World Electric Vehicle Journal Vol. 3 - ISSN 2032-6653 - © 2009 AVERE

EVS24
Stavanger, Norway, May 13-16, 2009

Design and Implementation of a Thermoelectric-Photovoltaic Hybrid Energy Source for Hybrid Electric Vehicles

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Abstract

With ever-increasing demand on energy conservation, there is fast growing interest in the technologies to improve the fuel economy for hybrid electric vehicles (HEVs), especially the exhaust gas waste heat energy recovery. Meanwhile, the use of solar energy in HEVs is also proposed to promote on-board renewable energy and hence improve their fuel economy. In this paper, an overview of on-board renewable energy sources is first presented. Then, a new thermoelectric-photovoltaic hybrid energy source is designed and implemented for HEVs. Finally, experimental results are given to verify the validity of the proposed system.

Keywords: HEV, hybrid energy source, renewable energy, energy recovery.

1 Introduction

With ever-increasing oil consumption and concern of environmental protection, there is fast growing interest in hybrid electric vehicles (HEVs) globally [1]. Compared to the internal combustion engine vehicle (ICEV), the HEV is more energy efficient due to the optimization of engine operation mode and recovery of kinetic energy into electricity [2]. Moreover, more electrical energy from the vehicle system can satisfy the higher electricity demand because of the installation of the air conditioner, the safety control system, and other miscellaneous vehicle-borne electronic devices [3]. So there is a pressing need to develop energy-efficient power sources for HEVs, including the on-board sole energy and hybrid energy sources [4], [5], as well as renewable energy sources, such as the waste heat recovery technology [6]-[8], wind energy [9]-[15], and solar energy conversion [16], [17].

As shown in Fig. 1, in a typical energy flow path of the ICEV, only about 25% of the fuel combustion energy is utilized to propel the vehicles, whereas about 40% is wasted in the form of waste heat of exhaust gas [7], [18]. It means that the fuel economy of ICEV can be increased by up to 20% simply by capturing the waste heat of exhaust gas and converting about 10% of it to electricity with thermoelectric (TE) modules. Consequently, the research on waste heat energy recovery of the exhaust gas in HEVs has been actively conducted in recent years [3], [6], and [18]-[20]. Furthermore, the thermoelectric generator (TEG) has unique advantages of being maintenance free, silent in operation, independent on weather or topography and involving no moving and complex mechanical parts, compared with other power generators such as the gasoline generator, and wind turbine [21]-[24].

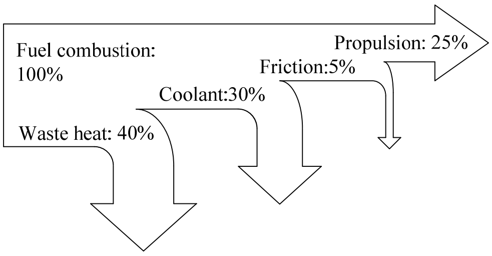


Figure 1: Typical energy flow path in an ICEV.

Benefited from the Seebeck effect, the TE modules can directly convert the heat energy to electrical energy. However, since the output power characteristics of the TEG are highly nonlinear and heavily depend on the heat source, cooling system, and external load, a proper power conditioning circuit and maximum power point tracking (MPPT) control are required [3]. On the other hand, the use of solar energy has been proposed for HEVs so as to promote the concept of on-board renewable energy and hence further improve their fuel economy. However, similar to those of the TEG, the output power characteristics of the photovoltaic (PV) panel are highly nonlinear and heavily depend on the irradiance, ambient temperature, and external load, a proper power conditioning circuit and MPPT control are also required.

Unfortunately, the PV array panel and TEG need to be separately operated now, even though they are installed in a same HEV. It means that two set of controlling units, DC-DC converters, charging battery packs, and even DC-AC inverters are needed, resulting in high cost, heavy weight, and large volume. Compared with the single TE or PV energy source, the TE-PV hybrid energy source can offer some definite advantages, namely the higher fuel economy due to the increase of on-board renewable energy, the better energy security due to the use of multiple energy sources, and the higher control flexibility due to the coordination for charging the same pack of batteries. So the TE-PV hybrid energy source is promising for the application to HEVs.

