Development of a Thermal Energy Harvesting Converter with Multiple Inputs and an Isolated Output

Yeu-Torng Yau 1, Kuo-Ing Hwu 2,* and Jenn-Jong Shieh 3

1 Department of Ph.D. Program, Prospective Technology of Electrical Engineering and Computer Science, National Chin-Yi University of Technology, No. 57, Sec. 2, Zhongshan Rd., Taiping Dist., Taichung 41170, Taiwan; pabloyau@scut.edu.tw
2 Department of Electrical Engineering, College of Electrical Engineering & Computer Science, National Taipei University of Technology, 1, Sec. 3, Zhongxiao E. Rd., Taipei 10808, Taiwan
3 Department of Electrical Engineering, College of Information & Electrical Engineering, Feng Chia University, No. 100, Wenhwa Road, Seatwen, Taichung 40724, Taiwan; jjshieh@fcu.edu.tw
* Correspondence: eaglehwu@ntut.edu.tw; Tel.: +88-62-2771-2171 (ext. 2159)

Abstract: In this paper, an isolated multi-input single-output (MISO) converter is developed and applied to a thermoelectric energy conversion system to harvest thermal energy. The thermoelectric generators have individual maximum power point tracking functions. Furthermore, such a converter has a high step-up voltage conversion ratio. In addition, the presented converter is imposed on the thermoelectric energy conversion system with the three-point weighting strategy adopted to realize the maximum power point tracking (MPPT). In this paper, the basic principles of this converter are first described and analyzed, and finally some simulated and experimental results are offered to verify the feasibility and effectiveness of such a thermal energy harvesting system.

Keywords: coupled inductor; FPGA; galvanic isolation; MISOC; thermal energy harvesting; thermoelectric module; three-point perturbation and observation method

1. Introduction

As generally recognized, from the point of view of industrial applications, 50% of generated electricity is used, while the remainder is wasted via heat. Accordingly, if the heat can be changed to electricity, then the energy conversion efficiency can be increased, and the pollution due to exhaust heat and emissions due to exhaust gas can be decreased [1]. At present, many methods have been proposed to recycle exhaust heat into electricity—for example, the organic Rankine cycle, combination of power and heat, thermoelectric generators (TEGs), etc.; of these, TEGs have many features, such as small size, no noise, easy maintenance, easy extension, etc. In fact, the process of recycling thermal energy is quite similar to that of recycling solar energy—both of which require the maximum power point tracking (MPPT) to harvest thermal energy efficiently.

Therefore, there are several configurations for converting heat to electricity using a TEG. TEG-based electrical systems can be divided into three types: single TEGs [2,3], distributed TEGs [2–4], and centralized TEGs [2]. The first type adopts a single heat source, while the other two types use multiple heat sources. However, the first type has a limited power level, the second type is limited in terms of size and cost, and the third faces the problem of the failure of one TEG.

Therefore, a multiple-input TEG system is proposed to conquer these disadvantages. To construct a single-stage thermoelectric energy conversion system with multiple TEG inputs, a high step-up converter is indispensable. The authors of [5–14] propose several kinds of multi-input single-output converters (MISOCs) with non-isolation. The authors of [6] utilized a switched-capacitor circuit so that a high voltage gain could be achieved.
The authors of [5,11,14] adopted elementary circuit configurations, leading to the corresponding voltage gains not being high. The authors of [11] employed an elementary circuit configuration together with an auxiliary circuit, such that the zero-voltage switching (ZVS) could be achieved but the accompanying voltage gain was not high. The authors of [6,9,10] utilized coupled inductors so that the voltage gains could be improved and the ZVS could be realized. However, if the number of input voltages is increased, then the number of coupled inductors and switches is increased, resulting in the huge size needed. The circuit concept displayed in [12] is derived from [14], and this converter adopts only a single inductor to obtain a result identical to that of [14], thus decreasing the size significantly; however, this converter employs an elementary circuit configuration, resulting in the voltage gain not being high; moreover, the control of such a converter is relatively complicated. The authors of [13,15] achieved high step-up voltage gains by utilizing bootstrap circuits; however, these circuits have automatic current balance, making them unsuitable for MPPT use. Consequently, the authors of [16] presented interleaved switches for the circuit shown in [15] to conquer this problem, so that each thermoelectric generator would have its own MPPT function.

For galvanic isolation to be considered, the authors of [17,18] proposed an isolated MISO high-step-up converter; however—considering that the higher the turns ratio, the greater the leakage inductance and the larger the primary-side current—the actual voltage conversion ratio remains not particularly high. In [19], the multiple inputs had individual resonant networks and coupled inductors, causing switches to have ZVS turn-on, the number of components to be relatively large, and the corresponding maximum voltage gain to be less than 1.5. In [20], a single coupled inductor was used to harvest energy from multiple heat sources; however, the duty cycle for each input has its own limitations, and the overall voltage gain is determined only by the turns ratio.

In fact, none of the converters described previously—except for the converter displayed in [16]—are used in thermoelectric systems. Accordingly, an isolated MISOC circuit is proposed herein and imposed on a thermoelectric energy conversion system.

2. Features of the Thermoelectric Module

The operation of the thermoelectric module is based on the Seebeck effect; this means that the movement of major P-type and N-type carriers due to temperature differences between the hot side and the cold side forms a current. In Figure 1a, the model of the thermoelectric module is represented by one open-circuit voltage $V_{oc}$ and one internal resistance $R_{teg}$. In this figure, the voltage across the variable load resistance $R_L$ is $V_{teg}$, and the current flowing into $R_L$ is $I_{teg}$. In Figure 1b, if $R_L$ is infinite, then $V_{teg}$ is equal to $V_{oc}$; if $R_L$ is zero, then $I_{teg}$ is equal to $I_{sc}$ (In Figure 1c), which is $V_{oc}$ divided by $R_{teg}$. Therefore, based on the maximum power transfer theory under the condition that $R_L = R_{teg}$ [21,22], we can find the maximum power point (MPP) at:

$$V_{teg} = 0.5V_{oc} \text{ and } I_{teg} = 0.5I_{sc}$$

(1)
Hence, the maximum power—represented as \( P_{mpp} \)—is identical to:

\[
P_{mpp} = 0.25V_{oc} \cdot I_{sc}
\]  

(2)

Accordingly, the P–I–V curves of TEG are drawn in Figure 2. From this figure, it can be seen that these curves are of high symmetricity.

