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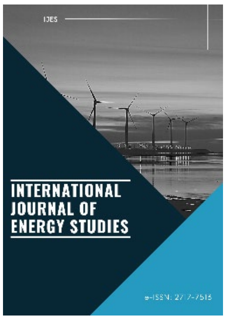

Research Article

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A high-efficiency hybrid energy system composed of fuel cell and thermoelectric generator for light electric vehicles

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Highlights

- A hybrid energy system combining a fuel cell (FC) and thermoelectric generator (TEG) is proposed to enhance efficiency through waste heat recovery without requiring additional fuel input
- The proposed system offers a cost-effective and lightweight solution for sustainable transportation technologies
- The Perturb and Observe (P&O) MPPT-based SEPIC converter is employed to ensure optimal power extraction from the FC, offering buck–boost functionality suitable for light electric vehicle (EV) applications.

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ABSTRACT

This study proposes a more effective utilization of fuel cell (FC) technology by integrating a thermoelectric generator (TEG), which harnesses waste heat to generate electrical energy. While the FC still requires hydrogen, the integration of a TEG enables supplementary power generation from waste heat without any additional fuel input, resulting in a more efficient and compact hybrid system. The Perturb and Observe (P&O) MPPT-based SEPIC converter is highlighted for use in light fuel cell electric vehicle (FCEV) applications due to its inherent buck–boost capability, making it particularly suitable for practical implementations. To achieve maximum efficiency and ensure stable operation of the TEG, the FC is operated at its nominal power of 93.75 W in this system. The integrated TEG system, combined with a high-efficiency boost converter, contributes approximately 5-W to the proposed hybrid energy system, which achieves an overall efficiency of 96.1%. The proposed hybrid energy system holds great potential for providing sustainable energy solutions in transportation applications.

Keywords: Fuel cell, Thermoelectric generator, Hybrid energy system, Electric vehicle

1. INTRODUCTION

The utilization of fossil fuels still plays a major role in the transportation sector and leads to adverse effects such as greenhouse gas emissions, global warming, air pollution, and noise . The overuse of petroleum causes the problems in conjuction with energy security and the long-term sustainability of the transportation sector. These challenges highlight the importance of research on renewable energy not only for the transportation but also other application areas [1], [2]. Fuel cells (FCs) have gained significant interest due to their highly efficient performance and adaptable power output ability among various clean energy sources, especially in transportation sector [3]. To enhance the overall system performance, efficiency, and realibility, the hybridization of FC is essential to adress the limitations of standalone fuel cell systems.

The use of a hybrid energy source approach in conjunction with FCEVs has attracted considerable attention as a means to improve system performance and maximize energy utilization. In hybridization structure of FCs include different energy units such as battery, supercapacitor, photovoltaics, flywheel, and superconducting magnetic energy storage (SMES) [4]. These sources present unique advantages based on the application requirements. While the use of supercapacitor enhances the power density of the FCs, the hybrid system needs complicated control methods to regulate the output voltage and power sharing [5]. Although the utilization of photovoltaic (PV) panels supports the power rating of the system, their implementation tends to be bulky and increases the overall size, making them less suitable for transportation applications [6]. A flywheel can assist FCEV system with a feature of high power density; however, it causes increased overall system size, cost and complex control methods. The SMES offers many advantages, including high power density and enhanced overall system efficiency, despite its increased size and cost [7].

The FCEV sector requires compact and flexible hybrid energy systems to ensure efficient operation in the real scenario. Thus, the TEG enables the conversion of fuel cell waste heat into electrical energy via the seebeck effect, enhancing system power and efficiency without requiring additional fuel or moving parts, unlike other heavy and costly hybrid systems. Therefore, the importance of TEG hybridization has recently increased due to its numerous advantages for the FCEV sector. Caglayan et al. discussed hybrid energy system comprising an FC and a TEG, utilizing a sliding mode controller based MPPT algorithm for both sources to achieve maximum energy extraction [8]. However, FC and TEG system connected to a common load and shared a DC bus that causes technical challenges such as voltage regulation problem and instability under load changes. The authors present a hybrid energy system incorporating PV, FC, TEG, and wind integration, offering flexible energy flow under different environmental conditions [9]. Nevertheless, the complicated system and control complexity are the main problems. There is a significant gap in the literature regarding the integration of TEG and fuel cell systems, particularly for transportation applications.

This paper investigates the TEG-assisted FC hybrid energy system for light EV charging applications to enhance the performance and efficiency of the system. Herein, the significance of SEPIC converter is highlighted together with FC integration such as step up/step down range and continuous input current with low ripple especially for commercial transportation applications. This approach aims to support researchers and pave the way for the commercial implementation of hybrid energy systems in transportation applications.

