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PAPERS

Design of a battery charging system fed by thermoelectric generator panels using MPPT techniques

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Thermal energy is a renewable energy source to generate electrical energy that is not fully developed. One device that converts thermal energy into electrical power is a thermoelectric generator (TEG). TEGs are available as modules of various sizes and voltage levels. This paper is about the design of a battery charging system powered by a TEG panel. The TEG panel is implemented using 150 TEG modules interconnected in series and parallel. Its power is transferred to a battery using two stages of DC/DC converters. The 1st stage is a Lou converter that is used for maximum power point tracking (MPPT) by a referenced perturb and observe (referenced P&O) algorithm. The 2nd stage is a bidirectional converter based on buck-boost modes of operation. The system is used to charge a 9 V 1.2 Ah battery. The proposed MPPT algorithm's performance is compared with a traditional P&O algorithm. The TEG panel provided 27.5 W at a ΔT of 30 ^{0}C. The designed system is simulated in MATLAB SIMULINK.

Keywords: Battery, charging, thermoelectric generator, P&O, Referenced P&O, TEG panel

1 Introduction

In the last few decades, the necessity for renewable energy sources (RES) has increased due to several important factors and challenges that the whole world faces [1]. There are some key reasons why renewable energy demand is increasingly, such as climate change mitigation, energy security and independence, technological advancements, and cost reduction, among others. Thus, there is a need to convert other forms of energy, such as heat, into electricity [2] using technologies that include thermoelectric generators. A TEG panel is designed to generate electrical power by utilizing a temperature gradient between its hot and cold sides [3]. By exposing the hot side to a heat source and the cold side to a relatively cooler environment, such as air or water, a TEG panel can convert the temperature difference into usable electrical energy. Battery charging using a TEG panel is an innovative approach that harnesses the temperature difference between the ambient environment and a TEG panel to generate electricity. TEGs are solid-state devices that can that can directly convert heat into electricity through the Seebeck effect [4-5]. By utilizing this effect, TEG panels provide an alternative solution for powering electric devices and systems in off-grid or remote locations. This offers self-sufficiency and reduced reliance on traditional energy sources. Application of TEG panels in battery charging is particularly beneficial in scenarios where traditional charging methods are impractical or unavailable. One significant advantage of using a TEG panel for battery charging is its ability to operate autonomously without relying on external power sources [6-7]. This makes it a suitable option for portable and remote applications where traditional power grids are inaccessible. Generally, the power supplied from a TEG panel is in DC form. Thus, there is a need to use good DC/DC converters for suitable power conditioning. With DC/DC converters, its required to use maximum power point tracking (MPPT) methods to extract and supply the required voltage for battery charging. Many researchers have employed different types of TEG modules and even TEG panels to create innovative thermoelectric generator designs. P. Kuchroo et al. [8] designed an energy collecting system employing TEGs integrated with solar panels. The TEGs are mounted on the back side of the PV panel. Both TEG and solar panels are connected in series to enhance the overall efficiency of this integration. S. N. M. Tawil and M. Z. Zainal [9] connected TEG and PV panels to a DC/DC step-up converter. A selector switch is used to manage the two sources of energy when the voltage exceeds 3 V. Their design is made for environments such as military operations that require sustainable energy resources. The work presented by A.E. Risseh *et al.* [10] designed a power converter for heavy-duty vehicle (HDV) waste heat using TEGs. Their design involves eight synchronous interleaved step-down converters. The

