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Conversion of Heat Generated During Normal PV Panel Operation into Useful Energy via a Hybrid PV-TEG Connection

Mohammed A. Qasim *‡, Vladimir I. Velkin **, Sergey E. Shcheklein **, Sajjad A. Salih **, Baseem A. Aljashaami **, Alaa Ahmad Sammour ***

*Nuclear Power Plants and Renewable Energy Sources Department,
Ural Federal University, 620002 Yekaterinburg, Russia, and, Department of Projects and Engineering Services, Ministry of Health, Baghdad 10047, Iraq

** Nuclear Power Plants and Renewable Energy Sources Department,
Ural Federal University, 620002 Yekaterinburg, Russia

*** Turbines and Engines Department, Ural Federal University,
Yekaterinburg 620002 Russia

(mohammed.a.k.qasim@gmail.com (M.A.Q); v.i.velkin@urfu.ru (V.I.V.); s.e.shcheklein@urfu.ru (S.E.S.); sajjadsaleh85@gmail.com (S.A.S); aljashamib@gmail.com (B. A. A.); alpharam.eng@gmail.com (A.A.S))

‡ Corresponding Author: Mohammed A. Qasim, Nuclear Power Plants and Renewable Energy Sources Department,
Ural Federal University, 620002 Yekaterinburg, Russia,
Tel: +7(999)-570-34-47, mohammed.a.k.qasim@gmail.com

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Abstract- Renewable energy systems such as photovoltaic (PV), thermoelectric generators (TEG) have recently become in high demand for cleaner energy production. In this study, a single PV panel is connected in series with a thermoelectric generator (TEG) panel as a hybrid PV-TEG system. A large amount of heat is dissipated in normal operation of PV panel. This heat can be absorbed by a TEG panel that is built from 32 TEG modules attached directly to the PV panel. The TEGs convert heat into useful electricity through the Seebeck effect. Energy output from the hybrid system is sensitive to stochastic operating conditions, leading to further reduction of efficiency. Therefore, to attain maximum available power in a hybrid system, four Maximum Power Point Tracking (MPPT) methods are used, where their output is modulated as pulses to drive a DC/DC boost converter. The study's main findings show the voltage and efficiency of the hybrid system are improved by 9.21 % and 18.16 %, respectively, in comparison to a PV panel alone. With sudden change in solar irradiance after 0.4 seconds of operation, the power of PV-TEG system is 25.4 W. This is still higher than in the case where only a PV panel is used, 20.9 W. While changing in different temperatures, recorded results shows improvement in efficiency of 27 % for the PV-TEG system over a PV panel alone, at ΔT 40 °C. MPPT by the IT2FLC method is still superior to other MPPT methods. Furthermore, a study of system expansion up to 20 PV-TEG hybrid panels is done. The results confirm the robustness of the proposed hybrid system over that of a PV panel alone.

Keywords Thermoelectric Generator, Hybrid, MPPT, PV-TEG, IT2FLC.

1. Introduction

For many years, expanding use of fossil fuels to generate electricity has led to huge environmental pollution worldwide. Recently, Renewable Energy Sources (RESs) have been developed to generate electrical energy in clean and environmentally friendly ways [1]. Most often, photovoltaic (PV) systems are installed for their clean energy as it comes from solar irradiation. However, PV cell efficiency is primarily dependent on prevailing environmental conditions, including the intensity of solar irradiation, temperature, and shading. Additionally, a great portion of the total energy is lost as heat. PV systems have a significant limitation as they convert only a small fraction of solar radiation into electricity [2]. Thus, due to their low efficiency, scientists and researchers have developed many techniques to increase PV panel power and efficiency.

Thermoelectric generators (TEGs) are solid-state energy conversion devices that derive electricity from heat. Recently, TEGs have received greater attention as independent and clean RESs [3]. TEGs have been used in various domestic and industrial applications and even in military aircraft and space shuttles [4]. Normally, TEGs are commercially available as small modules. If a thermal difference is applied across the surfaces of these modules, an electrical current will flow since TEGs are manufactured from p- and n-semiconductor material types based upon the Seebeck effect [5]. Generally, TEG modules are attached to hot areas that dissipate heat to generate electricity. Since PV panels dissipate high amounts of heat during their normal operation, it is possible to attach them to the hot side of PV panels, to generate an electric current.

