

Article

Applying a Multiple-Input Single-Output Interleaved High Step-Up Converter with a Current-Sharing Device Having Different Input Currents to Harvest Energy from Multiple Heat Sources

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Abstract: In this paper, a thermoelectric conversion system for multiple heat sources is proposed. For design convenience, the overall system employs only a single-stage converter. Such a converter uses coupling inductors and switched capacitors to increase the voltage gain. In order to reduce the high-frequency voltage oscillation of the turn-off of the main switches created from leakage inductors, two active clamp circuits with zero voltage switching (ZVS) turn-on are employed. By doing so, although the current-sharing device with interleave control is embedded in the proposed converter, the input currents can be unequal. Therefore, the inputs of the converter can operate under individual maximum power points and transfer the energy from different thermoelectric generators (TGs) to a single load. Furthermore, the main switches have low voltage stress during the turn-off period. As for the maximum power point tracking (MPPT) method, it utilizes a three-point-weighting method to improve the tracking stability. In addition, the number of inputs of this converter can be extended. The MPPT simulation is presented to verify the feasibility as well as several experimental waveforms to demonstrate the effectiveness. The field programmable gate array (FPGA) is used as a digital control kernel to control the thermoelectric conversion system.

Keywords: active clamping circuit; coupling inductor; switched capacitor; MPPT; FPGA; high step-up converter; three-point-weighting method; multi-input single-output; thermoelectric conversion system



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1. Introduction

Green energy includes solar, wind, thermal, hydro, tidal, biomass, thermal, etc. Although green energy is a clean and inexhaustible source, there are still many problems to overcome, such as the low voltage generated by green energy, the susceptibility to unstable voltages or currents due to external environmental influences, and the tendency for voltages or currents to fluctuate with load changes. To solve these problems, a step-up converter is usually connected to the back end of the thermoelectric generator (TG), with maximum power point tracking (MPPT) to extract energy steadily for the back-end equipment, or to a step-up or step-down inverter to convert DC power to AC power in parallel with the mains or for other loads [1,2], as shown in Figure 1.

Concerning multi-input single-output (MISO) converters, the topology proposed by [3] is a switched capacitor (SC) converter, which uses the superposition of capacitor voltages to improve the boost ratio. The circuit presented by [3] is a modification of the circuit [4] with a two-stage interleaved structure, which allows for a higher boost ratio for high currents but increases the number of elements. The structures proposed by [5,6] are simple and are derived from the conventional interleaved boost converter such that they use fewer

elements to improve the boost ratio. Consequently, the corresponding boost ratios are limited. The dual-input isolated high-boost structure proposed in [7] incorporates an active clamp circuit to reduce the voltage stress on the switches. The circuit presented by [8] is a dual-input converter derived from the interleaved structure of [9], and therefore is not suitable for systems with multiple MPPTs because this circuit has automatic balance of the input currents. The structure proposed by [10] is a dual-input converter derived from the quasi-Y-source structure. The circuit proposed by [11] is a modification of the conventional buck–boost converter into two inputs. The topology presented by [12] adopts a transformer to enable a full-bridge converter to possess multiple inputs. By doing so, it is not possible to extend more inputs due to the size limitation of the transformer.

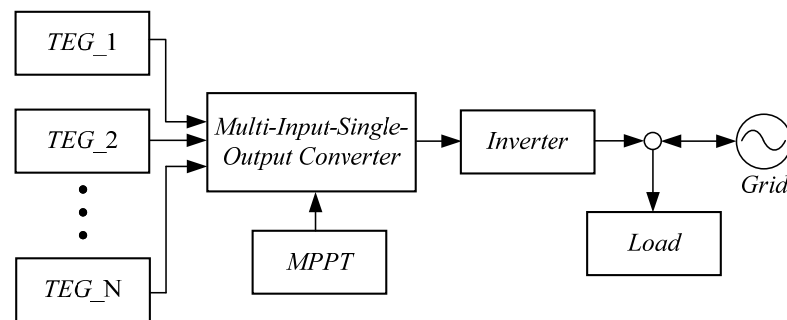


Figure 1. Block diagram of a thermoelectric system with multiple inputs.

In [13], one of the inputs of the multi-input converter is connected to batteries, which have bidirectional operation of charging and discharging circuits. Because of the need to consider the circuit path of the battery, the battery charging and discharging circuitry is more complex than normal. The circuit shown in [14] is composed of two interleaved boost circuits and employs two switches instead of two diodes to reduce conduction losses. In [15], a transformer and an interleaved boost circuit with switched capacitors are utilized to improve the boost ratio. In addition, an active clamping circuit is added to obtain ZVS turn-on of the switch.

The topology presented by [16] adopts an interleaved structure with switched inductors to form a three-port circuit and active clamping circuits to ensure all the switches have ZVS turn-on. In [17], a dual-input boost converter modified from the conventional boost converter possesses a simple structure and a wide input voltage range. However, the second input voltage needs to be of opposite polarity to the output voltage. Consequently, this structure cannot be extended with more inputs. In [18], a converter with a three-port circuit and bidirectional operation is proposed. In [19], a modification of the conventional buck–boost circuit is presented, whose duty cycle can be regulated so that the converter can operate in buck, boost, and buck–boost modes. In [20], a thermal energy harvesting converter with two inputs and an isolated output is proposed. In addition, the number of inputs can be extended.

As shown in Figure 2a, the MISO circuit modified from Figure 2b is applied to two heat sources [21]. Staggering the timing for the two maximum power traces solves the problem of two heat sources not being able to carry out individual MPPTs. This is because the capacitor C_2 has a role of automatic current sharing as well as energy transferring [9], as shown in Figure 2b. Speaking lucidly, the gate driving signals for the switches S_1 and S_2 are controlled by interleave, as shown in Figure 2a,b, but the gate driving signals for the switches S_3 and S_4 are controlled by time division, as shown in Figure 2a. By doing so, the capacitor C_2 in Figure 2a has only the role of transferring energy.

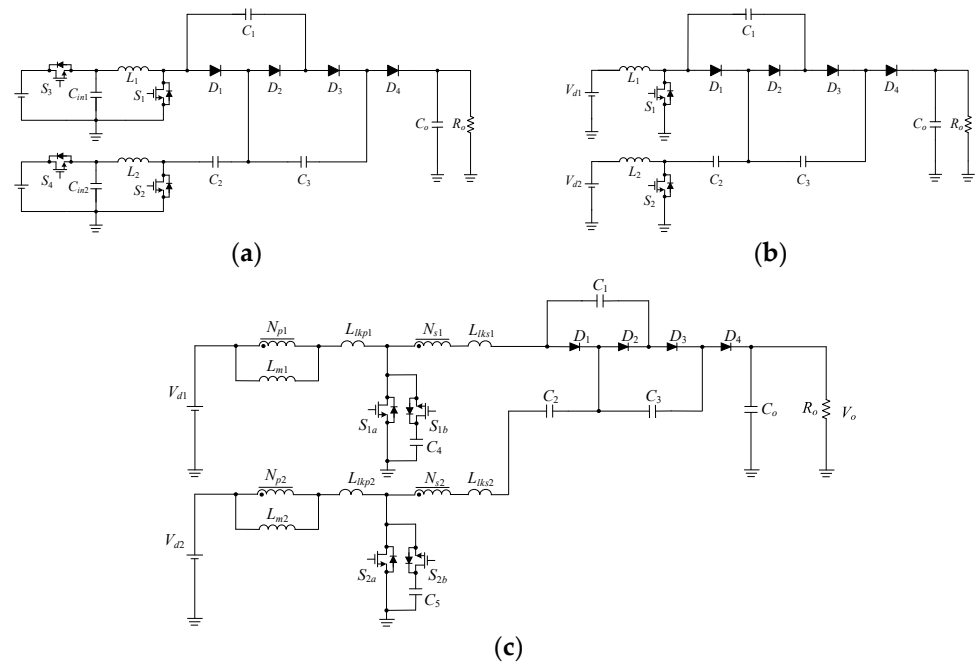


Figure 2. Interleaved MISO converter: (a) modified [21]; (b) existing [9]; (c) proposed.

As shown in Figure 2c, adding two active clamp circuits forces the two heat sources to realize the respective MPPTs although the proposed circuit is modified from Figure 2b. In more detail, the gate driving signals for the switches S_{1a} and S_{2a} are controlled by interleave, but the gate driving signals for the switches S_{1b} and S_{2b} are complementary to those for the switches S_{1a} and S_{2a} , respectively. By doing this, the capacitor C_2 has only the role of transferring energy. Moreover, the switches S_{1b} and S_{2b} have ZVS turn-on and the number of inputs can be extended. To sum up, the proposed converter has ZVS during the turn-on period and low voltages on the switches during the turn-off period, and the thermoelectric modules have individual MPPTs without staggering time.

2. Thermoelectric Module

2.1. P-I-V Curve

As shown in Figure 3, the thermoelectric generator (TG) can be considered as a Thevenin equivalent circuit for analysis convenience. V_{oc} is the open-circuit voltage at both ends of the TG; R_{teg} is the equivalent internal resistance; R_L is the load on the TG; V_{teg} is the output voltage of the TG; I_{teg} is the output current of the TG; I_{sc} is the short-circuit current of the TG. Accordingly, maximum power point tracking is required to obtain the maximum power transfer.