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utilized MPPT algorithm is called perturb and observe (P&O). D.C. Stand [11] compared the TEG potential applied under direct solar arrays with PV solar panels. Optimal heat harvesting lies in maintaining a temperature difference between the TEG sides that is minimally 26.31 K. The power unit is developed complementing the TEG energy harvesting with a Li-Po battery to assure continuous operation. Z.M. Dalala *et al.* [12] presented an interface of a boost DC/DC converter with TEGs for battery charging applications. There are double control loops for the current and voltage using DC/DC converters that have been analyzed to ensure source and load. Voltage stabilization, a power matching mode and an MPPT mode are integrated with the battery charger control algorithm. The work presented by S. Gomathi *et al.* is based on battery charging *via* a TEG panel [13]. Temperature is regulated on this panel by utilizing a Fresnel lens where the entire system is linked using a charge controller. The generated power increases with the temperature difference between the two TEG panel sides. This system has been implemented experimentally. The voltage obtained from the TEG panel is 2.18 V which was increased to 12 V through utilization of a DC/DC boost converter. H. Abedi *et al.* [14] exploited heat generated by catalytic combustion where a TEG is mounted to obtain electrical energy. It was found that the TEG efficiency is 3.4% at an electrical power of 5.3 W. System performance is tested experimentally for different rates of fuel flow. The goal for the designed circuit is to match the energy of a Type AA battery. B.R. Putri *et al.* [15] designed a SEPIC converter powered by PV solar panels for battery charging. Input power is controlled and maximized using a PI controller. The parameters of the PI controller are identified by employing the Cohen Coon method. There are 60 TEGs connected in series and attached under PV solar panels in the work of E. Zein *et al.* [16]. Heat dissipated by the solar panel is transferred to the TEG panel hot side. Concurrently, the TEG cold side is exposed to flowing water. Generated power is stored in a 3 V battery. The purpose of the current paper is to design a battery charging system supplied by a TEG panel. The design involves a combination of two DC/DC converters, one for the MPPT process and the other for the charging process. This paper has been arranged as follows. An introduction is first presented, followed by TEG panel and system description, MPPT methods, results and discussion, and finally conclusions.

2 TEG panel

The TEG is a device that converts thermal energy into electrical energy directly through the Seebeck effect. This effect occurs when a temperature difference between two semiconductor materials generates a voltage difference. Typically, TEGs are constructed of an array of thermoelectric modules, also known as thermoelectric couples. They are made up of two different types of materials with different thermoelectric properties, typically p-type and n-type semiconductors. Normally, ceramic/bismuth telluride materials are employed [17]. When a temperature gradient is applied across the thermoelectric module, the temperature difference generates an electrical potential and a current flow in the circuit, producing electrical power. A suitable change in temperature difference ($\Delta T = T_h - T_c$) enables electron flow from the n-type to p-type semiconductors. The generated voltage is [18]

$$V_{\mathrm{oc}} = \alpha \Delta T \tag{1}$$

where V_{oc} represents the open circuit voltage between TEG terminals, α represents the Seebeck coefficient in (V/K). As shown in Fig. 1, to make a model of TEG module in MATLAB SIMULINK, the equivalent circuit of a TEG consists of a voltage source at a specified ΔT, an internal resistance (R_{int}) and Seebeck coefficient that is linked in series [19]. *R* load is linked at the terminals of the TEG module. The TEG voltage is given in (2), where the internal resistance was assumed to be about 1.8 Ω in all calculations and results used in this research [17,19].

$$V_{\mathrm{TEG}} = \alpha \, \Delta T - R_{\mathrm{int}} I \tag{2}$$

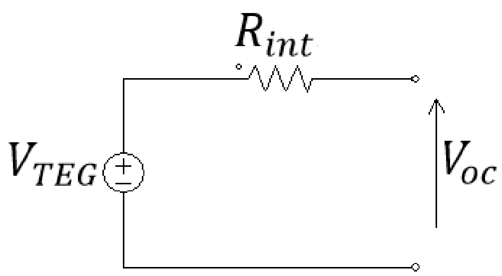

Fig. 1. Equivalent circuit of a TEG module

In Eqn (2), *I* is the current passing from the TEG module to the load. The maximum power obtained by the TEG module occurs at a condition where R_{int} of the TEG module has the same value as *R*. The TEG voltage at this condition is

$$V_{\mathrm{TEG(MPP)}} = \frac{V_{oc}}{2} \tag{3}$$

The TEG module maximum efficiency can be expressed as (4).

$$TEG\ \eta_{max} = \frac{T_h - T_c}{T_h} \frac{\sqrt{1+Z\overline{T}}-1}{\sqrt{1+Z\overline{T}}+\frac{T_c}{T_h}} \tag{4}$$

where $Z\overline{T}$ is known as the figure of merit [20]. A TEG panel is built by multiple TEG modules that are interconnected in parallel and series until achieving the required panel size and power level at different temperature values. The proposed TEG panel is constructed from 10 TEG modules connected in series representing one line. There are 15 lines connected in parallel. Thus, the total number of TEGs in the proposed panel is 150 [21].