![Figure 2. TEG P–I–V Curves.](image)

3. Three-Point Weighting Strategy for MPPT

Based on Figure 1, the three-point weighting strategy was adopted to derive the maximum power transfer from the TEG to the output. Figure 3 displays the operating procedure of this method, and the corresponding operation is shown in Figure 4 with three cases: for case 1, \( P_a > P_b > P_c \); for case 2, \( P_a < P_b < P_c \); for case 3, \( P_b > P_a \) and \( P_c \). As in case 3, the point of the maximum power can be obtained. Note that \( D_{mpp}, D_a, D_b, \) and \( D_c \) are defined to be the duty cycles at the maximum power point, point \( a \), point \( b \), and point \( c \), respectively.

![Figure 3. Operating procedure of the three-point weighting strategy for MPPT.](image)
Figure 4. Three cases for the three-point weighting strategy. (a), \( P_a > P_b > P_c \); (b), \( P_a < P_b < P_c \); (c), \( P_b > P_a \) and \( P_c \).

4. Proposed Isolated MISOC

Figure 5 shows the proposed two-input single-output isolated high-step-up converter, which is composed of one input inductor \( L \), one output inductor \( L_o \), one coupled inductor constructed by one inductance, one leakage inductance with the primary winding \( N_p \), the secondary winding \( N_s \), a turns ratio of \( n = N_p/N_s \), two main switches \( S_1 \) and \( S_2 \), three charge pump capacitors \( C_1, C_2, \) and \( C_3 \), three diodes \( D_1, D_2, \) and \( D_3 \), and one output capacitor \( C_o \). As for the output load, it consists of one output resistor \( R_o \).

Before dealing with this section, we must first define some symbols shown in Figure 5 and several constraints, as follows: (1) the two input voltages are signified by \( V_{in1} \) and \( V_{in2} \); (2) the two input currents are indicated by \( i_{in1} \) and \( i_{in2} \); (3) the output current is expressed by \( I_o \); (4) the output voltage is denoted by \( V_o \); (5) the voltages across \( C_1, C_2, \) and \( C_3 \) are represented by \( V_{C1}, V_{C2}, \) and \( V_{C3} \), respectively; (6) the pulse-width modulation (PWM) signals for \( S_1 \) and \( S_2 \) are signified by \( v_{gs1} \) and \( v_{gs2} \), respectively; (7) the voltages across \( L, L_m, L_o, N_p, N_s, \) and \( L_{lk} \) are indicated by \( v_L, v_{Lm}, v_{Lo}, v_{Np}, v_{Ns}, \) and \( v_{Lk}, \) respectively; (8) the voltages across \( D_1, D_2, \) and \( D_3 \) are described by \( v_{D1}, v_{D2}, \) and \( v_{D3}, \) respectively; (9) the currents in \( L, L_m, L_o, N_p, \) and \( N_s \) are signified by \( i_L, i_{Lm}, i_{Lo}, i_{Np}, \) and \( i_{Ns}, \) respectively; (10) the currents in \( D_1, D_2, \) and \( D_3 \) are denoted by \( i_{D1}, i_{D2}, \) and \( i_{D3}, \) respectively; (11) the duty cycles of \( v_{gs1} \) and \( v_{gs2} \) are expressed by \( D_a \) and \( D_b, \) respectively, under the same switching period of \( T_s \); (12) all the components are regarded as ideal, except for \( S_1 \) and \( S_2; \) (13) the converter works in the continuous current mode (CCM); (14) all of the waveforms are drawn in the steady state, and four states over one cycle are illustrated in Figure 6, to be analyzed as follows:
Figure 6. Illustrated waveforms relevant to the proposed isolated MISOC circuit.

4.1. Operational Behavior

State 1 \([t_0 \leq t \leq t_1]\): As illustrated in Figure 7, \(S_1\) and \(S_2\) are turned on, whereas \(D_1\), \(D_2\), and \(D_3\) are reverse-biased. During this time interval, \(L\) is magnetized by \(V_{in1}\), whereas \(L_m\), \(L_{lk}\), and \(L_o\) are magnetized by \(V_{in2}\) and \(C_1\). At the same time, \(C_2\) and \(C_3\) are series-connected, and release energy to the load. In addition, \(D_1\) is reverse-biased with the
voltage of $V_{in1} + V_{C1}$, $D_2$ is reverse-biased with the voltage of $(V_{in2} + V_{C1})/n + V_{C2}$, and $D_3$ is reverse-biased with the voltage of $(V_{in2} + V_{C1})/n + V_{C3}$ with $V_{C2} = V_{C3}$.

**Figure 7.** State 1 power flow.

State 2 [$t_1 \leq t \leq t_2$]: As illustrated in Figure 8, $S_1$ remains in the on-state, but $S_2$ is turned off, whereas $D_1$, $D_2$, and $D_3$ remain reverse-biased. During this time interval, $L$ is still magnetized by $V_{in1}$, whereas $L_m$, $L_{ik}$, and $L_o$ are demagnetized. Since $i_{Np}$ remains in the positive direction, the second-side circuit operation is the same as in state 1. In addition, the leakage inductance $i_{lk}$ releases energy as well as charging the parasitic capacitor of $S_2$, leading to a spike voltage on $S_2$. The moment $i_{N2}$ falls to zero, this state proceeds to the end.

