Multiple-Input DC-DC Converter for The Thermoelectric–Photovoltaic Energy System in Hybrid Electric Vehicles

Ying Fan, *Member, IEEE*, Luming Ge, Wei Hua, *Member, IEEE*
School of Electrical Engineering, Southeast University, Nanjing, China, 210096
E-mail: vickifan@seu.edu.cn; lulu1222@163.com; huawei1978@seu.edu.cn

***Abstract*—Thermoelectric generators (TEGs) can directly convert heat energy to electrical energy and have been employed in the automobile industry to recover waste heat energy. Meanwhile, solar energy can also be used in Electric Vehicles. In this paper, a thermoelectric–photovoltaic hybrid energy system composed of two TEGs and one photovoltaic generator is proposed for hybrid electric vehicles. A Ćuk-Ćuk-Ćuk multiple-input DC-DC converter (MIC) is adopted to draw power from different energy sources independently. The topology of this MIC is analyzed, including the basic units and synthesizing approach. The maximum power point tracking and asynchronous trigger control strategy is adopted. The simulation results are given to verify the theoretical analysis.**

***Index Terms*—Multiple-input converter, maximum power point tracking, thermoelectric, photovoltaic.**

I. INTRODUCTION

The shortage of oil and the increasing environmental problems have accelerated the development of hybrid electric vehicles (HEVs) [1]. Both internal combustion engine and electric motor are adopted in HEVs. However, the efficiency of engine is low, the whole fuel economy is decreased. For a typical engine only about 25% of the fuel energy is utilized for vehicle operation; whereas, 40% of the fuel energy is wasted as exhaust gas heat and 30% of the fuel energy is lost in the coolant system [2]. Thermoelectric generators (TEGs) can directly convert heat energy to electrical energy, hence TEGs are proposed to recover waste heat energy in the automobile industry [2]-[3]. Vehicle exhaust gas and radiator are the major waste heat sources. The temperature of exhaust gas ranges from 450-600℃ and radiator temperature is approximately 100℃. To get the best convert performance, different thermoelectric materials are selected to match different temperatures. Many research focus on exhaust gas for high temperature. In fact, it's much easier to extract heat energy from coolant than from gas [3]. Recently, the solar technology applied in the automobile has been paid much attention [4]. By mounting photovoltaic panel on the roof of HEVs, the fuel economy will be further increased.

The energy sources mentioned above possess different voltage and current characteristics. To regulate the two TEGs' output power and the photovoltaic generator (PVG)'s output power, DC-DC converters are needed. The traditional method is to adopt a DC-DC converter for each generator, as shown in Fig. 1. However, the system structure is complex and the cost is high. Therefore, a lot of researches have focused on multiple-input converter (MIC) [5]-[10]. A systematic approach to synthesize MICs is proposed by introducing pulsating voltage source cells (PVSCs) and pulsating current source cells (PCSCs) into basic pulse width modulation converters [8]. Another alternative method for generating MICs is proposed by combining PVSCs or PCSCs and then cascading them with the appropriate output filter [9]. A SEPIC-SEPIC MIC is employed in HEVs application [10]. This MIC with maximum power point tracking (MPPT) control scheme is used for collecting exhaust waste energy and solar energy. However, the coolant waste energy is not included.

In this paper, a thermoelectric-photovoltaic (TE-PV) hybrid energy system composed of two TEGs and one PVG is proposed for HEVs. The purpose of this paper is to propose a simple and low cost MIC to draw power from TEGs and PVG. In section II, the energy system will be described. The basic cells of MIC, Ćuk-type saw-tooth PVSC and output filter, will be analyzed and used to synthesize a Ćuk-Ćuk-Ćuk MIC. In section III, the MPPT and asynchronous trigger control strategy will be studied. In section IV, the simulation results will be given to verify the theoretical analysis. Finally, a conclusion will be analyzed in section V.

II. SYSTEM CONFIGURATION AND PROPOSED MIC

The proposed TE-PV hybrid energy system is shown in Fig. 2. TEGs are assembled at the exhaust pipe and the radiator respectively to convert waste heat energy to electrical energy. A PVG is installed on the vehicle roof to utilize the solar energy. TEGs and PVG are connected with a Ćuk-Ćuk-Ćuk MIC to regulate the generated DC power. Finally, the output power is used to charge a 36V battery.

The proposed Ćuk-Ćuk-Ćuk MIC is shown in Fig. 3. There are three input ports connected to TEGs and PVG. The topology of MIC is divided into three Ćuk-type saw-tooth PVSCs and one LC voltage source filter, as shown in Fig. 4.