The rest of the paper is further structured into three more sections. The proposed hybrid energy system architecture is presented in Section 2. Case studies and simulation results are evaluated in Section 3. Finally, the conclusions and future works are presented in Section 4.

2. THE PROPOSED HYBRID ENERGY SYSTEM ARCHITECTURE

The conventional power transmission structure of FCEVs comprise a FC stack with a hydrogen tank together with a unidirectional converter to set the required DC voltage for the system. The auxiliary source is also connected to the system as an optional unit to keep the required bus voltage. In hybridization structure of FCs includes various energy units, and the proposed system distinguishes itself through waste heat utilization and a compact design. The proposed hybrid energy system for light EV applications, is depicted in Fig.1. In this design, PEMFC structure is used due to its high efficiency and quick start-up process [10]. Along with FC, the TEG device is also used to assist FC by using directly conversion of waste heat to electricity. To prevent voltage regulation problem and instable operations under load change, the TEG is designed as an auxiliary power source and FC is designed as a main energy source for the proposed hybrid energy system.

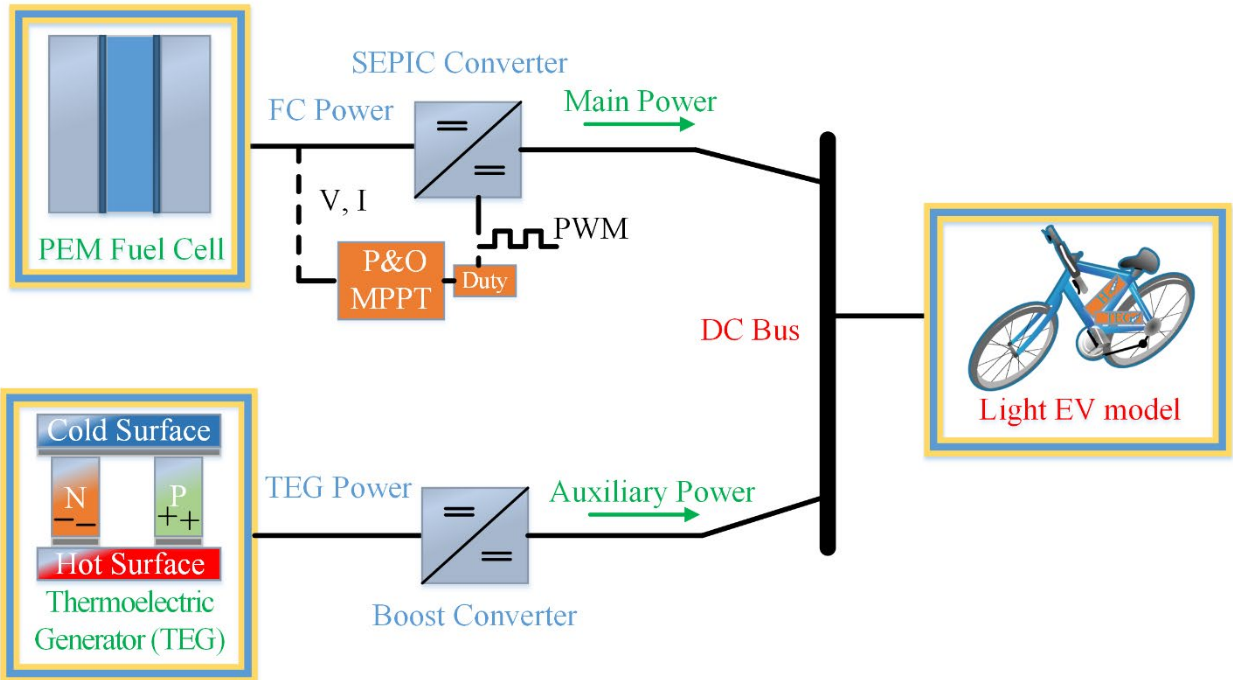


Figure 1. Hybrid energy system for light EV model

2.1. FC powered system design and modelling

The proposed FC powered system design and modelling are conducted in this section. Herein, the proposed system consists of a FC stack connected to a SEPIC converter employing the P&O MPPT method to supply the primary power for the light EV model.