3 System description

The system contains a TEG panel connected with DC/DC converter, which is known as a Lou converter. Another DC/DC converter for battery charging is called a bidirectional DC/DC converter. A battery is also required.

3.1 Luo converter

The elementary circuit of a super voltage lift DC/DC converter is also known as Luo converter. It was first introduced more than two decades ago [22]. Figure 2 shows a single stage elementary circuit of a Luo DC/DC converter.

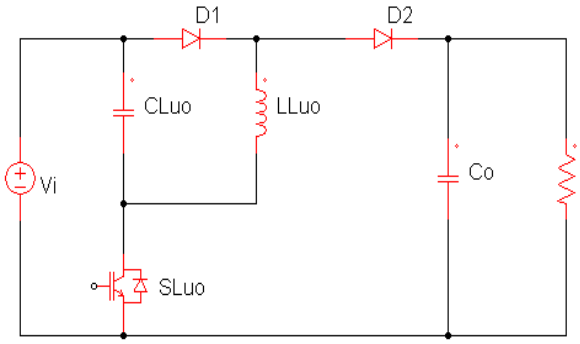

Fig. 2. DC/DC Luo converter elementary circuit

The capacitor voltage V_{CLuo} is charged by V_i. The inductor current i_{LLuo} flows and increases with V_i during charging duration DT and decreases with voltage $(V_R - 2V_i)$ during the switching period $(1-D)T$, where [23]

$$\Delta i_{LLuo} = \frac{V_i}{LLuo} DT = \frac{V_R - 2V_i}{LLuo}(1-D)T, \quad (5)$$

$$D = \frac{T_{on}}{T}, \quad (6)$$

$$V_R = \frac{2-D}{1-D} V_i. \quad (7)$$

D represents the duty cycle and T is the total switching time for S_{Luo}. Thus, the voltage gain of the Luo converter is $\frac{2-D}{1-D}$ of the converter input voltage, which means the converter output voltage is larger than its input voltage.

3.2 Bidirectional DC/DC converter

A non-isolated bidirectional DC/DC converter is depicted in Fig. 3. The converter is equipped with charging and discharging control schemes. Normally, it works in a buck and boost mode of operation. In boost mode, Switch S1 is turned ON and Switch S2 is turned OFF. The output voltage is higher than the input voltage resulting in battery charging. In the case of a buck mode, S1 is OFF and S2 is ON. The output voltage is less than input voltage resulting in battery discharge. A freewheeling diode helps to complete the circuit when using the boost or buck modes. In boost mode, the output voltage is expressed as [24-25]