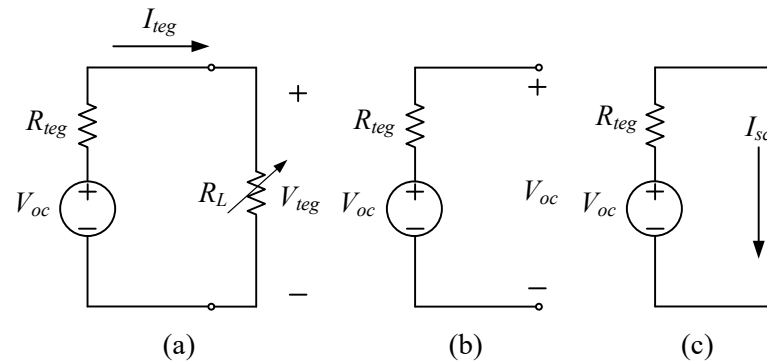


Figure 3. Thermoelectric generator: (a) Thevenin equivalent circuit; (b) open-circuit test; (c) short-circuit test.

As R_L is equal to R_{teg} , V_{teg} and I_{teg} can be shown as follows:

$$V_{teg} = \frac{V_{oc}}{2} \quad (1)$$

$$I_{teg} = \frac{V_{oc}}{2R_{teg}} = \frac{I_{sc}}{2} \quad (2)$$

From (1) and (2), the value at the maximum power point can be obtained:

$$P_{mpp} = \frac{V_{oc}}{2} \times \frac{I_{sc}}{2} = \frac{1}{4} V_{oc} \times I_{sc} \quad (3)$$

Therefore, the PVI curve of the TG can be plotted by using the results of (1)–(3), as shown in Figure 4.

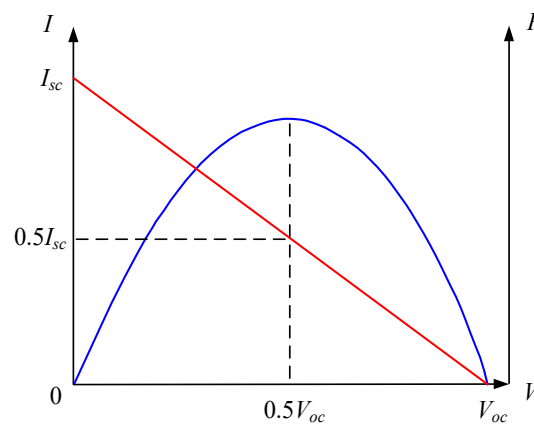


Figure 4. Curves for the TG: (1) blue line for P-V; (2) red line for I-V.

2.2. Measured Electrical Parameters of the used TG

Table 1 is used to describe the electrical parameters of the Marlow TG measured.

Table 1. Measured electrical parameters of the Marlow TG.

Electrical Parameter	Value
Maximum power point voltage (TC = 80 °C/TH = 250 °C)	4.05 V
Maximum power point current (TC = 80 °C/TH = 250 °C)	1.15 A
Maximum power (TC = 80 °C/TH = 250 °C)	3.1 W

3. Proposed MISO Converter

3.1. Converter Description

The circuit of the dual-input step-up converter proposed in Figure 5 consists of two input coupling inductors, four active switches S_{1a} , S_{1b} , S_{2a} and S_{2b} , two clamping capacitors C_4 and C_5 , three energy-transferring capacitors C_1 , C_2 , and C_3 , four diodes D_1 , D_2 , D_3 , and D_4 , one output capacitor C_o , and the load represented by the output resistor R_o .

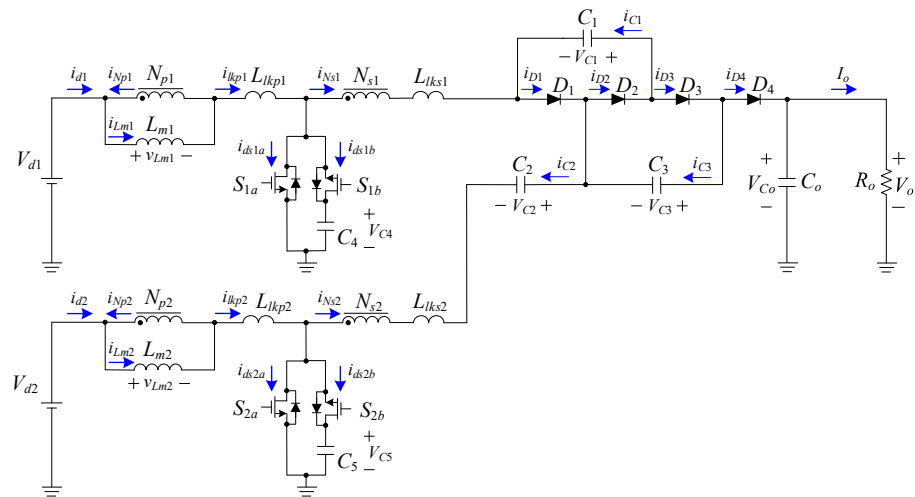


Figure 5. Proposed MISO circuit with current and voltage symbols defined.

Before proceeding with the analysis of the circuit operation, a brief explanation of the relevant symbols and the assumptions required is given.

- (1) V_{d1} and V_{d2} are the two input voltages; i_{d1} and i_{d2} are the two input currents; I_o is the output current; V_o is the output voltage.
- (2) $n = N_{s1}/N_{p1} = N_{s2}/N_{p2}$, where N_{p1} and N_{s1} are the primary and secondary windings of the first coupling inductor, respectively and N_{p2} and N_{s2} are the primary and secondary windings of the second coupling inductor, respectively. The currents i_{Np1} and i_{Ns1} are the currents flowing through the primary and secondary windings of the first coupling inductor, respectively, whereas the currents i_{Np2} and i_{Ns2} are the currents flowing through the primary and secondary windings of the second coupling inductor, respectively. The leakage inductances L_{lkp1} , L_{lks1} , L_{lkp2} , and L_{lks2} are the primary and secondary leakage inductances of the first and second coupling inductors, respectively.
- (3) L_{m1} is the magnetizing inductance of the first coupling inductor, and the voltage on and current in it are v_{Lm1} and i_{Lm1} , respectively; L_{m2} is the magnetizing inductance of the second coupling inductor, and the voltage on and current in it are v_{Lm2} and i_{Lm2} , respectively.
- (4) The voltages v_{gs1a} , v_{gs1b} , v_{gs2a} and v_{gs2b} are the gate driving signals for the switches S_{1a} , S_{1b} , S_{2a} , and S_{2b} , respectively; the voltages v_{D1} , v_{D2} , v_{D3} , and v_{D4} and the currents i_{D1} , i_{D2} , i_{D3} , and i_{D4} are the voltages on and currents in the diodes D_1 , D_2 , D_3 , and D_4 , respectively.
- (5) The voltages V_{C1} , V_{C2} , V_{C3} , V_{C4} , and V_{C5} and the currents i_{C1} , i_{C2} , i_{C3} , i_{C4} , and i_{C5} are the voltages and currents in energy-transferring capacitors C_1 , C_2 , and C_3 and clamping capacitors C_4 and C_5 , respectively.
- (6) T_s is the switching period of switches S_{1a} and S_{2a} , and the corresponding duty cycles are D_a and D_b , respectively.
- (7) k_1 and k_2 are the coupling coefficients of the first and second coupling inductors, respectively, equal to $k_1 = L_{m1}/(L_{m1} + L_{lkp1})$ and $k_2 = L_{m2}/(L_{m2} + L_{lkp2})$.
- (8) L_{11} and L_{12} are the primary-side and secondary-side self-inductances of the first coupling inductor, respectively; L_{21} and L_{22} are the primary-side and secondary-side self-inductances of the second coupling inductor, respectively.
- (9) The switches, diodes, inductors, and capacitors are considered ideal components.
- (10) The circuit is operated in the continuous current mode (CCM).
- (11) All the circuit operating principles are analyzed in the steady state.
- (12) The voltage conversion ratio is derived by assuming that the voltage drops caused by the leakage inductance are ignored.

Based on the above assumptions, Figure 6 shows the illustrated waveforms associated with the proposed circuit operation.