Over the last six years, many researchers investigated conversion of waste heat from the PV panels into useful electricity utilizing various Maximum Power Point Tracking methods. Kwan and Wu [6] used a Lock-On Mechanism (LOM) as an MPPT method. Their proposed MPPT provided the required pulses for a twin SEPIC DC/DC converter. Here, each input source is independent. The PV panel and TEG feed electrical voltage from each side of the converter. A LOM is used to reduce oscillations under steady state operation with improved MPP tracking. Mohd Tawil and Zainal [7] used a selector switch to choose the power source, either a PV or TEG system. Each source is joined to a separate DC/DC step-up converter to increase voltage levels for the loads. Their design is made to operate small power applications such as a cooling fan. Shatar et al. [8] developed a hybrid PV-TEG device for a precision agriculture system. A PV is used to supply loads and charge a battery bank with an appropriate MPPT. The TEG is only used for charging batteries. Belkaid et al. [9] developed a combination PV-TEG system. Electricity is supplied via solar radiation and the waste heat is recovered to attain optimal performance. For each source, a boost converter is used to perform an MPPT and each converter is connected to a load. The MPPT is based on an algorithm called a 'sliding mode'. The aim of their design is to achieve smart grid requirements. Ibrahim et al. [10] fabricated a hybrid PV-TEG device for pumping applications. One synchronous reluctance motor (SRM) is used as a load. The entire system is controlled in two ways. The first way is operation at the maximum torque per Ampere, while the second is running the system so that that it produces the maximum power under specified environmental conditions. To accomplish this strategy, a three-leg inverter is used instead of a DC/DC converter. Mirza et al. [11] developed an Arithmetic Optimization Algorithm (AOA), which is an MPPT algorithm, to control this hybrid PV-TEG system. They used a single DC/DC boost converter driven by an AOA to reach an MPP with high stability. A similar hybrid PV-TEG was made by Kanagaraj [12]. For the MPPT, a Fractional Order Fuzzy Logic Controller (FOFLC) was used. Performance of his proposed system was examined under various electrical and thermal operating conditions in a MATLAB Simulink environment. Ejaz [13] examined a hybrid PV-TEG device under Generalized Particle Swarm Optimization (GEPSO), an MPPT method. He compared it with the performance of Perturb and Observe (P&O), Cuckoo Search (CS), Incremental Conductance (INC), and normal PSO techniques for cases requiring tracking speed and accuracy.

Generally, previous studies neglected some issues. Choosing the appropriate electrical connections and assembly of TEG modules to obtain the appropriate voltage such issues. Where most PV-TEG systems link many thermoelectric modules in a series and parallel array to achieve the necessary power level. Expansion of the hybrid system to obtain more power or its exposure to unstable conditions is not considered. Therefore, creation of a hybrid system that addresses these issues is extremely important.

The current research seeks to develop a hybrid PV-TEG device. The dissipated heat from a PV panel during its normal operation converted into electricity, enhancing power generation as well as overall system effectiveness. For this purpose, a TEG panel is used that is made from several TEG modules that are connected both in series and parallel. These TEGs are subsequently attached to a PV panel. Then, they are connected electrically in series. Numerous MPPT algorithms were tested. The most effective one was chosen to achieve optimal system performance under stable and unstable conditions. Also, expansion of the proposed system to increase power and capacity was addressed. This paper consists of an introduction, proposed hybrid PV-TEG system, MPPT methods, results and discussion, and conclusions.

2. Proposed Hybrid PV-TEG System

The proposed hybrid system is comprised of a single PV and TEG panel electrically connected in series. The TEG panel has two surfaces. The first is a high-temperature side while the other is at a lower temperature. Its hot side is mounted on the back of a PV panel. The cooler side maintains its temperature using tap water flowing through aluminum radiator elements [14]. The details of each panel are discussed below.