$$V_{battery} = \frac{1}{(1-D)} V_s \quad (8)$$

In the buck mode, the output voltage is expressed by

$$V_{battery} = D\, V_s \quad (9)$$

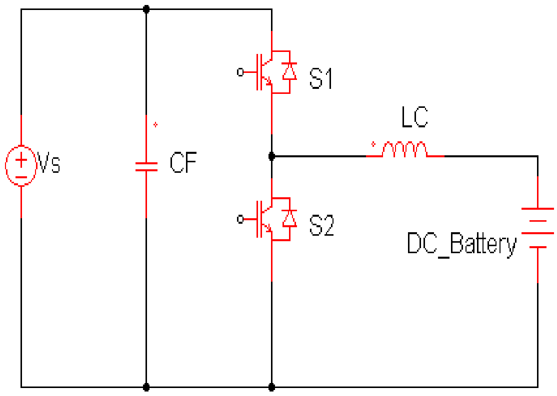

Fig. 3. Battery charging bidirectional DC/DC converter

3.3 Whole battery charging system

The whole system circuit is shown in Fig. 4. The source is represented by the TEG panel, which is constructed using 150 TEGs interconnected in series and parallel. The Luo converter is responsible for obtaining the maximum power point (MPP) of the TEG panel. The DC/DC bidirectional converter is responsible for regulating the charging voltage to the battery. MPPT control is done by tracking voltage and current measurements from the TEG panel. These measurements are used as variables in the selected MPPT algorithm to perform maximum power point tracking. Thus, the Luo converter feeds the bidirectional DC/DC converter by voltage at the maximum power point for different operating conditions, such as change in ΔT in the TEG panel. The battery charging voltage is regulated using PI controllers. Battery voltages and currents are measured. The measured battery voltage is compared with a set point and then used in a PI controller to obtain a battery reference current. This current is compared with the actual battery measured current and fed to another PI controller with a pulse width modulation (PWM) technique to achieve the required pulses to each of the S1 and S2 switches, with S1 ON and S2 OFF or *vice versa*.