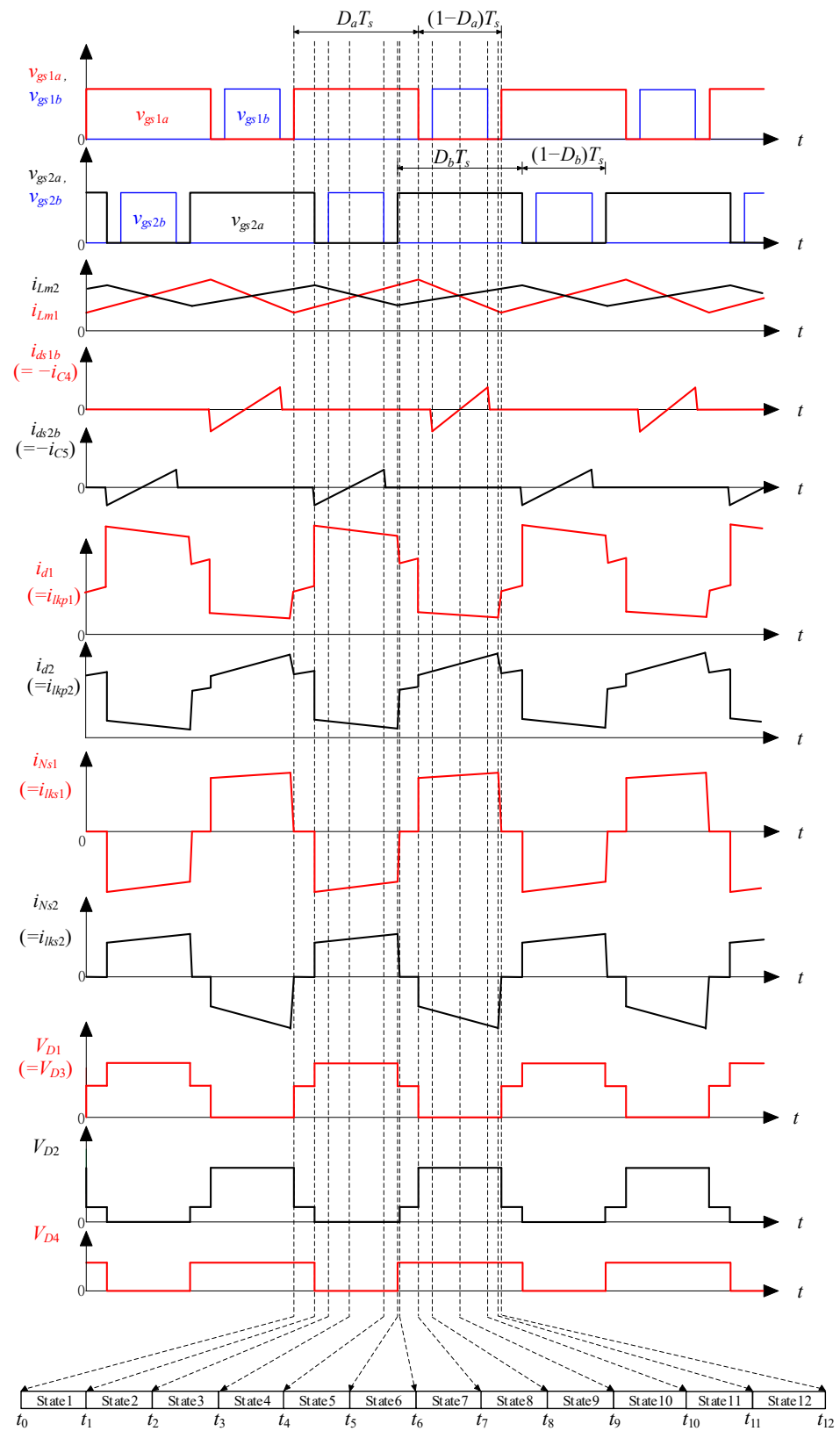


Figure 6. Illustrated waveforms associated with the proposed circuit operating.

3.2. Basic Operating Principles

3.2.1. State 1 [$t_0 \leq t \leq t_1$]

As shown in Figure 7, the switches S_{1a} and S_{2a} are on, the switches S_{1b} and S_{2b} are off, and the diodes D_1 , D_2 , D_3 , and D_4 are off. The input voltages V_{d1} and V_{d2} excite the magnetizing inductances L_{m1} and L_{m2} and the leakage inductances L_{lkp1} and L_{lkp2} , whose voltages on them are $k_1 V_{d1}$, $k_2 V_{d2}$, $(1 - k_1) V_{d1}$, and $(1 - k_2) V_{d2}$, respectively. The reverse-biased voltage of diode D_1 is $V_{C1} - V_{C2} + n(k_1 V_{d1} - k_2 V_{d2})$; the reverse-biased voltage of diode D_2 is $V_{C1} - V_{C2} - n(k_1 V_{d1} - k_2 V_{d2})$; the reverse-biased voltage of diode D_3 is $V_{C2} + V_{C3} - V_{C1} + n(k_1 V_{d1} - k_2 V_{d2})$; the reverse-biased voltage of diode D_4 is $V_o - V_{C2} - V_{C3} + nk_2 V_{d2}$. In addition, since all the four diodes are cut off, only the output capacitor C_o releases energy to the load in this state. Once the switch S_{2a} is turned off, state 1 comes to an end.

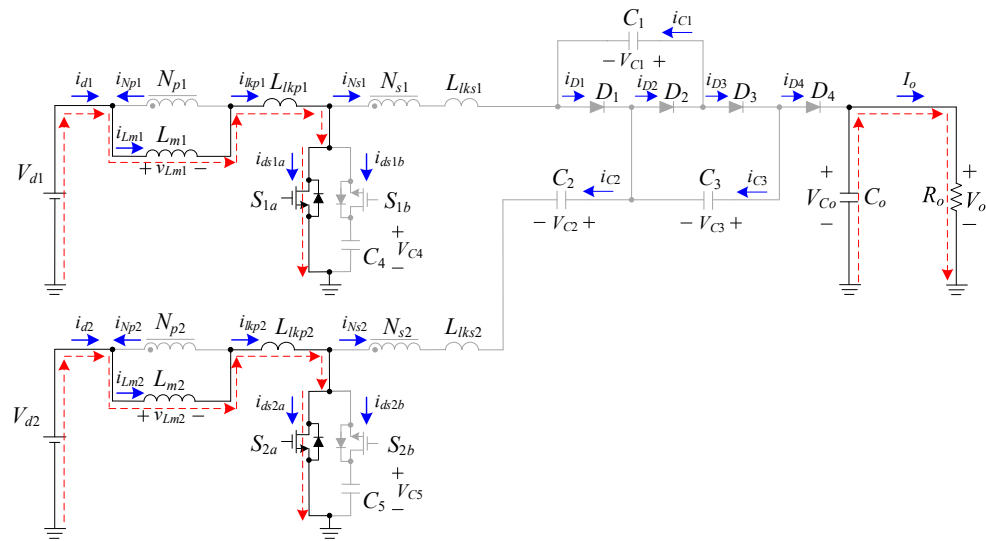


Figure 7. Circuit operation for state 1.

3.2.2. State 2 [$t_1 \leq t \leq t_2$]

As shown in Figure 8, the switch S_{1a} is on, the switches S_{1b} , S_{2a} , and S_{2b} are off, the diodes D_2 and D_4 are on, and the diodes D_1 and D_3 are off. During this state, the input voltage V_{d1} continues to excite the magnetizing inductance L_{m1} and the leakage inductance L_{lkp1} , whose voltages on them are $k_1 V_{d1}$ and $(1 - k_1) V_{d1}$, respectively. At the same time, the magnetizing inductance L_{m2} and the leakage inductance L_{lkp2} are demagnetized and the voltages on them are $k_2(V_{d2} - V_{C5})$ and $(1 - k_2)(V_{d2} - V_{C5})$, respectively, forcing diodes D_2 and D_4 to conduct. There are three key paths in this state. Path 1 is that the current i_{lkp2} flows through the body diode of S_{2b} and hence the leakage inductance L_{lkp2} releases energy to the clamping capacitor C_5 ; path 2 is that the energy-transferring capacitor C_2 charges the energy-transferring capacitor C_1 and at the same time the leakage inductance L_{lks1} is magnetized in the opposite direction with a voltage of $-nk_1 V_{d1} + V_{C1} + V_{C3} - V_o$; path 3 is that the energy-transferring capacitors C_2 and C_3 are connected in series and release energy to the load and at the same time the leakage inductance L_{lks2} is magnetized with a voltage of $V_{C5} - nk_2(V_{d1} - V_{C5}) + V_{C2} + V_{C3} - V_o$. It is worth mentioning that the two coupling inductors have transformer behavior. In addition, the diode D_1 is connected in parallel with the energy-transferring capacitor C_1 , which has a reverse-biased voltage of V_{C1} , and the diode D_3 is connected in parallel with the energy-transferring capacitor C_3 and has a reverse-biased voltage of V_{C3} , such that both the diodes D_1 and D_3 are cut off in this state. As the switch S_{2b} is turned on, state 2 ends.

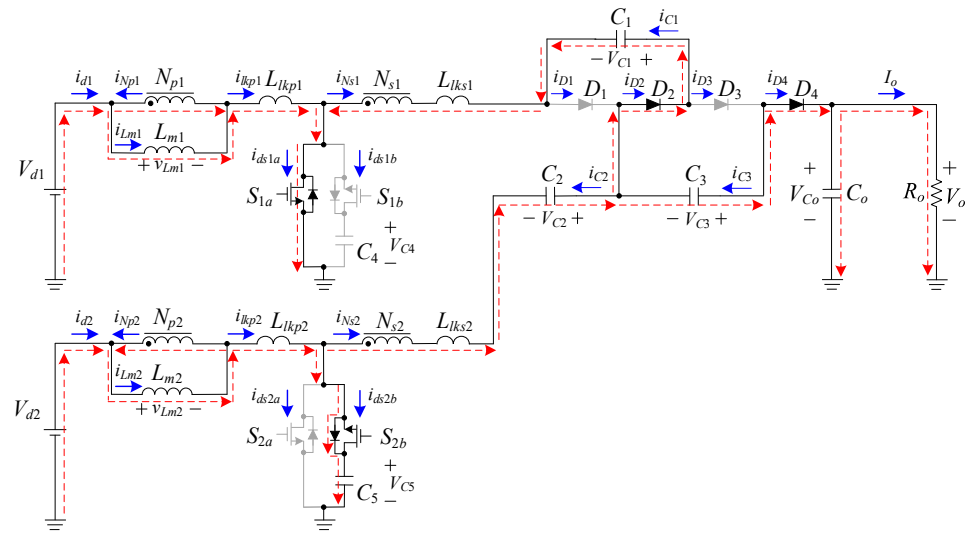


Figure 8. Circuit operation for state 2.

