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Bidirectional operation of the thermoelectric device for active temperature control of fuel cells

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HIGHLIGHTS

- The TE device's dual nature is used for temperature control and energy harvesting.
- The TEC mode is used to achieve active temperature control.
- The TEG mode is used to achieve energy harvesting about the optimal temperature.
- Simulations of the proposed system are conducted on MATLAB/Simscape.
- An experiment using hardware is presented to verify the proposed concept.

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ABSTRACT

The thermoelectric (TE) device enables a conversion interface between the heat transfer and the electricity domain. Specifically, it can operate bi-directionally – Heat can be converted to electricity via the thermoelectric generator (TEG) effect and vice versa via the thermoelectric cooling (TEC) effect. In most state of the art research, the TE device is operated either in the TEG mode or TEC mode but very seldom in both modes for a single control objective. This paper proposes a thermal management system for a fuel cell who exploits the bi-directional characteristics of the TE device to achieve both temperature control and the possibility for energy harvesting when active control is not required. The studied scenarios involve a time-based simulation involving heat generation levels that are typical of a 500 W rated operating proton exchange membrane fuel cell (PEMFC). The overall dynamic system is simulated using Simscape library components in Simulink and the controller itself is implemented using MATLAB s-functions. An experiment involving electric heaters to emulate the fuel cell's body heat is also conducted to verify the proposed combined TEG-TEC control approach.

1. Introduction

The thermoelectric (TE) device is a renewable energy technology who can generate electricity from a temperature gradient via the Seebeck effect (often also known as the thermoelectric generator (TEG) effect). The TE device can also generate a temperature gradient (hence pump heat power from the cold side to the hot side) if an electric current is applied. Operation in such a mode is based on the Peltier effect and is often known as the thermoelectric cooling (TEC) effect.

In comparison to other heating or cooling methods, the TE device is especially recognized in literature in that it is a robust, clean and noiseless electric power generator which does not require any active moving parts [1–3]. In terms of the TEG mode, applications include but not limited to the recovery of waste heat from automotive exhaust systems [4,5], the solar thermoelectric hybrid power system [6–8], hypersonic engines [9] and fuel cells [10]. Performance via the Seebeck effect is generally characterized by the thermocouple material characteristics and is quantified by using the ZT parameter where $ZT = \frac{\alpha^2\sigma}{\lambda}$. Here, α is the Seebeck coefficient, σ is the electrical conductivity and λ is the thermal conductivity. A larger value of ZT represents better Seebeck effect performance, therefore, research in the thermoelectric material field is committed to increase α, σ while minimizing λ [2,11,12]. In addition to materials research, the geometric design of the thermocouples, number of thermocouples and the TE device deign itself is also found to have significant impacts on the Seebeck performance [13–15]. For instance, the multi-objective optimization of the TEG in terms of the aforementioned parameters has been presented in various publications such as Refs. [14,16]. Exergy analysis of the TEG device is

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Nomenclature

α	seebeck co-efficient (V/K)
σ	electrical conductivity (S/m)
λ	thermal conductivity (W/(mK))
r_{TEG}	internal electrical resistance of a single thermocouple of the TEG (Ω)
R_{TEG}	total internal electrical resistance of the TEG (Ω)
n	number of thermocouples in a single TE module
n_t	total number of thermocouples in the overall TE device
N_p	number of parallel connected strings of TE modules in the device
N_s	number of series connected strings of TE modules in the device
l	length of Thermocouple (m)
A	surface Area (m^2)
T_{FC}	fuel cell body temperature (K)
T_1	temperature of TE device that is at the fuel cell side (K)
T_2	temperature of TE device end that is at the cooling side (K)
T_{amb}	temperature of the ambient environment (K)
Q_H	total heat flowing from the fuel cell to the TE device (W)
Q_L	total heat flowing from the TE cold side to the flow water of the liquid cooling system (W)
Q_L	total heat flowing from the TE device to the ambient environment (W)
Q_α	heat flowing because of the Seebeck Effect (W)
Q_K	heat flowing because of Fourier thermal conduction (W)
Q_J	heat flowing because of the Joules effect (W)
A_{In}	total TE contact area with fuel cell (m^2)
A_{Out}	total TE contact area with ambient environment (m^2)
A_{Module}	surface area of a single TE module (m^2)
E_{FC}	fuel cell heat energy storage buffer (J)
E_{HS}	heat sink heat energy storage buffer (J)
I_{TE}	TE device operating current (A)
V_{TE}	TE device operating voltage (V)
$V_{TE(OC)}$	TE device open circuit voltage (V)
i	current flowing through one string of TE modules in the device (A)
V_{OC}	open circuit voltage of the TE device (V)
I_{SC}	short circuit current of the TE device (A)