2.1 The PV Panel

Normally, a photovoltaic (PV) panel is modeled as a PN diode with parallel and series resistances and a source of current, as depicted in Fig. 1. The PV panel generates an electrical current (I_{PV}) when light strikes the PN junction where electron-hole pairs are formed [15-16]. I_{PV} can be calculated using equation (**1**), while equation (**2**) can be used to mathematically represent an ideal PV cell model [17],

$$I_{PV} = I_{ph} - I_s - I_{rs} \quad (1)$$

$$I_{PV} = I_{ph} - I_s \quad (2)$$

where I_s, I_{rs} are diode saturation current and resistance current, respectively, and I_{Ph} is current from incoming photons, denoted as [18],

$$I_{Ph} = (I_{sc} + K_i(T - T_o))\left(\frac{G}{G_o}\right) \quad (3)$$

I_{sc} , K_i , T , G are short-circuit current, current conductivity, module temperature, solar irradiance, respectively. T_o and G_o are the ambient temperature and solar intensity under standard test conditions (STC), respectively. Resistance current can be expressed as [18]:

$$I_{rs} = I_{scr}\left[\exp\left(\frac{q\,V_{oc}}{N_s\,KAT}\right) - 1\right] \quad (4)$$

I_{scr} denotes short circuit current, V_{oc} is open circuit voltage, q represents the electron charge, N_s denotes cells number of PV model, k is the Boltzmann constant ($1.38 \times 10^{-23} J$), and A is the diode ideality factor. The diode current can be determined by [18]

$$I_s = I_{rs}\left(\frac{T}{T_O}\right)^3 \exp\left[\frac{qE_g}{AK}\left(\frac{1}{T_O} - \frac{1}{T}\right)\right] \quad (5)$$

E_g denotes bandgap energy. Then equation **(2)** is rewritten as [17-18],

$$I_{PV} = N_p I_{ph} - N_p I_{rs}\left[\exp\left(\frac{q\,V_{pv}+I_{pv}R_s}{N_s KAT}\right) - 1\right] - \frac{V_{pv}+I_{pv}\,R_s}{R_{sh}} \quad (6)$$

where R_s denotes series resistance, R_{sh} is parallel resistance, and N_p represents the number of PV cells connected in parallel. It is possible to show the input power caused by solar irradiance as [19]

$$p_{in} = G\,A_{pv} \quad (7)$$

where, A_{pv} is the area of the photovoltaic module, PV panel efficiency expressed as [20]

$$\eta_{PV} = \frac{I_{mp}\,V_{mp}}{G\,A_{pv}} \quad (8)$$

where I_{mp}, V_{mp} are the maximum current and voltage of the photovoltaic module.

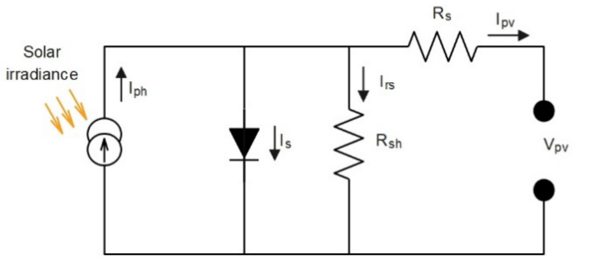


Fig. 1. Equivalent circuit of PV cell

2.2 The TEG Panel

A thermoelectric generator (TEG) transforms heat directly into electrical energy [21]. It has two surfaces; one is a hot surface while the other is cold. From the Seebeck phenomenon, a difference in temperature (ΔT) is established across these two surfaces. This difference results in an energy flow from a higher to lower level that finally produces a voltage across the TEG module. In most cases, these modules are manufactured from ceramic/bismuth telluride materials [22]. A TEG is simulated as single voltage source that is connected in series. This arrangement has an internal resistance, depicted in Fig. 2 [23].

Heat that is absorbed Q_h and dissipated Q_c by a TEG, where the sides are at different temperatures, are determined as [24]

$$Q_h = (K_p + k_n)(\Delta T) + (\alpha_p - \alpha_n)IT_h - \frac{I^2R}{2} \quad (9)$$

$$Q_c = (K_p + k_n)(\Delta T) + (\alpha_p - \alpha_n)IT_c + \frac{I^2R}{2} \quad (10)$$