3.2.3. State 3 [$t_2 \leq t \leq t_3$]

Before the start of state 3, the body diode of S_{2b} is on, so S_{2b} has zero voltage switching (ZVS) turn-on as shown in Figure 9. In addition, the energy-transferring capacitor C_5 is charged with a negative slope. The moment the current i_{C5} reaches zero, state 3 comes to an end.

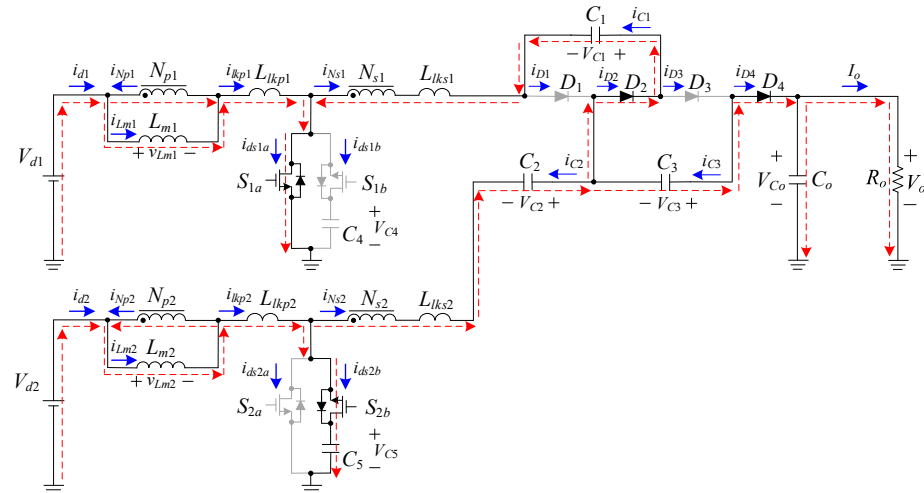


Figure 9. Circuit operation for state 3.

3.2.4. State 4 [$t_3 \leq t \leq t_4$]

As shown in Figure 10, the switches S_{1a} and S_{2b} are on, the switches S_{1b} and S_{2a} are off, the diodes D_2 and D_4 are on, and the diodes D_1 and D_3 are off. All the components except the clamping capacitor C_5 operate in the same state 3. Since the current i_{C5} rises in the opposite direction, the clamping capacitor C_5 is discharged. Once the switch S_{2b} is turned off, state 4 ends.

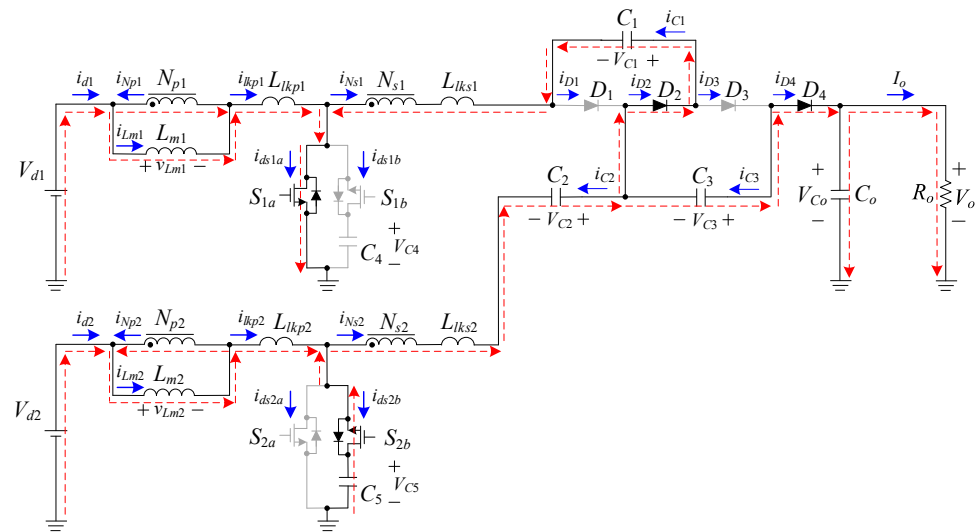


Figure 10. Circuit operation for state 4.

3.2.5. State 5 [$t_4 \leq t \leq t_5$]

As shown in Figure 11, the switch S_{1a} is on, the switches S_{1b} , S_{2a} , and S_{2b} are off, the diodes D_2 and D_4 are on, and the diodes D_1 and D_3 are off. During this state, the input voltage V_{d1} continues to excite the magnetizing inductance L_{m1} and the leakage inductance L_{lkp1} ; the magnetizing inductance L_{m2} and the leakage inductance L_{lkp2} continue to be demagnetized. As soon as the switch S_{2a} is turned on, state 5 comes to an end.

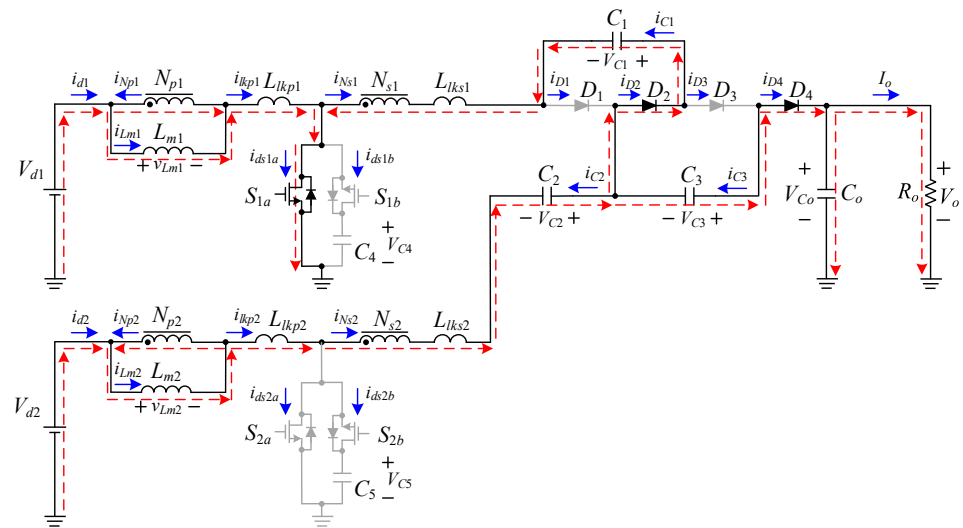


Figure 11. Circuit operation for state 5.

3.2.6. State 6 [$t_5 \leq t \leq t_6$]

As shown in Figure 12, the switches S_{1a} and S_{2a} are on, the switches S_{1b} and S_{2b} are off, the diode D_2 is on, and the diodes D_1 , D_3 , and D_4 are off. During this state, the input voltages V_{d1} and V_{d2} excite the magnetizing inductances L_{m1} and L_{m2} , respectively. The leakage inductances L_{lks1} and L_{lks2} charge the energy-transferring capacitor C_1 to achieve leakage inductance energy recovery.

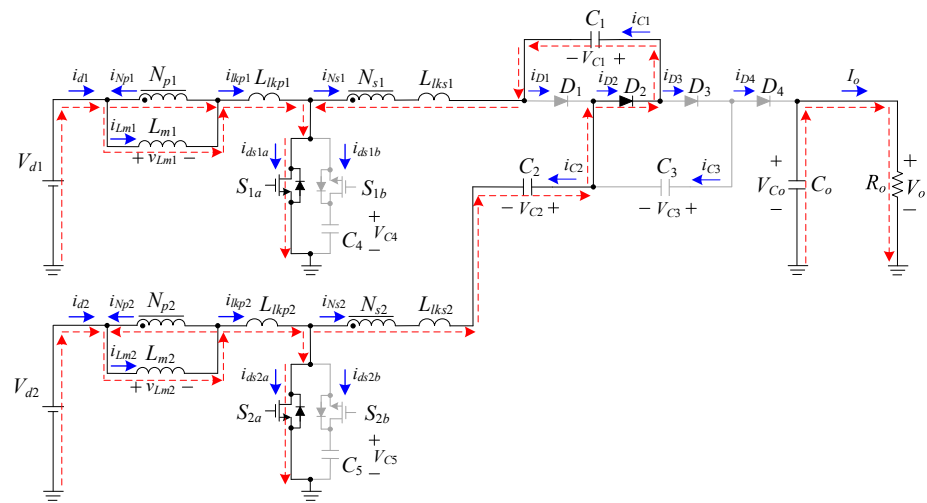


Figure 12. Circuit operation for state 6.

3.2.7. State 7 [$t_6 \leq t \leq t_7$]

The operation principle of this state is the same as that of state 1.

