

Analysis of TEG Based Non-galvanic isolated DC-DC Conversion System Employing Maximum Power Point Tracking Methods

S. EDWARD RAJAN¹, T.RAKESH²

¹Professor, ² Assistant Professor(Senior Grade), Department of Electrical and Electronics Engineering,

Mepco Schlenk Engineering College, Sivakasi, 626005, Tamil Nadu, India.

Email: sedward@mepcoeng.ac.in, trakesh@mepcoeng.ac.in

Abstract: In the present scenarios, the electricity generation from waste heat has become a popular in both research and industrial sectors. The waste heat recovering techniques mostly use ThermoElectric Generator (TEG), to convert heat energy into electrical energy. In this paper non-galvanic isolated high step-up DC-DC power converter with switched capacitor cells is proposed for the ThermoElectric power generation systems. The non-galvanic isolated DC-DC conversion system has the advantage of good output regulation and switched capacitor converter has a high voltage gain. Hence, the proposed converter has high voltage gain and excellent voltage regulation. Also, the Maximum Power Point Tracking (MPPT) using Perturb and Observe (P&O) and Incremental Conductance (INC) techniques are used to track the maximum power from the TEG. This paper presents the design and simulation of proposed converter with tracking controller using PSIM.

Keywords: Thermoelectric generator, switched capacitor, heat energy, voltage gain.

I. INTRODUCTION

In recent years, energy harvesting from waste heat has become a popular in both research and industrial world, as conventional power generation from fossil fuels and nuclear plants, are either facing global shortage crisis or simply quite costly. Energy from waste heat is most concerned, due to most of the electric energy generated from turbines are about one third of their energy and the remaining are released as heat energy and also 70% of heat energy released from the fuel by cars are wasted. The wasted heat energy has been harvested by various devices. But TEG has been mostly used in many applications to convert heat energy into electrical energy [1], [2]. The efficiencies of TEGs are low with existing technology. Many researches are going on to extract maximum power effectively from ThermoElectric.

TEGs are devices which generate electrical energy directly from heat energy using a phenomenon called the Seebeck effect. ThermoElectric system does not need maintenance, have high reliability, noiseless and can be used for long time.

The proposed converter is integrated with the low voltage ThermoElectric module for high voltage LED applications. Non-isolated high step-up DC-DC converter is used to regulate the output voltage of the converter and switched capacitor converter is used to obtain high voltage gain. Introducing coupled inductor with voltage multiplier with suitable turn's ratio, high voltage gain can be obtained. But the snubber circuit is needed to absorb the energy stored in the leakage inductor which leads to low efficiency and circuit complication [3] - [5]. In an isolated DC-DC converter, high voltage gain can be obtained by increasing turns ratio. But it leads to large leakage inductor which increases voltage stress of the switch. As a result, the converter efficiency is degraded [6], [7]. Among non-isolated converter, the conventional boost converter is mostly used for voltage step-up. In conventional boost converter higher output voltage can be obtained at an extreme value of duty cycle. As a result, this leads to large conduction loss, switching loss and low efficiency [8], [9].

Cascading of many boost converters, the higher voltage gain can be easily obtained. Increase in components leading to low efficiency and high cost [10]. The active clamp method is used in [11], [12] to suppress voltage spikes of the switch and reproduce the energy stored in the leakage inductor to the load which improves the efficiency of the converter. However the input current of the converter is pulsating and resonance between the leakage inductor and parasitic capacitor of the output diode is severe. The output regulation of non-isolated high step-up converter is good, but high voltage gain cannot be achieved for high efficiency. By using SC converter high voltage gain can be achieved, but output voltage cannot be regulated. The proposed system is obtained by introducing multiple capacitors into non-galvanic isolated converter. It has the advantage of both non-isolated high step-up DC-DC converter and switched capacitor converter. The maximum power is extracted from TEG using MPPT techniques. In this paper, the proposed system is analyzed and implemented with P&O and INC maximum power tracking techniques.

II. PROPOSED SYSTEM

The proposed TEG system has been shown in Fig.1.

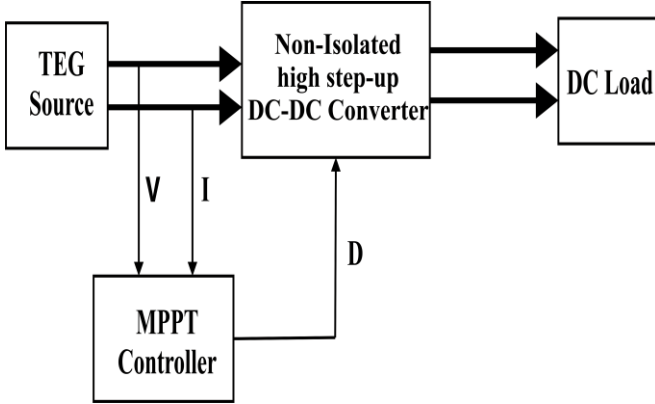


Fig. 1. Block diagram of the proposed system.