**Figure 8.** State 2 power flow.

State 3 [$t_2 \leq t \leq t_3$]: As illustrated in Figure 9, $S_1$ remains in the on-state, but $S_2$ remains in the off-state, whereas $D_1$ is turned off but $D_2$ and $D_3$ remain in the on-state. During this time interval, $L$ is still magnetized by $V_{in1}$, whereas $L_m$ and $L_o$ are still demagnetized, and charge $C_2$ and $C_3$, thereby causing $C_2$ and $C_3$ to be paralleled with $V_{C2} = V_{C3}$. Once the switch $S_1$ is turned off, this state ends.
Figure 9. State 3 power flow.

State 4 \([t_3 \leq t \leq t_4]\): As illustrated in Figure 10, \(S_1\) and \(S_2\) are both off, whereas \(D_1\), \(D_2\), and \(D_3\) are all reverse-biased. During this time interval, \(L\) releases energy to \(C_1\). In the meantime, \(L_m\) is still demagnetized, so the secondary-side circuit operation is the same as in state 3. As soon as \(S_1\) and \(S_2\) are turned on, this state comes to an end, and the next period starts.

Figure 10. State 4 power flow.

4.2. Output Voltage

To conveniently obtain the voltages on \(C_1\), \(C_2\), \(C_3\), and \(C_o\), only states 1, 3, and 4 are taken into account, and \(L_{lk}\) is omitted. First, the turns ratio of the transformer is defined as follows:

\[
\frac{N_p}{N_s} < 1 \text{ and } n < 1
\]  

(3)

As illustrated in state 1 in Figure 7, based on Kirchhoff’s voltage law, the respective voltages across the input inductor \(L\), the magnetizing inductance \(L_m\), and the output inductor \(L_o\) are:

\[
v_L = V_{in1}
\]

(4)

\[
v_{Lm} = V_{in2} + V_{C1}
\]

(5)

\[
v_{Lo} = \frac{1}{n} (V_{in2} + V_{C1}) + V_{C2} + V_{C3} - V_o
\]

(6)

As illustrated in state 3 in Figure 9, based on Kirchhoff’s voltage law, the respective voltages across the input inductor \(L\), the magnetizing inductance \(L_m\), and the output inductor \(L_o\) are:

\[
v_L = V_{in1}
\]

(7)

\[
v_{Lm} = -nV_{C2} = -nV_{C3}
\]

(8)

\[
v_{Lo} = V_{C2} - V_o = V_{C3} - V_o
\]

(9)
As illustrated in state 4 in Figure 10, based on Kirchhoff’s voltage law, the respective voltages across the inductor $L$, the magnetizing inductance $L_m$, and the output inductor $L_o$ are:

$$v_L = -V_{C1}$$

$$v_{Lm} = -nV_{C2} = -nV_{C3}$$

$$v_{Lo} = V_{C2} - V_o = V_{C3} - V_o$$

In the steady state, the input inductor $L$, the magnetizing inductance $L_m$, and the output inductor $L_o$ should obey the volt–second balance, so the respective associated equations can be attained based on (4) and (10), (5) and (8), and (6) and (9):

$$V_{in1}D_aT_s + (-V_{C1})(1 - D_a)T_s = 0$$  (13)

$$(V_{in2} + V_{C1})D_bT_s + (-nV_{C2})(1 - D_b)T_s = 0$$  (14)

$$[\frac{1}{n}(V_{in2} + V_{C1}) + V_{C2} + V_{C3} - V_o]D_bT_s + (V_{C2} - V_o)(1 - D_b)T_s = 0$$  (15)

Rearranging (13), (14), and (15), respectively, yields:

$$\frac{V_{C1}}{V_{in1}} = \frac{D_a}{1 - D_a}$$  (16)

$$V_{C2} = V_{C3} = \frac{1}{n}(V_{in2} + V_{C1})\left(\frac{D_b}{1 - D_b}\right)$$  (17)

$$V_o = \frac{2}{n}[V_{in2} + V_{C1}]\left(\frac{D_b}{1 - D_b}\right)$$  (18)

By substituting (16) into (17) and (18), the voltages $V_{C2}$ and $V_{C3}$ can be attained as follows:

$$V_{C2} = V_{C3} = \frac{1}{n} \left[\frac{V_{in2} + V_{in1}}{D_a}\left(\frac{D_b}{1 - D_b}\right)\right]$$  (19)

Therefore, the voltage $V_o$ can be represented as:

$$V_o = V_{C2} + V_{C3} = \frac{2}{n} \left[\frac{V_{in2} + V_{in1}}{D_a}\left(\frac{D_b}{1 - D_b}\right)\right]$$  (20)

### 4.3. Boundary Condition for $L$

For convenience of analysis, it is assumed that the input power and the output power are identical, the input power is separated, and the input currents for the two thermoelectric generators are the same, namely, $I_{in1} = I_{in2} = I_{in}$.

As there is no power loss in this operating converter, the following equation can be obtained:

$$P_o = P_{in1} + P_{in2} = P_{o1} + P_{o2}$$  (21)

where $P_o$ is the output power, and $P_{in1}$ and $P_{in2}$ are the two input powers of the two inputs, whereas $P_{o1}$ and $P_{o2}$ are the corresponding output powers of the two inputs.

From (21), the formula of the first output power is:

$$P_{o1} = P_{in1}$$

$$\Rightarrow V_{C1} \times I_{C1} = V_{in1} \times I_{in}$$  (22)

where $I_{C1}$ is the DC current in $C_1$. 
For convenience of analysis, by assuming that the load resistance of the first input is \( R_1 \), the current flowing through \( R_1 \) can be represented as follows:

\[
I_{C1} = \frac{V_{C1}}{R_1} \tag{23}
\]

Therefore, substituting (16) and (23) into (22) yields:

\[
\frac{V_{C1}^2}{R_1} = V_{in1} \times I_{in} = \frac{D_a^2 \times V_{in1}^2}{(1 - D_a)^2 \times R_1} \tag{24}
\]

Since the ripple current in \( L \)—represented as \( \Delta i_L \)—can be indicated by:

\[
\Delta i_L = \frac{v_L \times \Delta t}{L} \tag{25}
\]

Substituting (4) into (25) yields:

\[
\Delta i_L = \frac{V_{in1}}{L} D_a T_s \tag{26}
\]

Hence, as \( 2I_L > \Delta i_L \), \( L \) will work in CCM; that is:

\[
2I_L \geq \Delta i_L \Rightarrow 2 \times \frac{D_a \times V_{in1}}{(1 - D_a)^2 \times R_1} \geq \frac{V_{in1}}{L} D_a T_s \Rightarrow \frac{2L}{R_1 T_s} \geq (1 - D_a)^2 \Rightarrow K_L \geq K_{crit-L}(D_a) \tag{27}
\]

where \( K_L = \frac{2L}{R_1 T_s} \) and \( K_{crit-L}(D_a) = (1 - D_a)^2 \).