3.2.8. State 8 [$t_7 \leq t \leq t_8$]

As shown in Figure 13, the switches S_{1a} , S_{1b} and S_{2b} are off, and the diodes D_2 and D_4 are off, and the diodes D_1 and D_3 are on. During this state, the input voltage V_{d2} continues to excite the magnetizing inductance L_{m2} and the leakage inductance L_{lk2} , whose voltages on them are $k_2 V_{d2}$ and $(1 - k_2) V_{d2}$, respectively. At the same time, the magnetizing inductance L_{m1} and the leakage inductance L_{lk1} are demagnetized and the voltages on them are $k_1 (V_{d1} - V_{C4})$ and $(1 - k_1) (V_{d1} - V_{C4})$, respectively, forcing diodes D_1 and D_3 to conduct. There are three key paths: path 1 is that the current i_{lk1} flows through the body diode of S_{1b} and hence the leakage inductance L_{lk1} releases energy to the clamping capacitor C_4 ; path 2 is that the energy-transferring capacitor C_1 charges the energy-transferring capacitor C_3 ; path 3 is that the output capacitor C_o releases energy to the load. It is worth mentioning that the two coupling inductors have transformer behavior. In addition, the diode D_2 is connected in parallel with the energy-transferring capacitor C_1 and has a reverse-biased voltage of V_{C1} , and the diode D_4 has a reverse-biased voltage of $V_o - V_{C2} - V_{C3} + n V_{d2}$, so that both the diodes D_2 and D_4 are cut off in this state. As the switch S_{1b} is turned on, state 8 ends.

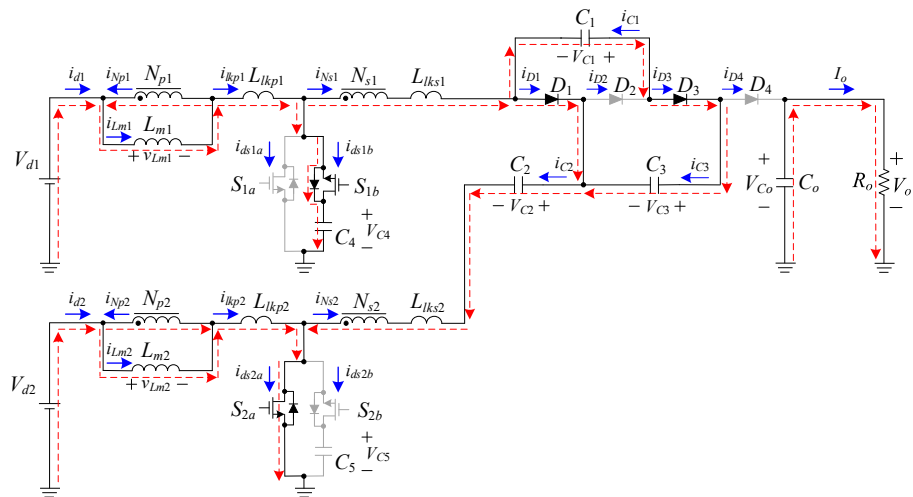


Figure 13. Circuit operation for state 8.

3.2.9. State 9 [$t_8 \leq t \leq t_9$]

As shown in Figure 14, before the start of state 9, the body diode of S_{1b} is on, so S_{1b} has zero voltage switching (ZVS) turn-on.

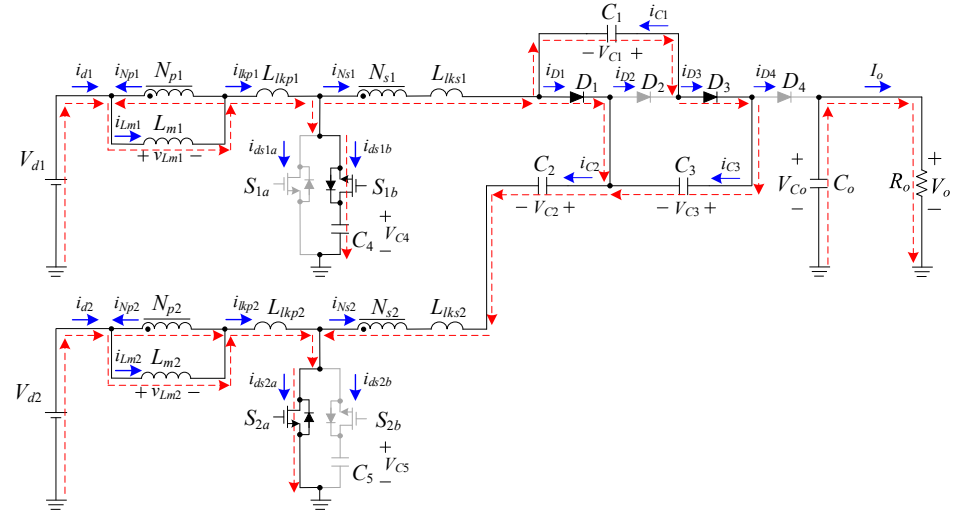


Figure 14. Circuit operation for state 9.

3.2.10. State 10 [$t_9 \leq t \leq t_{10}$]

As shown in Figure 15, the switches S_{2a} and S_{1b} are on, switches S_{1a} and S_{2b} are off, diodes D_1 and D_3 are on, and diodes D_2 and D_4 are off. All the components except the clamping capacitor C_4 operate in the same state 9. Since the current i_{C4} rises in the opposite direction, the clamping capacitor C_4 is discharged. Once the switch S_{1b} is turned off, state 10 ends.

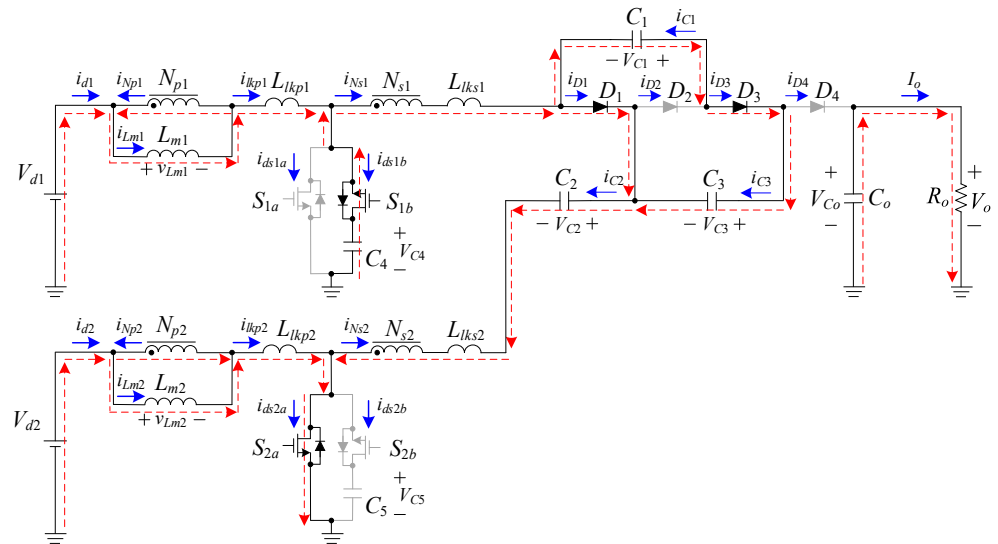


Figure 15. Circuit operation of state 10.

3.2.11. State 11 [$t_{10} \leq t \leq t_{11}$]

As shown in Figure 16, the switch S_{2a} is on, the switches S_{1a} , S_{1b} , and S_{2b} are off, the diodes D_1 and D_3 are on, and the diodes D_2 and D_4 are off. At the same time, the input voltage V_{d2} continues to excite the magnetizing inductance L_{m2} and the leakage inductance L_{lkp2} ; the magnetizing inductance L_{m1} and the leakage inductance L_{lkp1} continue to be demagnetized. As soon as S_{1a} is turned on, state 11 comes to an end.

$$v_{Lm2} = V_{d2} \quad (6)$$

From state 4 shown in Figure 10, the expression for the voltage on L_{m1} is the same as that state 1 but the voltage on L_{m2} is as follows:

$$v_{Lm2} = V_{d2} - V_{C5} \quad (7)$$

Additionally, the expressions for the voltages V_{C1} , V_{C5} , and V_o can be expressed as

$$V_{C1} = V_{C5} - n(V_{d2} - V_{C5}) + V_{C2} + nV_{d1} \quad (8)$$

$$V_o = V_{C5} - n(V_{d2} - V_{C5}) + V_{C2} + V_{C3} \quad (9)$$

$$V_{C5} = \frac{V_{d2}}{1 - D_b} \quad (10)$$

On the other hand, from state 9 shown in Figure 14, the expression for the voltage on L_{m2} is the same as that for state 1 but the voltage on L_{m1} is as below:

$$v_{Lm1} = V_{d1} - V_{C4} \quad (11)$$

At the same time, the voltages on C_2 , C_1 , and C_4 are given by

$$V_{C2} = V_{C4} - n(V_{d1} - V_{C4}) + nV_{d2} \quad (12)$$

$$V_{C1} = V_{C3} \quad (13)$$

$$V_{C4} = \frac{V_{d1}}{1 - D_a} \quad (14)$$

By substituting (14) into (12), the expression for V_{C2} is given by

$$V_{C2} = \frac{(n+1)V_{d1}}{1 - D_a} + n(V_{d2} - V_{d1}) \quad (15)$$

By substituting (10) and (12) into (8), the expression for V_{C1} can be obtained as

$$V_{C1} = \frac{(n+1)}{1 - D_a} V_{d1} + \frac{(n+1)}{1 - D_b} V_{d2} \quad (16)$$

By substituting Equations (10), (12)–(14), and (16) into Equation (9), the output voltage V_o is given by

$$V_o = \frac{2 + n(1 + D_a)}{1 - D_a} V_{d1} + \frac{2(1 + n)}{1 - D_b} V_{d2} \quad (17)$$

3.4. Unequal Currents between the Two Inputs

This subsection will show that the proposed structure has an automatic current sharing element embedded but does not have an automatic current sharing feature. To simplify the analysis, it is assumed that there is no loss in power conversion in this circuit, i.e., the input power is equal to the output power. According to (17), the power of the two inputs can be split and their DC output currents can be assumed to be the same, equal to I_o .