The voltage generates in ThermoElectric source depends on the temperature difference across the ThermoElectric module. TEG is a low voltage, high current device. To meet the load requirement, the low voltage is boosted up by the proposed system. The maximum power from TEG is obtained by applying the measured voltage and current into the MPPT controller. It generates a duty cycle, which controls the proposed system to obtain maximum power. The specification for the ThermoElectric module (TEHP1-24156-1.2) is shown in TABLE I.

TABLE I
SPECIFICATION OF THE MODULE (TEHP1-24156-1.2)

Parameter	Value
Hot Side Temperature T_h	300 °C
Cold Side Temperature T_c	30 °C
Open Circuit Voltage	14.4 V
Matched Load Resistance	2.4 Ω
Matched load output power	21.6 W
Heat flow across the module	≈ 415 W

A. Operating Principle

The operating principle mainly depends on charging and discharging of inductor and switched capacitor. The working of

this proposed converter is same as in interleaved version can be seen in [3], it involves when switch S is ON, the inductor charges and capacitors are connected in series to supply the load and when switch is OFF, inductor releases energy to charge the capacitors which are connected in parallel. The circuit diagram of proposed converter is shown in Fig. 2.

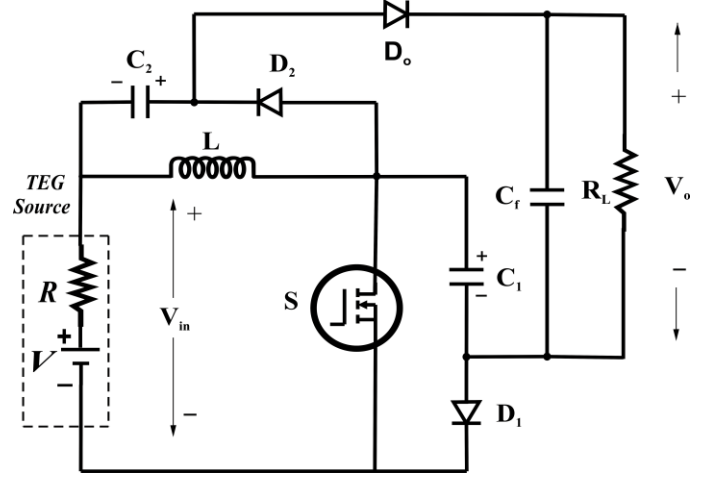


Fig. 2. Proposed DC-DC converter circuit.

B. Modes of Operation

During switch S is ON, the inductor L starts charging and switched capacitors C_1 , C_2 and voltage source are in series to supply the load is shown in Fig. 2a.

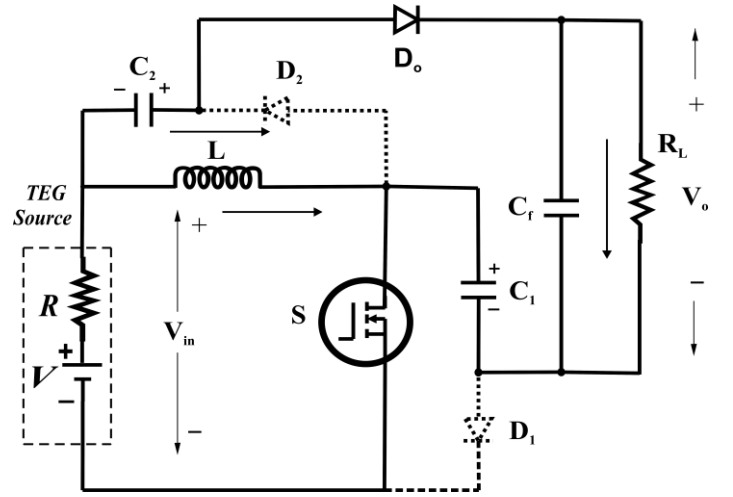


Fig. 2a. Switch (S) is ON.

During switch S is OFF, the inductor L starts discharging and discharging energy from the inductor L charges the SCs C_1

and C_2 , which is connected in parallel. The load is powered by filter capacitor C_f is shown in Fig. 2b.

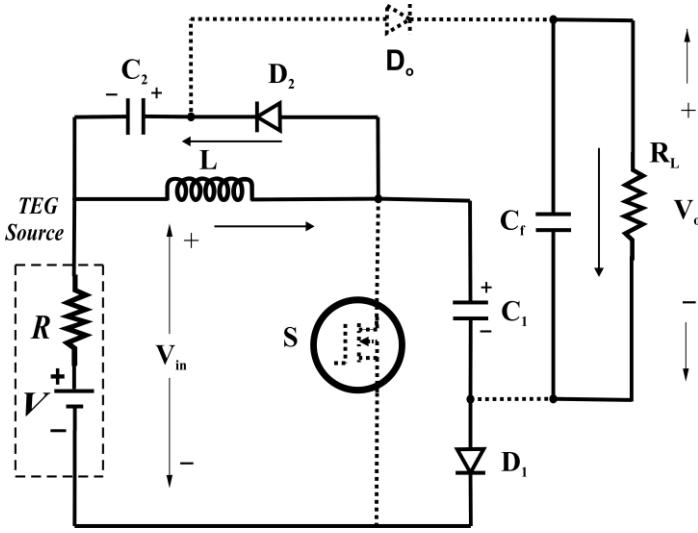


Fig. 2b. Switch (S) is OFF.