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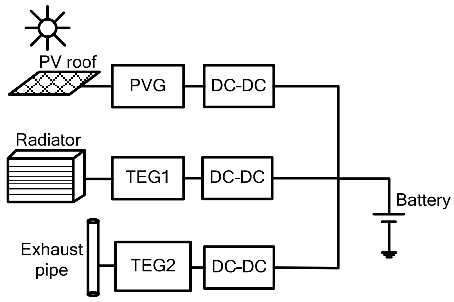

Fig. 1. TE-PV hybrid energy system

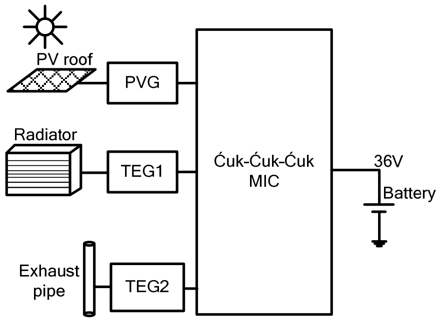

Fig. 2 Proposed TE-PV hybrid energy system

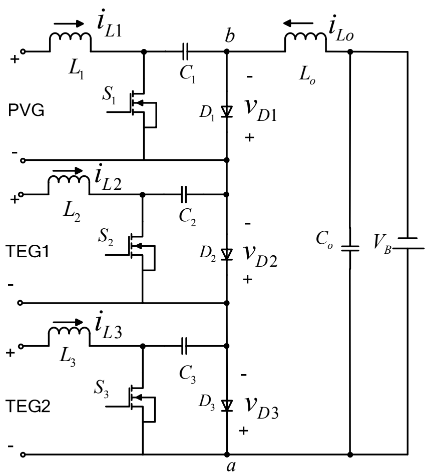

Fig. 3 Proposed Ćuk-Ćuk-Ćuk MIC

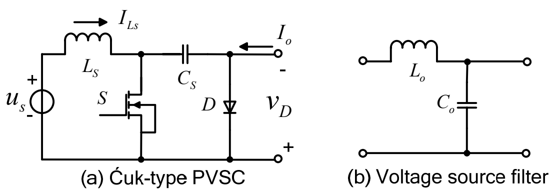

Fig. 4. Basic cells of MIC. (a) Ćuk-type saw-tooth PVSC. (b) Voltage source filter

A. Operation Principle of Ćuk-type Saw-tooth PVSC

In this paper, Ćuk-type PVSC is further classified as square PVSC and saw-tooth PVSC based on the waveform of v_D. The key difference is the capacitor C_s voltage continuous or not. If the Ćuk-type PVSC operated in discontinuous capacitor voltage mode (DCVM), it is a saw-tooth PVSC.

Firstly, the inductor current I_{Ls} and the output current I_o are assumed to be constant. According to the status of the power switch and diode, there are three operation modes during a switching period, as shown in Fig. 5.

Mode I: The power switch S is turned on. The voltage source u_s charges the inductor L_s. The capacitor C_s provides a path for output current I_o and the energy stored in C_s is released. Because of the C_s voltage, power diode D is reverse biased as an open circuit.

Mode II: The power switch S is turned on. The voltage source u_s still charges the inductor L_s. The energy stored in C_s has been fully released, so the voltage v_{Cs} decreases to zero. Power diode D provides a bypass path for output current I_o.

Mode III: The power switch S is turned off. Both of the voltage source u_s and the inductor L_s charge the capacitor C_s , and the voltage v_{Cs} increases. Power diode D provides a bypass path for inductor current I_{Ls} and output current I_o.

It can be seen that the output current I_o can flow into and out the Ćuk-type PVSC freely. Based on the previous analysis, the key waveforms of Ćuk-type saw-tooth PVSC are shown in Fig. 6. The waveforms of a PVSC output voltage, namely the diode voltage v_D are saw-toothed. The capacitor C_s voltage v_{Cs} and v_D in the respective modes can be expressed as

$$v_{Cs}=\begin{cases}\frac{I_o}{C_s}(-t+\delta T_s) & 0<t<\delta T_s\\ 0 & \delta T_s<t<dT_s\\ \frac{I_{Ls}}{C_s}(t-dT_s) & dT_s<t<T_s\end{cases} \tag{1}$$

$$v_D=\begin{cases}v_{Cs} & 0<t<\delta T_s\\ 0 & \delta T_s<t<T_s\end{cases} \tag{2}$$

where d and δ is the duty ratio for power switch S and diode D, respectively, and T_s is the switching period.