2.1.1. FC stack

The FC is a device that converts chemical energy derived from hydrogen fuel into electrical energy through an electrochemical reaction. The maximum achievable cell voltage of a PEMFC is approximately 0.7 V; therefore, multiple cells are connected in series to obtain the required voltage level [11]. To regulate the output voltage and achieve the desired voltage level, various DC-DC converter topologies have been employed with FCs in the literature [12]. Fig.2 illustrates the conventional equivalent circuit of the PEMFC and Fig.3 presents the voltage (V)&(P) power characteristics of the system versus current (I). The obtained FC voltage is derived and formulated as in Eq.1 [13]. The ideal cell voltage is stated as V_{Nernst} and derived as in Eq.2 , the concentration voltage is referred as V_{Con} and derived as in Eq.3, the activation and ohmic losses are stated as V_{Act} and V_{Ohm}, respectively and determined as in Eq.4 and Eq.5 [14].

$$V_{FC} = V_{Nernst} - (V_{Con} + V_{Act} + V_{Ohm}) \tag{1}$$

$$V_{Nernst} = E_0 - (8.5\ x\ 10^{-4})(T_{FC} - 298.15) + 4.308\ x\ 10^{-5}\ T_{FC}\ In(P_{H_2}\sqrt{P_{O_2}}\ ) \tag{2}$$

$$V_{Con} = -b\ In[1 - \frac{I_{FC}}{I_{Max}}] \tag{3}$$

$$V_{Act} = \xi_1 + \xi_2 T_{FC} + \xi_3 T_{FC} \ln(\frac{P_{O_2}}{5.08\ x\ 10^6\ e^{-(\frac{498}{T_{FC}})}}) + \xi_4 T_{FC} \ln(I_{FC}) \tag{4}$$

$$V_{Ohm} = (R_M + R_C) I_{FC} \tag{5}$$

Here, E_0 denotes the standart reference voltage reported as 1.229 V [15]. T_{FC} represents the FC operating voltage in Kelvin. P_{O_2} and P_{H_2} denote the partial pressures of oxygen and hydrogen, respectively. I_{FC} and I_{max} correspond to the instantaneous and maximum currents of FC, respectively. This symbol ξ represents the empirical coefficients in activation voltage. The resistances R_M and R_C refer to the membrane and contact resistances, respectively.