III. ANALYSIS OF PROPOSED CONVERTER

A. Voltage Gain Expression of Proposed Converter

The converter voltage gain V_g can be calculated during the switch S conduct as shown in Fig. 2a can be expressed as

$$V_g = \frac{2}{1-D} \quad (1)$$

In general, the voltage gain can be expressed as

$$V_g = \frac{V_o}{V_{in}} \quad (2)$$

Sub. (1) in (2), the output voltage V_o can be expressed as

$$V_o = \frac{2V_{in}}{1-D} \quad (3)$$

where,

V_{in} - is the input voltage in V
 D - is the duty cycle

B. Design of Inductor L

The inductor L is designed to limit the maximum ripple current to 20% of maximum average inductor current.

When $P_o = 17.87$ W and $V_{in} = 8.74$ V, the average maximum inductor $I_{L-max} = 2.4$ A. Then the ripple current $\Delta i_L = 0.4$ A.

The ripple current of the inductor can be expressed as

$$\Delta i_L = \frac{V_{in}DT}{L} \quad (4)$$

Sub. (3) in (4), it becomes

$$\Delta i_L = \frac{V_o(1-D)DT}{2L} \quad (5)$$

where,

I_o - is the output current in A
 Δi_L - is the ripple current in A
 T - is the Time in μs

C. Switched Capacitors C_1 and C_2

Here SC delivers voltage to the load. So it is considered as a voltage source. There exists small ripple voltage at switching frequency on the capacitor because SCs are regarded as a voltage source. When switch S is on the sum of the voltages of C_1 , C_2 and the input voltage is larger than the output voltage. The ripple voltage of capacitor C_1 and C_2 is given by

$$\Delta V_{c1} = \frac{I_o T}{C_1} \quad (6)$$

$$\Delta V_{c2} = \frac{I_o T}{C_2} \quad (7)$$

where,

ΔV_{c1} & ΔV_{c2} - is the ripple voltage of switched capacitor C_1 and C_2 in μF

D. Filter Capacitor C_f

The ripple voltage of filter capacitor is limited to 1% of output voltage, hence the capacitance C_f can be expressed as

$$C_f = \frac{P_o}{2\Pi f_{line} \Delta V_o V_o} \quad (8)$$

where,

P_o - is the output power of the converter in W
 f_{line} - is the line frequency in Hz

The values calculated from the analysis of the proposed converter are tabulated in Table II.

TABLE II

SPECIFICATIONS FOR THE PROPOSED CONVERTER

Components	Values	$R_{\text{dson}}/ \text{ESR } (\Omega)$
Capacitor ($C_1 = C_2$)	82 μF	-
Inductor L	180 μH	0.05
Filter Capacitor (C_f)	220 μF	0.3
Switching frequency (f_s)	100 KHz	-
Switch (S)	-	0.23
Load resistance (R_L)	1444 Ω	-

IV. SIMULATION CIRCUIT AND SIMULATED RESULTS OF PROPOSED CONVERTER

The proposed converter with thermoelectric power generation system has been simulated and analyzed using PSIM software package. The simulation circuit and simulated waveforms are shown in Fig. 3. and Fig. 4.

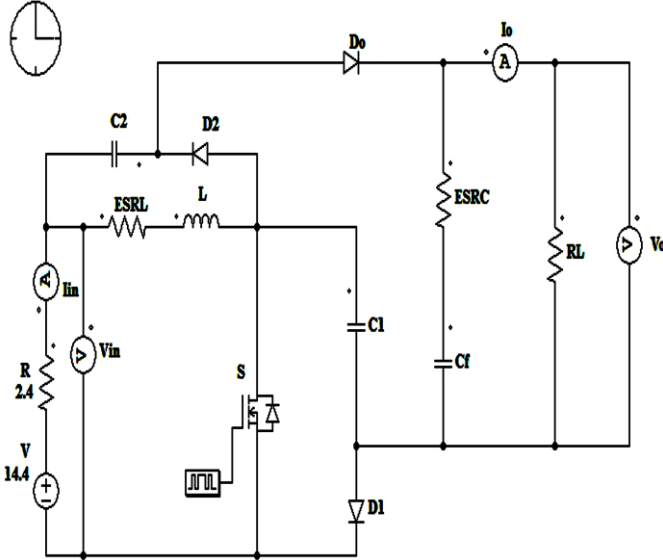
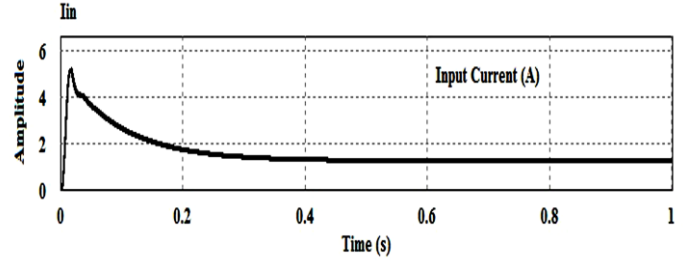