where K_p and k_n are the thermal conductivity values of the p-type and n-type TEG materials, α_p and α_n values are the Seebeck coefficients for p-type and n-type TEG materials, respectively. I represents the current and R is the resistance at the terminals of a TEG module. This is shown in Fig. 3. $\Delta T = (T_h - T_c)$, where T_h and T_c are the hot and cold temperatures on opposite sides of a TEG, respectively. From the input-output power balance equation then [24],

$$W = Q_h - Q_c = V.I \quad (11)$$

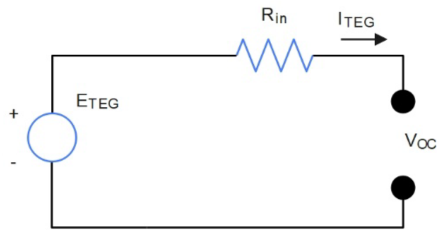


Fig. 2. Equivalent circuit of a TEG module

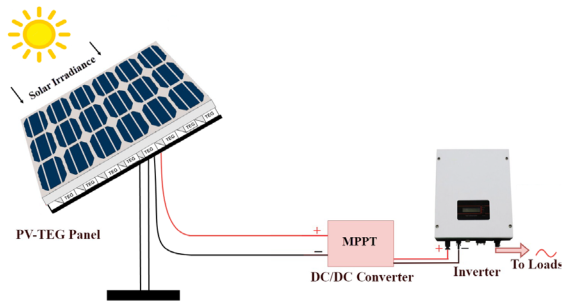


Fig. 3. The proposed hybrid PV-TEG system

Rearranging of equations (**9**) and (**10**), the terminal voltage is expressed by

$$V = (\alpha_p - \alpha_n)(T_h - T_c) - IR \quad (12)$$

Substituting $\alpha = (\alpha_p - \alpha_n)$ and $\Delta T = (T_h - T_c)$, equation (12) becomes

$$V = \alpha \times \Delta T - IR \quad (13)$$

The open circuit voltage (V_{oc}) is determined by

$$V_{oc} = \alpha \times \Delta T \quad (14)$$

Maximal efficiency of a TEG is represented as [25]

$$TEG\ \eta_{max} = \frac{T_h - T_C}{T_h}\,\frac{\sqrt{1+Z\overline{T}}-1}{\sqrt{1+Z\overline{T}}+\frac{T_C}{T_h}} \quad (15)$$

where $Z\overline{T}$ is the 'figure of merit' [26]. Voltage of a TEG can be increased by employing a greater number of TEG modules used.

When heat from radiation is transferred to the hot side of TEGs, it is transformed into additional electrical power, even though it is not converted to electricity by the PV panel. Finally, the system overall electrical efficiency can be representing as follows in equation (**16**), were the P_L is load output power of the system [27-29]

$$\eta_{overall} = \frac{P_L}{G\,A_{pv}} \quad (16)$$

Our proposed hybrid PV-TEG device is illustrated in Fig. 3. Heat generated from the PV panel during its normal operation is absorbed at the TEG hot side, mounted adjacent to the opposite surface of the PV panel. This generated thermal energy can be converted into electrical energy by the TEG panel. Since the panels are connected in series, generated voltages at the terminals of TEG panels are summed to yield the system voltage. Using more TEG modules will increase the overall system voltage and power.

3. MPPT methods

All Maximum Power Point Tracking (MPPT) methods operate a system at the Maximum Power Point (MPP) for their respective power-voltage (PV) curves, as depicted in **Fig. 4**.

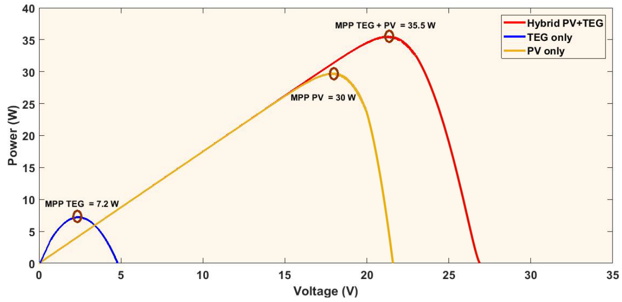


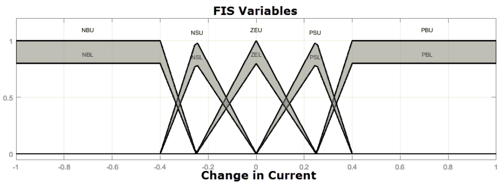
Fig. 4. PV curves for the TEG panel, PV panel, and hybrid PV-TEG system

In this figure, it can be noted that the MPP of TEG panel is 7.2 W when $\Delta T = 30$ °C. Also, the MPP of the PV panel is 30 W when the solar irradiance is 1000 W/m2 at 25 °C. Thus, due to the series connection of PV and TEG panels, the total power at the MPP is increased to 35.5 W for each the PV and TEG panel under the same operating conditions.