Subscripts and superscripts

p	p-type type thermopile
n	n-type type thermopile

Abbreviations

TE	thermoelectric
TEG	thermoelectric Generator
TEC	thermoelectric Cooler
PEMFC	proton exchange membrane fuel cell
LT-PEMFC	low temperature proton exchange membrane fuel cell
HT-PEMFC	high temperature proton exchange membrane fuel cell

also popularly considered with example references being that of Refs. [9,17]. Other publications also deal with the electronics aspect of the TEG where Ref. [18] deals with the side effects of mismatch between multiple TE devices connected in series or parallel. It is worth noting most previously presented publications such as the ones aforementioned analyze the TEG by using steady state models. The small signal model of the TEG was also proposed recently in Ref. [19] where it extended the DC model of the TEG into the dynamic regimes.

The TEG is also very popularly considered in energy harvesting applications because the device can virtually be used passively to extract electrical energy from a heat source without the requirement of any moving parts. A popular application is that of energy harvesting from a human body in Refs. [20–23], which are used to power portable waistbands that are typically used for health monitoring purposes. Specifically, Ref. [23] focused on using the human body as a heat source to power an accelerometer whereas Ref. [22] investigated the potentials of using inorganic bulk materials for the same application. The TEG has also been applied in Ref. [24] to power sensors that monitor a gas turbine's health by energy harvesting from the gas turbine itself. In this context, the requirement for long and numerous power cables to supply power to each individual sensor can be eliminated, thus increasing the reliably of the sensing equipment. TEG based energy harvesting systems to harvest energy from asphalt pavements have even been studied recently in Ref. [25] where it was shown that up to 160kWh energy could be recovered in a day for a 1 km length and 10 m width road. Overall, energy harvesting is very beneficial in that it can reduce the charging requirements on batteries, eliminate wired power connections that are otherwise necessary in conventional implementations or even reduce the size requirements of grid level power plants.

In terms of the TEC mode, applications include the active cooling of photovoltaic (PV) cells [26], power electronic switches [27], high powered LEDs [28] and fuel cells [29]. Performance characterization in the TEC mode is often quantified using the co-efficient of performance (COP), the maximum cooling capacity and the maximum allowable operating current in the TEC mode [30]. Similar to the TEG case, performance in the TEC mode is also sensitive to that of the three thermocouple material characteristics α, σ and $\lambda$and also the thermocouple numbers and geometric design [26]. The control of the TE device in the TEC mode from the electronics perspective is also considered in Ref. [27] for active temperature control. Moreover, Ref. [31] proposed using the supercooling effect in a two-stage TE device where the supercooling effect involves using large amplitude current pulses to improve the transient response in the TEC mode. Recently, the study of the TEC as a thermoelectric energy conversion unit (TECU) for both heating and cooling has been conducted in Refs. [32,33] by using steady state models. Here, active air cooling is applied to both the cold and hot sides of the TEC module and the subsequent exhausted air are used separately to achieve the respective cooling and heating functions.

In the meantime, the proton exchange membrane fuel cell (PEMFC) is attractive for the automotive application where the key features include low operating temperature and low maintenance requirements [34]. However, the PEMFCs have a narrow operating temperature range where a low temperature (LT) variant typically operates within 60 °C to 95 °C and at a nominal value of ≈80 °C [35]. Analogously, the high temperature (HT) variant operates in the range of 120 to 180 degrees Celsius with nominal values at ≈160 °C [36]. Such prescribed operating temperature ranges typically exist as a trade-off between increased efficiency due to the increasing temperature and issues regarding the membrane properties at high temperatures [36]. In addition to the operating temperatures, PEMFCs operate with conversion efficiencies in the order of 40–55% which means a significant amount of heat is generated during operation. Thus, it is important to provide an effective thermal management system for the PEMFC so that it can retain its optimal output efficiencies and reliability. A common cooling technique for the PEMFC is that of using the oxygen supply fan [37] but this method typically lacks versatility because it couples together the cooling and oxygen supply dynamics. Thus, for higher power applications (> 1 kW), external active liquid or gas cooling systems are more commonly adopted [38]. Recently, the application of the TE device into