From (27), it can be seen that if \( K_L \geq K_{crit-L}(D_a) \) holds, \( L \) works in CCM; if not, \( L \) will work in the discontinuous current mode (DCM). Hence, the boundary curve between two modes can be plotted as shown in Figure 11.

![Figure 11](image_url)

**Figure 11.** Boundary curve between CCM and DCM for \( L \).

### 4.4. Boundary Curve of \( L_m \)

For convenience of analysis, it is assumed that the input power \( P_{in} \) is identical to the output power \( P_o \), that the input power is separated, and that the input currents for the two thermoelectric generators are the same, namely, \( I_{in1} = I_{in2} = I_{in} \). At the same time, from Figure 5, it can be seen that the average current is zero for the charge pump capacitors \( C_2 \) and \( C_3 \). Therefore, the average current in the secondary-side winding, \( I_{Ns} \), is identical to
the average current in the output inductor, $I_{Lo}$. Figure 12 shows the equivalent model for the DC current analysis of the coupled inductor.

**Figure 12.** Equivalent model for DC current analysis of the coupled inductor.

According to state 2 and (5), the primary-side voltage $v_{Np}$ can be expressed as follows:

$$v_{Np} = v_{Lm} = V_{in2} + V_{C1}$$  \hspace{1cm} (28)

Since there is no power loss in the circuit, the resulting equation can be attained as:

$$P_{in} = P_o = V_o \times I_o$$  \hspace{1cm} (29)

Rearranging (29) yields:

$$V_o \times I_o = (V_{in2} + V_{C1}) \times I_{in}$$  \hspace{1cm} (30)

where:

$$I_o = \frac{V_o}{R_o}$$  \hspace{1cm} (31)

From Figure 12, the average current of $i_{Lm}$ can be represented by:

$$I_{Lm} = I_{Np} + I_{in}$$  \hspace{1cm} (32)

and:

$$I_{Np} = \frac{I_{Ns}}{n} = \frac{I_o}{n}$$  \hspace{1cm} (33)

Rearranging (30) yields:

$$I_{in} = \frac{V_o}{V_{in2} + V_{C1}} \times I_o$$  \hspace{1cm} (34)

Substituting (18) and (28) into (34) yields:

$$I_{in} = \frac{2}{n} \times \left( \frac{D_b}{1 - D_b} \right) \times I_o$$  \hspace{1cm} (35)

Substituting (33) and (35) into (32) yields:

$$I_{Lm} = \frac{I_o}{n} \left( 1 + \frac{D_b}{1 - D_b} \right)$$  \hspace{1cm} (36)

Substituting (31) into (36) yields:

$$I_{Lm} = \frac{V_o}{nR_o} \left( 1 + \frac{D_b}{1 - D_b} \right)$$  \hspace{1cm} (37)

In addition, the ripple current of $i_{Lm}$, $\Delta i_{Lm}$, can be obtained as follows:

$$\Delta i_{Lm} = \frac{v_{Lm} \times \Delta t}{L_m}$$  \hspace{1cm} (38)
Substituting (28) into (38) yields:

$$\Delta i_{Lm} = \frac{V_{in}^2 + V_{C1} D_b T_s}{L_m}$$  \hspace{1cm} (39)$$

Therefore, as $2I_{Lm} \geq \Delta i_{Lm}$, the magnetizing inductance $L_m$ will operate in CCM; that is:

$$2I_{Lm} \geq \Delta i_{Lm} \Rightarrow 2 \times \frac{2V_o}{R_o} \left( \frac{1 + D_b}{1 - D_b} \right) \geq \frac{V_{in}^2 + V_{C1}}{V_o} \times \frac{D_b}{\left(1 - \frac{1}{1 + D_b} \right)}$$

$$\Rightarrow \frac{2I_{Lm}}{R_o T_s} \geq n \times \frac{n(1 - D_b)}{2D_b} \times \frac{D_b}{\left(1 - \frac{1}{1 + D_b} \right)}$$

$$\Rightarrow \frac{2I_{Lm}}{R_o T_s} \geq \left[ \frac{n(1 - D_b)}{2(1 + D_b)} \right] \times \frac{2D_b}{\left(1 + D_b \right)} \times \frac{D_b}{\left(1 - \frac{1}{1 + D_b} \right)}$$

$$\Rightarrow K_{Lm} \geq K_{crit,Lm}(D_b)$$

where $K_{Lm} = \frac{2I_{Lm}}{R_o T_s}$ and $K_{crit,Lm}(D_b) = \left[ \frac{n(1 - D_b)}{2(1 + D_b)} \right] \times \frac{2D_b}{\left(1 + D_b \right)}$.

From (40), under the turns ratio $n = 0.5$, if $K_{Lm} \geq K_{crit,Lm}(D_b)$ holds, the inductance $L_m$ will operate in CCM; if not, $L_m$ will work in DCM. Accordingly, the boundary curve between CCM and DCM can be drawn as shown in Figure 13.