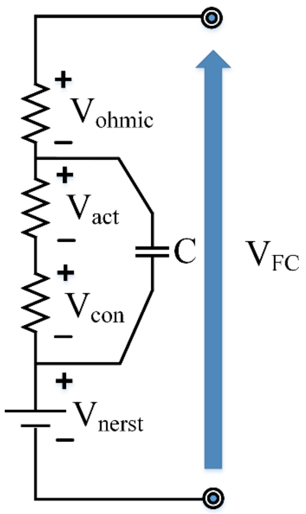


Figure 2. Hybrid energy system for light EV model

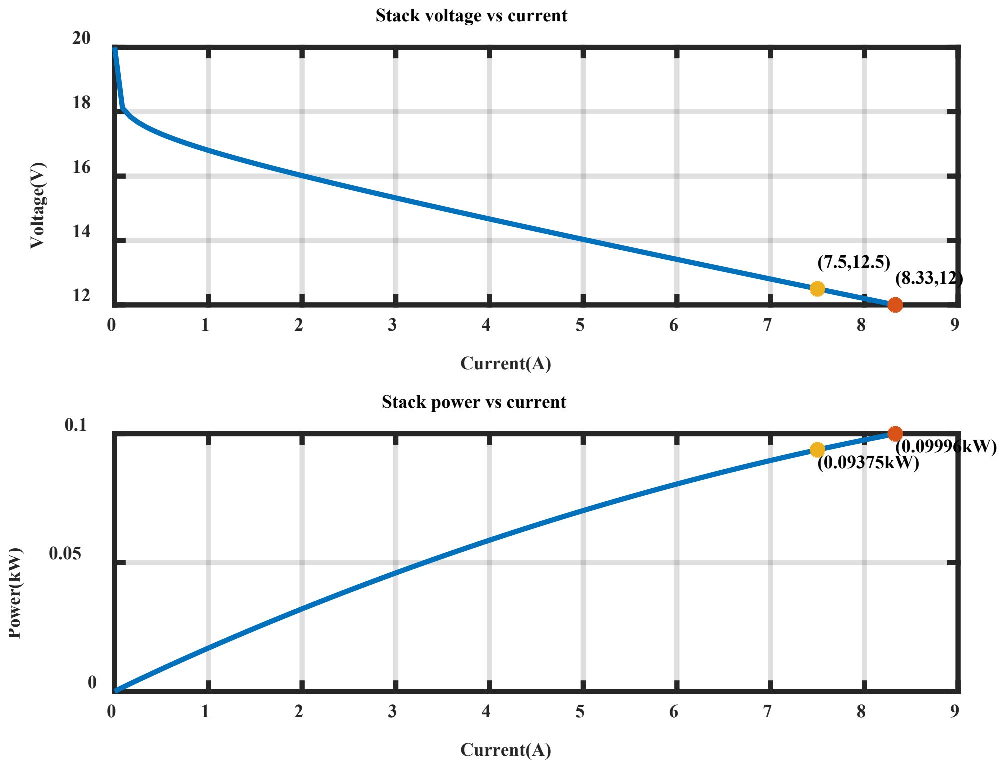


Figure 3. The electrical characteristics of the PEMFC in the proposed system

2.1.1. SEPIC converter design with P&O MPPT

Recently, the output power of the FC stacks has extended to as high as 100 kW ranges in the transportation sector. As the power output of the FC increases, its corresponding output voltage also rises. Due to the fluctuating voltage of the FC caused by load variations or changes in fuel supply, the SEPIC converter stands out compared to other DC-DC converter topologies. In commercial FC applications, the buck-boost type converters are the most suitable option for achieving voltage matching [16]. Due to negative polarity of buck-boost converter and the pulsating input current of Zeta converter, SEPIC converter plays a key role in FC powered transportation applications due to its continuous input current feature. The conventinal SEPIC converter is depicted in Fig. 4. Here, C_{in} and C_{out} are input and output capacitors. The inductors L_1 and L_2 play role in reducing current ripple in the system. C_s is a coupling capacitor that isolates the input side from the output side in the event of a short-circuited load. The role of diode D_1 is to handle peak current levels and endure reverse voltage stress.

The P&O MPPT method offers simple implementation and low computational requirement in renewable energy applications as shown in Fig.5. Due to the slow voltage and current dynamics, this algorithm can be a good candidate for the tracking the MPP in FC powered applications.

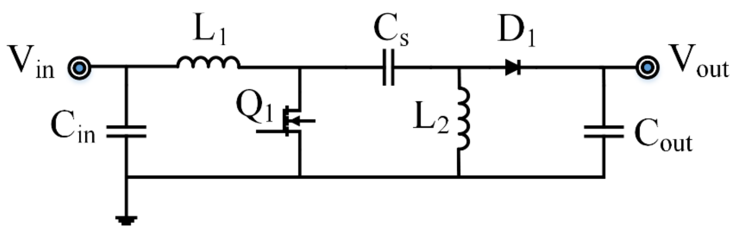


Figure 4. Conventional SEPIC converter topology

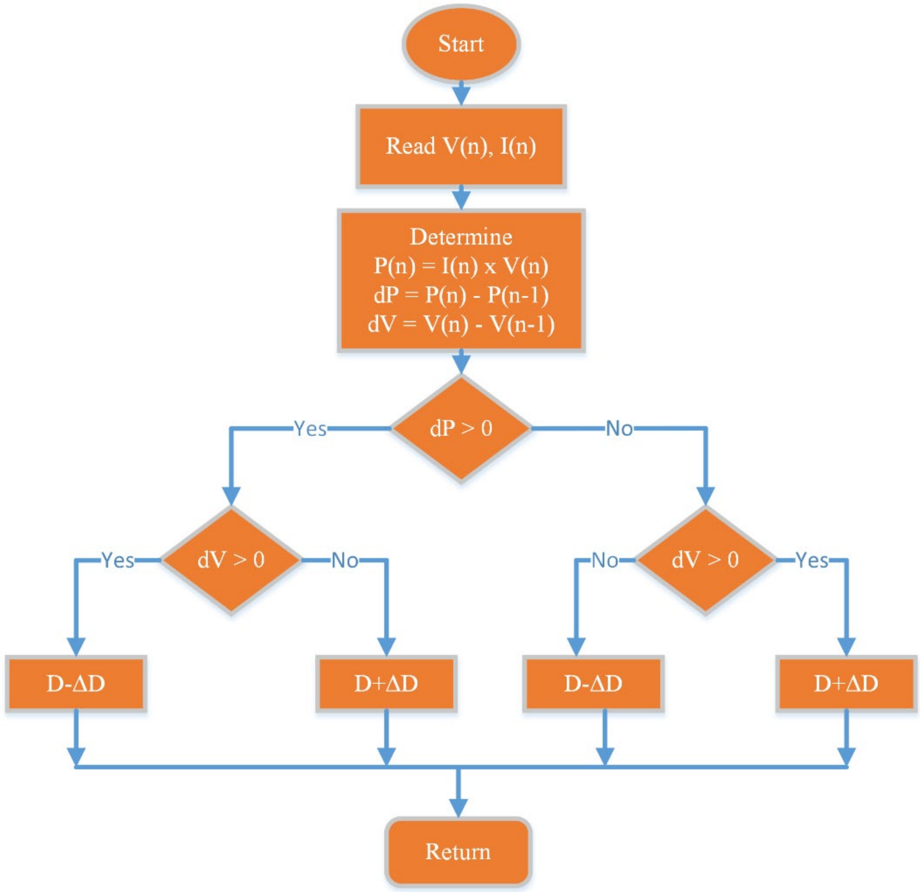


Figure 5. Conventional P&O MPPT method

The design process of a FC powered SEPIC converter operating in continuous conduction mode begins with the determination of the minimum and maximum duty cycles as follows [17]. According to the determined current ripple, inductance values are calculated as in Eq (8-9).The selection of the coupling capacitor is also a critical step, as it isolates the input from the output in the event of a short-circuited load considering Eq. (10) and (11). The input and output capacitances should be appropriately rated to withstand the RMS currents, which are calculated as follows:

