Energy Conversion and Management 177 (2018) 55–63

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Energy management for thermoelectric generators based on maximum power point and load power tracking

Shi-jun Wu, Shuo Wang, Can-jun Yang*, Ke-ren Xie

State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, Hangzhou 310027, China

ARTICLE INFO

Keywords:
Energy management strategy
Supercapacitor
Load power tracking
Fuzzy logic
Maximum power point tracking

ABSTRACT

Thermoelectric generators (TEGs) can be widely applied to directly convert thermal energy into electricity. Herein, we propose an energy management system for TEGs to achieve efficient energy storage and use. Specifically, we consider both the generally unstable power generation given the variable temperature difference between the hot and cold sides of TEGs and the variable load that requires the inclusion of a storage unit consisting of a battery and supercapacitor for improving the system performance. The supercapacitor mitigates energy fluctuations and reduces transients in the bus voltage, and the battery acts as a backup energy source, storing energy and delivering electricity when the load power demand is high. In addition, we propose a novel threshold control strategy based on the bus voltage intervals for the energy management system that incorporates maximum power point tracking (MPPT) and load power tracking (LPT) to maintain energy balance among the system units. MPPT aims to provide an efficient collection of thermal energy, and LPT based on fuzzy logic is used to maintain a stable bus voltage when the DC load power demand is low. The experimental results verify that the proposed LPT approach regulates the evaluated variations in DC load power with an average error of 3.5% and that the energy management properly operates under variable load power and battery state of charge.

1. Introduction

Public interest on renewable energy sources is increasing due to growing concerns for environmental protection, and solar, wind, and hydrogen energy sources have been exploited and developed for many years [1]. Recently, thermal energy has been used as a suitable power source for various applications [2]. Thermoelectric devices convert thermal energy into electricity according to the Seebeck effect, and thermoelectric generators (TEGs) provide a clean, convenient, safe, and environmentally friendly energy solution.

TEGs have been applied in areas such as electricity generation in extreme environments, waste heat recovery in transportation and industry, domestic production in different countries, microgeneration for sensors and microelectronics devices, and solar thermoelectric generation [2], and specific solutions have been developed [3–7]. To improve TEG efficiency, optimization of the generation and dimensions of segmented TEGs has been proposed [8]. Many fundamental studies on thermoelectricity using low-cost materials and thermoelectric processing schemes have also been carried out [9–11]. Likewise, to predict TEG performance, a transient model based on the coupling of electric conduction and heat transfer has been derived [12]. Moreover, maximum power point tracking (MPPT) has been constantly improved to increase the generation efficiencyof TEG modules [13–16].

Nevertheless, TEGs still exhibit some limitations that prevent their widespread use. For instance, TEGs provide an unstable energy supply under varying thermal conditions, thus requiring energy management to regulate power generation. Likewise, the generally dynamic load demand requires additional storage devices for the mitigation of power fluctuations. The development of suitable energy management strategies can enhance the performance of TEGs and other systems, as demonstrated in areas such as photovoltaic generation and hybrid energy systems [17–19]. In [17], the authors investigate a power management architecture that utilizes both supercapacitor cells and a lithium battery as energy stores for a photovoltaic-based wireless sensor network. This shows that hybrid energy storage dramatically reduces the number of charge/discharge cycles of the battery, thus improving the battery lifetime. In [18], a diesel generator is introduced as another backup power beside of the photovoltaic generation, battery and supercapacitor, and an energy management strategy is proposed to achieve coordination between these sources. Furthermore, a hybrid system composed of a fuel cell, photovoltaic panel, battery and supercapacitor is also proposed. Energy management is focused on the maximum

---

* Corresponding author.
E-mail address: ycj@zju.edu.cn (C.-j. Yang).

https://doi.org/10.1016/j.enconman.2018.09.040
Received 7 May 2018; Received in revised form 3 September 2018; Accepted 12 September 2018

power point tracking of each source [19].

Compared to energy management of photovoltaic generation, energy management for TEGs has not been extensively developed thus far. In [20], the authors propose a power management circuit featuring an ultralow-power controller and a Dickson charge pump with a variable number of stages as a DC/DC converter. In [21], the authors present a micropower DC/DC upconverter and a controller chipset for a miniature thermogenerator. Both of these publications are dedicated to developing the ultralow-power management integrated circuits for micropower TEGs. Hybrid energy storage and management strategies for TEGs have not been discussed.

In many scenarios, there is a need to use TEGs to power a standalone system with varying load power demand. For instance, a seafloor observatory contains a variety of sensors and instruments that operate at different power levels and time periods. Therefore, the load power periodically changes over a great range. The thermal energy of seafloor hydrothermal vents can be exploited to power seafloor instruments [3,4]. However, the temperatures of the heat source and heat sink in such extreme environments are not stable. Hence, it is necessary to investigate broader energy management solutions for guaranteeing resilience under varying loads in extreme environments while extending the system lifetime.

