



Complementary performance enhancement of PV energy system through thermoelectric generation



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ABSTRACT

The solar insolation received on earth have different components in which power is embedded. Out of many, visible spectrum and thermal spectrum are separately used to harvest energy through solar thermal or solar photovoltaic systems respectively. Photovoltaic (PV) panels are reported to experience undesirably high temperature rise due to heat accumulation from solar radiation which is not actively converted into electricity. This undesirable heat decreases conversion efficiency of PV panels. Thermoelectric module (TEM) in coordination with PV panel is proposed to recover and convert this waste heat energy to useful electrical energy. This paper demonstrates the capability of proposed system for electrical power generation from waste heat developed in PV panel in addition to generation from PV systems. Dynamic model of photovoltaic thermoelectric hybrid (PTH) system is developed in SIMULINK/MATLAB environment based on electrical and thermal characteristics of the material. Simulation results for maximum energy harvesting for PTH system are presented under dynamic perturbations in solar radiations. Proposed control scheme ensures maximum energy harvesting without allowing system to operate at temperature out of prescribed limits for PV or TEM. It has been observed in the simulation that PTH system effectively handles the load and source transitions, which validates the scheme.

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1. Introduction

Energy requirement is increasing at an alarming rate and world is facing critical problems regarding energy deficiencies. Solution to this situation lies in shifting on dependencies of energy requirement from conventional energy sources to renewable energy sources. Solar energy, a clean and abundantly available renewable source of energy is seriously being researched as strong

Abbreviations: PV, Photovoltaic; TE, Thermoelectric; TEM, Thermoelectric module; TEC, Thermoelectric cooler; TEG, Thermoelectric generator; PTH, Photovoltaic Thermoelectric Hybrid; MPP, Maximum power point; MPPT, Maximum power point tracking

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Nomenclature

a	Short circuit current temperature coefficient (%/C)
C_{mod}	Heat capacity of module (J/kg K)
G	Solar irradiance (kW/m ²)
I	TEG current (A)
I_d	Diode current (A)
I_L	Light generated current (A)
I_0	Reverse saturation current of a diode (A)
I_{pv}	PV cell current (A)
I_{sc}	Short circuit current of the PV cell (A)
k	Boltzmann's constant (1.38×10^{-23} J/K)
K	Thermal conductance of TEG (W/K)
K_1	Thermal conductance between thermoelectric generator and heat source (W/K)
K_2	Thermal conductance between thermoelectric generator and heat sink (W/K)
n	Diode ideality factor (typically between 1 and 2)
q	Electric charge (1.69×10^{-19} C)
q_{conv}	Convected heat (W)
q_{cond}	Conducted heat (W)

q_h	Heat transfer from the heat source to the TEG(W)
q_c	Heat transfer from TEG to heat sink(W)
q_{rad}	Radiated heat (W)
q_e	Heat at hot side of TEG (W)
R_s	Series resistance (Ω)
R_{sh}	Parallel resistance (Ω)
T	Absolute temperature (K)
T_{amb}	PV module temperature (K)
T_{ref}	Reference temperature (K)
T_a	Temperature of heat absorbing junction of TEG (K)
T_e	Temperature of heat emitting junction of TEG (K)
T_h	TEG Hot side temperature (K)
T_c	TEG cold side temperature (K)
$T_p(x)$	Temperature at specified length of TEG (K)
V_{pv}	PV Output voltage (V)
V_{TEG}	TEG output voltage (V)
w_s	wind speed (m/s)
α	Seebeck coefficient (V/K)
$\alpha(T)$	Seebeck coefficient at specified temperature(V/K)
$\alpha(x)$	Seebeck coefficient at specified length of TEG (V/K)

contender for future energy solutions. Photovoltaic (PV) system is noiseless, free of moving parts having less maintenance and operational costs and can be produced near load centers, hence can be efficiently utilized and integrated in power systems.

Conversion efficiency of commercial PV modules has been reported very low in the range of 12–18% [1]. PV technology utilizes only visible spectrum of solar insolation, whereas the infrared (IR) spectrum is converted into heat which in turn increases the operating temperature of solar PV system and adversely affect its power generation. In summers temperature of the panel reaches 243–253 K while acting as virtual black body [2–3]. This unwanted heat cannot be recycled effectively by conventional methods. Since heat generated in PV system is low in temperature and low in density, thus conventional thermodynamic cycles cannot be used for the generation of electrical power. Thermoelectric (TE) generation technology appears to have advantages in this area of low grade waste heat recovery. Thermoelectric module can be used as a Thermoelectric Generator (TEG) to produce electric power when temperature gradient is available.

Thermoelectric technology is reported as waste heat recovery system in automobiles reusing the waste heat from internal combustion engine and using it for electrical work [4–5]. Author [6] developed the thermoelectric waste heat recovery system using 24 TEG modules. This system is connected to the exhaust pipe of automobiles and results show that 12.41 W electrical power is generated for the temperature difference of 30 K. Although conversion efficiency of TEG is very small, TEG find its application as waster heat recovery system; as the input thermal energy is available at no cost then low conversion efficiency is not a serious issue. In such cases thermoelectric converters have not only demonstrated potential scope but proved to most economical and viable option of power generation. Thermoelectric technology being environment friendly and categorized under green technology is strongly advocated for increased use in day-to-day life [7–11]. It has been reported in the literature that thermoelectric figure of merit for thermoelectric (TE) modules fabricated using quantum wall (QW) and quantum dot (QD) technology may be greater than the bulk value [12–13] which can increase the conversion efficiency of TE modules. Hi-Z technologies have developed the TE module with figure of merit four times more than currently available materials [14]. A case of PV, TE and thermal

hybrid system reported to have enhancement in electrical power output with high efficiencies [15]. Research is reported in PV-TE hybrid system both for material and balance of systems [16–20] presenting the possibility of PV-TE integrated system.

The hybridization of PV-TE as integrated module is in the initial stage of research with no substantial and proven power electronic circuits so far reported for cogeneration with such different sources. This paper deals with a dynamic model devising converters for integrating PV and thermoelectric generators (TEG) for optimum performance. A MATLAB/SIMULINK based model of TEG and photovoltaic thermoelectric hybrid (PTH) in two dimensions (both in time and space), compatible with SimPowerSystem (SPS) is developed to explore the interface with power converter circuits to produce usable form of electricity. A maximum power point tracking (MPPT) system is also proposed which operates both PV system and TEG at respective maximum power point (MPP) and evacuates maximum energy developed by PTH. The MPPT controller corroborates each other such that operating point settles down to a temperature quickly to extract the maximum energy from the system. The presented simulation result demonstrates the effectiveness of the control scheme to produce power with increased efficiency. The rest of the section in this paper is organized as follows: in Section 2 architecture of PTH system is described; Section 3 explains the governing equations for PV operation and computational model developed for maximum power point tracking; Section 4 introduces modeling of TEG system considering temperature dependent parameters of TEG along with converter and current controller; Section V explains the integration of PV and TEG system using power converter interface; Section 6 presents computational results of PTH system and Section 7 concludes the paper.

2. System configuration

For purpose of power generation, TEG is attached to the rear side of PV panel. Temperature difference between panel and ambient provides opportunity for TEG to operate in generator mode. Heat is utilized in TEG which otherwise would have got rejected into the environment as a waste heat. A virtual heat pump thus created allows lowering the temperature of PV panel which in

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