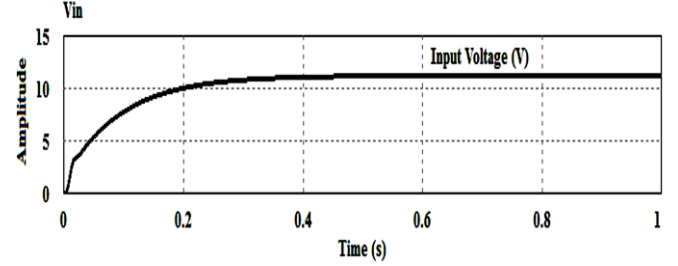
Fig. 3. PSIM-Simulation circuit of proposed converter.

From the simulation results, it has been observed that the converter produces the output voltage of 139.61V, output

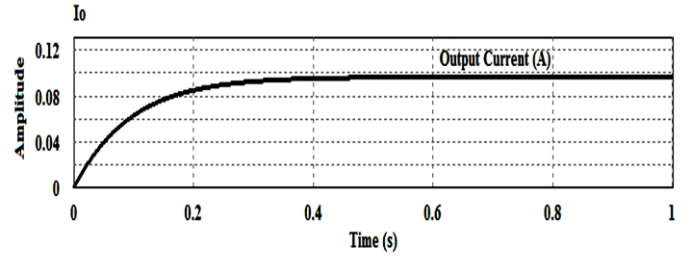
current of 0.096A and efficiency of 87.51% at a duty cycle of 0.85 for the load resistance of 1.444 k Ω .



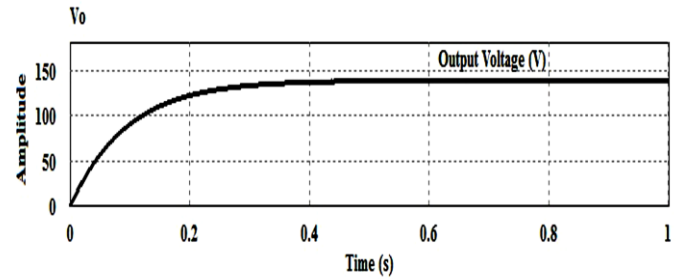
a) Waveform of input current (A).



b) Waveform of input voltage (V).



c) Waveform of output current (A).



d) Waveform of output voltage (V).

Fig. 4. Simulated results of proposed converter.

A. Duty Cycle (D) vs. Voltage Gain (V_g)

The change in voltage gain V_g with respect to duty cycle (D) for temperature difference (ΔT) of 270 $^{\circ}\text{C}$ is shown in Fig.5.

From Fig. 5. it shows that the voltage gain increases as the duty cycle, increase till it reaches maximum duty cycle of 0.95.

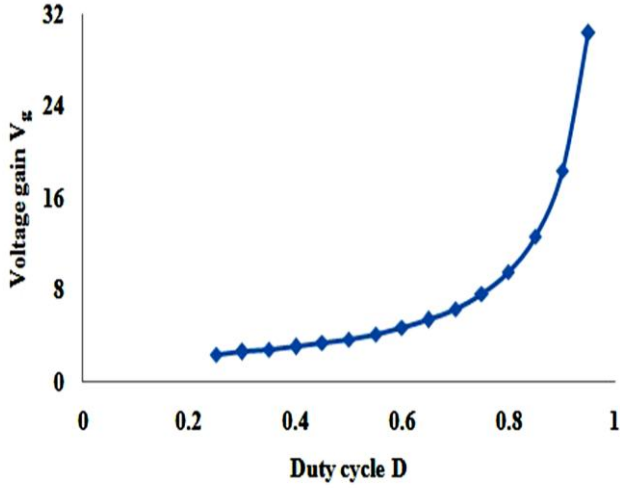


Fig. 5. Duty cycle D vs. voltage gain V_g .

B. Duty cycle (D) vs. Output power (P_o)

The change in output power with respect to duty cycle for temperature difference (ΔT) of 270°C is shown in Fig. 6. The proposed converter attains maximum power of 17.87 W at a duty cycle of 0.90.