As shown in Figure 5, the input currents I_{d1} and I_{d2} can be expressed as

$$I_{d1} = I_{Lm1} - I_{Np1} \quad (18)$$

$$I_{d2} = I_{Lm2} - I_{Np2} \quad (19)$$

Next, the DC component of the coupling inductor is analyzed. According to the ampere-second balance, the average current in the capacitor is zero, so the following equations can be obtained as follows:

$$I_{Np1} = \frac{N_{s1}}{N_{p1}} \times I_{Ns1} = \frac{N_{s1}}{N_{p1}} \times I_o = nI_o \quad (20)$$

$$I_{Ns2} = I_{Np2} = 0 \quad (21)$$

By substituting (18) into (20), the expression for the current I_{d1} can be obtained as

$$I_{d1} = I_{Lm1} - nI_o \quad (22)$$

Additionally, substituting (19) into (21) yields the expression for current I_{d2} as

$$I_{d2} = I_{Lm2} \quad (23)$$

Because there is no loss of power conversion in the circuit, the following equation can be obtained as

$$V_o I_o = V_{d1} I_{d1} + V_{d2} I_{d2} \quad (24)$$

and also, multiplying (17) by I_o yields

$$V_o I_o = \frac{2 + n(1 + D_a)}{1 - D_a} V_{d1} I_o + \frac{2(1 + n)}{1 - D_b} V_{d2} I_o \quad (25)$$

By comparing (24) and (25) to find the relationship between the input currents I_{d1} and I_{d2} and the output current I_o , the following Equations (22) and (23) can be obtained as

$$I_{d1} = \frac{2 + n(1 + D_a)}{1 - D_a} I_o = I_{Lm1} - nI_o \quad (26)$$

$$I_{d2} = \frac{2(1 + n)}{1 - D_b} I_o = I_{Lm2} \quad (27)$$

From (26), I_{Lm1} can be obtained as

$$I_{Lm1} = \frac{2(1 + n)}{1 - D_a} I_o \quad (28)$$

By substituting (23) and (26) into (18) and (19), the DC components of the input currents can be found as

$$I_{d1} = \frac{2(1 + n)}{1 - D_a} I_o - nI_o \quad (29)$$

$$I_{d2} = \frac{2(1 + n)}{1 - D_b} I_o \quad (30)$$

The two input currents will not be identical even if D_a is equal to D_b , according to (29) and (30).

3.5. Extension of Number of Phases

The number of phases can be extended by $2N$, where N is a positive integer. Figure 18 shows the four-phase interleaved converter.

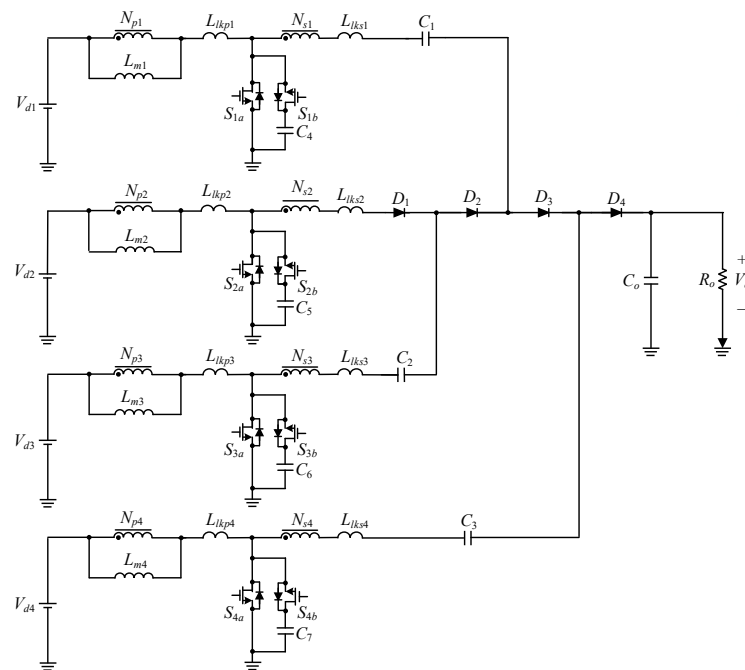


Figure 18. Four-input single-output interleaved high step-up converter.

4. Hardware Circuit Design

4.1. Thermoelectric Module Specifications

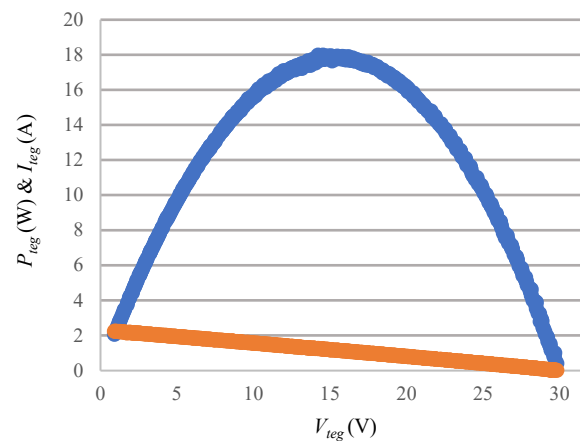
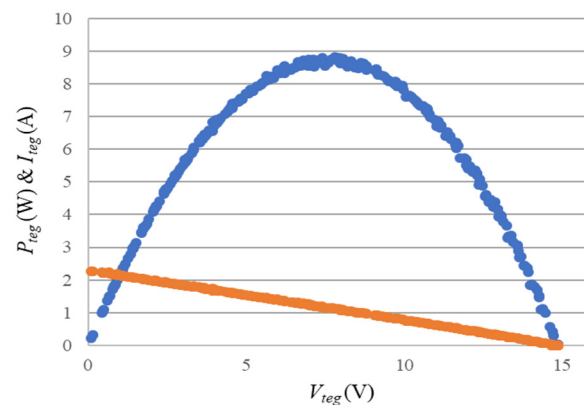
The thermoelectric generator (TG), named TG12-8, is manufactured by Marlow Industries, Inc. Since this converter has two inputs, the first input is composed of four pieces of TGs connected in series, and the second input is composed of two pieces of TGs connected in series. Table 2 shows the associated information on the first thermoelectric module and Table 3 shows the associated information on the second thermoelectric module. Figures 19 and 20 show the measured curves for the first and second thermoelectric modules, respectively. These measured curves for the two thermoelectric modules are based on the Prodigit 9842-MPPT function under constant voltage mode, sweeping so as to obtain the data relevant to power vs. voltage (PV) and voltage vs. voltage (IV), and then plotting these data by using Microsoft Excel.

Table 2. Specifications of the first thermoelectric module.

First thermoelectric Module Specification	Name or Value
TG product name	TG12-8
TG size	40 × 40 × 3.2 mm
Number of TGs	4 in series
Max. Power @ MPP (P_{mpp1})	18.52 W
Voltage @ MPP (V_{mpp1})	16.22 V
Current @ MPP (I_{mpp1})	1.145 A
Open-circuit voltage (V_{oc1})	30.26 V
Short-circuit current (I_{sc1})	2.43 A
Cold-side temperature	80 °C
Hot-side temperature	250 °C

Table 3. Specifications of the second thermoelectric module.

Second Thermoelectric Module Specification	Name or Value
TG product name	TG12-8
TG size	40 × 40 × 3.2 mm
Number of TGs	2 in series
Max. Power @ MPP (P_{mpp2})	9 W
Voltage @ MPP (V_{mpp2})	7.67 V
Current @ MPP (I_{mpp2})	1.177 A
Open-circuit voltage (V_{oc2})	14.07 V
Short-circuit current (I_{sc2})	2.46 A
Cold-side temperature	80 °C
Hot-side temperature	250 °C

**Figure 19.** Curves for the first thermoelectric module: (1) blue line for P-V; (2) orange line for I-V.**Figure 20.** Curves for the second thermoelectric module: (1) blue line for P-V; (2) orange line for I-V.

As can be seen from Figure 19, the maximum power point of the first TG has 18.52 W at half of the open-circuit voltage and short-circuit current of the first thermoelectric module, with values of $V_{mpp1} = 16.22$ V and $I_{mpp1} = 1.145$ A. As can be seen from Figure 20, the maximum power point of the second thermoelectric module has 9W at half of the open-circuit voltage and short-circuit current of the second thermoelectric module, with values of $V_{mpp2} = 7.67$ V and $I_{mpp2} = 1.177$ A.

