THE THEORETICAL EVALUATION ON PHOTOVOLTAIC-THERMOELECTRIC (PV-TEG) CO-GENERATION SYSTEM PERFORMANCE

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ABSTRACT. TEG is an electrical device that produces energy as a result of the difference in hot and cold junctions. There are many studies that have been conducted on the use of TEG in solar PV systems. PV cell depends on solar irradiation and temperature while TEG depends on the temperature difference. TEG uses heat waste produced from solar PV systems and produces extra energy. A simulation study was conducted using MATLAB software where the solar PV system and TEG are connected in parallel. In this study, the maximum power point tracking converter using the Incremental Conductance (Inc) method is used to achieve the optimal energy. Another consideration is the solar PV system is limited to non-shading conditions. The obtained results show that the PV-TEG co-generation system produced 17% more energy when compared to a standalone PV system. By modifying the temperature and irradiance, the efficiency of PV-TEG co-generation is also compared to PV standalone.

KEYWORDS: PV-TEG Hybrid; Thermoelectric Generator, MPPT; Incremental Conductance;

1 INTRODUCTION

In solar PV systems, the problem of energy waste is difficult to avoid and has an impact on efficiency performance. PV panels absorb sunlight and convert it into electrical energy through the photovoltaic effect. During this conversion process, a portion of the sunlight's energy is transformed into electrical energy, while the remaining energy is dissipated as heat. Solar panels can become hot during operation, especially under high solar irradiance. With poor ventilation conditions, high heat temperatures affect the results and the energy produced will decrease. This heat is considered waste heat since it does not contribute to electricity generation but instead needs to be dissipated to prevent thermal damage to the panels (Qasim, M. A., Velkin, V. I., Shcheklein, S. E., Salih, S. A., Aljashaami, B. A., & Sammour, A. A., 2022), M.A. However, this waste heat can be exploited systematically by using a thermoelectric (TEG) device and producing excess energy (Saleh, U.A, Johar M.A, Jumaat S.A.B, M.N, & Jamaludin, 2021). TEG transforms thermal energy (heat waste) into electricity through the Seebeck effect (Hsueh, Shieh, & Yeh, 2015). The temperature difference between the two surfaces has a nonlinear effect on the TEG material's internal resistance and therefore difficult in generates the maximum power in TEG. (Montecucco & Knox, 2014). Utilization of a DC-DC converter with maximum power point tracking (MPPT) in TEG configuration aid in the achievement of the maximum power. The MPPT DC-DC converter is a power electronics device that uses various control techniques to modify the duty cycle to regulate voltage and current in order to extract the greatest power output from the source. Amid these controls technique, Perturb and observe (P&O) (Abdelhakim Belkaid, Colak, & Kayisli, 2017; Gautam, Raut, Neupane, Ghale, & Dhakal, 2016), Incremental Conductance (Inc) (A Belkaid, Colak, & Isik, 2016), fractional short-circuit current (Aboudrar, El Hani, Mediouni, Bennis, & Echchaachouai, 2017), fractional open-circuit voltage (Bharath & Suresh, 2017), Neural network (Heidari, 2016), fuzzy logic control (Abdourrziq, Ouassaid, & Maaroufi, 2016; Ahmed Ali, Hasan, & Marwala, 2014; Soufi, Bechouat, Kahla, & Bouallegue, 2014) that is mostly used because of their robustness, stability, decreased response time and easy to implement (Abdelhakim Belkaid, Gaubert, & Gherbi, 2016). To enhance the energy gathered, the PV-TEG co-generation system features dual DC-DC converters using different controllers (Verma, Kane, & Singh, 2016). The PV-TEG co-generation has two different input sources; therefore, this system requires a DC-DC converter independently to yield the power of the different sources to the load. The PV solar system and TEG system are connected in parallel while the Incremental Conductance technique is applied for both parts of the co-generation system. This study is to develop a co-generation system consisting of a PV solar system and a thermoelectric generator and compare the results achieved to PV standalone system.