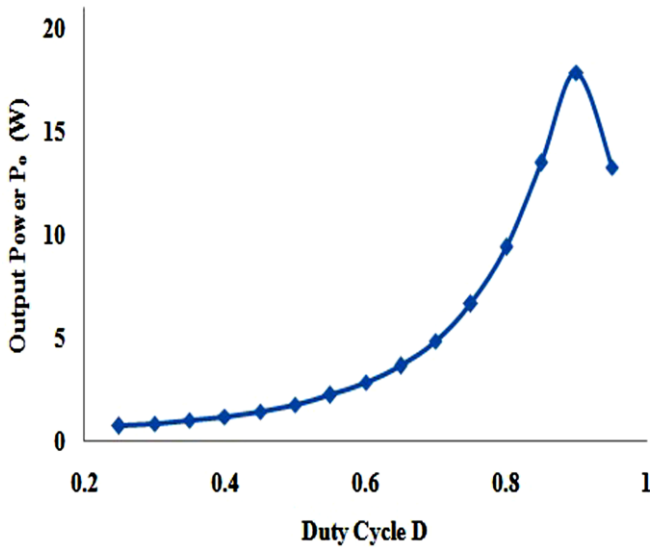


Fig. 6. Duty cycle vs. output power P_o (W).

C. Duty Cycle (D) vs. Efficiency (η)

The change in efficiency with respect to duty cycle for temperature difference (ΔT) of 270°C is shown in Fig. 7. The efficiency increases as the duty cycle increases till at a particular duty cycle. The proposed converter reached maximum efficiency of 87.51% at a duty cycle of 0.85. Afterwards it starts to decrease because of conduction loss in switch S is shown in Fig. 7.

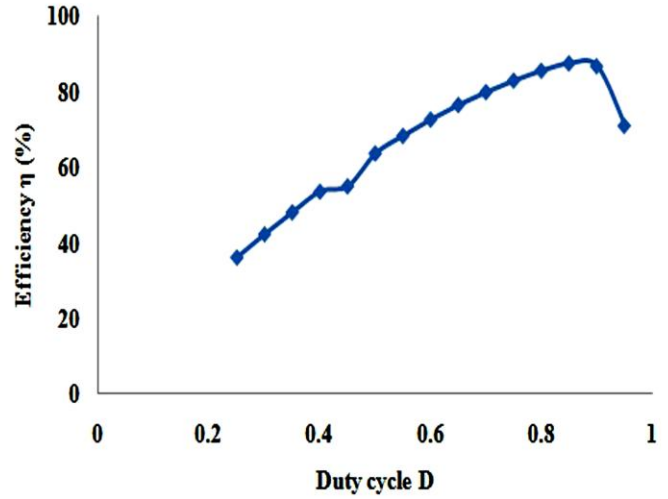


Fig. 7. Duty cycle D vs. efficiency η (%).

D. Output power (P_o) vs. Efficiency (η)

The change in efficiency with respect to output power for temperature difference (ΔT) of 270°C is shown in Fig. 8. The change in efficiency of the proposed converter depends on the output power of the converter. When the output power is 13.49 W the proposed non-isolated high step-up DC-DC converter attains a maximum efficiency of 87.51% for ΔT of 270°C .

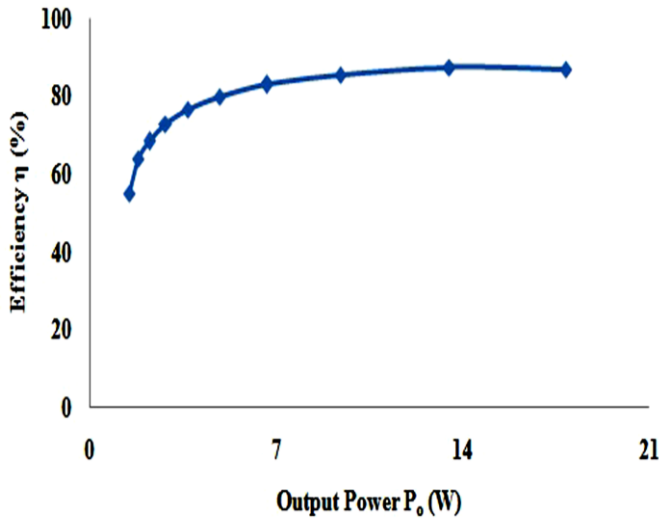


Fig. 8. Output power P_o (W) vs. efficiency η (%).

V. MAXIMUM POWER POINT TRACKING

Maximum power tracking technique is introduced into the ThermoElectric field over the last few years. The output power of a ThermoElectric module change with change in temperature. The efficiency of ThermoElectric module is low, hence it is desirable to operate at the Maximum Power Point (MPP). Maximization of power improves the utilization of the ThermoElectric module. A maximum power controller is connected at the output of ThermoElectric is used for extracting the maximum power from the ThermoElectric module and transferring that power to the load.

Over the past few years, many maximum power tracking techniques have been developed. The most common techniques are P&O, INC and constant voltage/constant current [13] - [15]. This paper presents P&O and INC technique for proposed system.

A. P&O Technique

P&O is the simplest and most commonly used technique. In this technique the voltage of the ThermoElectric module is perturbed. If the power drawn from the ThermoElectric module increases, further adjustments made in that direction until there is no increase of power. The direction of perturbation must be reversed to attain maximum power, if the power drawn from the ThermoElectric module decreases. The simulation circuit and simulated results for proposed converter with P&O technique is shown in Fig. 9 and Fig. 10.