$$Dmin = \frac{V_{out}+V_D}{V_{max}+V_{out}+V_D} \tag{6}$$

$$Dmax = \frac{V_{out}+V_D}{V_{in}+V_{out}+V_D} \tag{7}$$

$$\Delta I_L = I_{in} x 40\% = I_{out} x \frac{V_{out}}{V_{in\_min}} x\ 40\% \tag{8}$$

$$L_1 = L_2 = L = \frac{V_{in\_min}}{\Delta I_L\ x\ f_{SW}} x\ Dmax \tag{9}$$

$$I_{Cs\ (rms)} = I_{out}\ x \sqrt{\frac{V_{out}+V_D}{V_{in\_min}}} \tag{10}$$

$$\Delta V_{Cs} = \frac{I_{out} x D_{max}}{C_s x f_{sw}} \tag{11}$$

$$I_{Cin(rms)} = \frac{\Delta I_L}{\sqrt{12}} \tag{12}$$

$$I_{Cout(rms)} = I_{out}\ x \sqrt{\frac{V_{out}+V_D}{V_{in\_min}}} \tag{13}$$

$$C_{out} \geq \frac{I_{out}\ x\ D}{Vripple\ x\ 0.5\ x\ f_{sw}} \tag{14}$$

Herein, V_D denotes the forward voltage drop of the diode, f_{sw} represents the switching frequency, and ΔI_L indicates the inductor current ripple. ΔV_{Cs} denotes the peak to peak ripple voltage on coupling capacitor. $I_{Cin(rms)}$ and $I_{Cout(rms)}$ indicate the rms currents of the capacitors, and C_{out} denotes the determination of the output capacitor value. The parameter values of the designed FC powered system is given in Table 1.

Table 1. Parameter values of the designed FC powered system

Parameter	Value	Unit
PEMFC		
Power rating	100	[W]
Maximum operating values	[8.33, 12]	[A, V]
Nominal operating values	[7.5, 12.5]	[A, V]
Voltage values at (0A, 1A)	[20, 16.8]	[V, V]
Number of cells	20	[-]
Switching frequency	10	[kHz]
SEPIC Converter		
Inductor values (L_1,L_2)	240	[uH]
Capacitor values (C_1,C_2)	300, 2200	[uF]
Duty cycle values (Dmin, Dmax)	(0.479, 0.53)	[-]

2.2. TEG powered system design and modelling

The conventional TEG equivalent circuit is depicted in Fig.6 (a) and the output characteristics of the system is demonstrated in Fig.6 (b). TEG modules composed of TE materials, generate a voltage that is directly proportional to the applied temperature gradient [18]. These materials connected in series to enhance the output voltage and in parallel to enhance the thermal characteristics of the TEG. The application area of TEGs is broad, encompassing a wide range of systems from vehicles to shipboard platforms [19]. The open-circuit voltage, the internal resistances, and the delivered power through the TEG are determined as follows: [20]

$$V_{OC} = N\, \sigma_{TEG}\, \Delta T \tag{15}$$

$$R_{int} = N\, R_{TE} \tag{16}$$

$$P = {V_{OC}}^2 \frac{R_L}{(R_{int}+R_L)^2} \tag{17}$$

Where, V_{OC} is the open-circuit voltage of the TEG, N denotes the series connected TE materials, σ_{TEG} is the seebeck coefficient (V/K), ΔT $(T_h - T_c)$ denotes the temperature difference between hot and cold surfaces in Kelvin. R_{int} denotes the internal resistances of the TEG, and R_L denotes the load resistances of the TEG terminals.

Due to the low-voltage output characteristics of the TEG system, a boost converter is preferred for its voltage step-up capability and simple control structure in the proposed system as depicted in Fig.7. The parameters of the designed TEG powered system is given in Table 2.

