EFFECT OF LOAD VARIATIONS ON MAXIMUM POWER POINT TRACKING WITH INCREMENTAL CONDUCTANCE METHOD FOR NON-ISOLATED BOOST CONVERTERS IN THERMOELECTRIC GENERATORS

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Abstract

The efficiency of thermoelectric generators (TEGs) used to convert waste heat into electrical energy is low. Therefore, TEGs are powered by converters with embedded maximum power point tracking (MPPT) algorithms. However, depending on the converter used, the operation of the MPPT algorithms may be adversely affected by the load connected to the converter. Therefore, it is important to know the lower and upper limit values of the load used. In this study, a thermoelectric generator (TEG) model and a non-isolated boost converter model are designed in MATLAB/Simulink environment and the monitoring of the maximum power point (MPPT) according to the connected load value is investigated. The incremental conductance (INC) MPPT algorithm is used for MPPT. MPPT does not occur until the load resistance of the boost converter is equal to the internal resistance TEG. MPPT can be performed if the load resistance is greater than or equal to the internal resistance value. For very high values of the load resistance of the boost converter, a decrease in MPPT performance is observed. Finally, it is appropriate that the load resistance connected to the TEG system should be up to three times the TEG internal resistance, provided that its value is not less than the TEG internal resistance.

Keywords: Thermoelectric generator, Maximum power point tracking, Boost converter, Load limits

INTRODUCTION

The possibility of renewable and sustainable energy sources being the main energy policy in the future will necessitate the efficient implementation of these sources [1]. Therefore, waste heat recovery systems show promise in reducing energy waste [2]. One of the technologies used for this purpose is thermoelectric generators (TEGs). TEGs are semiconductor devices that work with the Seebeck effect and convert the temperature difference between their surfaces into electrical energy [3]. Since low efficiency is the biggest disadvantage of TEG systems, TEGs must be operated at near full capacity [4]. Full capacity operation of TEGs is related to taking maximum power from TEGs [5]. Therefore, maximum power point tracking (MPPT) methods embedded in DC-DC converter applications are used to capture the maximum power point (MPP) of a TEG system [6]. In addition to the temperature difference and material properties, another parameter that plays an important role in the amount of power produced is the load used in the system.

According to the maximum power theorem, the MPP value is obtained by matching the TEG internal resistance with the load resistance [7]. Impedance matching occurs when the duty cycle of the boost converter connected between the TEG and the load is adjusted with MPPT algorithms [8].

Attar et al. [9], conducted a study to find the optimum electrical load resistance in TEG systems without a boost converter with an embedded MPPT. Dileep and Singh [10] drew attention to the connection between converters and load resistors. However, although many studies have been done using DC-DC converters and load resistors, the relationship between selected load resistors, converter and input impedance is not mentioned. Although not seen in many studies, parameters such as internal resistance are hidden in other parameters and are used indirectly. In many studies on TEG systems and MPPT algorithms in the literature, fixed loads are generally used when evaluating TEG efficiency and MPPT performances, and no information is given about why this load value is chosen. As a result, in studies carried out under different load conditions, the limits of the load resistance value must be determined according to the converter planned to be used. This can only be accomplished by considering the converter formulation and input impedance. This study highlights the considerations in selecting the load resistor used to deliver maximum power from the TEG system with a step-up converter with embedded MPPT algorithms and determines the limits of the load resistance.

THERMOELECTRIC GENERATORS

The electrical equivalent circuit of the TEG consists of a temperature dependent voltage source and an internal resistor R_{int} as seen in **Figure 1**. The load is connected to supply power from R_L, TEG. When this load value and the internal resistance of the TEG are equal ($R_{int} = R_L$), the power transmitted from the TEG reaches the maximum power point (MPP) [11]. As the load value changes, the power value transmitted from the TEG decreases.