A number of topologies of power conditioning circuits for small scale power generators have been proposed in the last decades [25]-[30]. For example, several dc-dc converter topologies have been proposed for TE conversion, such as the Ćuk converter [3], the SEPIC converter [8] and the boost-buck cascade converter [31], [32]. However, these topologies can not meet the requirements of the hybrid energy sources. Considering the operation requirements of HEVs, the topology of the TE-PV hybrid energy source must satisfy the following features. Firstly, the output voltage from the TEG or PV panel may widely and dynamically vary according to external physical factors. So the topology needs to cater for a large range of input voltage variation caused by different temperature difference and insolation. Secondly, the hybrid energy source needs to charge the battery or directly supply electrical energy to the vehicle power network. Since the input voltage changes in a wide range, a DC-DC converter, having step-up and step-down characteristics, is required to serve for power conditioning. For example, the output voltage range of a typical TEG is 0-25 V, which needs to be converted to 12.3-16.5 V for battery charging [32]. Thirdly, the MPPT needs to be realized for both TEG and PV panel. At last, the power from TEG and PV panel needs to be delivered to the load individually or simultaneously.

In order to fully utilize the TEG and PV panel, various MPPT algorithms have been developed, such as the load matching method [33], the curve-fitting scheme [34], the incremental conductance technique [35], the ripple correlation algorithm [36], and the perturbation and observation (PAO) method [37]. Moreover, the fuzzy logic [38] and neural network [39] have also been adopted for MPPT. The PAO method is one of the commonly used MPPT algorithms in practice because of its simplicity and system independence.

In this paper, an overview of on-board renewable energy sources is presented. Then, a new TE-PV hybrid energy source is proposed and implemented for HEVs. Finally, experimental results are given to verify the validity of the proposed system. Specifically, in Section 2, an overview of the previous research on on-board renewable energy sources will be presented. In Section 3, a new TE-PV hybrid energy source will be designed and implemented for HEVs. The TE-PV hybrid energy source with a MPPT control strategy enables both the TEG and the PV panel simultaneously achieving the maximum output power. The analysis shows that the power conditioning circuit can satisfy the requirements of the TE-PV hybrid energy system. The experimental verification will be given in Section 4 to support the validity of the proposed system. Finally, a conclusion will be drawn in Section 5.

2 Overview of On-board Renewable Energy Sources

2.1 TE Energy Sources

The thermoelectric effects, including the Seebeck effect and Peltier effect, are the direct conversion of heat energy to electric voltage and vice versa. The Seebeck effect is the conversion of temperature differences directly into electricity. This effect was first discovered by Thomas Seebeck in 1821, who found that a current existed in a conductive loop formed of two metals joined in two places when a temperature gradient existed between the junctions. In contrast, the Peltier effect was first observed in 1834 by Jean Peltier, who found the reverse of the Seebeck effect. Based on the Seebeck effect, a TEG source is composed of the heat source, the TE modules, and the cooling system.

The selected TE material needs to offer high energy conversion efficiency which is measured by the figure of merit:

$$ZT = \frac{S^2 T}{\kappa \rho} \qquad (1)$$

where S is the thermoelectric power, T is the absolute temperature, κ is the total thermal conductivity and ρ is the electrical resistance [19]. It should be noted that the TE material can not be used at all temperature ranges, namely low temperature materials for less than 500 K such as $(Bi,Sb)_2(Te,Se)_3$, mid temperature materials for 550 K to 850 K such as PbTe or PbSnTe, and high temperature materials for about 1200 K such as SiGe alloys [40]. In order to achieve the highest average ZT over the entire operating temperature range of the heat source, different TE elements can be employed. The thickness both within each element and between individual elements can be adjusted to achieve the thermoelectric compatibility [1], [7]. To accommodate elements of different thicknesses and thermal expansion coefficients, a new arrangement of TE elements is proposed to constitute a more effective TE module [41].

To maintain higher temperature difference across the TE module, the cooling system and thermal contact process should be well-designed. The preferable and effective heat and cooling sources with higher efficiency used in laboratory may be a “liquid-liquid” generator [42]. The heat source in [43] uses propane-fired TEG, which is also adopted as the heat source in the commercial TEG in the market. Then, the thermal medium liquid, FC5312 for instance in [44], heats the TE module via heat exchanger. Normally, a heat sink incorporating water cycling is used to cool the TE module, according to the comparison between the air-cooling and water-cooling [45]. The heat sink geometry, the fin design, and heat pipe design are studied in [46]-[48], respectively.