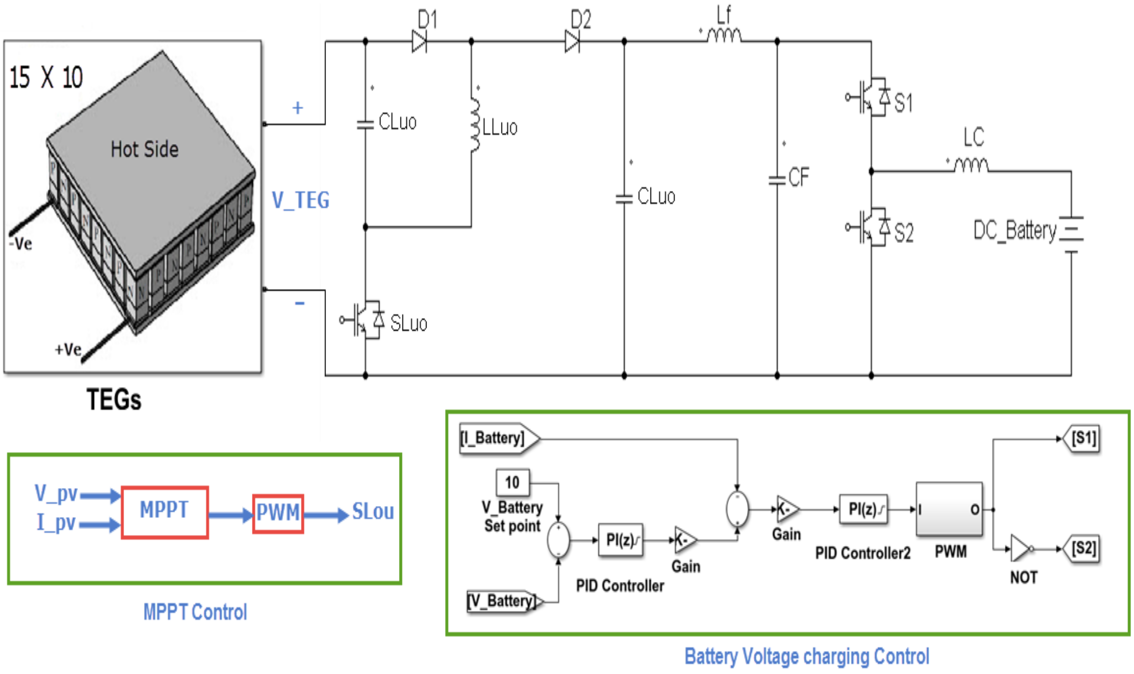

Fig. 4. Proposed system for battery charging using a TEG panel

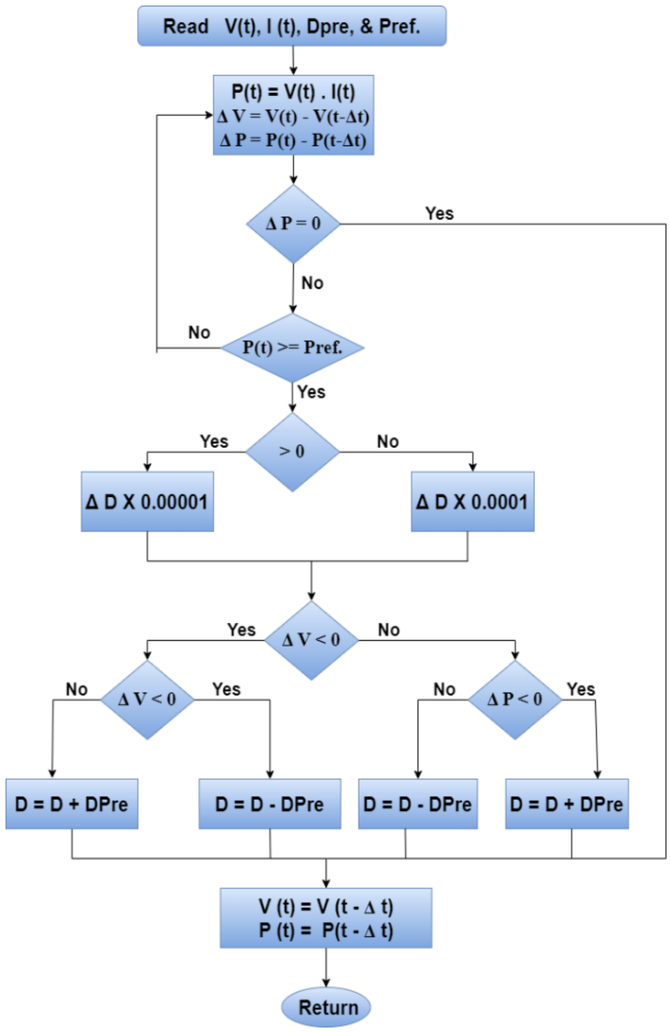

Fig. 5. Flowchart of the referenced P&O algorithm

4 MPPT methods

Generally, maximum power point tracking (MPPT) can be employed either as a technique, through an algorithm, or even both. As with any other types of RESs, MPPT methods are applicable to TEG panels using changes in ΔT and or load conditions. Normally, perturb and observe (P&O) is the conventional MPPT algorithm. It works recurrently to either decrease or increase pulse width of the duty cycle of a switching device for a DC/DC converter. This algorithm compares the source power of the current cycle to its value at the previous cycle. A P&O algorithm flow chart is shown in [26]. In this paper, the proposed MPPT algorithm is called a referenced power P&O (referenced P&O) algorithm. A flowchart of this algorithm is shown in Fig. 5. Referenced P&O is a modification of the traditional P&O algorithm. In the referenced P&O algorithm, a comparison is made between a reference value of the source power to the current value of source power represented by the TEG panel. The proposed MPPT algorithm's aim is to increase the response speed and accuracy over that of the conventional P&O MPPT algorithm.

5 Results and discussion

MATLAB SIMULINK is a software packaged that is used to simulate an entire proposed system. The bidirectional DC/DC converter is connected in series with the Luo converter. Specifications of the charging system are listed in Table 1. The simulations are made for P&O and referenced P&O algorithms. Ten TEG modules are connected in series for a TEG line. There are 15 TEG lines are connected in parallel for a 15×10 TEG panel. The TEG panel is based a previously reported practical design of a 150 TEG panel [21].

The results of system input power (Pi) during startup are shown in Fig. 6. It is hypothesized that ΔT is 30 ^{0}C for both sides of the TEG panel. Based on other experimental measurements, the ΔT value of the TEG panel is set to this value since T_h is (60 ~ 65) ^{0}C and T_c is (25 ~ 30) ^{0}C. Figure 6 shows that the fastest and more accurate response is made when the referenced P&O algorithm is used instead of the conventional P&O algorithm. It was found that the MPP is 27.5 W.