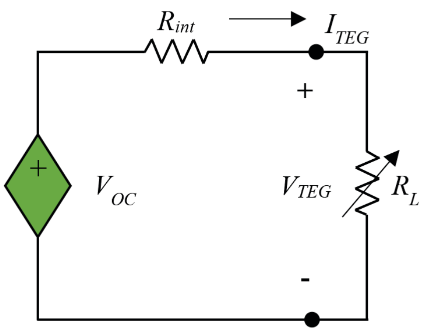

***Fig. 1.** Electrical equivalent circuit of TEG*

When the power value delivered from the TEG is at the MPP point, the open circuit voltage and short circuit current are at their half values as described below:

$$V_{MPP} = V_{OC}/2 \text{ and } I_{MPP} = I_{SC}/2 \quad (1)$$

where, V_{MPP} and I_{MPP} are voltage (V) and current (A) at maximum power point, respectively. I_{SC} is the short-circuit current (A). The MPP can be determined with these values. The current value passing through the TEG is given below:

$$I_{TEG} = V_{OC}/(R_{int} + R_L) \quad (2)$$

where, I_{TEG}, R_{int}, and $R_L$are TEG current (A), TEG internal resistance (Ω), and load resistance (Ω), respectively. The power delivered from the TEG depending on the load resistance and internal resistance is as follows:

$$P = \frac{V_{OC}^2}{(R_{int} + R_L)^2} \cdot R_L \quad (3)$$

where, P is the power (W) generated from the TEG. As can be seen from Equation 3, the power produced from the TEG depends on the internal resistance of the TEG, R_{int} and the load resistance connected to the TEG, R_L. The MPPT methods are used with a converter to deliver maximum power from the TEG by equalizing the load resistance to the internal resistance of the TEG. This synchronization is done with the duty cycle sent to the switching element of the converter by the MPPT algorithm. Therefore, as the load connected to the converter changes, the value of the duty cycle sent to the switching element also changes. The important point here is that the switching element works in harmony with the duty cycle. Therefore, it is desirable for the duty cycle to operate the switching element stably. Therefore, the load connected to the converter must also be within certain limits.

METHOD

Table 1 shows the properties of the TEG system designed for simulation studies in this study. Since the efficiency of TEG systems used for waste heat recovery is low, it is very important to use an MPPT control algorithm.

***Table 1.** Properties of TEG system*

Characteristics	TEG system
Output Power at MPP (P_{MPP})	57 W
Output Voltage at MPP (V_{MPP})	20.5 V
Output Current at MPP (I_{MPP})	2.8 A
Open circuit voltage (V_{OC})	41 V
Short circuit current (I_{SC})	5.61 A
Internal Resistance	7.3 Ω
Hot-side temperature	200°C
Cold-side temperature	30°C

MPPT algorithms adjust the duty cycle of the converter switching element in a TEG system consisting of TEG, converter, and load. In this study, INC MPPT algorithm is used to track the maximum power, and a designed boost converter employed to match the impedance The flowchart of INC algorithm is given in **Figure 2**. [12].

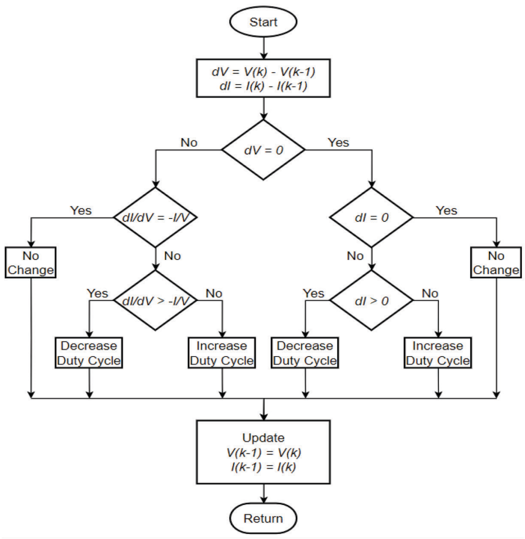

Fig. 2 *Incremental conductance algorithm*

RESULTS

Table 1 shows that the maximum power that can be obtained from the TEG system is 57 W and the total internal resistance of the TEG is 7.3 Ω. Since maximum power can be obtained when the load resistance is equal to the internal resistance, it is clear that maximum power cannot be obtained at load resistance values other than 7.3 Ω without using a converter.

