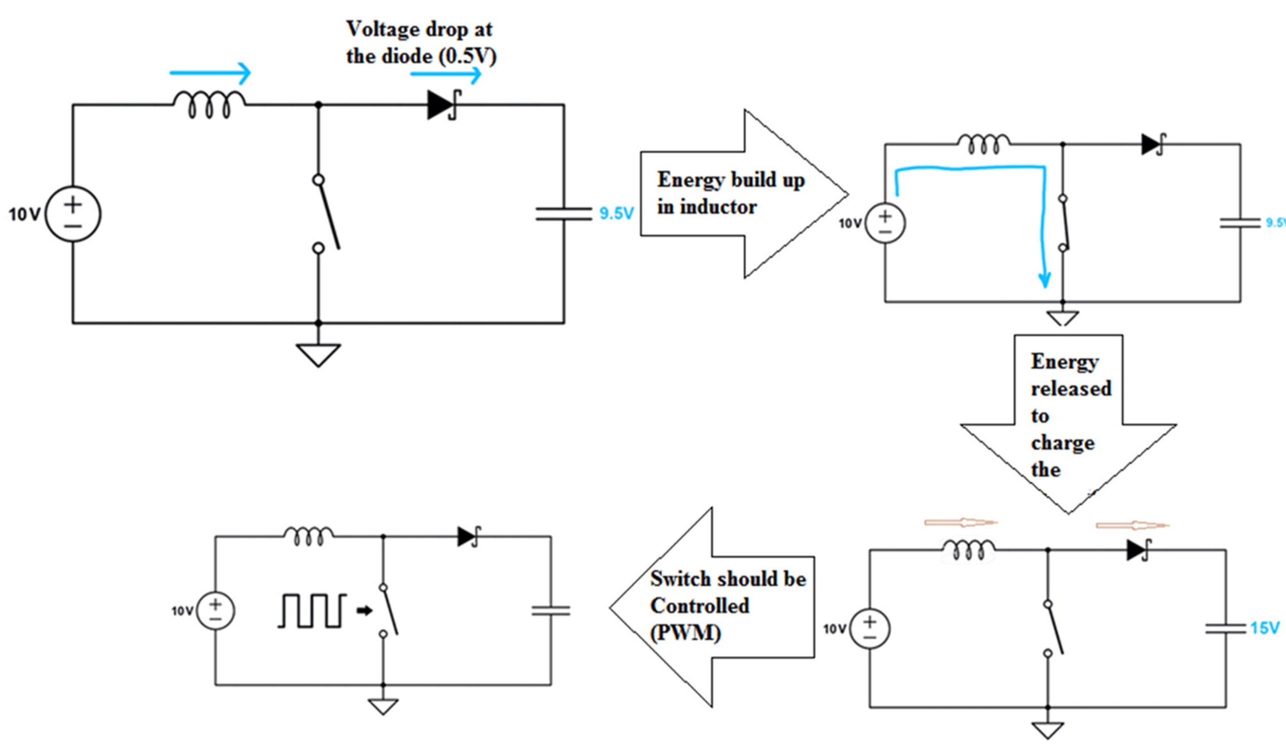


**Fig. 5.** Functioning of a boost converter.

**Table 2**
Summary of the qualities and implications of different dc–dc converters due to their application on TEG systems: modified from Twaha et al. (2016).

| Converter | Features | Application | Advantage | Limitation |
|---|---|---|---|---|
| Boost | · Converts from a low voltage to higher voltage<br>· Load current smaller than the input current<br>· Most commonly used<br>· Middle and low levels in the conversion network | · Suitable for TEG with unstable internal resistance and output voltage | · Precise and flexible conversion factor | · Requires a large inductance to get high efficiency |
| Buck | · Converts from a higher voltage to a lower voltage<br>· PWM controlled | · Where a lower voltage level is needed to supply the load | · Precise and flexible conversion factor | · High voltage ripples at the output<br>· Higher flux density due to large size of inductance. |
| Push-pull | · High level conversion of high power<br>· Step-up and step-down tasks<br>· Multiple outputs due to transformer isolation | · High power application (range of kWs)<br>· Fairly good efficiency | · Less likely to cause saturation than in the fly-back converter<br>· Hence smaller size | · More complex<br>· MOSFETs must be able to handle twice the input voltage<br>· Hence used for low voltage application |
| Cu'k | · Middle level conversion<br>· Continuous output current<br>· Can boost or buck the voltage | · Suitable for sensitive environments | · Stable input and output terminal currents<br>· Easy to cancel ripples (by adjusting inductors)<br>· Emit less RF noise | |
| Buck-boost | · Increase and decrease the output voltage<br>· Load voltage is inverted | | | |
| Fly-back | · Increase or decrease the output voltage<br>· Transformer is used<br>· Multiple output can be obtained<br>· Output energy is stored as magnetic energy and released to the load later. | · Where multiple outputs are required | · No separate inductor is needed since the transformer is used for storage<br>· Cost effective<br>· Multiple outputs are possible. | · Very high peak currents |

methods are reported which can be applied to stabilize the voltage and current generated from the TEG as well as the output power, thereby enhancing the performance of the whole TEG system. The first and straightforward technique is to use impedance matching whereby the usefulness of matching the TEG power output with the electrical load is demonstrated in the simulation and experimental work (Lesage et al., 2013).

By enhancing the heat transfer within the TEG device, its performance can be improved. The heat flux into the TEG can be increased by properly positioning the high temperature heat pipes within the gas flow. The recovery of waste heat using TEG from a low carbon vehicle revealed that a higher power output of 450 W at a speed of 5000 rpm can be achieved with the installation of TEG heat exchanger between the muffler and catalytic converter (Wang et al., 2016). Additionally, if the TEG heat exchanger is adjacent to the outlet of a catalytic converter, the power output of 705 W at 6000 rpm is obtained for a single sub pipeline, resulting into a total of 1410 W for a dual pipeline system.

Another method involves the adjustment of the boundary temperature and the number of TEG units. In this method, three ways are suggested to improve TEG power output: raising the hot-side temperature; lowering the cold-side temperature and increasing the quantity of modules (Liu et al., 2015b). An independent cooling system can be used to lower the temperature of the cold side. Alternatively, the hot-side temperature can also be increased but this is limited to a certain level. Equally, the number of TEG modules used in the system is also limited by some factors such as cost and space.