In this paper, we propose an energy management system for TEGs involving hybrid energy storage to handle varying temperature and load conditions. Unlike in the abovementioned research, the following improvements are achieved in the present work. First, the supercapacitors are directly connected to the bus to stabilize the bus voltage and assist maximum power point tracking of the TEGs, thus simplifying the architecture design. Second, a novel threshold control strategy based on the bus voltage intervals for the energy management system is proposed. This strategy combines MPPT and load power tracking (LPT) to properly distribute the energy generated by the TEGs to the storage and consumption units in complicated load conditions. The paper is organized as follows. Section 2 describes the energy management system and storage unit operation. Section 3 details the proposed control strategy and LPT based on fuzzy logic. The experimental results are presented in Section 4. Finally, the conclusions are presented in Section 5.

2. System architecture

The proposed energy management system consists of a controller, a hybrid energy storage system composed of a battery and supercapacitors, and a DC/DC converter. Fig. 1 shows that the energy produced by the TEGs is transferred from the input of the DC/DC converter to the bus directly connected in parallel to both the load and supercapacitors, through an interface circuit unit to the battery. By using the energy management strategy, the DC/DC converter realizes MPPT or LPT depending on the system status. In addition, the supercapacitors store extra power for the bus, absorb fluctuations, and assist in MPPT, whereas the battery is used a backup power source due to its high energy density [22]. When the DC load is low, the battery is charged by thebus, and when the DC load is high and the TEGs cannot supply the required power, the battery discharges through the interface circuit to the bus to stabilize the bus voltage.

2.1. DC/DC converter

The buck converter illustrated in Fig. 1 is the main component of the proposed energy management system. The input voltage V_{in}, open-circuit voltage V_{oc}, bus voltage V_{bus}, and output power P_g are regularly monitored by the controller, and the buck converter can operate in MPPT, LPT, or be disconnected from the bus. The relation between V_{in}, V_{bus}, and duty cycle D of the pulse width modulation (PWM)signal is given by

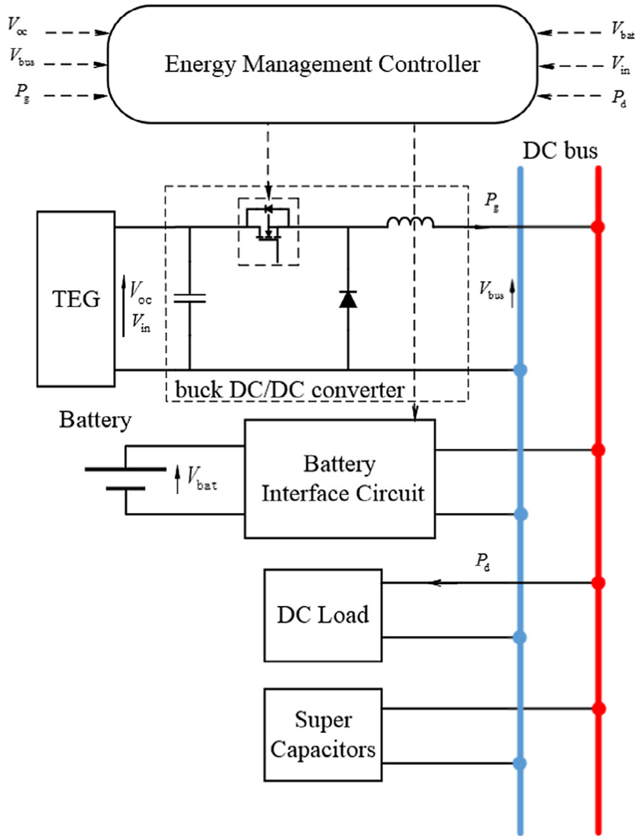

Fig. 1. Architecture of the proposed energy management system for TEGs.

$$\frac{V_{bus}}{V_{in}} = D \tag{1}$$

2.2. Supercapacitor

The supercapacitors are another essential component in the proposed energy management system because they are efficient and have a high lifetime in terms of charge–discharge cycles [23]. In addition, supercapacitors can reduce bus voltage oscillations and absorb energy fluctuations due to their fast response and high power density [22]. In our approach, supercapacitors also assist MPPT, as explained in Section 3.3.

2.3. Battery

The state of charge (SOC) is used to determine the energy stored in the battery based on the open-circuit voltage. The SOC of a lead–acid battery can be calculated by

$$\mathrm{SOC(t)} = \frac{V_{bat_{OC}}(t) - V_{bat\_min}}{V_{bat\_max} - V_{bat\_min}} \tag{2}$$

where $V_{bat_{OC}}(t)$ is the battery open-circuit voltage and V_{bat_min} and V_{bat_max} are the open-circuit voltages when the battery is fully discharged and charged, respectively [24]. Hence, $V_{bat_{OC}}(t)$ determines the energy stored in the battery [25].

Voltage thresholds can be used to indicate the values at which the fully discharged and charged states are prevented. For instance, an overvoltage threshold $V_{bat\_max\_th}$ can be set to $0.9V_{bat\_max}$ and an undervoltage threshold $V_{bat\_min\_th}$ can be set to $1.1V_{bat\_min}$. Consequently, when $V_{bat_{OC}}(t) < V_{bat\_min\_th}$, the battery is in an undervoltage condition; when $V_{bat_{OC}}(t) > V_{bat\_max\_th}$, the battery is in an overvoltage condition; and when $V_{bat\_min\_th} < V_{bat_{OC}}(t) < V_{bat\_max\_th}$, the batter is in a normal state.