Under the steady-state condition, the average current across C_s is zero. That is

$$I_o\delta T_s-I_{Ls}(1-d)T_s=0 \tag{3}$$

Hence the relationships between I_{Ls} and I_o can be deduced as

$$I_o=(1-d)I_{Ls}/\delta \tag{4}$$

The saw-tooth PVSC input energy from the voltage source u_s is

$$E_{in}=\int_0^{T_s}u_sI_{Ls}dt=u_sI_{Ls}T_s \tag{5}$$

From (1) and (2), the PVSC output energy is

$$E_{out} = \int_0^{T_s} v_D I_o dt = \int_0^{\delta T_s} v_D I_o dt + \int_{\delta T_s}^{T_s} v_D I_o dt$$
$$= \int_0^{\delta T_s} v_{Cs} I_o dt + 0 = \frac{I_o^{\,2} \delta^2 T_s^2}{2C_s} \tag{6}$$

Based on the assumption of no energy loss, the input energy equals the output energy, that is

$$E_{in} = E_{out} \tag{7}$$

From (4) ~ (7), the input resistance of saw-tooth PVSC can be obtained as

$$r_{in} = \frac{u_s}{I_{Ls}} = \frac{T_s}{2C_s}(1-d)^2 \tag{8}$$

B. Synthesizing Approach of Ćuk-Ćuk-Ćuk MIC

To obtain a constant voltage, the output voltage waveforms of PVSCs should be filtered out before supplying load [8], [9]. In fact, a basic Ćuk converter can be obtained by connecting the output of Ćuk-type PVSC with the input of LC voltage source filter shown in Fig. 4. Similarly, Ćuk-Ćuk-Ćuk MIC is synthesized by three Ćuk-type saw-tooth PVSCs in series and cascading with the filter. Fig. 7 shows the configuration of Ćuk-Ćuk-Ćuk MIC.

When the inductors L_1, L_2, L_3 and the inductor L_o is large enough, the current through L_1, L_2, L_3 and L_o would be considered as constant. Then the assumption about PVSC made in the former part can be satisfied. Because of the output current I_{Lo} flowing into and out of a Ćuk-type PVSC freely, three PVSCs can work simultaneously. When the PVG doesn't work at night, its corresponding power diode D_1 would provide a bypass path for output current I_{Lo}. The others can still work normally without disturbance. Each PVSC can work simultaneously or individually which greatly enhances the control flexibility.

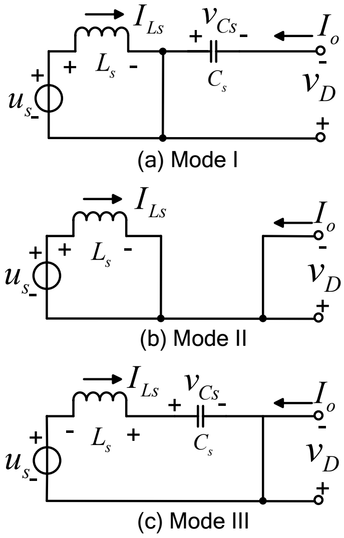

Fig. 5. Operation modes of Ćuk-type saw-tooth PVSC

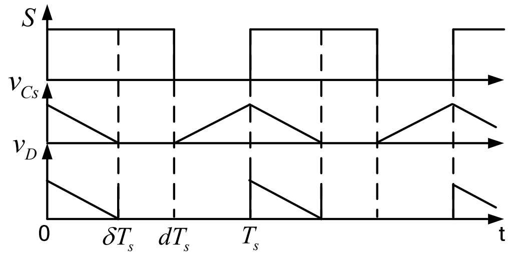

Fig. 6. Key waveforms of Ćuk-type saw-tooth PVSC

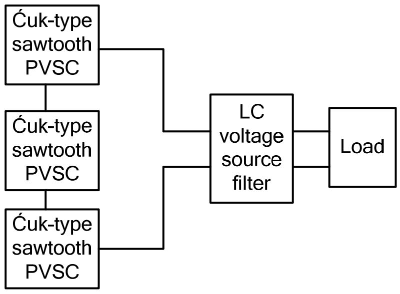

Fig. 7. Configuration of Ćuk-Ćuk-Ćuk MIC

Furthermore, as indicated in (8), the input resistance of Ćuk-type saw-tooth PVSC associates with T_s , d and C_s only as shown in (8). For a PVSC, the capacitance of C_s is fixed. By controlling the power switches, the input power of each Ćuk-type saw-tooth PVSC can be regulated independently. From this point, the control independence of Ćuk-Ćuk-Ćuk MIC can be compared with three separate DC-DC converters.