The application of dc-dc converter is another technique that can be used to improve the performance of TEG system. The dc-dc converter is an electronic circuit capable of converting from one source of direct current (DC) to another DC voltage. It is important in a situation where a higher voltage is needed from a lower voltage (boosting) or a low voltage is needed from a higher voltage (bucking). It is also applied to regulate the voltage from unregulated sources such as TEG devices, solar cells etc. therefore, several configurations of dc-dc converters are available to suit different applications. Many of the readily available dc-dc converters are designed to work under a (nearly) constant voltage source and therefore their performance may not be as expected when connected to a variable current source like a TEG or PV system (Abusorrah et al., 2013). Therefore, the choice of a right converter affects the optimum performance of the whole system. In this case a proper

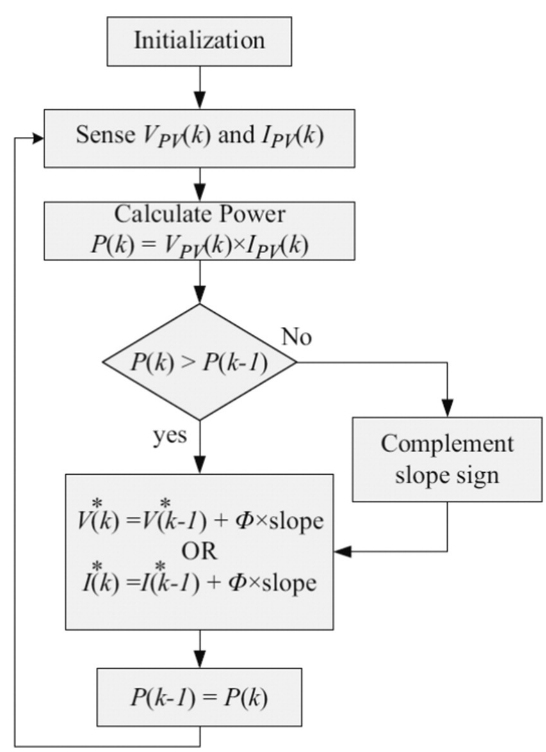


**Fig. 6.** Flow chart of conventional perturb and observe (P&O) method (Ishaque & Salam, 2013).

criterion has to be followed to choose the best dc-dc converter. Table 2 presents the summary of the qualities and the implications of applying different dc-dc converters to TEG system.

### *The maximum power point tracking (MPPT) system*

The purpose of applying the MPPT algorithm is to ensure that at any temperature difference, the maximum power is obtained from TEG device. This is achieved by matching the TEG's MPP with the operating voltage and current of the MPPT controlled-converter.

The dc-dc converters with MPPT have generally found application in PV system but can also be applied in TEG system. The MPPT methods can be divided into two main groups: the first based on voltage feedback and the second based on regulating the generated power. The method based on voltage feedback works in such a way that a predetermined reference voltage is compared with TEG module voltage in a feedback loop (Roshan & Moallem, 2013). The second method is based on regulating the generated power by sensing the PV/TEG module voltage and current to track the MPP. Perturb and Observe (P&O) and incremental conductance (IC) are the examples of this method. The MPPT functionality is normally integrated into the dc-dc converter to achieve higher power-extracting efficiency (Taghvaee et al., 2013).

The MPPT algorithm operates by sensing the current and voltage of the TEG. By using the current and voltage, TEG power is calculated