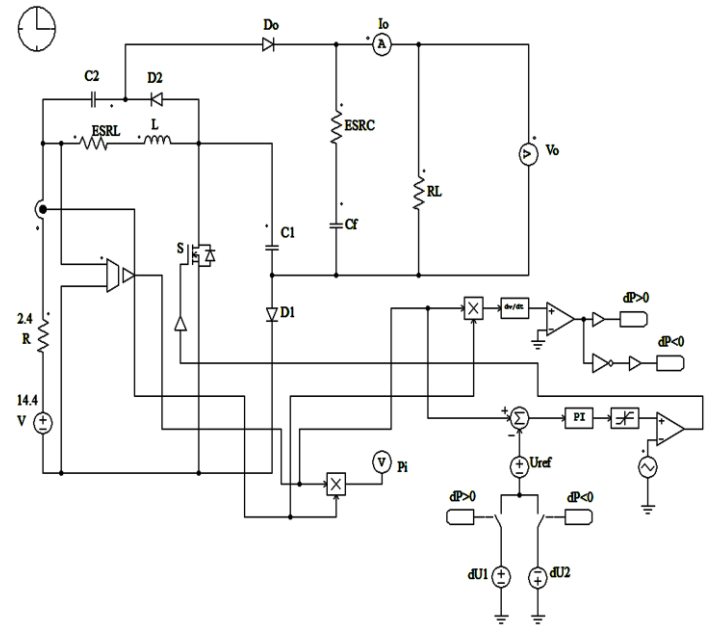
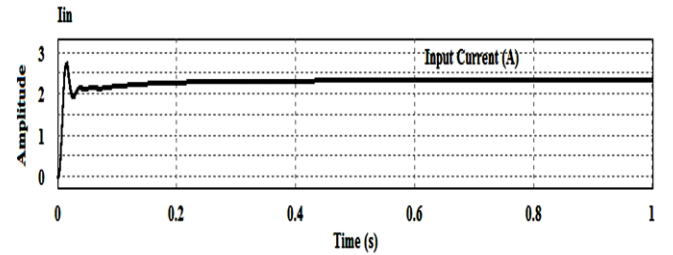
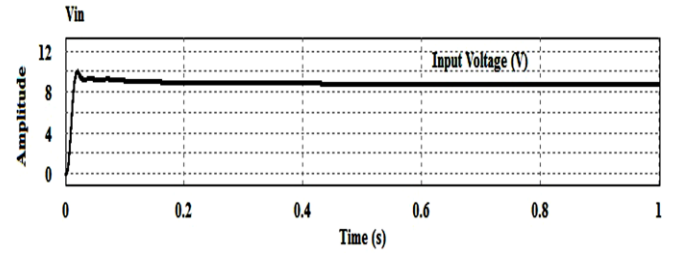


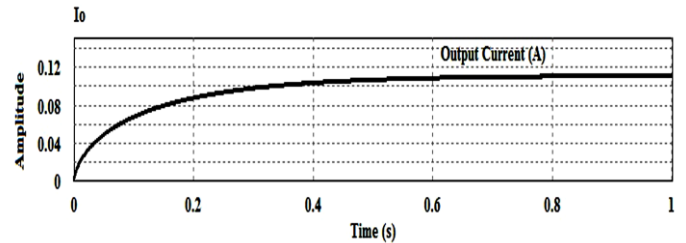
Fig. 9. Simulation circuit of P&O technique.



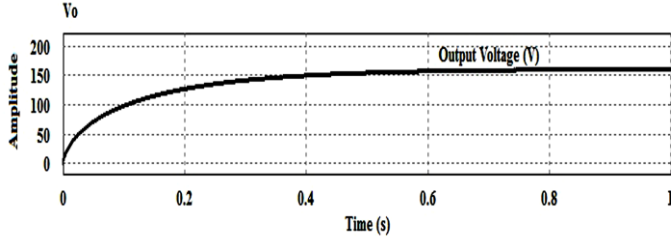
a) Waveform of input current (A).



b) Waveform of input voltage (V).



c) Waveform of output current (A).



d) Waveform of output voltage (V).
Fig. 10. Simulated results for INC technique.

From the simulation results, it has been observed that the converter along with P&O technique tracked the maximum power of 20.87 W and produces the output voltage of 160.79 V at a duty cycle of 0.87.

B. INC Technique

INC technique is the most common technique used for tracking maximum power of the ThermoElectric module. It uses the conductance (I/V) and incremental conductance (dI/dV) for deciding whether Maximum Power Point is found or not. The controller measures incremental changes in ThermoElectric module current and voltage to predict the effect of change in voltage. If the conductance is equal to incremental conductance then MMP is reached. By using power equation incremental conductance can be obtained as follows

$$P = IV \quad (9)$$

Applying chain rule the (9) becomes

$$\frac{dP}{dV} = \frac{d(VI)}{dV} \quad (10)$$

$$\frac{dP}{dV} = I + V \frac{dI}{dV} \quad (11)$$

At MPP $dP/dV = 0$. With the above (10), the following set of rules is found

$$\frac{dI}{dV} = -\frac{I}{V} \text{ at MPP – no change in Duty cycle} \quad (12)$$

$$\frac{dI}{dV} > -\frac{I}{V} \text{ left of MPP – increment in Duty cycle} \quad (13)$$

$$\frac{dI}{dV} < -\frac{I}{V} \text{ right of MPP – decrement in Duty cycle} \quad (14)$$

The controller regulates the duty cycle of the proposed converter until the condition $dI/dV = -I/V$ is achieved. The

simulation circuit and simulated results for proposed converter with INC technique is shown in Fig. 11 and Fig. 12.