Simulations are made for 14 different load resistance cases. Each case represents different load resistances which are 1 Ω, 3 Ω, 5 Ω, 7.3 Ω, 9 Ω, 11 Ω, 13 Ω, 15 Ω, 20 Ω, 25 Ω, 30 Ω, 40 Ω, 50 Ω, 60 Ω. The behavior of MPPT algorithms is examined against these load resistors that change in 0.5 seconds. In the first four cases where the load resistance is less than the internal resistance, the MPPT algorithms should try to achieve the maximum output voltage and maximum power at the converter output by producing the minimum duty cycle. The MPPT algorithm produces a minimum duty cycle since the converter cannot perform impedance matching, and power is obtained through the resistor thanks to the voltage directly shared on the load.

The power values obtained from TEG over the load resistor of the INC algorithms and the duty cycle values produced by the algorithms are shown in **Figure 3**. Furthermore, the delivered power from the TEG values and the duty cycles generated by the MPPT algorithm are given numerically in **Table 2**. As can be seen, the tracking efficiency and the transferred power are highest when the load resistance value is slightly higher than the internal resistance value. As the value of the load resistor increases, the obtained power and tracking efficiency decrease.

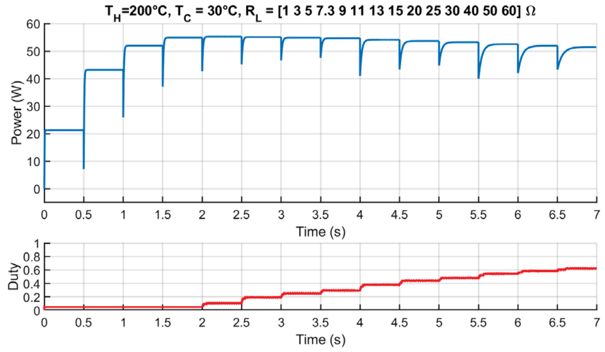

Fig. 3 *The power delivered over the load resistor (1–60 Ω) by the INC algorithm and the duty cycle produced by the algorithm.*

Table 2 *The power obtained from the TEG, tracking efficiency of INC MPPT algorithm (η_{MPPT}%), and produced duty cycle by INC MPPT algorithm for $R_L = 1\text{–}60\ \Omega$*

	R_L (Ω)	Power (W)	η_{MPPT} (%)	Duty cycle
Case 1	1	21.3	37.37	0.05
Case 2	3	43.21	75.81	0.05
Case 3	5	51.94	91.12	0.05
Case 4	7.3	54.90	96.32	0.05
Case 5	9	55.23	96.90	0.108
Case 6	11	55.08	96.63	0.192
Case 7	13	54.88	96.28	0.253
Case 8	15	54.65	95.88	0.295
Case 9	20	54.14	94.98	0.381
Case 10	25	53.64	94.10	0.441
Case 11	30	53.24	93.40	0.482
Case 12	40	52.5	92.11	0.543
Case 13	50	51.91	91.07	0.585
Case 14	60	51.45	90.26	0.623

CONCLUSION

Due to their low efficiency, TEGs are used with converters with the MPPT algorithm to extract maximum power from them. Thanks to the duty cycle generated by the MPPT algorithms, the converters make an impedance match between the load connected to them and the TEG internal resistance. However, the load connected to the converters must have limits. In this study, studies are carried out with the boost converter. The simulation results show that the load connected to the boost converters has to be higher than the internal resistance of the TEG, and the power obtained and the MPPT performance decrease as the value of the load resistance increases. As a result, it has been observed that the use of load resistors with values up to about three times the internal resistance is more acceptable in terms of performance.

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