2 THE DESCRIPTION OF PV-TEG CO-GENERATION SYSTEM CONFIGURATION.

The considered PV-TEG systems consist of a PV panel, thermoelectric generator, DC-DC Boost Converter with Incremental Conductance controller, and the load as illustrated in Figure 1. The following sections provide explanations of the main system components of the PV-TEG co-generation system.

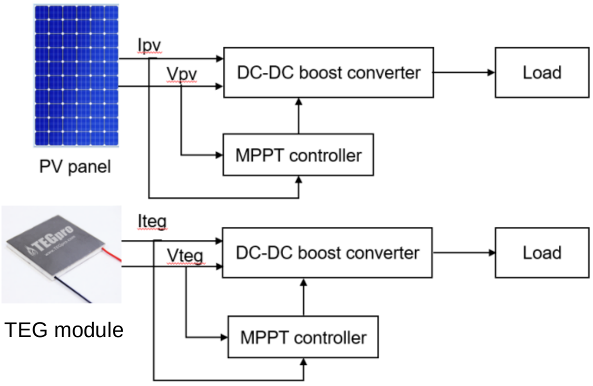

Figure 1: PV-TEG co-generation system block diagram

2.1 PV panel

The developed single diode model, as shown in Figure 2, is used to represent the solar panel, which is then implemented using the MATLAB/Simulink programme. Four parameters: Current source (I_L), diode, series resistance (R_s), and shunt resistance (R_{sh}) are considered.

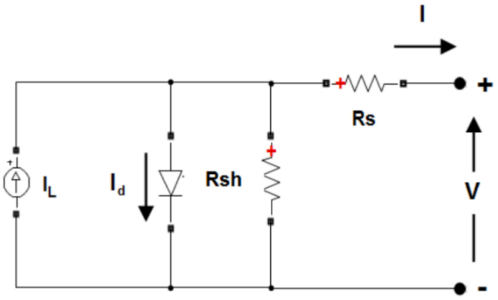

Figure 2: Equivalent electrical circuit of the PV cell.

The diode I-V characteristics are defined by the (1) and (2) where I_d and V_d are diode current (A) and voltage (V), I_0 is diode saturation current (A), *nl* is diode ideality factor, *k* = Boltzman constant (1.3806e-^{23} J.K^{-1}), q = Electron charge (1.6022e-^{19} C), T is cell temperature (K) and N_{cell} is the number of cells connected in series in a module. The curves of I-V and P-V are plotted as shown in Figure 3(a) and (b) respectively.

$$I_d = I_0 \left[exp\left(\frac{V_d}{V_T}\right) - 1 \right] \tag{1}$$

$$V_T = \frac{kT}{q}\ x\ nl\ x\ N_{cell} \tag{2}$$

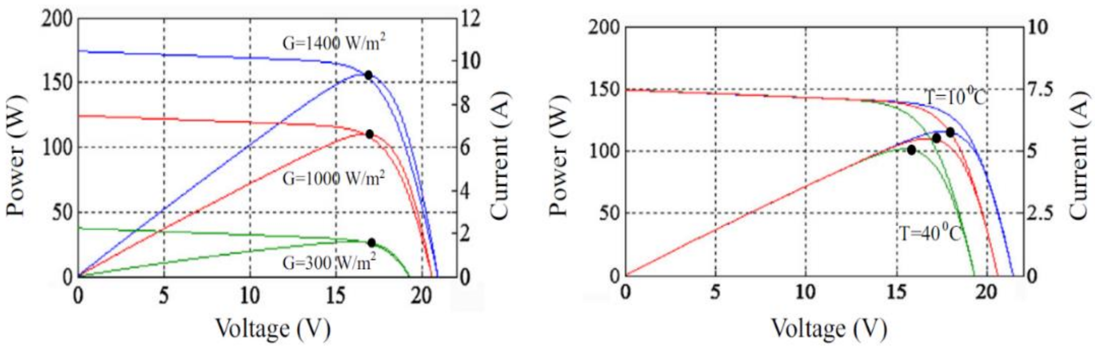

Figure 3: I-V and P-V curves (a) at varying solar irradiation (b) at varying temperature (Chin, Salam, & Ishaque, 2015).

2.2 Modelling of the TEG

The thermoelectric module is a two-way device that able in the transformation of heat into electricity.