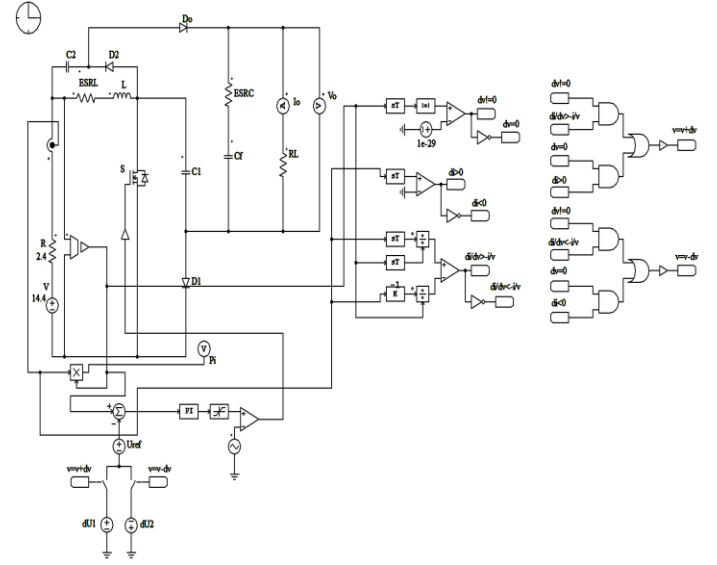
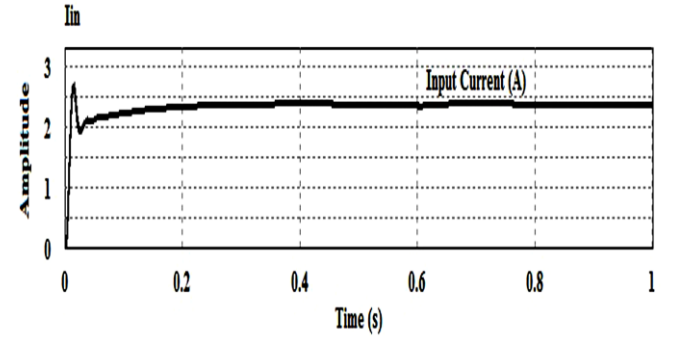
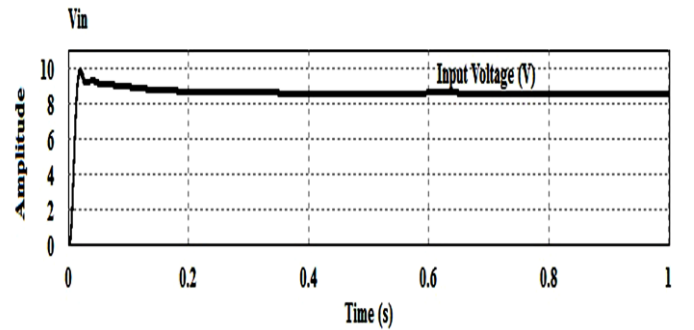


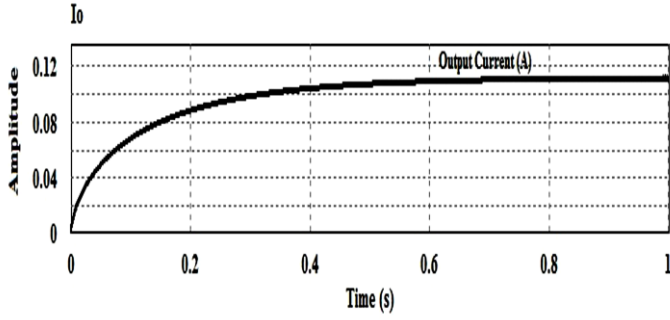
Fig. 11. Simulation circuit of INC technique.



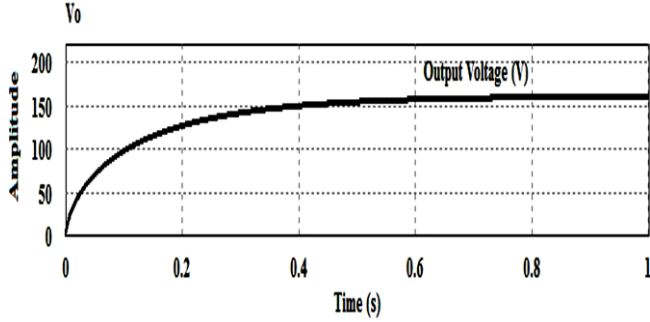
a) Waveform of input current (A).



b) Waveform of input voltage (V).



c) Waveform of output current (A).



d) Waveform of output voltage (V).