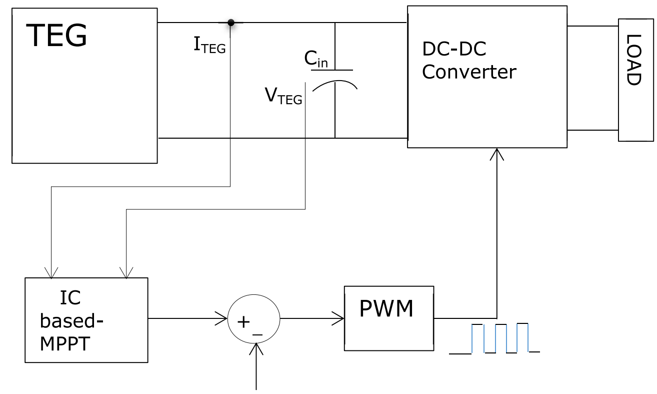


**Fig. 8.** Block diagram of the proposed TEG power conditioning system.

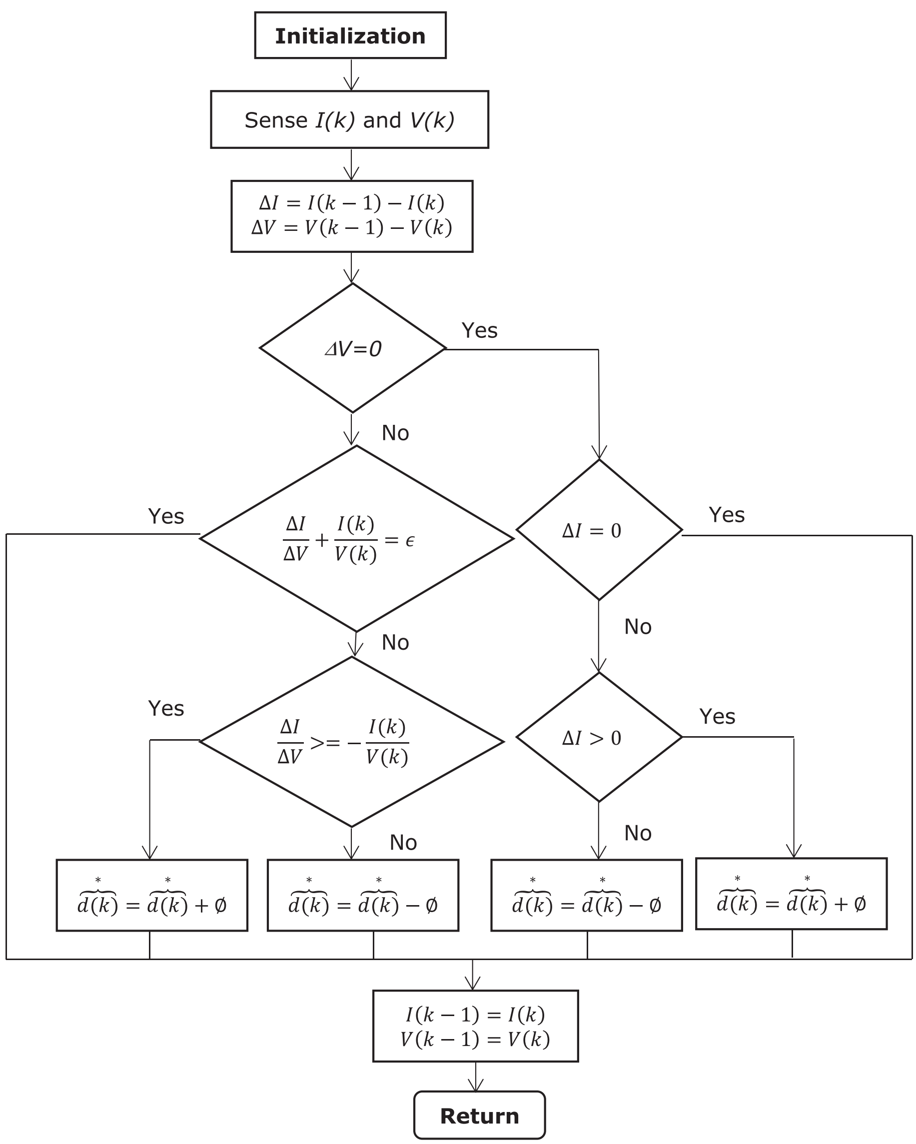


**Fig. 7.** Basic flow chart of incremental conductance (IC) method (Ishaque et al., 2014).

and compared with the present value of MPP. Accordingly, the duty cycle of the converter is adjusted to match the MPP, thereby forcing the converter to extract the maximum power. This is referred to as the direct duty cycle MPPT control. The duty cycle is computed directly in the MPPT algorithm. The direct control method is advantageous because it simplifies the tracking structure and reduces the computation time, and less tuning effort is needed for the gain. However, a proportional–integral (PI) or hysteresis controller can be used instead to adjust the duty cycle of the converter. This makes the MPPT control circuit complicated and much effort is needed to tune the PI gains while producing similar optimal results as the direct control method.

*The perturb & observe and incremental conductance methods*

The P&O algorithm whose working principle is demonstrated in Fig. 6 introduces a perturbation (Φ) in the operating voltage and current of TEG/PV array. As a result, the change in the operating power is observed. The relative increase in the operating power indicates that

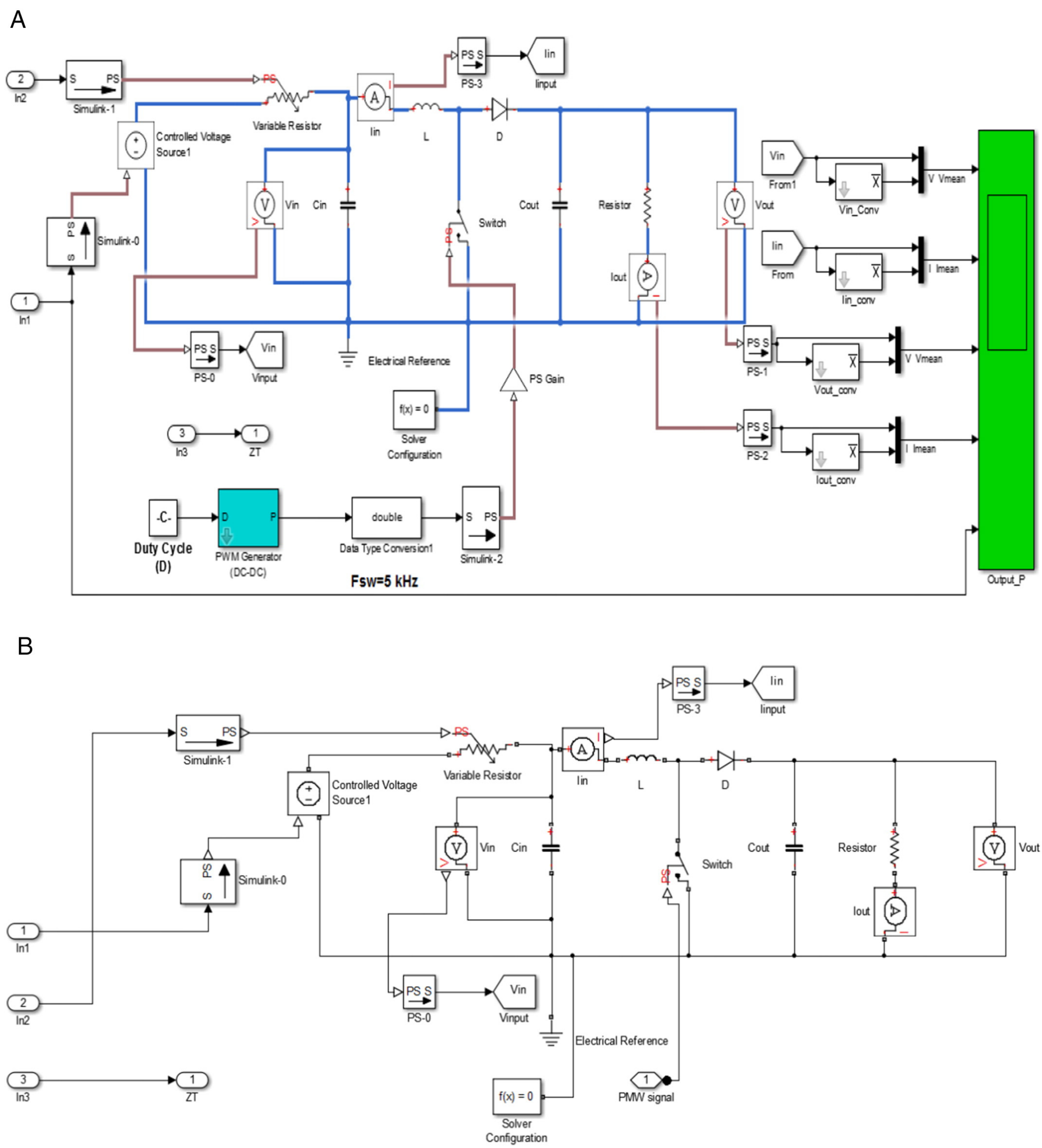


**Fig. 9.** A. Boost converter circuit implemented: with direct PWM signal. B. Boost converter circuit implemented: with MPPT.