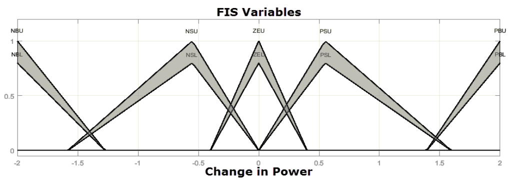
Several MPPT methods are used in this research. They include the Perturb & Observe (P&O) and the Incremental Conductance (IC) methods, as well as other techniques similar to the P&O algorithm. These other methods are a Fuzzy Logic Controller (FLC) and Interval Type-2 Fuzzy Logic Controller (IT2FLC). The P&O technique, FLC, and IT2FLC identify the point where the slope of the ΔP/ΔV curve is flat, i.e., zero [30]. This is the MPP of a particular system. The FLC and IT2FLC are similar in the number of their Membership Functions (MFs) and rules. However, in the IT2FLC, there are upper and lower side MFs, as shown in Fig. 5. The amplitude of the lower MFs is 0.8, whereas that of the upper MFs is 1. For each FLC, there are two inputs and one output called the 'Change in Current' and 'Change in Power'. For each input, the MFs are NB (Negative Big), NS (Negative Small), ZE (Zero), PS (Positive Small), and PB (Positive Big). The Universe of Discourse (UoD) of the 'Change in Current' is $(-1 \text{ to } +1)$ and that of the 'Change in Power' is $(-2 \text{ to } +2)$. The fuzzy inference system of each FLC is the Sugeno type. Defuzzification in IT2FLC is done using the Karnik-Mendel (KM) algorithm [31]. The MFs as well as the rules implemented for a FLC are done in MATLAB through its Fuzzy Logic toolbox [32-34]. To achieve better performance, all the MFs are made asymmetrical between inputs. The output of the MPPT method is used to modulate a high frequency carrier to achieve the required pulse duty cycle for a DC/DC converter, such as a boost converter [35-38]. Figure 6 represents the surface of the relationship between each input of an FLC and IT2FLC as well as their corresponding outputs, which is the duty cycle.

4. Results and discussion

Both panels are modelled and connected in series as shown in Fig. 7. A bypass diode connected between the panels serves as protection against defects or TEG panel malfunction. System specifications are given in Table 1. Simulations are done using the P&O algorithm, IC algorithm, FLC, and IT2FLC MPPT methods.



(a)



(b)