The installation of the TE modules and heat exchanges has two popular methods: the parallelepiped arrangement and the sandwiched arrangement. The parallelepiped TE modules arrangement can transfer the heat from the heat source directly [49], which may be used in the waste heat recovery of the tailpipe in HEVs [50], [51]. The sandwiched TE modules arrangement [52] transfers the heat from the heat source indirectly, which is used in most “liquid-liquid” generator as one layer or multiple layers [40], [47], [53], and [54]. It is noticed that the increasing number of the TE modules with a single heat sink may decrease the total output power, which needs to be optimized [55].

Multiple methods have been used to analyze the heat model and predict the performance of the TEG, such as the entropy generation minimization, power maximization technique, and exergy-based method [56], [57]. Actually, the influence of fluid flow rate, heat exchanger geometry, inlet temperatures, and fluid properties of the power supplied all affect the performance of the TEG. Furthermore, the effect of the pulsing output also has been studied in [58].

Nowadays, the TEG has been widely applied in various fields as power supply. Considering the low efficiency which limits its employment, the TEG can be used in two kinds of applications. On the one hand, as pointed by [59], when the heat input is waste heat type, the low efficiency is not a problem any more. On the other hand, when the heat can be further utilized, the TEG can be parasitically applied without disturbing the original function [52].

2.2 TE-PV Hybrid Energy Sources

Till now, three types of hybrid TE energy sources have been proposed. In these hybrid TE-PV energy sources, the maximum power point (MPP) is not tracking with proper power conditioning system, which may be operated at a relatively low efficiency.

The TE modules are affixed to the rear of the PV panel to decrease its temperature [60], [61]. Then, the lower temperature can improve the efficiency of the PV panel. The measured results show that when the solar irradiance and the ambient temperature are 778 W/m^2 and 32 ºC respectively, the conversion efficiency would have an increase of 5.2% than the single PV panel. Basically, the main function of the TEG is to improve the efficiency of the PV panel.

The TE modules and PV panels are integrated in mobile computing platforms to potentially extend the battery life [62], [63]. The TE module on the CPU, which may be used as TEG or TE cooler (cooling the CPU), TE module on the chipset, and PV panel are connected with a two-level asynchronous Dixon charge pump. An appropriate system DC bus can be maintained between 2 V to 6 V with the output of 550 mW.

In some systems, the PV panel and TEG will work separately to charge the battery for higher energy reliability. In a radio network power supplier, a commercial TEG (Global Thermoelectric, type: 5120, output power 120W) is used with PV panels for better economic viability [64], [65]. Another similar system is also proposed as an energy management system [66]. The main function of the TEG is to provide power when the PV panel can not work.

3 Design of TE-PV Hybrid Energy Source

3.1 Modelling

Assuming that the contact loss and the output characteristics between the conversion elements of same type are ignorable, the model of the TEG and PV panel can be simplified as a single TE module model and a single PV panel model, proportionally with the corresponding numbers in series or in parallel.

The equivalent circuit of a PV panel is shown in Fig. 2. Normally, the PV panel is regarded as a current source shunted by a diode with a series resistor and a parallel resistor. Its numerical description is given by:

$$I = I_L - I_0\left\{\exp\left[\frac{q(V+IR_S)}{AKT}\right]-1\right\} - \frac{V+IR_S}{R_{Sh}}, \qquad (2)$$

where I and V are the output current and output voltage of the PV panel, respectively, I_L is the generated current under a given insolation, I_0 is the reverse saturation current, q is the charge of an electron, A is the ideality factor for a p-n junction, K is the Boltzmann constant, T is the absolute temperature, and R_S and R_{Sh} are the intrinsic series and parallel resistance, respectively.

As the irradiance decreases, the output power and the short circuit current of the PV panel will decline, while the internal resistance increases. When the surface temperature keeps rising, the open circuit voltage will decrease, and deteriorate the output power slightly. The interconnection of the PV panel array is shown in Fig. 3. In the PV panel array, each panel is paralleled with a by-pass diode to bypass the possibly failed PV panel. And at each panel string, a diode is connected to avoid the electricity flowing back from the battery or circulating between the parallel strings.

The equivalent circuit of a TE module is simply represented by a voltage source connecting with an internal resistor in series. Both the internal resistance and the output power of the TE module increase with the temperature difference across the TE module. Similarly, the interconnection of the TE modules is configured like that of the PV panel array.