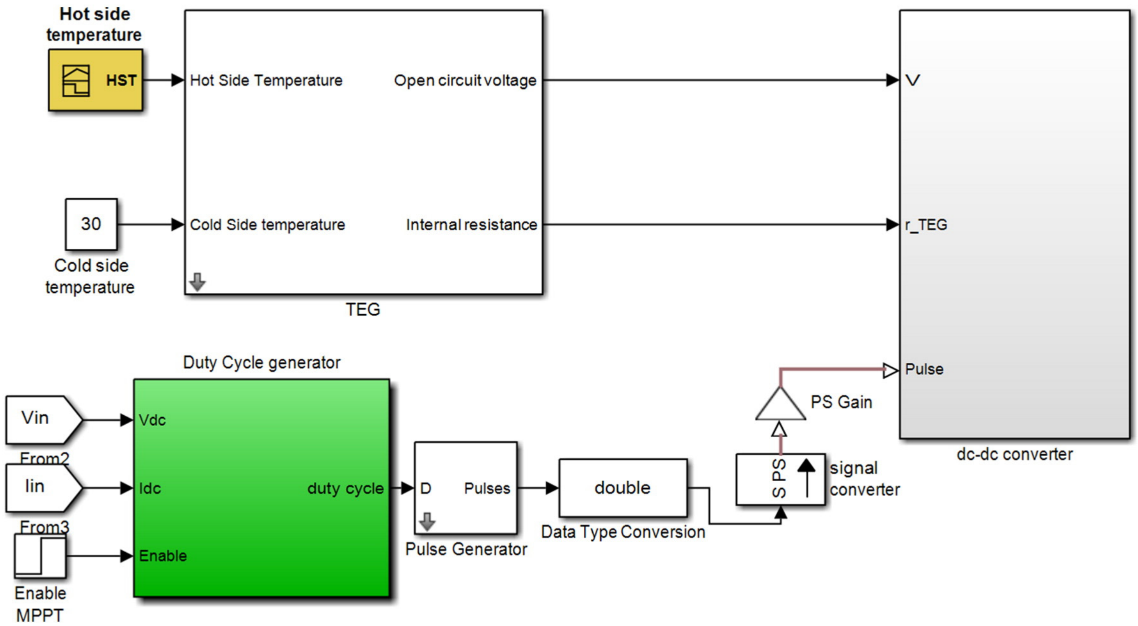


**Fig. 10.** The proposed TEG power conditioning system modelled in Simulink.

the converter is approaching the MPP. Similarly, during the succeeding sampling cycle, the slope (direction) of perturbation is maintained whereas the reference current and voltage are further increased by Φ value. Once the vicinity of MPP is reached, with each new perturbation (with alternating sign polarity), the algorithm will go back and forth around the MPP. Consequently, it does not reach exactly the MPP but it oscillates around that point indefinitely (Ishaque & Salam, 2013).

The IC method operates by incrementally comparing the ratio of derivative of conductance with the instantaneous conductance. This is due to the fact that at MPP, the derivative of power with respect to voltage (dP/dV) is zero, i.e.

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I + V\frac{dI}{dV} = 0 \tag{15}$$

After re-arranging Eq. (15)

$$-\frac{\boldsymbol{I}}{\boldsymbol{V}} = \frac{\boldsymbol{dI}}{\boldsymbol{dV}} \cong \frac{\Delta \boldsymbol{I}}{\Delta \boldsymbol{V}} \tag{16}$$

where I and V are the TEG output current and voltage; ΔI and ΔV are the increments of TEG output current and voltage, respectively. The basic rules for IC can be written as:

$$\begin{cases} {}^{dI}\!/_{dV} = -{}^{I}\!/_{V}, & \textit{At MPP} \\ {}^{dI}\!/_{dV} > -{}^{I}\!/_{V}, & \textit{Left of MPP} \\ {}^{dI}\!/_{dV} < -{}^{I}\!/_{V}, & \textit{Right of MPP}. \end{cases} \tag{17}$$

It can be noticed that the MPP condition (dI/dV + I/V = 0) rarely exists in practical application; hence, another alternative yet an effective way to utilize the IC is proposed by a number of researchers (TECTEG MFR, n.d.). The idea is to generate a marginal error Ɛ using the instantaneous conductance and the incremental conductance. Mathematically, it can be written as:

$${}^{dI}\!/_{dV} + {}^{I}\!/_{V} = 0. \tag{18}$$

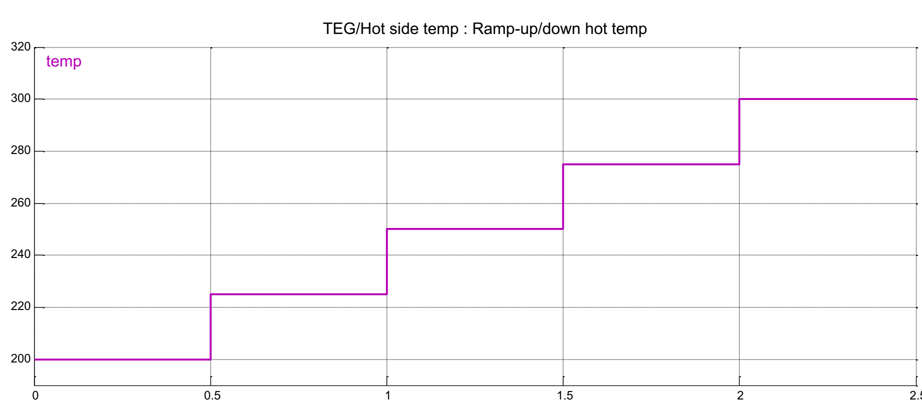


**Fig. 11.** The hot side temperature input to the TEG system.

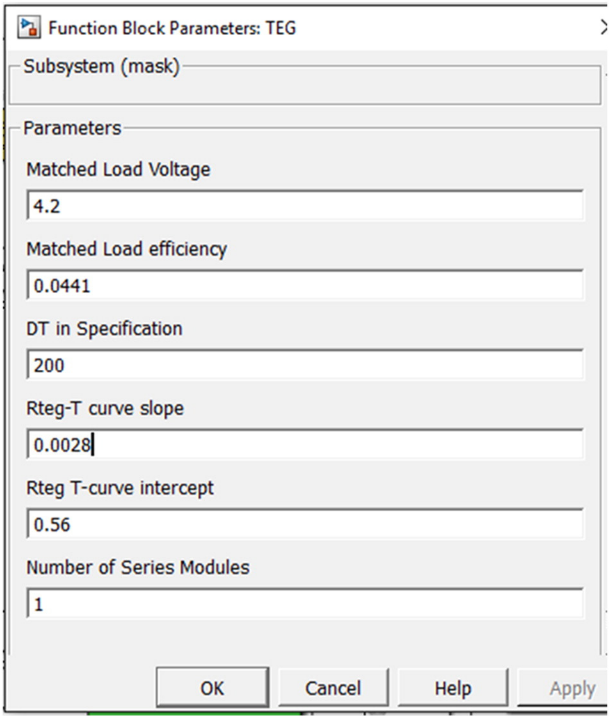


**Fig. 12.** TEG block parameter adjustment in the simulation model.

From Eq. (18), it can be seen that the value of ε is zero at MPP. Hence, based on the amount of ε and using the rules of Eq. (17), a basic flow chart for IC is depicted in Fig. 7.

## The proposed TEG power conditioning system

The proposed TEG power conditioning circuit consists of four main components: the TEG, the dc-dc converter, MPPT and the PWM signal generator. Fig. 8 shows a block diagram of the proposed circuit.

The boost converter circuit implemented with direct PWM signal is shown in Fig. 9A and the boost converter circuit implemented with MPPT is given in Fig. 9B.

## Results and discussion

As indicated earlier, the modelling is performed in Simulink. So, Fig. 10 shows the modelled circuit from which the results are obtained for analysis.