The transformation from electrical energy into thermal energy by using Peltier effect while Seebeck effect is applied to transform thermal energy into electrical energy. The voltage generated by a TEG is corresponds to the temperature difference between hot and cold junction. From Figure 4, a voltage source V_{oc} is connected in series to TEG's internal resistance R_{TEG} and (3) (4) and (5) are derived to represent the voltage across TEG (V_{TEG}) as a function of the produced current, I_{TEG}.

$$V_{TEG} = V_{oc,TEG} - R_{TEG}.I_{TEG} \tag{3}$$

$$V_{oc,TEG} = n\,(T_H - T_C) \tag{4}$$

$$R_{TEG} = nR_{th} \tag{5}$$

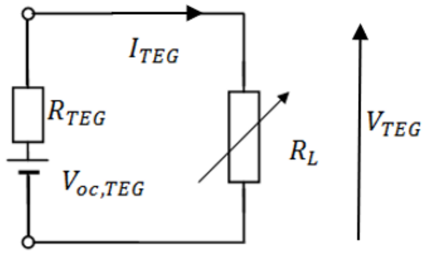

Figure 4: The TEG's electrical circuit in its equivalent form

2.3 DC-DC Boost Converter

DC-DC converters is a power converter device widely employed in renewable power generation system. The converters enable the use of desired output voltage to compliment the requirement of the load thus secure optimal operation. Several types of DC-DC converter topologies used in PV system such as Buck, Boost, Buck-Boost, CUK and SEPIC topologies. In this study, the DC-DC Boost converter is selected because of its low cost, good performance, simplified design and able to increase the output voltage (Abdelhakim Belkaid, Colak, KAYISLI, BAYINDIR, & BULBUL, 2018). The components required for Boost converter is depicted in Figure 5 and the circuit can mathematically derived by applying Kirchhoff's Law as (6) and (7).

$$\frac{d_{iL}}{dt} = \frac{V_{in}-V_O}{L} + \frac{V_O}{L}\,.\,\mathrm{u} \tag{6}$$

$$\frac{dV_O}{dt} = -\left(\frac{V_O}{RC_2} + \frac{i_L}{C_2} - \frac{i_L}{C_2}\right).\mathrm{u} \tag{7}$$

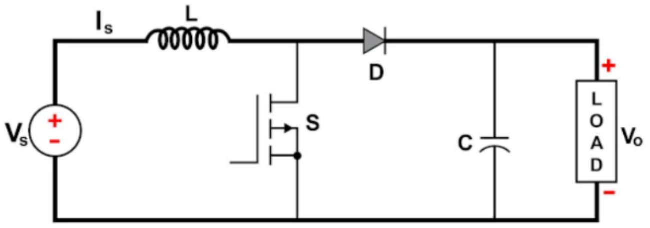

Figure 5: Configuration of DC-DC Boost converter

2.4 MPPT control

The operation of MPPT requires continuously tracking and adjusting the operating point to the maximum power point (MPP) to extract the highest power output of the PV solar and TEG system. Incremental Conductance algorithms (Table 1) continuously measures the voltage and current of the PV panel and TEG system, then obtain the instantaneous power output. The value of instantaneous power output is compared with the previous power measurement. The MPP is determined and MPPT adjust the operating point to maintain the voltage at MPP to maximize power extraction.

Table 1: Methodology based on incremental conductance algorithm (A. Ali et al., 2020)

Mode	Perturbation	MPP Level	Status
Mode-1	$\frac{dP}{dV} = 0 \quad \frac{\Delta I}{\Delta V} = -\frac{I}{V}$	At MPP	Hold $V_{PV} = V_{M}P_{M}$
Mode-2	$\frac{dP}{dV} > 0 \quad \frac{\Delta I}{\Delta V} > -\frac{I}{V}$	The left side of MPP	Increase voltage until $V_{PV}=V_{MPP}$
Mode-3	$\frac{dP}{dV} < 0 \quad \frac{\Delta I}{\Delta V} < -\frac{I}{V}$	Right side of MPP	Decrease the voltage until $V_{PV}=V_{MPP}$

3 PV-TEG PARAMETERS AND CHARACTERISTICS

In this study a PV panel model Sunpower SPR-200-BLK-U is used and the parameter under standard test condition, STC (1000W/m^2, 1.5AM and 25°C) is shown in Table 2. The solar irradiance and temperature are setup varied from 400W/m^2 to 1000W/m^2 and from 25°C to 60°C.