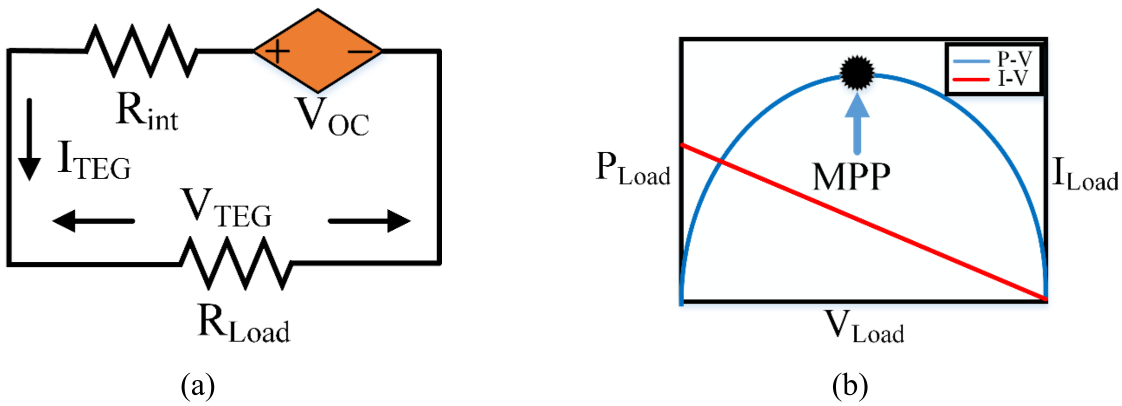


Figure 6. (a) Conventional TEG equivalent circuit, (b) output characteristics of the TEG

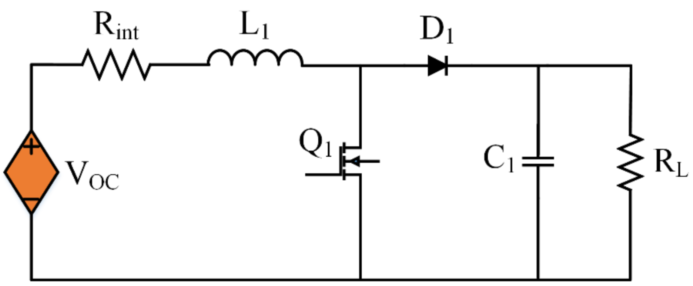


Figure 7. TEG with boost converter topology

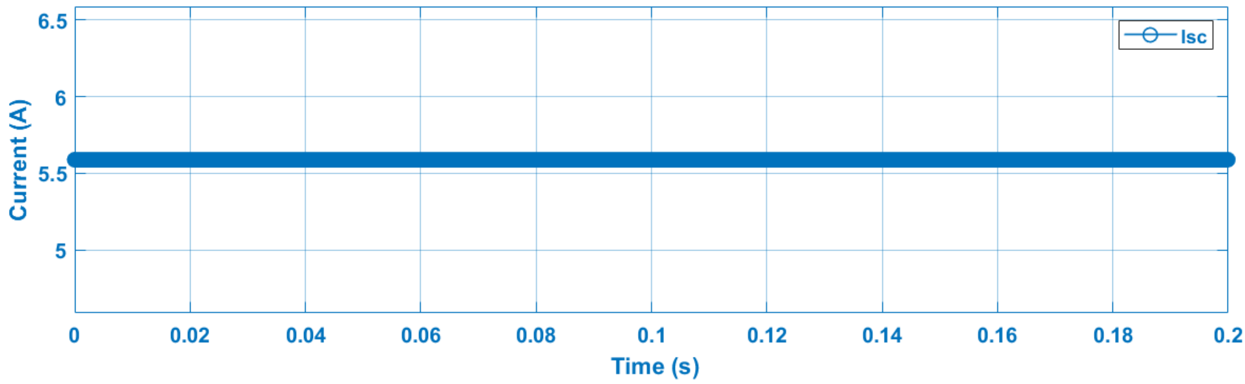
Table 2. Parameter values of the designed TEG powered system

Parameter	Value	Unit
TEG		
Ouput power at MPP	11	[W]
Ouput voltage at MPP	4.1	[V]
Ouput current at MPP	2.8	[A]
Open circuit voltage	8.19	[V]
Short circuit current	5.61	[A]
Internal resistance	1.46	[ohm]
Hot side temperature	200	[degree]
Cold side temperature	30	[degree]
Boost Converter		
Inductor values (L_1)	100	[uH]
Capacitor values (Cin,Cout)	147, 100	[uF]