The cold side temperature is set as 30 °C whereas hot side temperatures is set at 200 °C, 225 °C, 250 °C, 275 °C and 300 °C in order to test the performance of the converter system at 200 °C–300 °C temperature range. The hot side temperature input to the TEG system is shown in Fig. 11 in a ramp function. The simulated model is designed in such way that it is possible to change the number of TEG modules in series as shown in Fig. 12. Therefore, the results are shown with different number of TEG modules in series.

The results are presented with instantaneous and steady state values of voltage and power. In addition, the values of efficiencies of the MPPT and the converter are also reported and discussed.

Fig. 13 shows the instantaneous voltages of the system. Obviously the open circuit voltage is higher than any other voltage values. As seen from Fig. 13, the input voltage to the converter is unstable; the level of instability is demonstrated by the size of the output voltage trace. As observed from Fig. 13, the output voltage from the converter is relatively stable and depending on the requirement, the voltage can also be boosted to higher value. In this case, the input temperature is a ramp function where the temperature is uniform at each temperature level of 0.5 s. However, with a non-uniform temperature input to the TEG system, the converter is equally capable of tracking the maximum power point. This is demonstrated by the replication of the ramp temperature input as seen from the output of the converter.

Fig. 14 shows the values of power from TEG as well as to and from the converter. The output power from TEG is a product of the open circuit voltage seen in Fig. 13 and the highly unstable input current with a lot of harmonics. Similarly the input power to the converter is a product of input voltage to the converter and the highly unstable

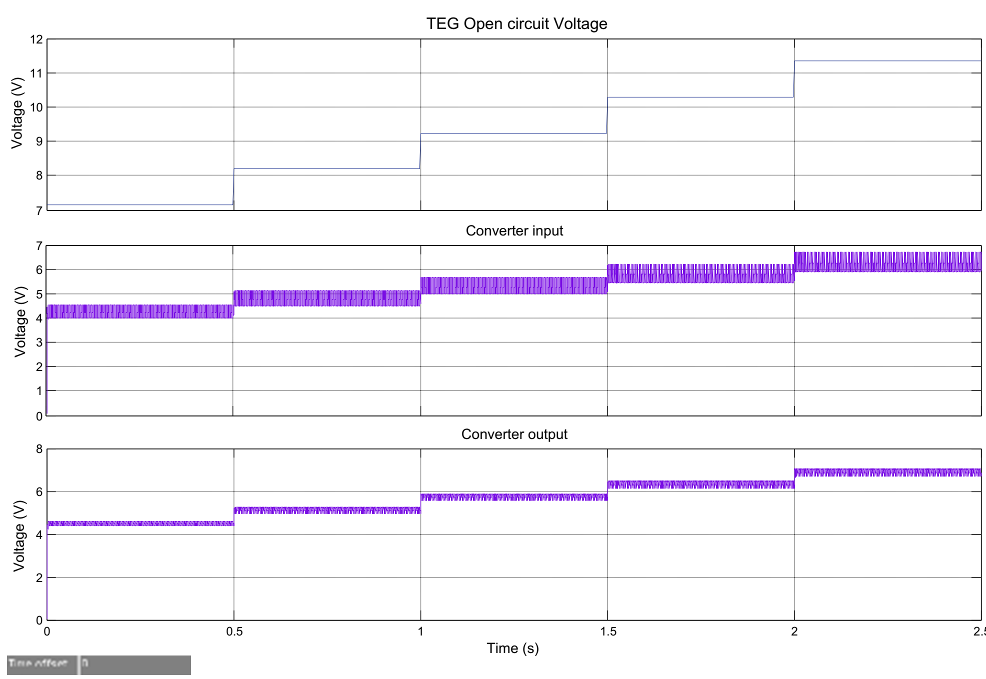


**Fig. 13.** The instantaneous values of voltage for the systems.

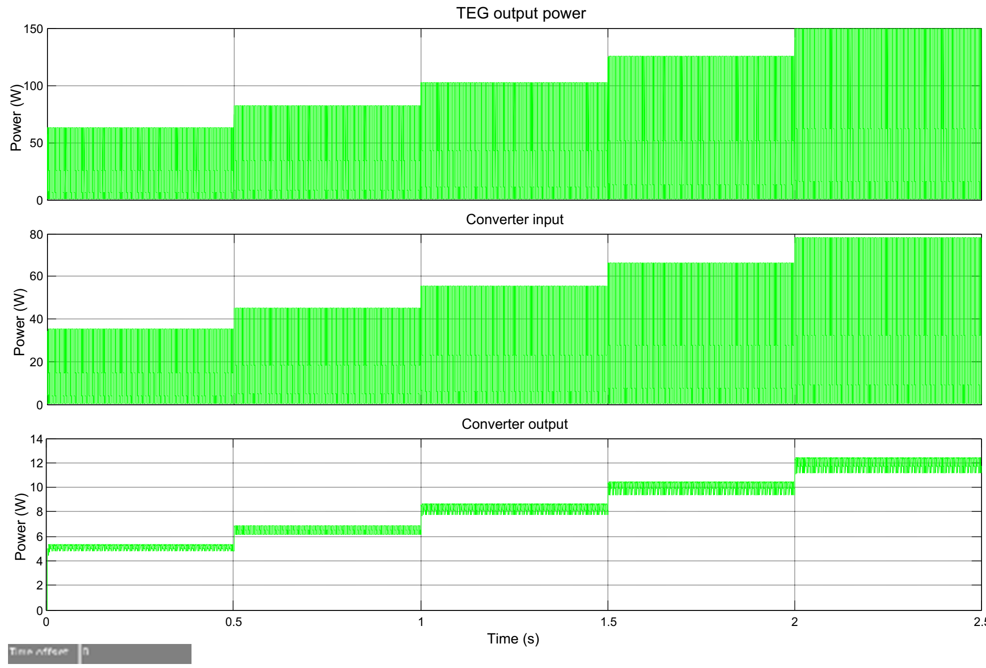


**Fig. 14.** Values of power from TEG as well as to and from the converter.

input current. Therefore, the input power to the converter is unstable due to the relatively unstable voltage and the highly unstable current with several harmonics. As observed in Fig. 14, the output power is relatively stable with fewer harmonics. This is due to the filtering done by the converter because of the presence of the filter circuit in form of a low pass filter. With proper tuning of the filter circuit, the stability of the output can be improved.

At steady state, the values of voltage and power of the system are recorded by computing the average values at each hot side temperature level. The input and output voltages of the converter are demonstrated in Fig. 15 where input and output voltages of the converter are shown for the ten TEG modules in series. It is observed that at a temperature value of 200 °C, the input voltage to the converter is about 41.18 V which is boosted to 48.64 V. Likewise, with a single TEG in series at the same temperature and an input voltage of 4.18 V, the output voltage is stepped up to 4.5 V as illustrated in Fig. 16.