Table 2: SunPower SPR-200-BLK-U specification under STC

Parameter	Value
Maximum Power (W)	200
Open Circuit Voltage V_{oc} (V)	47.8
Short-circuit current I_{sc} (A)	5.4
V_{mp} (V)	40
I_{mp} (A)	5
Temperature coefficient of V_{oc} (%/deg.C)	-0.2984
Temperature coefficient of I_{sc} (%/deg.C)	0.046093

Thermoelectric generators typically consist with TEs connected in series. The TEG absorbs the heat at the hot side and discharges heat at the cool side through energy transformation process. The model used in this study is TE-MOD-1W2V-40S with parameter shown in Table 3. Figure 6 shows the schematic of PV-TEG co-generation system by using MATLAB/Simulink software.

Table 3: TEG design parameter TE-MOD-1W2V-40S

Variables		**Value**
Internal Resistance	Rint (Λ)	3.25
Thermal Conductance	Kteg (W/K)	1
Module Seebeck Coefficient	Steg_u (V/K)	0.1155
Number module in series	Ns	2
Number module in parallel	Np	4

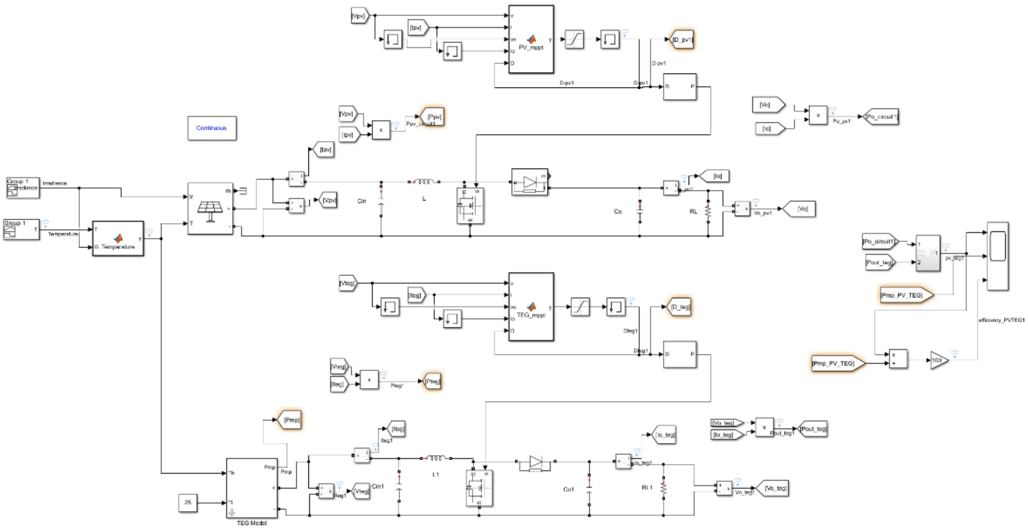

Figure 6: The configuration of PV-TEG co-generation

4 RESULTS AND DISCUSSION

The profile for irradiance and temperature as shown in Figure 7 is utilized in this simulation to evaluate the PV-TEG co-generation system compared to PV standalone system. The irradiance rises from 400 W/m^2 to 900 W/m^2 and remains constant at 1000 W/m^2 at 0.6s. The temperature on the TEG's hot-side remains constant at 35°C for 0.5s and increases gradually as the irradiance at its highest form.