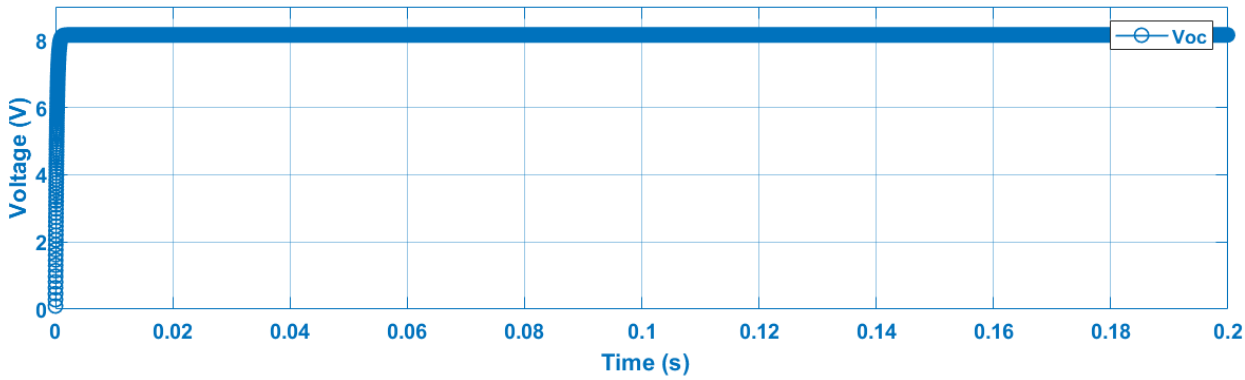
3. SIMULATION RESULTS AND DISCUSSIONS

The performance of the proposed hybrid energy system has been analyzed and discussed in this section. The proposed TEG-assisted FC system is developed and simulated through MATLAB Simulink environment. The system design is based on the data provided by the manufacturer, KRYOTHERM, for the TGM-199-1.4-0.8 module. Figure 8 depicts the open-circuit voltage and short-circuit current measurements based on the manucfacturer datas. The obtained results indicate that the designed TEG system demonstrates good agreement with the manufacturer's data. Due to the low voltage behaviour of the TEG device, three modules have been employed in the proposed system. Thus, the open-circuit voltage is tripled, while the short-circuit current remains unchanged due to the series connection of the modules.

In the linear region of the FC, voltage stability is enhanced and efficiency is improved due to reduced activation, ohmic, and concentration losses. Therefore, the SEPIC converter is designed to operate the FC in the linear region. As shown in Fig. 9, the output voltage of the converter reaches around 15 V, which is consistent with the theoretical expectation. The output power of the FC powered system is shown in Fig.10 (a), while the output power of the hybrid system is depicted in Fig.10 (b). Thus, the designed TEG system contributes approximately 5 W of output power to the hybrid system. The mean efficiency of the hybrid system is also measured around 96.1 % that is highly suitable for the transportation applications.



(a)



(b)

Figure 8. TGM-199-1.4-0.8 module: (a) short circuit current, (b) open circuit voltage

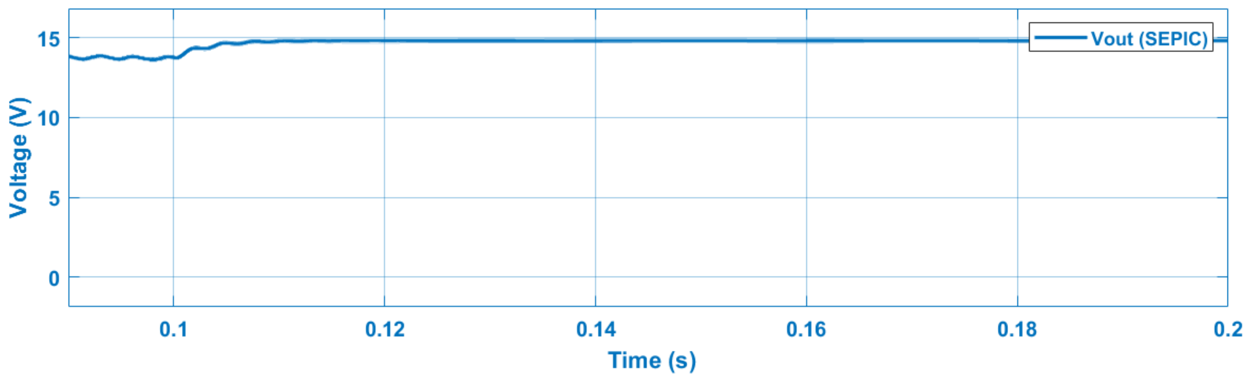
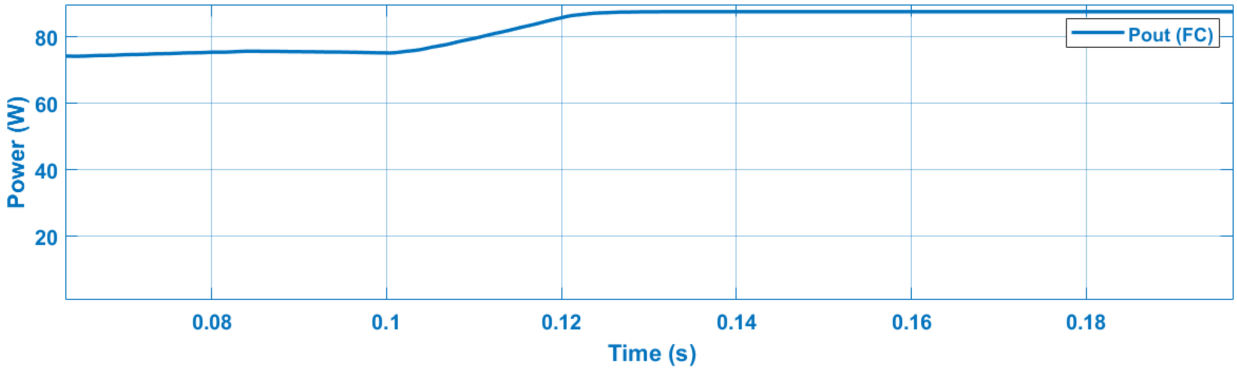
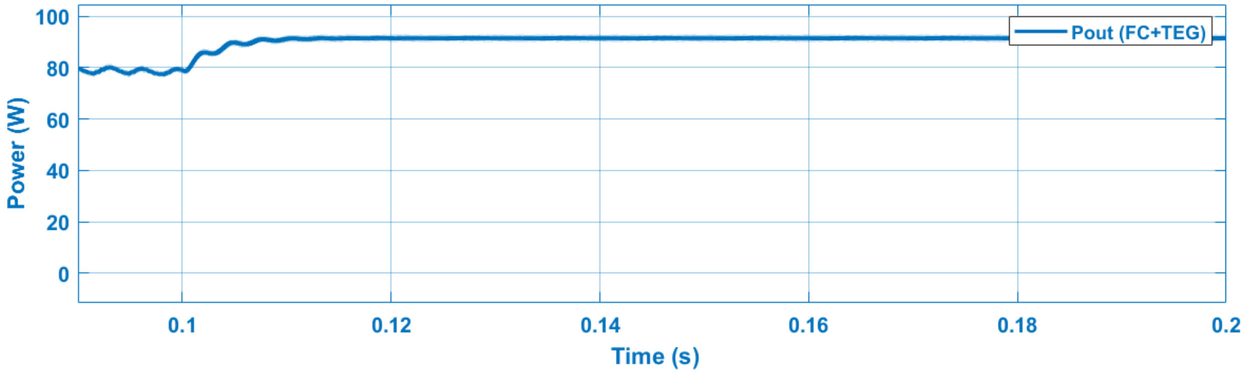