4.2. System Configuration and Its Specifications

Figure 21 shows the system configuration of the proposed circuit applied to a thermoelectric conversion system with two thermoelectric modules at individual inputs. The main power stage is a dual-input high-boost circuit with a digital control kernel based on FPGA to control the system. The FPGA calculates and then sends the duty cycles to the gate drivers to achieve the maximum power tracking. For the voltages and currents to be sampled, analog-to-digital converters (ADCs) are used. The sensed signals are sent to MPPT modules after ADCs via FPGA-embedded series peripheral interfaces (SPIs). Furthermore, the voltage-sensing resistors are used as voltage dividers, the current-sensing resistors are used as current sensors, and the FPGA, named CycloneEP1C3T100, is used as a control kernel, which needs a 20 MHz oscillator and has 2910 logic gates, 104 I/O ports, 59,904 RAM bits, and a phase-lock loop. In addition, the design software is based on the very high-speed hardware description language (VHDL) and Table 4 shows the system specifications.

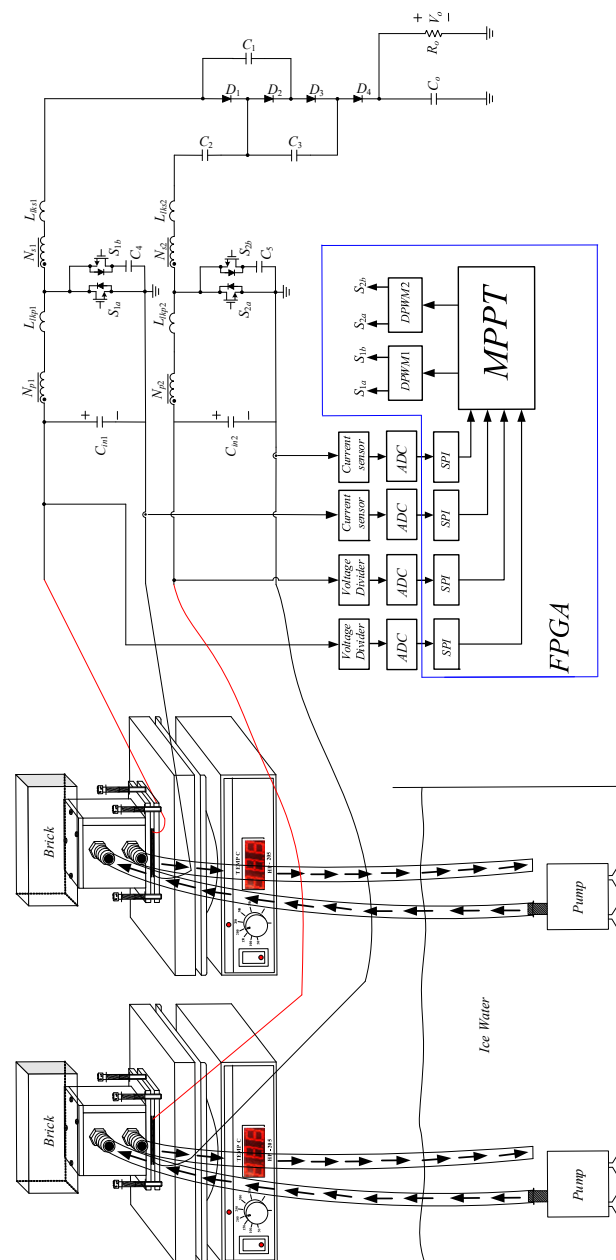


Figure 21. System configuration.

Table 4. System specifications.

System Specification	Name or Value
System operation mode	Continuous conduction mode (CCM)
First input voltage (V_{d1})	16.22 V
Second input voltage (V_{d2})	7.67 V
Rated output voltage (V_o)	400 V
Rated output current ($I_{o, rated}$)/power ($P_{o, rated}$)	68.8 mA/27.52 W
Minimum output current ($I_{o, min}$)/power ($P_{o, min}$)	17.2 mA/6.88 W
First duty cycle (D_a)	0.575
Second duty cycle (D_b)	0.572
First duty frequency (f_s)/period (T_s)	100 kHz/10 μ s

4.3. Voltage Stresses of Switches and Diodes

The voltage across the switches S_{1a} and S_{1b} during the turn-off period can be found from states 9 and 1, respectively, as follows:

$$V_{ds1a} = V_{ds1b} = V_{C4} = \frac{V_{d1}}{1 - D_a} = \frac{16.22}{1 - 0.575} = 38.17\text{V} \quad (31)$$

The voltages across the switches S_{2a} and S_{1b} during the turn-off period are given by states 3 and 1, respectively, as follows:

$$V_{ds2a} = V_{ds2b} = V_{C5} = \frac{V_{d2}}{1 - D_b} = \frac{7.67}{1 - 0.572} = 18\text{V} \quad (32)$$

In state 2, the voltage across diodes D_1 and D_3 are as follows:

$$V_{D1} = V_{C1} \quad (33)$$

$$V_{D3} = V_{C3} \quad (34)$$

Substituting the results of (13) and (16) into (33) and (34) yields

$$V_{C1} = V_{C3} = \frac{(n+1)}{1 - D_a} V_{d1} + \frac{(n+1)}{1 - D_b} V_{d2} = 224.34\text{V} \quad (35)$$

The voltages across the diodes D_2 and D_4 in state 8 are as follows:

$$V_{D2} = V_{C1} = 224.34\text{V} \quad (36)$$

$$V_{D4} = V_o - V_{C2} - V_{C3} + nV_{d2} = 71.4\text{V} \quad (37)$$

4.4. Component Specifications

Table 5 is used to describe the specifications of the used components.

Table 5. Component specifications.

Component	Specification
MOSFET switches S_{1a} , S_{1b} , S_{2a} , S_{2b}	IRF3205Z
Diodes D_1 , D_2 , D_3	SFF1008G
Diodes D_4	STPS20H100CT
Energy-transferring capacitors C_1 , C_3	100 μ F Electrolytic Capacitor
Energy-transferring capacitor C_2	68 μ F Electrolytic Capacitor
Clamping capacitors C_4 , C_5	10 μ F Electrolytic Capacitor
Output capacitor C_o	22 μ F Electrolytic Capacitor
Coupling inductor 1/Coupling inductor 2	$L_{m1} = 365.6 \mu\text{H}$, $n = 3$ / $L_{m2} = 87.3 \mu\text{H}$, $n = 3$
Isolated gate driver	FOD3182

5. Maximum Power Point Tracking

5.1. MPPT Algorithm

If a thermoelectric module is to provide maximum power output in different temperature ranges and temperature differences, maximum power tracking is required to operate the thermoelectric module at the maximum power point. In addition, the PV characteristic curve of a thermoelectric module is similar to that of a solar cell. However, the difference between them is that the PV characteristic curve of a thermoelectric module is more symmetrical. Consequently, according to this feature, a maximum power tracking method based on three-point-weighting MPPT is relatively suitable for thermoelectric modules in practice.

Figure 22 shows the MPPT flow chart used in this paper. The principle of this control method is to calculate the power value by continuously detecting the output power value at three points and comparing their power magnitudes. First of all, set a duty cycle of D_b at the reference point b , and detect the output voltage and current of the thermoelectric module to calculate the power value P_b ; sequentially, increase the duty cycle by one unit of disturbance, i.e., $D_b + \Delta D$, to obtain the second duty cycle of D_c at the point c , and detect and calculate the power value of P_c ; then reduce the duty cycle by one unit of disturbance, i.e., $D_b - \Delta D$, to obtain the third duty cycle of D_a at the point a , and detect and calculate the power value of P_a . By doing so, the power sampling procedure is completed. Afterwards, if the power P_a is greater than or equal to the power P_b , the weight value of W_1 will be increased by one, and if not, the weight value of W_1 will be decreased by one; if the power P_b is greater than or equal to the power P_c , the weight value of W_2 will be increased by one, and if not, the weight value of W_2 will be decreased by one. Eventually, calculate the weight value to determine the direction of movement of the reference point. If the sum of W_1 and W_2 is $+2$, then the point c is used as the new reference point with the duty cycle of D_c ; if the sum of W_1 and W_2 is -2 , the point a is used as the new reference point with the duty cycle of D_a ; if the sum of W_1 and W_2 is 0 , then the reference point b remains unchanged with the duty cycle of D_b . After completing the above actions, the weight value is returned to zero and the above actions are repeated to achieve maximum power point tracking.