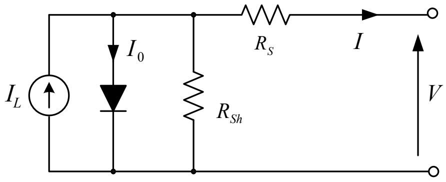


Figure 2: The equivalent circuit of a PV panel.

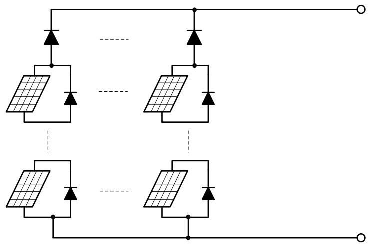


Figure 3: The interconnection of the PV panel array.

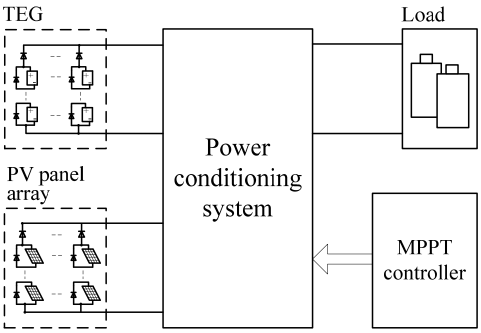


Figure 4: The proposed hybrid energy system.

3.2 System configuration

Fig. 4 shows the configuration of the proposed TE-PV hybrid energy source for HEV. The hybrid energy system with MPPT control is implemented, including the TEG, the PV panel, the power conditioning circuit, a DSP controller, and a 12 V 24 Ah battery as the load. In practice, the MPPT controller measures the output voltages and currents of the TEG and PV array panel, respectively, and generates the switching signals to the conditioning circuit according to the MPPT algorithm.

The TEG branch of the hybrid energy system includes 18 pieces of Bi-Te TE modules (Model TEP1-12656-0.6), a 3.5 kW induction heater, and a water cooling system. These TE modules are connected as 6 pieces electrically in series and 3 branches in parallel.

The PV panel branch has 9 pieces of polycrystalline-silicon PV panels (Model SR10-36), 20 pieces of tungsten halogen lamps, and an AC transformer to adjust the irradiance. All PV panels are connected electrically in parallel.

3.3 Power conditioning circuit with MPPT

Using the Thevenin's theorem, the TEG or PV panel array can be simply represented by a voltage source with an internal resistor. The power conditioning circuit can track the MPP of the energy source by tuning its duty cycle of the PWM switching signal to enable the input resistance $r_{in} = V_i / I_i$ equal to the internal resistor of the energy source r_g, as shown in Fig. 5.

The hybrid TE-PV energy system is studied to extract maximum power of the whole system. The circuit diagram of the hybrid energy system is shown in Fig. 6. According to the previously mentioned criteria of the hybrid energy system, this circuit is particularly suitable to serve as the power conditioning circuit.

The SEPIC have step-up and step-down characteristics with a wide input voltage. Furthermore, the SEPIC has a low-ripple input current. The SEPIC is mainly operated in three modes: continuous current mode (CCM), discontinuous inductor current mode (DICM), and discontinuous capacitor voltage mode (DCVM) [67]. Generally speaking, the CCM is relatively more suitable for high voltage, high current input application, the DICM is for high voltage, low current input application, and the DCVM is for low voltage, high current input application [68]. Since the TEG and PV panel are low voltage inputs and the battery is a high current energy storage unit, the SEPIC circuit operates in the DCVM in the following analysis.

With the big enough inductors and output capacitor, the input resistance of each branch in the DCVM does not directly associate with the load R_L [68]. It means that the MPP can be tracked exactly the same as the single SEPIC circuit if and only if the two branches are both in the DCVM. Setting the duty cycles d_1T_s and D_1T_s for the TEG branch, and d_2T_s and D_2T_s for the PV panel branch, the key waveforms of the hybrid energy system are explicated in Fig. 7. Since the input resistances of two branches can be adjusted separately, the PAO method is used separately to track the MPPs of the TEG branch and PV panel branch.