Subsequently, the average power is shown in Fig. 17 for a single TEG module. As expected the average output power from TEG is higher than the input power to the converter. This is due to the high open circuit voltage $V_{oc\text{-}TEG}$ seen in Fig. 16. In all cases, the output power increases with the temperature. This is attributed to the increase in the temperature difference (which is responsible for the Seebeck effect) as the hot side temperature increases.

### *Verification of simulation results*

The results of this study are compared with those presented in literature (Li, 2011). In the literature (Li, 2011), the author studied a similar TEG/boost converter model with the same TEG parameters but with P&O based MPPT method. Comparing with an open circuit voltage of 7.2 V at 200 °C for the current study in Fig. 16 with that (about 7.2 V at the same temperature) of the previous study in Fig. 18A, the results of both cases agree. This means there was no source of error in the TEG circuit. The difference in the results arises in the input voltage to the converter. As observed in Figs. 16 and 17a, the input voltages to the converter are 4.1 V and 3.6 V at 200 °C for the current (IC based

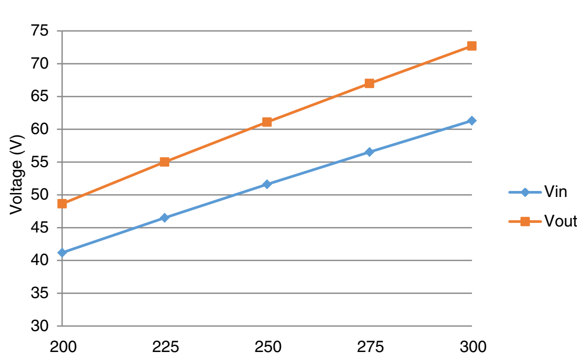


**Fig. 15.** Average input and output voltages of the converter at different temperatures for the ten TEG modules in series.

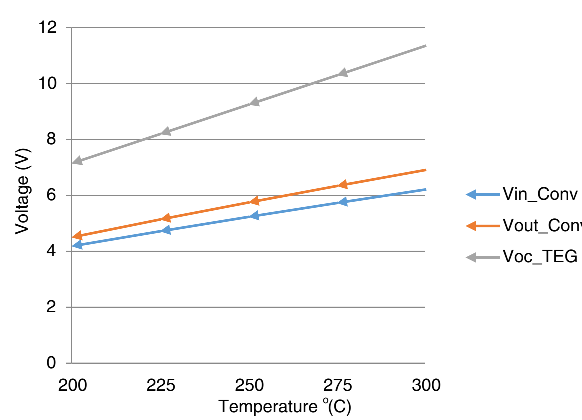


**Fig. 16.** Average input, output voltages of the converter and open circuit voltages of TEG at different temperatures for a single TEG module.

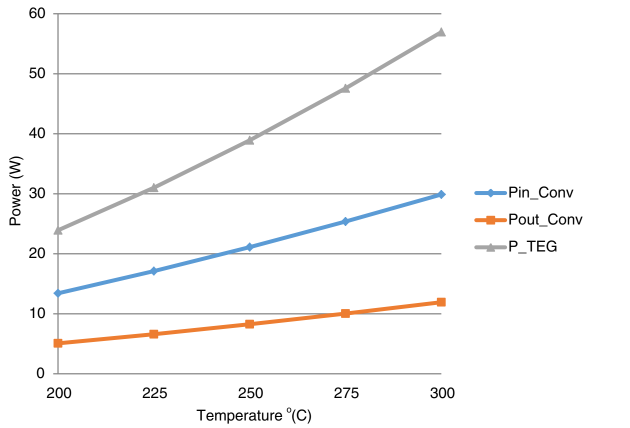


**Fig. 17.** Average input and output powers of the converter and TEG output power at different temperatures for a single TEG module.

MPPT) and previous (P&O based MPPT) methods respectively. Similarly, the input power to the converter is 13.4 W and 13.1 W at 200 °C as indicated in Figs. 17 and 18B for the IC and P&O based MPPT methods respectively. The errors arise due to several factors; these include looping errors in the MPPT algorithm leading to the simulation errors; component tolerances in the MPPT circuit these affect the output parameters of the converter and MPPT circuitry. Another cause of the difference in the results of both cases is the difference in the computing capability of the MPPT algorithms where it can be observed that when the voltage is compared alone, the IC based MPPT is more robust and less prone to errors than P&O method because it is able to extract higher voltage than the P&O based MPPT algorithm.

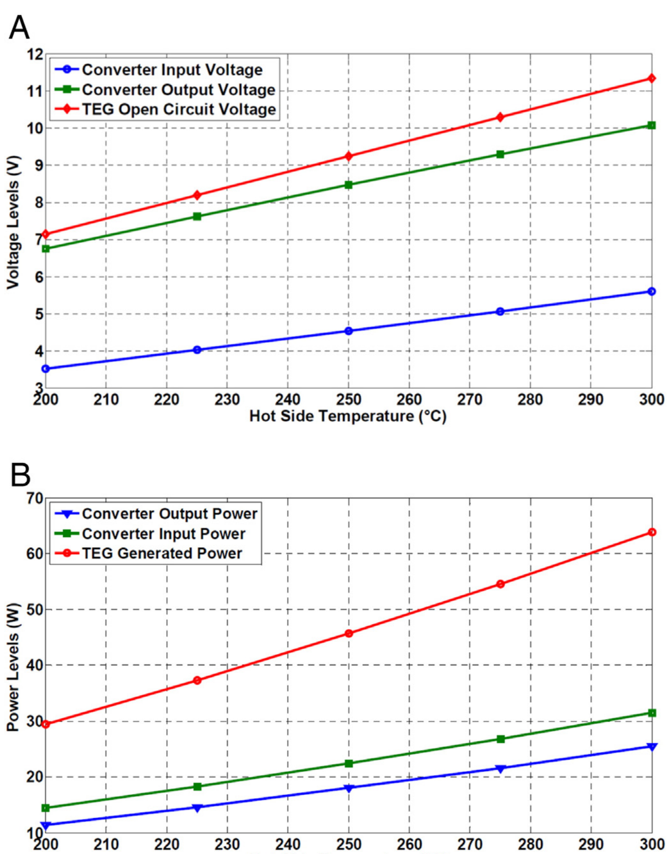


**Fig. 18.** A. Converter input and output voltages and TEG open circuit voltages with P&O method (Li, 2011). B. Power input and output of converter and power output of TEG with P&O method (Li, 2011).