Fig. 5. MFs of IT2FLC inputs (a) Change in Current, (b) Change in Power

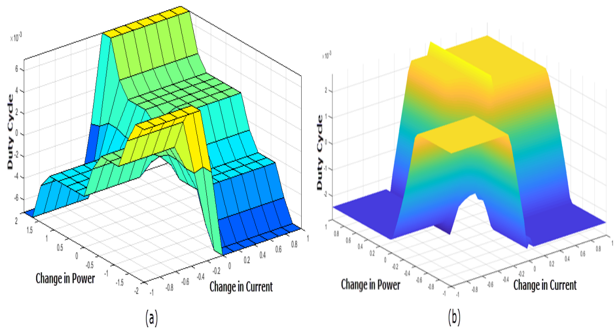


Fig. 6. Surface of inputs and outputs of (a) FLC as MPPT and (b) IT2FLC as MPPT

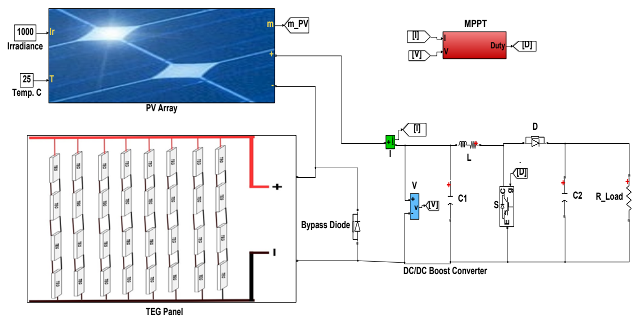


Fig. 7. Proposed PV-TEG system as a Simulink model

Each of the four TEG modules are connected in series, representing a TEG line. Eight TEG lines are connected in parallel to form a 4×8 TEG panel. The PV panel is made based on a 30 W 'AMERESCO SOLAR' PV module with a '30J' code [39]. It is made of 36 crystalline silicon cut cells in series.

Table 1. Specifications of the proposed hybrid PV-TEG system

System Portion	Component	Specifications
PV Panel	Maximum Power	30 W
	Open Circuit Voltage	22.1 V
	Voltage at MPP	17.9 V
	Short Circuit Current	1.7 A
	Rated solar irradiation and temperature	1000 W/m^2 at 25 ˚C
C.B. DC/DC converter	S	IGBT
	L	1 mH
	C_1	4000 µF
	C_2	2000 µF
TEG panel	No. of TEG modules	32 (4 TEGs in series × 8 parallel)
	Materials	Ceramic/Bismuth Telluride

4.1 System Startup

During system startup, the solar irradiance is 1000 W/m^2 and ΔT is 30 ˚C. The reason for selecting such value of ΔT and solar irradiance values is that the normal T_h value is (~60–65) ˚C and T_c is (~25–30) ˚C based on other experimental measurements for solar irradiance at midday as well as the temperatures of the PV panel and normal tap water, respectively. Figure 8 shows the response of system startup for each MPPT method. The fastest response for the system is with the IT2FLC MPPT method, followed by FLC, the P&O algorithm, and finally the IC algorithm. Also, at a steady state, the smooth response of input power (P_i) for the whole system is best for the IT2FLC MPPT method followed by the FLC, IC algorithm, and finally the P&O algorithm. For each method, the selected load value is 30 Ω. The total MPP is 35.45 W, which is 18.16% greater than the MPP of the PV panel alone.

Figure 9 shows simulation results of the output voltage of the boost converter. In this figure, the best output voltage stability is with the IT2FLC MPPT method followed by the FLC, IC algorithm, and finally the P&O technique. Under an identical load, the output voltage of the proposed hybrid system is 32 V, which is 9.21% higher than in the case when only a PV panel is used. In this case, the output voltage will be 29.3 V. Table 2 comparatively shows the changes in input power (ΔP_i), output voltage (ΔV_o), input power (P_i) and output power (P_o) along with efficiency of the DC/DC power conversion.

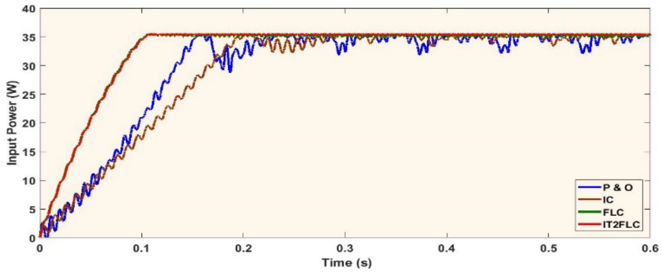


Fig. 8. Hybrid PV-TEG input power with various MPPT methods

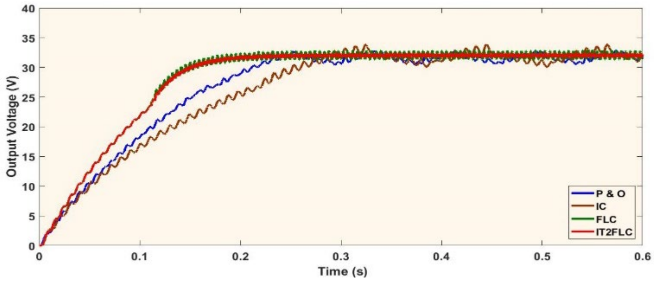


Fig. 9. Hybrid PV-TEG output voltage using various MPPT methods

Table 2. Comparative performance using various MPPT methods at a load of 30 Ω

MPPT Method	ΔP_i (W)	ΔV_o (V)	P_i (W)	P_o (W)	Efficiency (%)
P & O	3.5	2.8	33.65	31.32	93.1
IC	1.7	2.74	34.55	32.89	95.2
FLC	0.3	1.43	35.19	33.78	96
IT2FLC	0.07	0.66	35.4	34.12	96.4