Figure 9. SEPIC output voltage



(a)



(b)

Figure 10. Output power: (a) FC powered system, (b) hybrid powered energy system

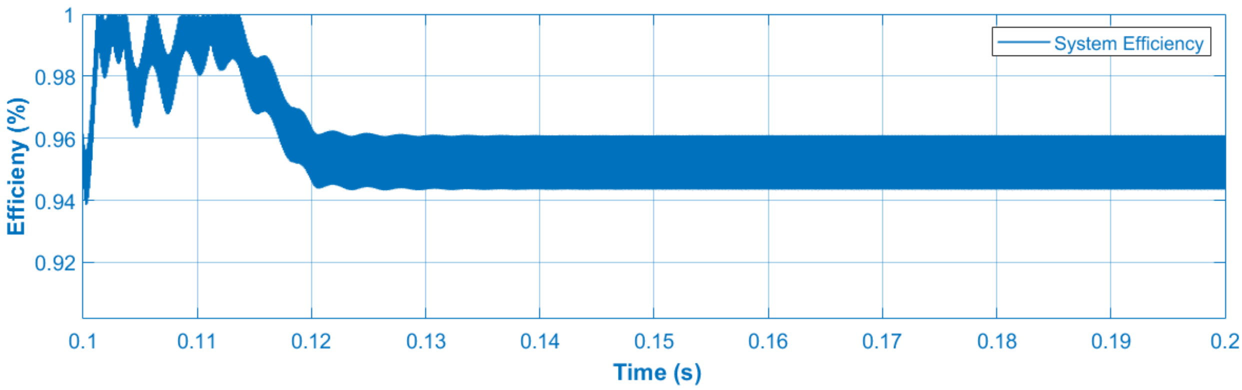


Figure 11. System efficiency

4. CONCLUSION

In this study, a systematic analysis of the TEG-assisted FC hybrid energy system is presented within the context of a light EV model. A 100-W FC stack is designed to operate at its maximum power point using a conventional SEPIC converter, which maintains the system within the linear region due to its buck-boost capability. The integrated TEG module contributes around 5-W of output power to the hybrid energy system. The average efficiency of the hybrid energy system is measured at 96.1%, demonstrating the suitability of the proposed light EV model. Compared to other heavy and costly FC hybridization methods, the proposed system enhances overall power and efficiency by converting fuel cell waste heat into electrical energy, without the need for additional fuel or moving parts. Future work will focus on the optimal design of the hybrid energy system using a modified SEPIC converter to achieve a wide voltage conversion range and high efficiency for practical applications.

DECLARATION OF ETHICAL STANDARDS

The author of the paper submitted declares that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Mehmet Zahid Erel: Conceptualization, system modeling, simulation, manuscript writing

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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