![Figure 13. Boundary curve between CCM and DCM for $L_m$.](image)

4.5. Boundary Condition for $L_o$

The average current of the output inductor $I_{Lo}$ is identical to the output current $I_o$, namely:

$$I_{Lo} = I_o$$ \hspace{1cm} (41)$$

Additionally:

$$I_o = \frac{V_o}{R_o}$$ \hspace{1cm} (42)$$

According to (41), and by substituting (20) into (42), the following equation can be expressed:

$$I_{Lo} = \frac{2}{{\pi}} \left[ V_{in}^2 + V_{in1} \left( \frac{D_b}{1 - D_b} \right) \right] \left( \frac{D_b}{1 - \frac{1}{1 + D_b}} \right) \frac{D_b}{\left(1 - \frac{1}{1 + D_b} \right)}$$

$$\Rightarrow \frac{2I_{Lo}}{R_o} \geq \left[ \frac{n(1 - D_b)}{2(1 + D_b)} \right] \times \frac{2D_b}{\left(1 + D_b \right)} \times \frac{D_b}{\left(1 - \frac{1}{1 + D_b} \right)}$$

Moreover, the ripple current of $i_{Lo}$, represented as $\Delta i_{Lo}$, can be obtained as follows:

$$\Delta i_{Lo} = \frac{v_{Lo} \times \Delta t}{L_o}$$ \hspace{1cm} (44)$$
Substituting (4) into (44) yields:

$$\Delta i_{Lo} = \frac{1}{n} \left( V_{in2} + V_{C1} + V_{C2} + V_{C3} - V_o D_b T_s \right) \quad (45)$$

Substituting (16) and (20) into (45) yields:

$$\Delta i_{Lo} = \frac{1}{n} \left[ V_{in2} + \left( \frac{D_a}{1-D_a} \right) V_{in1} \right] D_b T_s \quad (46)$$

Substituting (4) into (25) yields:

$$\Delta i_L = \frac{V_{in1}}{L} D_a T_s \quad (47)$$

Therefore, as $2I_{Lo} \geq \Delta i_{Lo}$, the output inductor $L_o$ operates in CCM; that is:

$$2 \times \frac{1}{n} \left[ V_{in2} + V_{in1} \left( \frac{D_a}{1-D_a} \right) \right] \left( \frac{D_b}{1-D_b} \right)$$

$$\geq \frac{1}{n} \left[ V_{in2} + \left( \frac{D_a}{1-D_a} \right) V_{in1} \right] D_b T_s$$

$$\Rightarrow \frac{2 L_o}{K_{Lo} T_s} \geq \frac{(1-D_b)}{2}$$

$$\Rightarrow K_{Lo} \geq K_{crit,Lo}(D_b) \quad (48)$$

where $K_{Lo} = \frac{2L_o}{K_{Lo} T_s}$ and $K_{crit,Lo}(D_b) = \frac{(1-D_b)}{2}$.

From (48), it can be known that if $K_{Lo} \geq K_{crit,Lo}(D_b)$ holds, the output inductor $L_o$ works in CCM; if not, $L_o$ operates in DCM. Therefore, the boundary curve between CCM and DCM can be sketched as shown in Figure 14.

![Figure 14. Boundary curve between CCM and DCM for $L_o$.](image)

### 4.6. Topology Extension

As displayed in Figure 15, the proposed converter can be expanded to $N$ inputs, where $N$ is a positive integer; hence, its input count will be increased such that the thermal energy from all of the sources can be recycled.
5. Design Considerations

5.1. Thermoelectric Module Specifications

The thermoelectric modules adopted herein are called TGM-199-1.4-0.8, made by Kryotherm Co. There are two inputs in the proposed converter: the first input is fed by four series-connected thermoelectric modules, while the second input is fed by two series-connected thermoelectric modules. The associated specifications are displayed in Tables 1 and 2.

Table 1. Specifications for the first thermoelectric module.

<table>
<thead>
<tr>
<th>Part Name</th>
<th>TGM-199-1.4-0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>40 × 40 × 3.2 mm</td>
</tr>
<tr>
<td>Number</td>
<td>Four in series</td>
</tr>
<tr>
<td>Maximum Power ($P_{mpp1}$)</td>
<td>23.2 W</td>
</tr>
<tr>
<td>Voltage at MPP ($V_{mpp1}$)</td>
<td>14 V</td>
</tr>
<tr>
<td>Current at MPP ($I_{mpp1}$)</td>
<td>1.653 A</td>
</tr>
<tr>
<td>Open Voltage ($V_{oc1}$)</td>
<td>27.6 V</td>
</tr>
<tr>
<td>Short Current ($I_{sc1}$)</td>
<td>3.25 A</td>
</tr>
<tr>
<td>Cold-Side Temperature</td>
<td>80 °C</td>
</tr>
<tr>
<td>Hot-Side Temperature</td>
<td>180 °C</td>
</tr>
</tbody>
</table>
Table 2. Specifications for the second thermoelectric module.

<table>
<thead>
<tr>
<th>Part Name</th>
<th>TGM-199-1.4-0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>40 × 40 × 3.2 mm</td>
</tr>
<tr>
<td>Number</td>
<td>Two in series</td>
</tr>
<tr>
<td>Maximum Power ($P_{mpp2}$)</td>
<td>11.68 W</td>
</tr>
<tr>
<td>Voltage at MPP ($V_{mpp2}$)</td>
<td>7.5 V</td>
</tr>
<tr>
<td>Current at MPP ($I_{mpp2}$)</td>
<td>1.56 A</td>
</tr>
<tr>
<td>Open Voltage ($V_{oc2}$)</td>
<td>13.95 V</td>
</tr>
<tr>
<td>Short Current ($I_{sc2}$)</td>
<td>3.246 A</td>
</tr>
<tr>
<td>Cold-Side Temperature</td>
<td>80 °C</td>
</tr>
<tr>
<td>Hot-Side Temperature</td>
<td>180 °C</td>
</tr>
</tbody>
</table>