4.2 Effect of Change in Solar Irradiance and Change in Temperature

In Fig. 10, when the simulation time is 0.4 s, solar irradiance was decreased from 1000 to 700 W/m^2. Even if the value of input power is decreased to 25.4 W, the power is still higher than in the case where only a PV panel is used, 20.9 W. Comparing the steady-state cases in Figs. 8 and 9, the MPPT by the IT2FLC method is still superior to other MPPT methods. Figure 11 represents the change in output voltage with variation of solar irradiance. In this figure, due to the decrease in the amount of incident irradiation, the output voltage decreased from 32 V to 27.1 V. In both Figs. 9 and 10, it is assumed that the system is working at a ΔT value of 30 ˚C.

In Fig. 12, the solar irradiance is held at 1000 W/m^2, while ΔT is changed from zero to 40 ˚C. From experimental data [14], there is a linear relationship between an increased ΔT and the input power. In this figure, when ΔT is 40 ˚C, the input power is 38.1 W, which is 27% higher than when only a PV panel is used. A linear relationship between the input power and ΔT can be obtained through regression analysis. The resulting expression for the data of Fig. 12 is

$$\text{Input power} = 27.44+0.26\,\Delta T \quad (17)$$

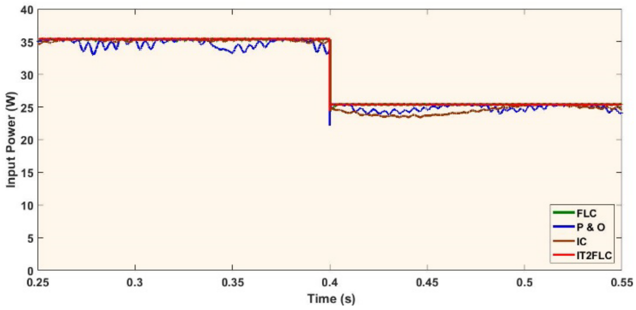


Fig. 10. Hybrid PV-TEG input power with a sudden decrease in solar irradiance (from 1000 to 700 W/m^2)

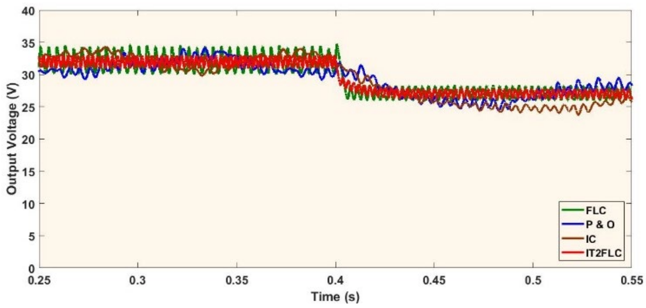


Fig. 11. Hybrid PV-TEG output voltage with a sudden decrease in solar irradiance (from 1000 to 700 W/m^2)

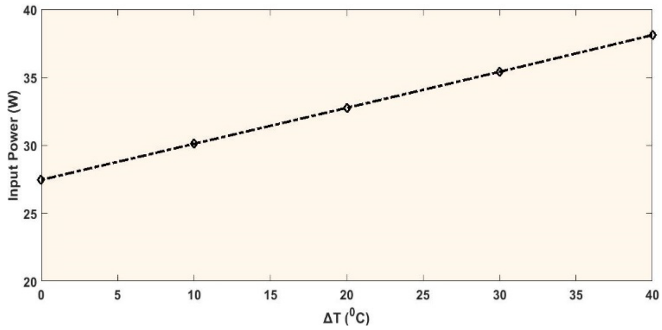


Fig. 12. Hybrid PV-TEG input power at various ΔT values (0 to 40 ˚C)

From this equation, if ΔT is zero, the input power is 27.44 W, whereas it should be 30 W. The decrease from 30 W to 27.44 W is due to internal resistance of the TEG. This occurs since when ΔT is zero, the voltage of TEG panel is 0 V as well, indicating a short circuit in the TEG. If there is a reduction in the positive branch of the TEG panel due to a bypass diode, then the input power will become 29.1 W instead of 30 W owing to losses in the bypass diode. The state of this diode is shifted from the OFF to the ON state only when the + branch of the TEG panel is disconnected.