Table 1. Proposed system specifications

Portion	Component	Specifications
Bidirectional DC/DC converter	L_c	0.57 mH
	S_1 & S_2	IGBT
Lou Converter	L_{Lou}	1 mH
	C_{Lou}	300 µF
	C_{Lou}	500 µF
	L_f	1 mH
	C_f	47 µF
TEG panel	No. of TEG modules	150 (10 TEGs in series × 15 in parallel)
	Materials	Ceramic/Bismuth Telluride
	Model number	SP1848-27145
	Open-circuit voltage (v)	4.5 V
Battery	Voltage	9 V
	Rated capacity	1.2 Ah
	Type	Lithium-Ion
	Response time	0.1 s

The results of system input power (P_i) during startup are shown in Fig. 6. It is hypothesized that ΔT is 30 °C for both sides of the TEG panel. Based on other experimental measurements, the ΔT value of the TEG panel is set to this value since T_h is (60 ~ 65) °C and T_c is (25 ~ 30) °C. Figure 6 shows that the fastest and more accurate response is made when the referenced P&O algorithm is used instead of the conventional P&O algorithm. It was found that the MPP is 27.5 W.

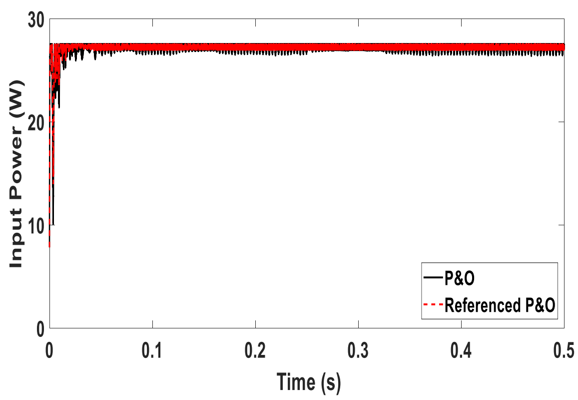

Fig. 6. Input power response during system startup

Figures 7 and 8 represent the charging voltage and current for a 9 V battery. In Fig. 7, the battery voltage is 10 V, which is the same as the set point. The reason for setting this value is to make the charging voltage higher than the nominal battery voltage, 9 V. Figure 8 shows the charging current of the battery where its value is -2.01 A. Normally, the charging current of each battery should be negative indicating that the current passes through it in the opposite direction than in the discharge mode. In both Figs. 7 and 8, the referenced P&O algorithm shows superior performance, in terms of accuracy, voltage and current stability, to the P&O algorithm.

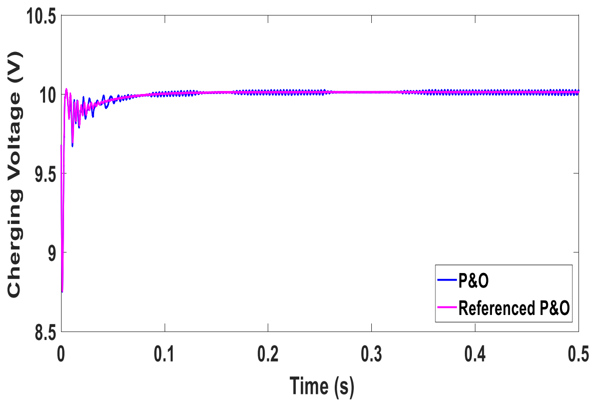

Fig. 7. Battery charging voltage

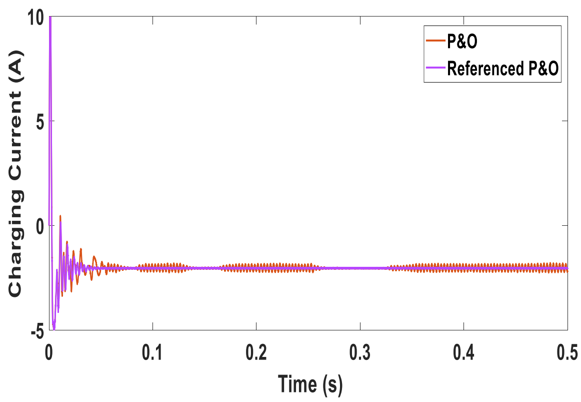

Fig. 8. Battery charging current

Figure 9 shows the percentage of state of charge (SoC). In the beginning of the simulation, the SOC is set at 45%. It shows that the SoC using the referenced P&O algorithm is higher and faster than when the P&O algorithm is used.