5.2. System Configuration Together with Design Concept and Experimental Strategy

Figure 16 shows the proposed isolated MISOC converter along with two thermoelectric generators, with an FPGA control kernel. According to Tables 1 and 2, the first TEG under MPPT has an output voltage of 14 V, and its output current is 1.653 A, whereas the second TEG under the MPPT has an output voltage of 7.5 V and an output current of 1.56 A. Therefore, the sum of the power generated from the two TEGs is 34.88 W. Accordingly, based on the above-mentioned factors, and by prescribing the output voltage of the converter at 100 V, Tables 3 and 4 display the system specifications and the respective converter specifications. An efficiency curve can be attained under the output voltage regulated at 100 V. Afterwards, the MPPT algorithm is imposed on this converter to harvest thermal energy; hence, some waveforms are measured. Moreover, under the control of MPPT, the needed digital signals—containing the input voltages and currents—are created after the analog-to-digital converters (ADCs), the field-programmable gate array (FPGA) shown in Table 5 is utilized to control such a system, and the gate-driving signals generated by the FPGA are passed to the switches. Note that since this circuit focuses on harvesting thermal energy, the output voltage sensor and the corresponding voltage mode controller are not displayed in Figure 16.

Table 3. System specifications.

<table>
<thead>
<tr>
<th>Operating Mode</th>
<th>CCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Input Voltage ($V_{in1}$)</td>
<td>7.5 V</td>
</tr>
<tr>
<td>Second Input Voltage ($V_{in2}$)</td>
<td>14 V</td>
</tr>
<tr>
<td>Rated Output Voltage ($V_o$)</td>
<td>100 V</td>
</tr>
<tr>
<td>Rated Output Current ($I_{o,\text{rated}}$) / Power ($P_{o,\text{rated}}$)</td>
<td>34.88 mA/34.88 W</td>
</tr>
<tr>
<td>Minimum Output Current ($I_{o,\text{min}}$) / Power ($P_{o,\text{min}}$)</td>
<td>34.88 mA/3.488 W</td>
</tr>
<tr>
<td>Switching Frequency ($f_s$) / Power ($T_s$)</td>
<td>100 kHz/10 µs</td>
</tr>
<tr>
<td>$n = N_p/N_s$</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Figure 16. Thermoelectric system with the proposed isolated MISOC.
Table 4. Component specifications used in the isolated MISOC.

<table>
<thead>
<tr>
<th>Components</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOSFET Switch $S_1$</td>
<td>IRF3205 Z</td>
</tr>
<tr>
<td>MOSFET Switch $S_2$</td>
<td>STB120NF10T4</td>
</tr>
<tr>
<td>Diode $D_1$</td>
<td>STPS30L30CT</td>
</tr>
<tr>
<td>Diodes $D_2$, $D_3$</td>
<td>STPS20H100CT</td>
</tr>
<tr>
<td>Charge Pump Capacitor $C_1$</td>
<td>150 $\mu$F Electrolytic Capacitor</td>
</tr>
<tr>
<td>Charge Pump Capacitors $C_2$, $C_3$</td>
<td>47 $\mu$F Electrolytic Capacitor</td>
</tr>
<tr>
<td>Output Capacitor $C_0$</td>
<td>68 $\mu$F Electrolytic Capacitor</td>
</tr>
<tr>
<td>Input Inductor $L$</td>
<td>100 $\mu$H</td>
</tr>
<tr>
<td>Output Inductor $L_o$</td>
<td>4.32 mH</td>
</tr>
<tr>
<td>Coupled Inductor $L_m$</td>
<td>$L_m = 330$ $\mu$H, $n = 0.5$</td>
</tr>
<tr>
<td>Isolated Gate Driver FOD3182</td>
<td></td>
</tr>
</tbody>
</table>

Table 5. EP3C5E144C8N specifications.

<table>
<thead>
<tr>
<th>Device</th>
<th>Logic Elements</th>
<th>Total RAM Bits</th>
<th>18 $\times$ 18 Multipliers</th>
<th>PLLs</th>
<th>User I/O Pins</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP3C5E144C8N</td>
<td>5136</td>
<td>423936</td>
<td>23</td>
<td>2</td>
<td>94</td>
</tr>
</tbody>
</table>

5.3. Calculation of Duty Cycles

Based on (39), with $D_a$ equal to 0.6, the value of $D_b$ will be calculated to be 0.4975.

$$V_o = \frac{2}{n} \left[V_{in2} + V_{in1} \left(\frac{D_a}{1 - D_a}\right)\right] \left(\frac{D_b}{1 - D_b}\right) \Rightarrow 100 = \frac{2}{0.5} \left[14 + 7.5 \left(\frac{0.6}{1 - 0.6}\right)\right] \left(\frac{D_b}{1 - D_b}\right) \Rightarrow D_b = 0.4975$$ \hspace{1cm} (49)

5.4. Design of $L$

By assuming that the inductor $L$ works in CCM above $0.1 I_{mmp1}$, and according to the following equation, the value of $L_{min}$ can be derived as follows:

$$L_{min} = \frac{v_l \times D_a \times T_s}{2 \times 0.1 I_{mmp1} \div D_a} = \frac{7.5 \times 0.6^2 \times 10 \mu}{2 \times 0.1 \times 1.56} = 86.54 \mu H$$ \hspace{1cm} (50)

Eventually, the value of $L$ is set at 100 $\mu$H.

5.5. Design of $L_o$

By assuming that the inductor $L_o$ works in CCM above $I_{o, min}$, and according to the following equations, the value of $L_{o, min}$ can be derived as follows:

$$v_{L_o} = \frac{1}{n} \left[V_{in2} + \left(\frac{D_a}{1 - D_a}\right) V_{in1}\right] = \frac{1}{0.5} \left[14 + \left(\frac{0.6}{1 - 0.6}\right) \times 7.5\right] = 50.5 V$$ \hspace{1cm} (51)

$$L_{o, min} = \frac{v_{L_o} \times D_b \times T_s}{2 \times I_{o, min}} = \frac{50.5 \times 0.4975 \times 10 \mu}{2 \times 34.88 m} = 3.6 mH$$ \hspace{1cm} (52)

Eventually, the value of $L_o$ is set at 4.32 mH.
5.6. Design of \( L_m \)

By assuming that the inductor \( L_m \) operates in CCM above \( I_{o,min} \), and according to (40), the value of \( L_{m,min} \) can be derived as follows:

\[
L_{m,min} = \frac{n(1-D_b)^2}{4(1+D_b)} \times T_s \times \frac{V_o}{I_{o,min}}
\]

\[
= \frac{0.5(1-0.4975)^2}{4(1+0.4975)} \times 10 \mu \times \frac{100}{34.88} = 302 \ \mu \text{H}
\]

Eventually, the value of \( L_m \) is set at 330 \( \mu \text{H} \).