*Performance comparison of IC and P&O techniques*

Fig. 19A and B show the matched powers of P&O and IC based MPPT methods respectively. At 200 °C, the respective matched power outputs are 14.3 W and 13.4 W for P&O and IC. From these power values at different temperatures, it is possible to compute the MPPT matched efficiencies. Therefore, Fig. 20A and B show the MPPT matching efficiencies for P&O and IC methods respectively. The matching efficiencies for the 200 °C–300 °C temperature range are 99.92%–99.95% and 99.46 °C–99.97% for P&O and IC methods. Hence, P&O algorithm is slightly more efficient than the IC based MPPT technique. It should also be noted that the MPPT matching efficiency of IC method degrades as the hot side temperature increases as observed in Fig. 20B.

The converter efficiencies for the P&O and IC based methods are shown in Fig. 21A and B in the ranges 78.52%–81% and 87.1%–88.7% respectively. It is observed that the corresponding converter efficiencies in the current study are higher than those in the previous study. This is attributed to the proper tuning of the converter circuitry. However, in both cases the conversion efficiency increases with the hot side temperature.

*Converter output without MPPT*

In this case, the converter switch is controlled with direct PWM signal as shown in Fig. 9A. Theoretically the conversion ratio M(D) is

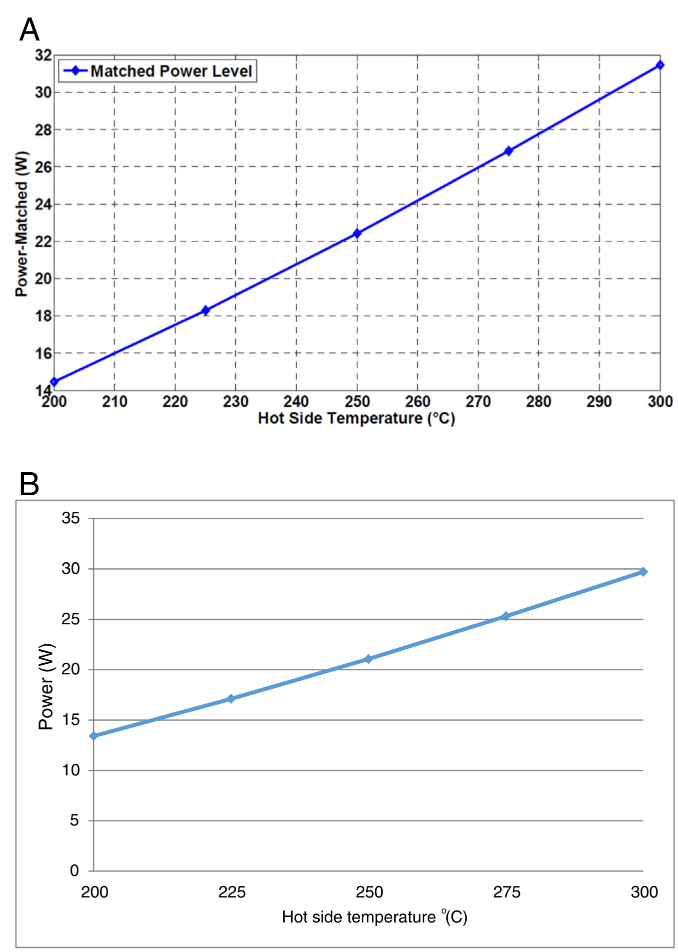


**Fig. 19.** A. Input power to the converter under the matching condition in previous work (P&O method) (Li, 2011). B. Input power to the converter under the matching condition in present work (IC method).

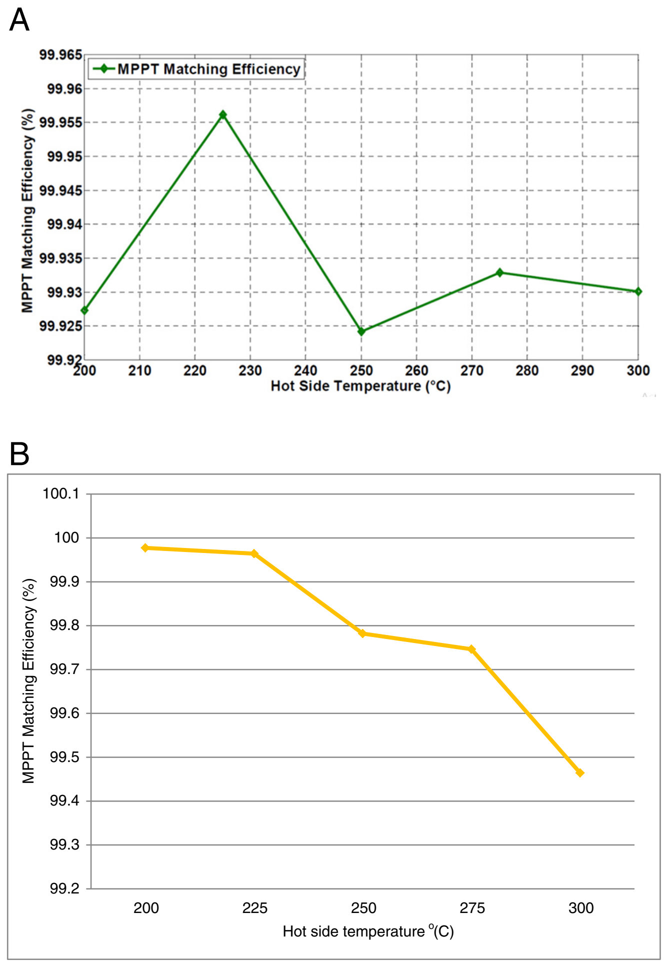


**Fig. 20.** A. MPPT matching efficiency at different hot side temperatures for P&O method (Li, 2011). B. MPPT matching efficiency at different hot side temperatures for IC method.

defined as the ratio of the dc output voltage V to the dc input voltage $V_g$ under steady-state condition i.e.

$$M(D) = \frac{V}{V_g} = \frac{1}{1-D} \tag{19}$$

where D is the duty cycle.

Ideally the conversion ratio of a boost converter increases with the duty cycle, and the ideal converter efficiency of 100% is obtained with M (D) = 1 when D = 0. This is illustrated in Fig. 22a. However, as M (D) tends to infinity, D tends to one. This is because at D = 1 the output voltage of the converter is zero or minimum while the current is maximum. Fig. 22b shows the conversion ratio obtained from the simulation. It is observed that the maximum efficiency is achieved at M (D) = 0.88 when D = 0. However, the conversion ratio M (D) has an increasing trend which is related to the theoretical one.

Fig. 23 shows the output voltages of the converter at different values of D, it can be observed that at D = 0, the highest values of output voltages are obtained and hence the converter efficiencies are computed at these values. The use of direct PWM signal can provide different voltage levels to the load at different duty cycles. This is useful when loads of different voltage levels are to be supplied one at a time.