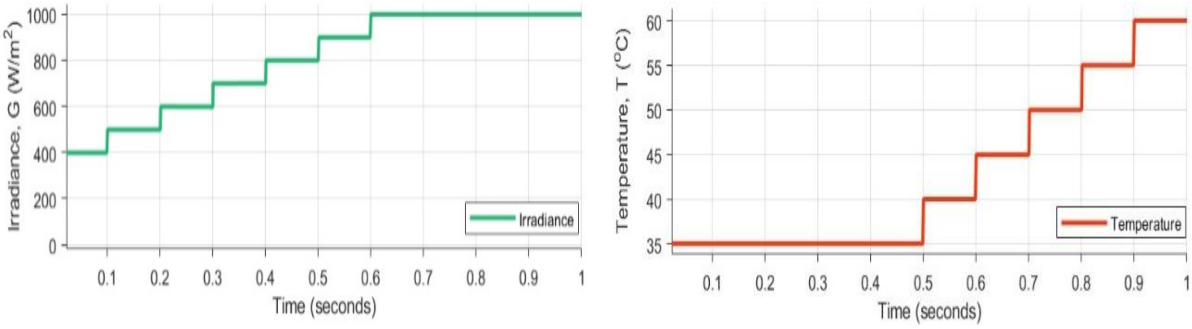

Figure 7: The profile for irradiance and temperature.

The PV-TEG co-generation system able to generate more power than standalone PV by the output power of PV-TEG co-generation is shown in Figure 8. When the temperature difference between the hot and cold side of TEG is high, the maximum power output from this PV-TEG co-generation can be extracted. It is common knowledge that as the temperature in the PV panel rises, the output power of PV is decreasing, but the TEG generator's thermal technology allows it to extract more power. This system results in production of 1.5% up to 17% additional energy depends on the profile of irradiance and temperature; with overall efficiency by 89.7%. This coincide with (Babu & Ponnambalam, 2018) that PV-TEG configuration results in production of 5% additional at STC condition. The overall efficiency of this system as illustrated in Figure 9.

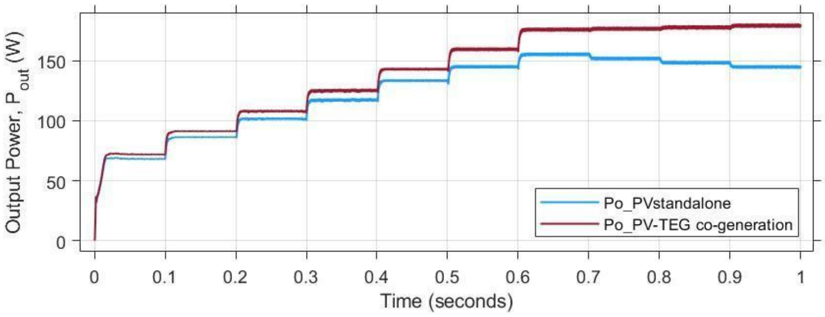

Figure 8: The output power of PV-TEG co-generation system

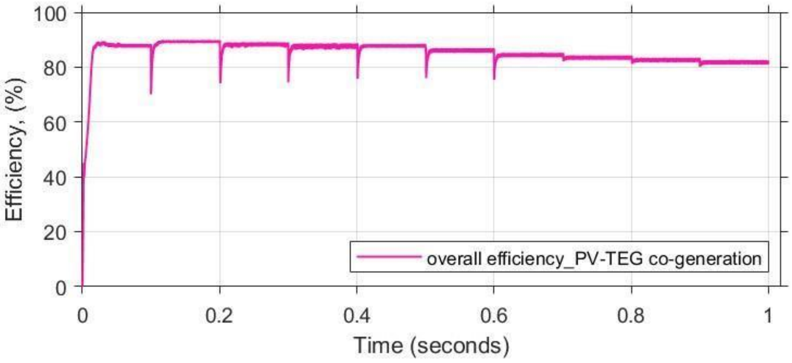

Figure 9: The overall efficiency of PV-TEG co-generation system.

5 CONCLUSION

This study discusses the integration of thermoelectric generators (TEGs) into PV systems to increase their energy conversion efficiency. The MPPT DC-DC Boost converter employs the Incremental Conductance algorithm, which improves MPP tracking performance in terms of fast tracking and precision. The validity of PV-TEG system was tested under varying irradiance and temperature and from simulation confirmed that the TEG module increased the output power of the PV-TEG co-generation system up to 17% compared to PV standalone, and 89.7% efficiency was obtained for the specified solar irradiance and temperature as a result. In the future, this work can be extended to another new high performance MPPT algorithm.

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