III. Control Strategy

A. MPPT Algorithm

Both TEG and PVG has a single maximum output power point at a certain external environment. To improve conversion efficiency, the MPPT algorithm is adopted. The perturbation-and-observing (PAO) algorithm is used to implement MPPT [11]. By changing the duty ratio d of power switches at a fixed switch period T_s, the input resistance of saw-tooth PVSC can be regulated. When the input resistance matches with the internal resistance of TEG or PVG, MPPT can be achieved.

B. Asynchronous Trigger Control

Due to the independence of MIC, each switch can be triggered synchronously or asynchronously. In the synchronous trigger mode, switches S_1, S_2 and S_3 are turned on at the same time. From the Ćuk PVSC operation principle analysis, diode D_1, D_2 and D_3 would be turned off synchronously. In asynchronous trigger mode, switches S_1, S_2 and S_3 are turned on asynchronously, diode D_1, D_2 and D_3 would be turned off asynchronously. In Fig. 3, the filter input voltage, namely the voltage potential between node a and node b v_{ab} is

$$v_{ab} = v_{D1} + v_{D2} + v_{D3} \tag{9}$$

where v_{D1}, v_{D2} and v_{D3} is the voltage of diode D_1, D_2 and D_3 respectively. In both modes, the voltage waveforms of v_{D1}, v_{D2}, v_{D3} and v_{ab} are shown in Fig. 8.

It can be seen clearly that the waveforms of v_{ab} are much smoother in asynchronous trigger mode than in synchronous trigger mode. Therefore, the L and C parameters can be reduced, leading to lower cost and lighter weight.

IV. Simulation Results

To verify the proposed MIC control strategy, the simulation results are given. The Ćuk-type saw-tooth PVSC is built as a modular circuit, the main circuit parameters are shown in Table I. TEGs and PVG are simulated by a DC voltage source in series with a resistor, respectively.

TABLE I
CIRCUIT PARAMETERS

Contents	Value
L_1,L_2,L_3	800μH
C_1,C_2,C_3	0.1μF
L_o	1mH
C_o	1mF
Battery	36V,15Ah
Switching frequency	50kHz

The duty ratio of each switch is fixed at first, and the PAO MPPT algorithm is employed at 0.2s to optimize duty ratio. Battery power is significantly improved, as shown in Fig. 9. The minus means battery is charging.

The simulated waveforms of filter input voltage v_{ab} and inductor current i_{Lo} in synchronous and asynchronous trigger modes are shown in Fig. 10, respectively. In the synchronous trigger mode, diode D_1, D_2 and D_3 are turned off synchronously. The voltage potential v_{ab} varies acutely in a period. The ripple of inductor current i_{Lo} is approximately 0.6A. In the asynchronous trigger mode, the turn-off time of each diode is interleaved. v_{ab} and i_{Lo} varies 3 times in a period. The ripple of i_{Lo} is minimized to 0.3A with the same filter. The simulation results verify the theoretical analysis.