5.7. Design of \( C_1 \)

By assuming that the maximum ripple voltage of \( C_1 \) is 1% of \( V_{C1} \), and based on the following equations, the value of \( C_{1,min} \) can be worked out as follows:

\[
V_{C1} = \frac{D_a}{1-D_a} \times V_{in1} = \frac{0.6}{1-0.6} \times 7.5 = 11.25 \text{ V}
\]

\[
C_{1,min} = I_{o,\text{rated}} \times \frac{(1-D_b)T_s}{0.01 \times V_{C1}} = \frac{1.56}{0.6} \times \frac{(1-0.6)10 \mu}{0.01 \times 11.25} = 92 \ \mu \text{F}
\]

Eventually, the value of \( C_1 \) is set at 150 \( \mu \text{F} \).

5.8. Design of \( C_2 \) and \( C_3 \)

By assuming that the maximum ripple voltage of \( C_2 \) or \( C_3 \) is 0.1% of \( V_{C2} \) or \( V_{C3} \), respectively, and based on (17), the value of \( C_{2,min} \) or \( C_{3,min} \) can be worked out as follows:

\[
V_{C2} = V_{C3} = \frac{1}{n} (V_{in2} + V_{C1}) \left( \frac{D_b}{1-D_b} \right) = \frac{1}{0.5} \left( 14 + 11.25 \right) \left( \frac{0.4975}{1-0.4975} \right) = 50 \text{ V}
\]

\[
C_{2,min} = C_{3,min} = I_{o,\text{rated}} \times \frac{(1-D_b)T_s}{0.001 \times V_{C2}} = 0.3488 \times \frac{(1-0.4975) \times 10 \mu}{0.001 \times 50} = 35.1 \ \mu \text{F}
\]

Finally, the value of \( C_2 \) or \( C_3 \) is set at 47 \( \mu \text{F} \).

5.9. Design of \( C_o \)

By assuming that the maximum ripple voltage of \( C_o \) is 0.1% of \( V_{C0} \) and based on [21], the value of \( C_{o,min} \) can be worked out as follows:

\[
\Delta i_{Lo} = \frac{1}{n} (V_{in2} + V_{C1}) \times D_b \times T_s \div L_o
\]

\[
= \frac{1}{0.5} \times (14 + 11.25) \times 0.4975 \times 10 \mu \div 4.32m
\]

\[
= 0.0587 \ \text{A}
\]

\[
ESR = \frac{0.001 \times V_o}{\Delta i_{Lo}} = \frac{0.001 \times 100}{0.0587} = 1.704 \ \Omega
\]

\[
ESR \times C_{o,min} = 50 \sim 80 \mu \Rightarrow C_{o,min} = \frac{80 \mu}{1.704} = 46.08 \ \mu \text{F}
\]

Eventually, the value of \( C_o \) is set at 68 \( \mu \text{F} \).

5.10. Converter Topology Comparison

In Table 6, two circuits shown in [19] and [20] are employed as comparisons. The number of components is used as a comparison item, to be described below. From Table 6, it can be seen that the proposed converter has the smallest number of components.
Table 6. Comparison between the existing [19,20] and the proposed circuits.

<table>
<thead>
<tr>
<th>Component No.</th>
<th>[19]</th>
<th>[20]</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Inductor</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Coupled Inductor</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Switch</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Diode</td>
<td>4</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Charge Pump Capacitor</td>
<td>4</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

6. Simulated and Experimental Results

6.1. Simulated Results

A PSIM-based simulation was utilized to demonstrate the feasibility of this system with the designed resistance of $313 \Omega$ (100 V/348 mA) used as a load. Since in the PSIM software only a solar cell model can be utilized, the parameters of this model were modified to simulate TEG operation. There are three examples to be discussed, as follows:

In example 1, displayed in Figure 17, it can be seen that the generated power relevant to TEG1 is 22.976 W, and this value is close to the MPP power of 23.142 W, while the generated power relevant to TEG2 is 11.029 W, and this value is close to the MPP power of 11.7 W. Summing the two powers yields 34.005 W, and this value is almost the same as the output power of 34.065 W. Moreover, the output voltage is 98.81 V, which is close to 100 V. In addition, the corresponding duty cycles of $D_c$ and $D_d$ are 0.578 and 0.52, respectively, and these values are somewhat different from 0.6 and 0.4975 under voltage mode control, respectively.

In example 2, displayed in Figure 18, the short current $I_{sc}$ of TEG1 is three times that of TEG1 in Figure 17. From Figure 18, it can be seen that the generated power relevant to TEG1 is 67.004 W, and this value is close to the MPP power of 69.426 W, while the generated power relevant to TEG2 is 11.029 W, and this value is close to the MPP power of 11.7 W. Summing the two powers yields 77.454 W, and this value is close to the output power of 76.835 W. Moreover, the output voltage is 148.39 V, and this is because the more the power is transferred, the higher the output voltage.

Figure 17. Simulation example 1.
In example 3, displayed in Figure 19, the open voltage $V_{oc}$ of TEG1 is four times that of TEG1 in Figure 17. From Figure 19, it can be seen that the generated power relevant to TEG1 is 85.951 W, and this value is close to the MPP power of 85.956 W, while the generated power relevant to TEG2 is 11.28 W, and this value is close to the MPP power of 11.7 W. Summing the two powers yields 97.231 W, and this value is close to the output power of 93.81 W. Moreover, the output voltage is 163.97 V, and this is because the more the power is transferred, the higher the output voltage.