If there is a change in ΔT from 30 to 40 ^{0}C during steady state operating, as shown in Figure 10, the Pi is changed from 27.5 W to 49 W. Also, the battery charging voltage shows some flicker lasting for a fraction of a second and then returns to its normal value. After this change in the ΔT value, it can be noted that the referenced P&O has better stability for ΔT changes than the P&O algorithm.

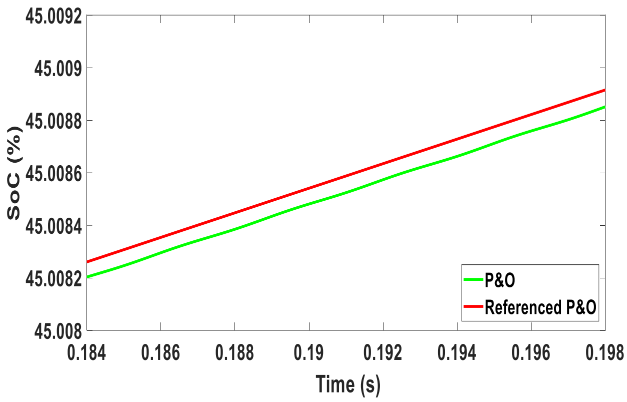

Fig. 9. Battery SOC (%)

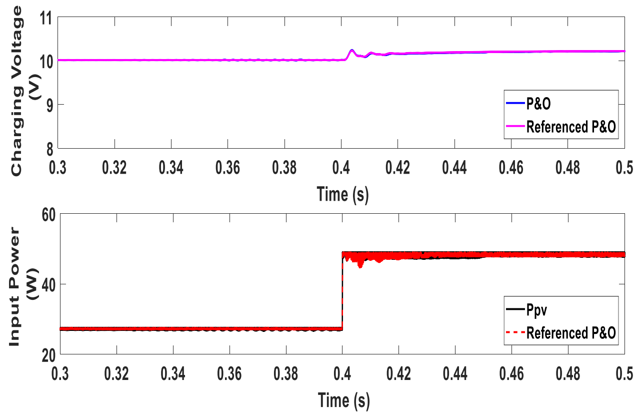

Fig. 10. Change in input power and battery charging voltage with ΔT changed from 30 to 40 °C

6 Conclusions and work features

The proposed charging system is built using a combination of a Luo converter and bidirectional DC/DC converter. MPPT is done through a Luo converter and a charging process through a bidirectional DC/DC converter. It is possible to conclude from this paper that the design can efficiently use the maximum power from a TEG panel to charge a 9 V battery with 1.2 Ah rated capacity. The referenced P&O algorithm produces a more rapid response and more stable power from a TEG panel at its maximum level than the P&O algorithm. It was found that the rate of change of the charging voltage is 0.027 V in the case when the traditional P&O algorithm is used whereas its value is 0.0025 V in the case when referenced P&O algorithm is used. Also, the SoC in the case when Referenced P&O is higher by 0.002 % than the normal P&O algorithm. With increased TEG panel size or by connecting many TEG panels, it is possible to charge batteries at higher voltages and rated capacities.

In the near future, it is planned to experimentally implement this system by maximizing the TEG panel power rating to charge higher voltage batteries or by connecting this TEG panel with solar PV panels to create a hybridized system that can effectively produce more energy [27–30]. In this manner, electrical energy may be obtained in two different ways—first from a solar panel, then from a TEG panel. This idea will also reduce the normal working temperature and enhance the efficiency of PV panels.

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