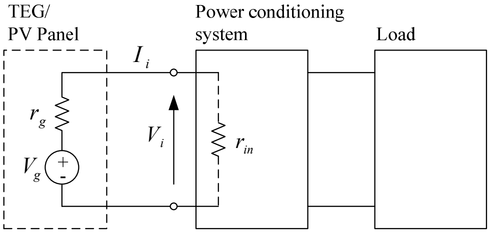


Figure 5: The power conditioning circuit.

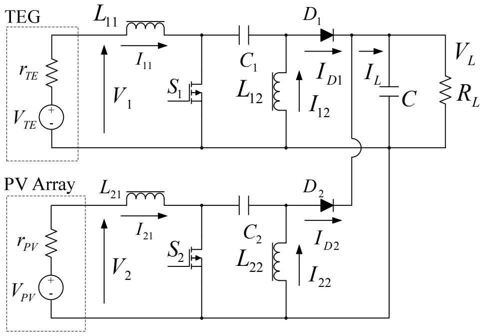


Figure 6: Circuit diagram of hybrid energy system.

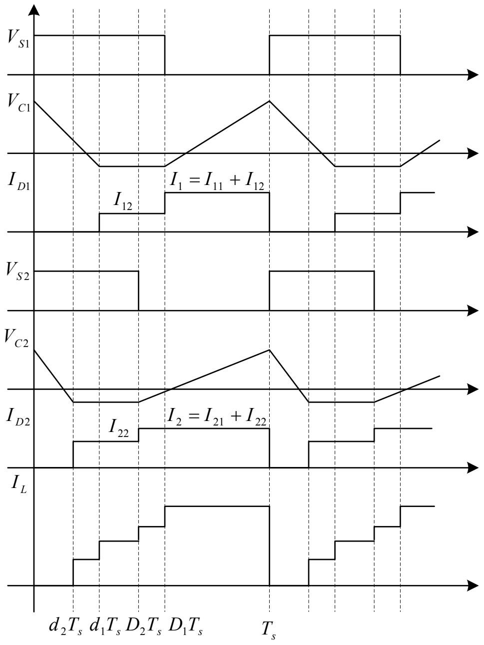


Figure 7: Key waveforms of hybrid energy system.

4 Experimentation of TE-PV Hybrid Energy Source

At the beginning of the experiment, the output characteristics of the TEG and PV panel are measured at specific working conditions by changing a rheostat as the external load. When the temperature of the cold-side of the TEG is fixed at around 50 ºC, the output characteristics of the TEG are recorded at different hot-side temperatures, 120 ºC, 170 ºC, and 220 ºC, as shown in Fig. 8. With the surface temperature of around 40 ºC, the output characteristics of the PV panel are shown in Fig. 9.

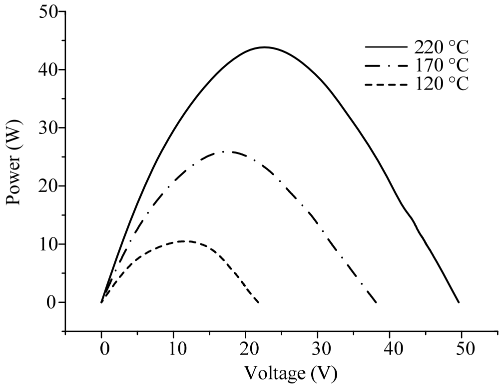


Figure 8: Output characteristics of TEG branch.

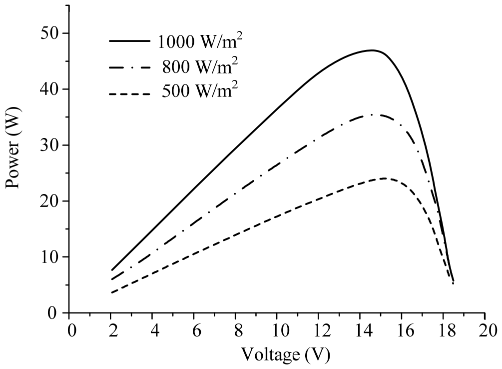


Figure 9: Output characteristics of PV panel branch.