Fig. 12. Simulation results of INC technique.

The simulation results show that the maximum power tracked from the ThermoElectric module is 21.06 W by the INC technique which is greater than the maximum power tracked by the P&O technique for the same value of duty cycle. The comparison between P&O and INC techniques is shown in TABLE III.

TABLE III
COMPARISON OF PERFORMANCE OF TRACKING TECHNIQUES

Tracking Techniques	D	V_{in} (V)	I_{in} (A)	P_i (W)
P&O	0.87	8.522	2.449	20.87
INC		8.332	2.528	21.06

V. CONCLUSION

This paper has presented the non-isolated high step-up DC-DC converter with switched capacitor cells for ThermoElectric power generation systems. The proposed converter has produced a high voltage gain without the uses of transformer, coupled inductor and snubber circuit. Also, the proposed converter with TEG has achieved an efficiency of 87.51%. Moreover, on analyzing the proposed converter with P&O and INC technique, it has proved that the INC technique tracks a maximum power of

21.06 W which is greater than the P&O technique at the same duty cycle of 0.87.

References

- [1] J. A. B. Vieira and A. M. Mota., "Thermoelectric generator using water gas heater energy for battery charging", in *Proc. IEEE Int. Conf. Control Appl.*, pp. 1477–1482, July 2009.
- [2] T. Kyono, R. Suzuki, and K. Ono. "Conversion of unused heat energy to electricity by means of thermoelectric generation in condenser". *IEEE Trans. Energy Convers.* Vol. 18, no. 2, pp. 330–334, Jun. 2003.
- [3] K. Tseng and C. Huang, "High step-up high-efficiency interleaved converter with voltage multiplier module for renewable energy system," *IEEE Trans. Ind. Electron.*, vol. 61, no. 3, pp. 1311–1319, Mar. 2014.
- [4] C. Young, M. Chen, T. Chang, C. Ko, and K. Jen, "Cascade Cockcroft–Walton voltage multiplier applied to transformerless high stepup dc–dc converter," *IEEE Trans. Ind. Electron.*, vol. 60, no. 2, pp. 523–537, Feb. 2013.
- [5] S. Chen, T. Liang, L. Yang, and J. Chen, "A boost converter with capacitor multiplier and coupled inductor for ac module applications," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1503–1511, Apr. 2013.
- [6] W. Li and X. He, "Review of non-isolated high-step-up dc/dc converters in photovoltaic grid-connected applications," *IEEE Trans. Ind. Electron.*, vol. 58, no. 4, pp. 1239–1250, Apr. 2011.
- [7] D. Meneses, F. Blaabjerg, O. Garcia, and J. A. Cobos, "Review and comparison of step-up transformerless topologies for photovoltaic AC—Module application," *IEEE Trans. Power Electron.*, vol. 28, no. 6, pp. 2649–2663, Jun. 2013.
- [8] M. Prudente, L. L. Pfitscher, G. Emmendoerfer, E. F. Romaneli, and R. Gules, "Voltage multiplier cells applied to non-isolated dc–dc converters," *IEEE Trans. Power Electron.*, vol. 23, no. 2, pp. 871–887, Mar. 2008.
- [9] Y. Hsieh, J. Chen, T. Liang, and L. Yang, "Novel high step-up dc–dc converter for distributed generation system," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1473–1482, Apr. 2013.
- [10] K. Park, G. Moon, and M. Youn, "Nonisolated high step-up stacked converter based on boost-integrated isolated converter," *IEEE Trans. Power Electron.*, vol. 26, no. 2, pp. 577–587, Feb. 2011.

- [11] T. Wu, Y. Lai, J. Hung, and Y. Chen, "An improved boost converter with coupled inductors and buck-boost type of active clamp," in Conf. Rec. *IEEE IAS Annu. Meeting*, vol. 1, pp. 639–644, 2005.
- [12] Q. Zhao and F. C. Lee, "High-efficiency, high step-up dc-dc converters," *IEEE Trans. Power Electron.*, vol. 18, no. 1, pp. 65–73, Jan. 2003.
- [13] J. Kim and C. Kim, "DC-DC Boost converter with variation-Tolerant MPPT Technique and Efficient ZCS Circuit for Thermoelectric Energy Harvesting Applications" *IEEE Trans. on Power electron.*, vol. 28, no. 8, Aug. 2013.
- [14] A. Montecucco and A. R. Knox, "Maximum power point tracking converter based on the open-circuit voltage method for thermoelectric generators" *IEEE Trans on power electron.*, vol. 30, no. 2, Feb. 2015.
- [15] D. Sera, T. Kerekes, S. V. Spataru and R. Teodorescu, "On the perturb-and-observe and incremental conductance MPPT methods for PV systems," *IEEE journal of Photovoltaics*, vol. 3, no. 3, Jul. 2013.