*Variation of voltage with TEG modules*

A number of scenarios are considered here with the number of TEG modules varied from 1, 5 and 10 in order to investigate how the

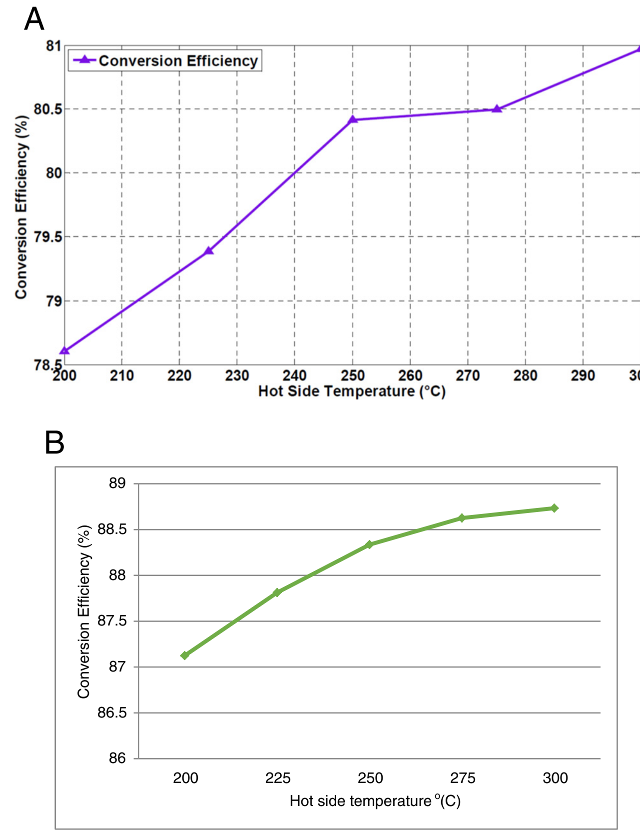


**Fig. 21.** A. Conversion efficiency of the converter at different hot side temperatures for P&O method (Li, 2011). B. MPPT matching efficiency at different hot side temperatures for IC method.

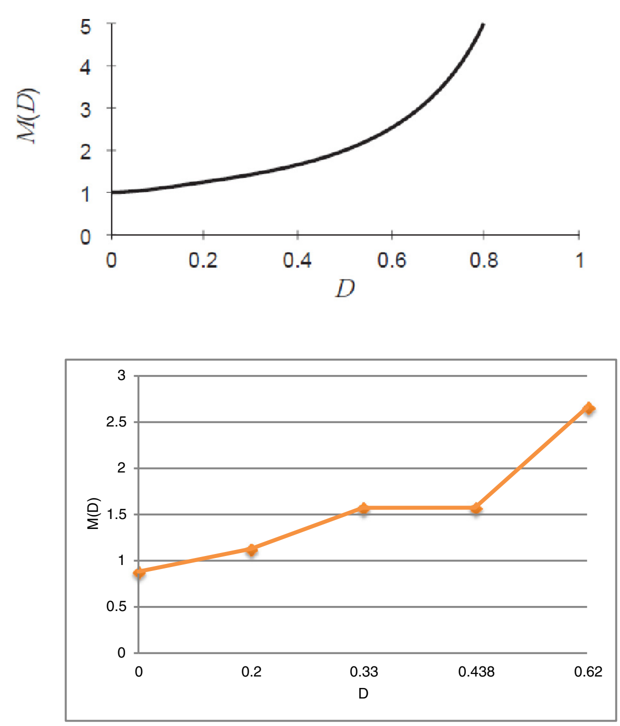


**Fig. 22.** a. Theoretical conversion ratio of boost converter. b. Conversion ratio of a boost converter obtained from the simulation.

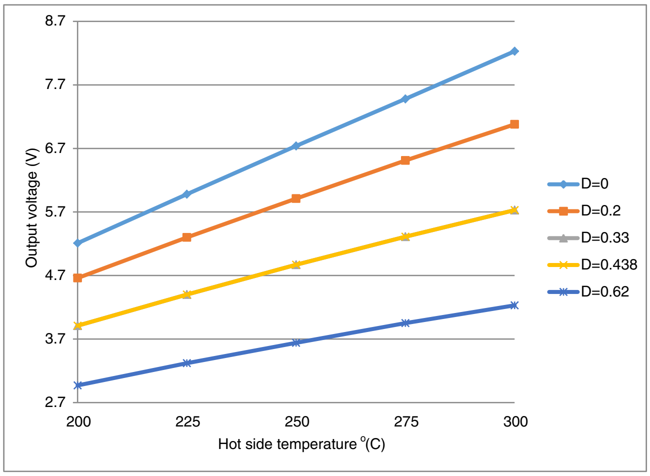


**Fig. 23.** Output voltages of the converter at different values of D.

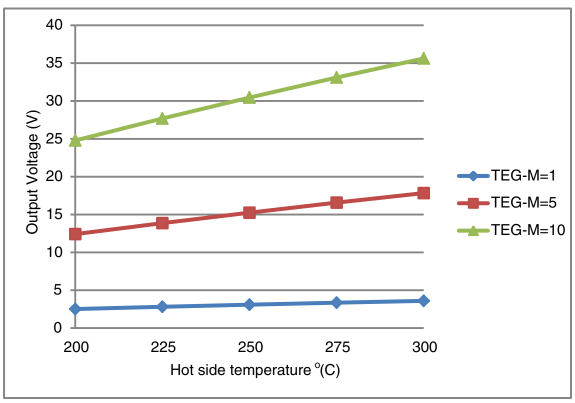


**Fig. 24.** The relationship between the converter input voltage and the hot side temperature.

variation in the number of TEG modules affects the output voltage of the TEG and converter. It can be observed from Fig. 24 that there is a linear relationship between the converter input voltages and the hot side temperature. Similarly, there is a direct relationship between the number of TEG modules and converter input voltage i.e. as the number of TEG modules (TEG-Mn) is increased, the voltage also increases.

## Conclusion

A proper power conditioning circuitry is necessary to stabilize and improve the voltage and power generated from TEG before it is supplied to the load. In this work the performance of a dc-dc converter with MPPT enabled by incremental conductance (IC) method has been done. It has been observed that the IC based MPPT approach is able to track the maximum power point but with relatively lower efficiencies than those of the P&O based MPPT method. The matching efficiencies within a temperature range of 200 °C–300 °C are in the ranges of 99.92%–99.95% for P&O and 99.46%–99.97% for IC method. However IC based method has higher voltage gain and converter efficiency than the P&O based MPPT method. Therefore, the dc-dc converters are able to improve the steady state performance of TEG system as well as boosting the voltage to the desired level, hence improving the overall performance of TEG system. Although both P&O and IC are two classical algorithms that can be implemented to extract maximum power from TEG, the comparative study has established that P&O technique outperforms the IC method.

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