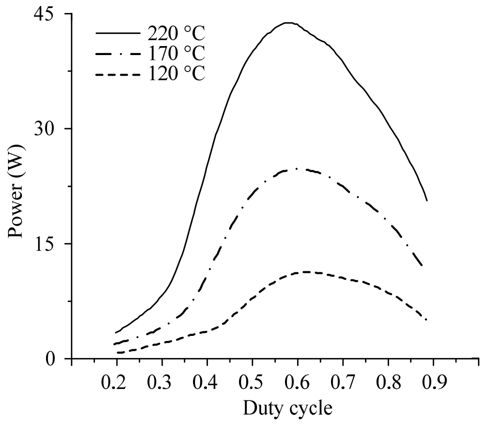
It is obvious that the output power of TEG and PV panel are heavily dependent on the external physical factors. The power output of the TEG and PV panel increase with the irradiance and temperature difference, respectively. With varying external load, the output power changes significantly. These figures show the necessity of the power conditioning circuit. At the same time, the internal resistances of TEG and PV panel can be obtained, which equal the resistance of the rheostat at the MPPs.

With the measured output characteristics of the TEG and PV panel, the power conditioning circuit can be designed. By tuning the duty cycle of the PWM switching signal, the MPP can be tracked at each branch as shown in Fig. 10.

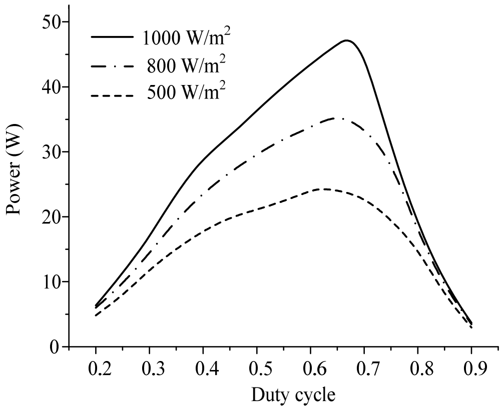
In the experiment, the initial duty cycle of the switching signal is 40%, and the Δd is set as 0.5%. In order to test the dynamic performance of the hybrid system, a 10 Ω resistor load is suddenly connected in parallel with a 12 Ω resistor at 10 s.

Fig. 11 shows the response of the output power of the PV panel branch and the response of the load current. It confirms that the MPPT controller can maintain the MPP operation even under a sudden load change.

In order to verify the MPPT control method, a comparison is carried out. One is based on a fixed PWM signal with 50 kHz frequency and 65% duty cycle to the system; the other one is driven by the MPPT controller with a PWM signal at constant 45 kHz and initial duty cycle 65%. The reason to choose 65% is that the MPP of both branches can be roughly achieved according to Fig.10. The result in Fig. 12 shows that the TE-PV hybrid energy system can achieve the MPP to the battery under different external factors.



(a) TEG output power.



(b) PV panel array output power.

Figure 10: The output power versus the duty cycle of SEPIC branches.

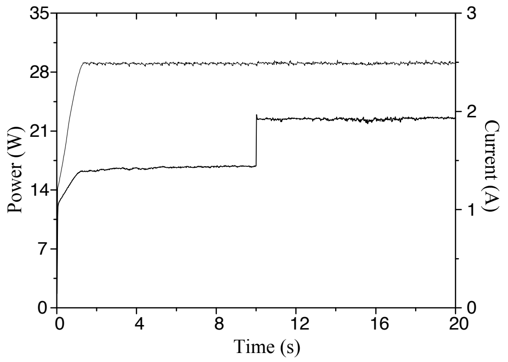


Figure 11: Output power of PV panel branch and load current under sudden load change. (Upper trace: power, lower trace: current).

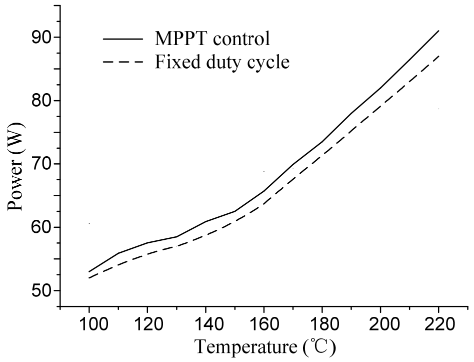


Figure 12: Comparison of output power.

5 Conclusion

In this paper, an overview of on-board renewable energy sources, with emphasis on TE energy sources and TE-PV hybrid energy sources, has been presented. Consequently, a new TE-PV hybrid energy source has been designed and implemented for HEVs. The experimentation confirms that the proposed systems can perform MPPT successfully.

Acknowledgments

This work was supported by a grant (Project code: 200807176032) from the Committee on Research and Conference Grants, The University of Hong Kong, Hong Kong Special Administrative Region, China.

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