**Figure 19.** Simulation example 3.

### 6.2. Efficiency Curve

An efficiency curve can be attained under the output voltage regulated at 100 V, with the electronic load working in the constant current (CC) mode. From Figure 20, it can be seen that the efficiency at 10% load is ~72.2%, the efficiency at 100% load is ~85.2%, and the maximum efficiency is ~87.2%. The reason that the efficiency is not high is the low current in the load.

**Figure 20.** Efficiency curve.
6.3. Measured Waveforms

After the efficiency curve is finished, the MPPT algorithm is applied to the proposed converter to demonstrate the maximum power transfer, with some illustrated waveforms given. Note that for MPPT experiments, an electronic load works in the constant voltage (CV) mode.

In the following section, the waveforms shown from Figures 21–26 are measured under MPPT. Figure 21 shows the gate-driving signals $v_{gs1}$ and $v_{gs2}$ for $S_1$ and $S_2$, respectively, and the voltages across $S_1$ and $S_2$, called $v_{ds1}$ and $v_{ds2}$, respectively; Figure 22 displays the gate-driving signal $v_{gs1}$ for $S_1$, the voltage across $D_1$, the current flowing through $L$—represented as $i_L$—and the voltage across $C_1$; Figure 23 shows the gate-driving signal $v_{gs2}$ for $S_2$, and the voltages across $D_2$ and $D_3$, represented as $v_{D2}$ and $v_{D3}$, respectively; Figure 24 displays the gate-driving signal $v_{gs2}$ for $S_2$, the input current $i_{in2}$, the secondary-side current $i_{Ns}$, and the output current $i_{Lo}$; Figure 25 shows the output voltage $V_o$, and the voltages across $C_2$ and $C_3$, represented as $V_{C2}$ and $V_{C3}$, respectively; Figure 26 displays the output voltage $V_o$, and the input voltages $V_{in1}$ and $V_{in2}$, which are created from TEG1 and TEG2, respectively.

Figure 20. Curve of efficiency versus load current.

Figure 21. Waveforms measured under the thermoelectric system: (1) $v_{gs1}$; (2) $v_{gs2}$; (3) $v_{ds1}$; (4) $v_{ds2}$. 

![Figure 20](image-url)
Figure 22. Waveforms measured under the thermoelectric system: (1) \( v_{gs1} \); (2) \( v_{D1} \); (3) \( i_L \); (4) \( V_{C1} \).

Figure 23. Waveforms measured under the thermoelectric system: (1) \( v_{gs2} \); (2) \( v_{D2} \); (3) \( v_{D3} \).

Figure 24. Waveforms measured under the thermoelectric system: (1) \( v_{gs2} \); (2) \( i_{in2} \); (3) \( i_{Ns} \); (4) \( i_{Lo} \).
Figure 25. Waveforms measured under the thermoelectric system: (1) $V_o$; (2) $V_{C2}$; (3) $V_{C3}$.

Figure 26. Waveforms measured under the thermoelectric system: (1) $V_o$; (2) $V_{in1}$; (3) $V_{in2}$.

From Figure 21, it can be seen that the maximum voltages across $S_1$ and $S_2$ are approximately 20 V and 50 V, respectively. From Figure 22, it can be seen that the maximum voltage across the diode $D_1$ is ~25 V, with high-frequency oscillation due to the parasitic capacitance of $D_1$ resonating with the line parasitic inductance, while the voltage across $C_1$ is ~13 V, and the average value of $i_L$ is ~2.3 A, implying that the average value of $i_{in1}$ is ~1.6 A, and that TEG1 works at MPP. From Figure 23, it can be seen that the maximum voltages across the diodes $D_2$ and $D_3$ are ~100 V, with high-frequency oscillation due to the parasitic capacitances of $D_2$ and $D_3$ resonating with the line parasitic inductance and the secondary-side leakage inductance $L_{Lk2}$. From Figure 24, it can be seen that the average value of $i_{Lo}$ is 350 mA, and the average value of $i_{in2}$ is ~1.5 A, implying that TEG2 works at MPP. Figure 25 shows that the value of $V_o$ is ~100 V, while the values of $V_{C2}$ and $V_{C3}$ are ~50 V, meaning that the voltages across the two capacitors $C_2$ and $C_3$ can be kept constant at the desired value. Figure 26 shows that the value of $V_o$ is ~100 V, the value of $V_{in1}$ is ~7.5 V, and the value of $V_{in2}$ is ~14 V, implying that the two TEGs operate under individual MPPs. Figure 27 shows photos of the proposed thermoelectric system containing the MISOC circuit and the thermoelectric platform.
Figure 27. Photos of the proposed thermoelectric system: (a) MISOC circuit; (b) thermoelectric platform.

7. Conclusions

The presented isolated MISOC circuit was analyzed and imposed on a one-stage thermal energy harvesting system. In this system, TEGs possess individual MPPT functions, thus rendering the thermal energy harvesting more efficient. Moreover, the presented converter has a relatively high step-up ratio. Furthermore, the input count can be increased, indicating that more TEGs can be connected to such a converter with individual MPPT functions. Finally, future works should aim to increase the power level along with the soft switching technology applied.

Author Contributions: Conceptualization, Y.-T.Y. and K.-I.H.; methodology, Y.-T.Y.; software, J.-J.S.; validation, Y.-T.Y., K.-I.H. and J.-J.S.; formal analysis, Y.-T.Y.; investigation, J.-J.S.; resources, Y.-T.Y.; data curation, J.-J.S.; writing—original draft preparation, K.-I.H.; writing—review and editing, K.-I.H.; visualization, J.-J.S.; supervision, K.-I.H.; project administration, K.-I.H.; funding acquisition, J.-J.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Science and Technology, Taiwan, under the Grant Number: MOST 110-2221-E-035-050.
Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

References