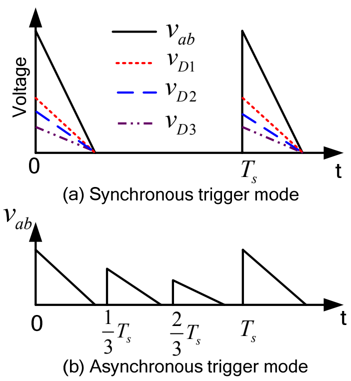

Fig. 8. Voltage waveforms in synchronous and asynchronous trigger modes

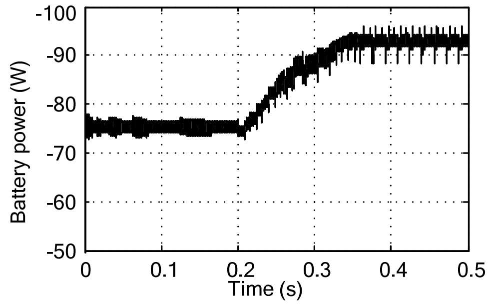

Fig. 9. Simulated battery power with MPPT algorithm

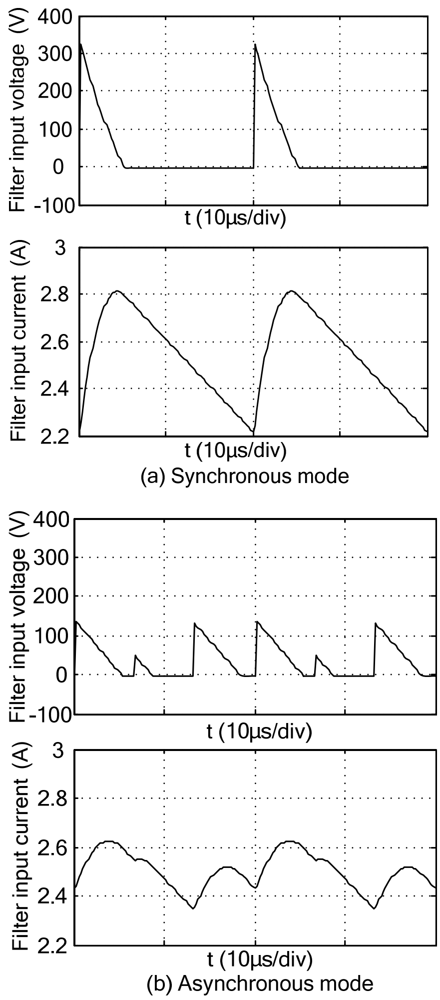

Fig. 10. Simulated waveforms in two trigger modes

V. Conclusion

A Ćuk-Ćuk-Ćuk MIC is proposed for TE-PV hybrid energy system in HEVs in this paper. The operation principle and the control strategy are analyzed. The proposed MIC has the following advantages: The MIC can draw power from different energy sources simultaneously or individually; each energy source can be regulated independently; the input currents are continuous with little disturbance to TEG or PVG. Therefore, the proposed MIC is suitable for Hybrid Electric Vehicles.

ACKNOWLEDGMENT

This work is supported and funded by the funding (Project No. 50729702) from the National Natural Science Foundation of China, by the funding from the Chang Jiang Chair Professorship at Southeast University, Nanjing, and the funding (Project No. BE 2008130) from the Key Technology R&D Program of Jiangsu Province, China. Thanks to Mr. Xiaodong Zhang in the University of Hong Kong for his support.

REFERENCES

[1] K. T. Chau and C. C. Chan, "Emerging energy-efficient technologies for hybrid electric vehicles," *Proceedings of the IEEE*, vol. 95, pp. 821-835, Apr. 2007.

[2] F. Stabler, "Automotive applications of high efficiency thermoelectrics," *Proceedings of DARPA/ONR/DOE High Efficiency Thermoelectric Workshop*, pp. 1-26, Mar. 2002.

[3] J. Yang, "Potential applications of thermoelectric waste heat recovery in the automotive industry," *International Conference on Thermoelectrics*, pp. 170-174, 2005.

[4] J. T. Simburger, E. J. Simburger, G. Johanson, and M. Bagnall, "PV prius," *IEEE World Conference on Photovoltaic Energy Conversion*, Waikoloa, HI, 2006, pp. 2404-2406.

[5] Y. M. Chen, Y. C. Liu, and S. H. Lin, "Double-input PWM DC/DC converter for high/low voltage sources," *IEEE Transactions on Industrial Electronics*, vol. 53, pp. 1538-1544, 2006.

[6] Y. Li, X. B. Ruan, and D. S. Yang, "A new double-input DC-DC converter," *Transactions of China Electrotechnical Society*, vol. 23, pp. 77-81, Jun. 2008.

[7] Y. Li, X. B. Ruan, D. S. Yang, and F. X. Liu, "Interleaved dual-edge modulation scheme for double-input buck converter," *Transactions of China Electrotechnical Society*, vol. 24, pp. 139-146, Apr. 2009.

[8] Y. C. Liu and Y. M. Chen, "A systematic approach to synthesizing multi-input DC–DC converters," *IEEE Transactions on Industrial Electronics*, vol. 24, pp. 116-127, 2009.

[9] Y. Li, X. B. Ruan, D. S. Yang, and F. X. Liu, "Multiple-input DC/DC converters without buffer cells," *Transactions of China Electrotechnical Society*, vol. 24, pp. 73-79, May 2009.

[10] X. Zhang, K. T. Chau, and C. C. Chan, "Design and implementation of a thermoelectric-photovoltaic hybrid energy source for hybrid electric vehicles," *International Electric Vehicle Symposium*, May 2009, Paper No. 2130104.

[11] C. Yu and K. T. Chau, "Thermoelectric automotive waste heat energy recovery using maximum power point tracking," *Energy Conversion and Management*, vol. 50, pp. 1506-1512, Jun. 2009.