At the same operating conditions of Section 4.1 and applying equation (15), the $TEG\ \eta_{max}$ is 1.42 % where $Z\bar{T}$ is taken from [14],[40-41]. Also, photovoltaic panel efficiency η_{PV} can be determined using equation (8). At 1000 W/m^2 and (0.358 × 0.796) m^2 of A_p, η_{PV} is 10.53%. Using equation (16), the overall efficiency for the proposed hybrid PV-TEG is 12.44 %. This indicates an increased efficiency of 18.167 %. At various operating conditions, both η_{PV} and $TEG\ \eta_{max}$ will have different values, so the total efficiency will be different as well.

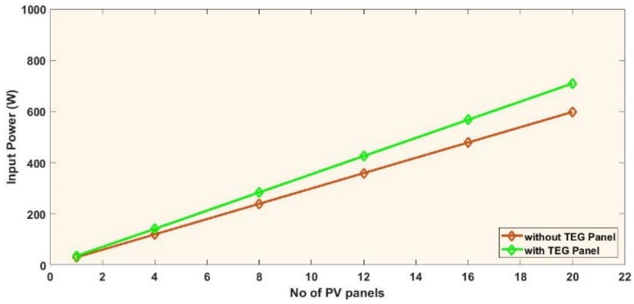


Fig. 13. The difference between the input power at many PV panels alone or connected with TEG panels

4.3 Effect of System Expansion

At the operating conditions of Section 4.1, multiple items of the proposed hybrid PV-TEG systems are considered as one unit. Each unit is connected in parallel and there is only one central DC/DC boost converter for MPPT purposes. This enables system expansion to increase the input power. It is required now to check the benefit and gain from the hybrid system over connecting individual PV panels in parallel, *i.e.*, not as a hybrid system. Figure 13 reveals the effect of increasing the total input power of the hybrid system rather than connecting only a PV panel. In this figure, there is an 18.16% power increase using PV-TEG over a PV panel alone. Also, as the number of hybrid units increases, the input power becomes much greater.

5. Conclusion

The current work presents a hybrid renewable PV-TEG system. A 30 W PV panel is connected in series with a (4×8) TEG panel. The system is simulated under various changes in solar irradiance and ΔT values with different MPPT methods. It can be concluded:

1. The efficiency of the proposed system is 18.16 % greater than for only a PV panel alone when the solar irradiance and ΔT are $1000\ W/m^2$ and $30\ °C$, respectively. Also, the proposed hybrid system showed a 9.215 % increased voltage over a PV panel alone.

2. With sudden change in solar irradiance from 1000 to 700 W/m^2 after 0.4 seconds of operation, the efficiency of PV-TEG system is 12.73 %. This is still higher than in the case where only a PV panel is used, with a resulting efficiency of 10.48 % and this mean improvement in efficiency of 21.53 % in comparison with PV panel alone. Also, the hybrid system showed a 4.5 W increased in power over a PV panel alone.

3. With changes in deferent temperatures from 0 to 40 ℃, and solar irradiance held to 1000 W/m^2. The power of PV-TEG system and PV panel alone are 38.1 W, 30 W respectively, at ΔT 40 ℃. This means increase of 8.1 W. Also, the PV-TEG system records an improvement in efficiency of 27 % . Here, the positive effect of improving the system appears when the different temperatures are increased.

4. Additionally, the expansion of the hybrid system to 20 PV-TEG hybrid panels has positive effects. The outcomes support the suggested hybrid system's superior robustness to a PV panel alone.

5. Furthermore, four MPPT methods are examined. IT2FLC has superior performance to other examine algorithms for transient behavior as well as in steady-state operation. The IT2FLC MPPT method can be practically applied, but it requires a high-performance microprocessor to function properly. Otherwise, the system response will suffer in reaching the correct MPP with changing operational conditions.

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