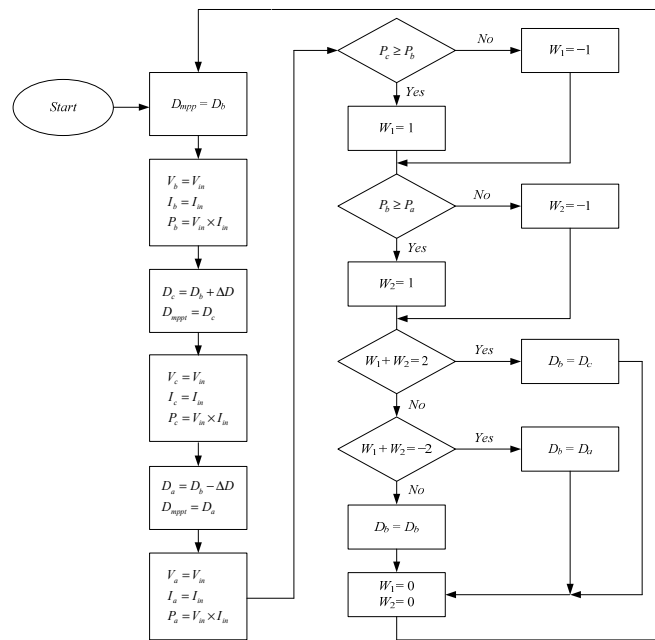


Figure 22. Flow chart of the three-point-weighting MPPT.

5.2. MPPT Simulation

In this subsection, the simulation of the proposed MISO circuit applied to a thermoelectric conversion system is used to verify its feasibility based on the power simulation (PSIM) software. Therefore, the simulation environment is constructed by analog devices as shown in Figure 23. From this figure, it can be seen that both thermoelectric modules can be traced to individual maximum power points without need of staggered switching; the first thermoelectric module outputs 18.56 W shown in a green circle, almost corresponding to 18.52 W, shown in Table 2; the second thermoelectric module outputs 9.03 W, shown in the purple circle, almost corresponding to 9 W shown in Table 3; both the two thermoelectric modules output 27.23 W shown in the red circle, almost corresponding to 27.51 W, shown in Table 4; the output voltage can be increased to 399.85 V, shown in a blue circle, almost corresponding to 400 V, shown in Table 4.

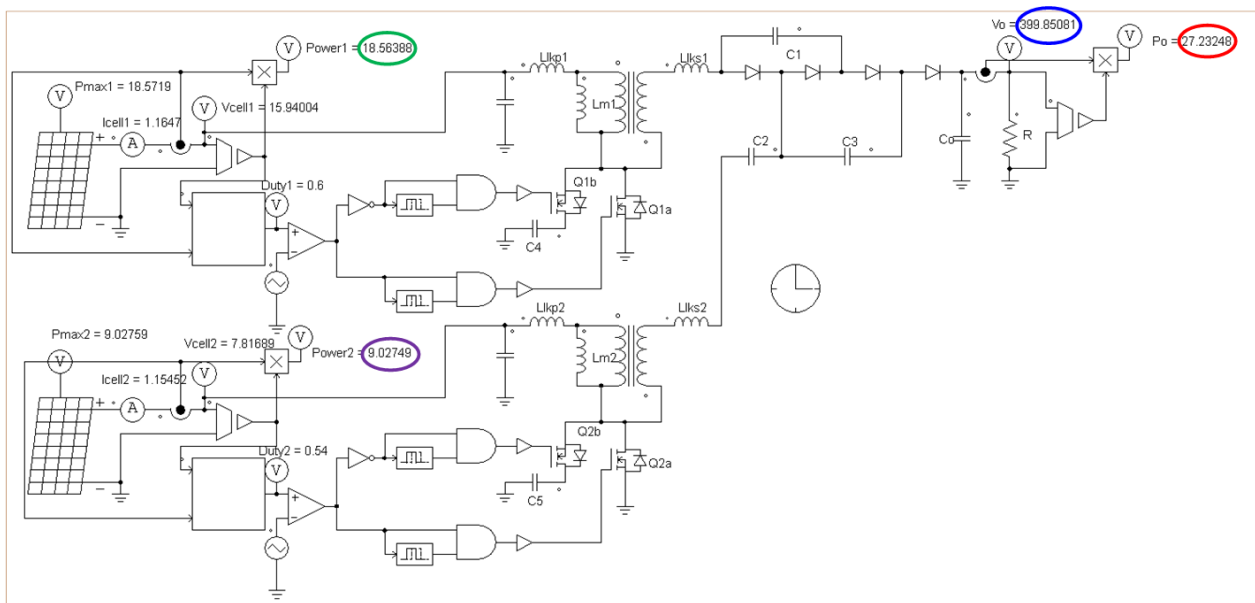


Figure 23. Simulation of the proposed MISO circuit applied to a thermoelectric conversion system.

6. Experimental Results

In this subsection, the experimental results are used to demonstrate the effectiveness of the proposed MISO circuit. The digital control kernel based on the FPGA is adopted herein. From Figure 24, it can be seen that the gate driving signals v_{gs1a} and v_{gs1b} are interleaved and v_{gs1b} and v_{gs2b} are complementary to v_{gs1a} and v_{gs2a} , respectively. From Figures 25 and 26, it can be seen that when the switches S_{1a} , S_{1b} , S_{2a} , and S_{2b} are turned off, the leakage inductance of the coupling inductor, the parasitic inductance on the line, and the parasitic capacitance of the switch resonate together, so the voltage spike and ring on v_{ds1a} , v_{ds1b} , v_{ds2a} , and v_{ds2b} will be generated. As shown in Figure 27, the resonance of the leakage inductance with the diode capacitance from state 6 to state 7 and from state 12 to state 1 causes the current spike and oscillation in the input currents i_{d1} and i_{d2} due to the reverse recover current of the diode D_1 . As can be seen from Figure 28, the energy-transferring capacitors C_1 , C_2 , and C_3 can be stabilized at a certain value for any load. Figures 29 and 30 show that the switches S_{1b} and S_{2b} have ZVS turn-on but are turned on with the resonance between the diode capacitance and the leakage inductance, thereby yielding the voltage spike and oscillation on v_{ds1b} and v_{ds2b} . From Figure 31, it can be seen that the diodes D_1 and D_3 have the same operating behavior and the oscillation is caused by the magnetizing inductance resonating with the diode capacitance. From Figure 32, it can be seen that the output voltage V_o of the proposed circuit can reach 400 V. From Figure 33, it can be seen that the efficiency can be up to 89.27% at 100% load. Figure 34 shows a photo of the experimental setup.

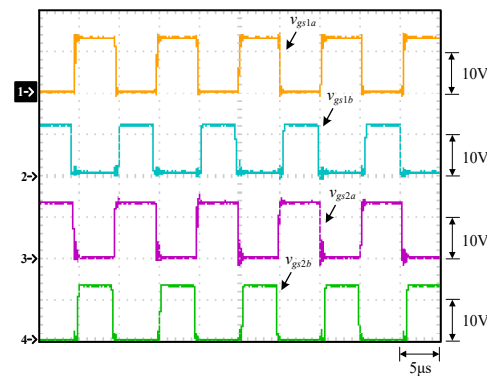


Figure 24. Measured waveforms relevant to gate driving signals: (1) v_{gs1a} ; (2) v_{gs1b} ; (3) v_{gs2a} ; (4) v_{gs2b} .

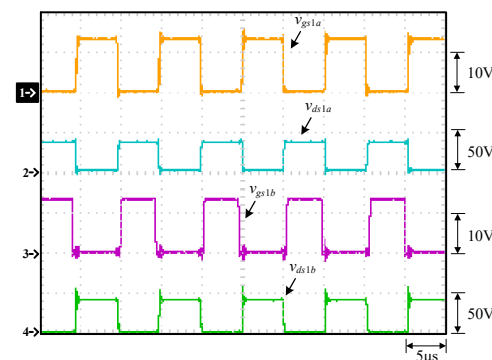


Figure 25. Measured waveforms relevant to S_{1a} and S_{1b} : (1) v_{gs1a} ; (2) v_{ds1a} ; (3) v_{gs1b} ; (4) v_{ds1b} .

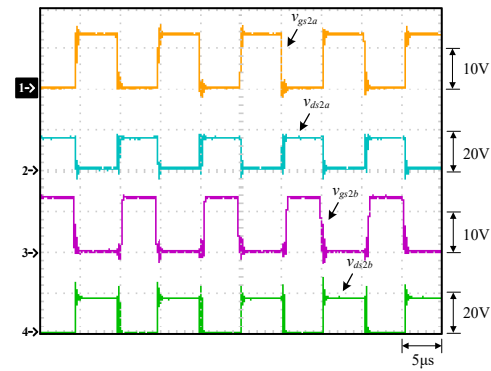


Figure 26. Measured waveforms relevant to S_{2a} and S_{2b} : (1) v_{gs2a} ; (2) v_{ds2a} ; (3) v_{gs2b} ; (4) v_{ds2b} .

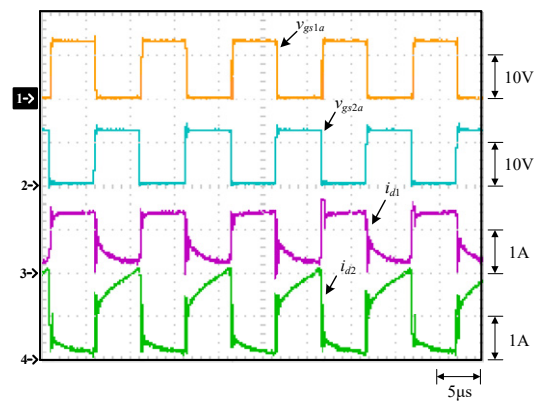


Figure 27. Measured waveforms relevant to two input currents: (1) v_{gs1a} ; (2) v_{gs2a} ; (3) i_{d1} ; (4) i_{d2} .

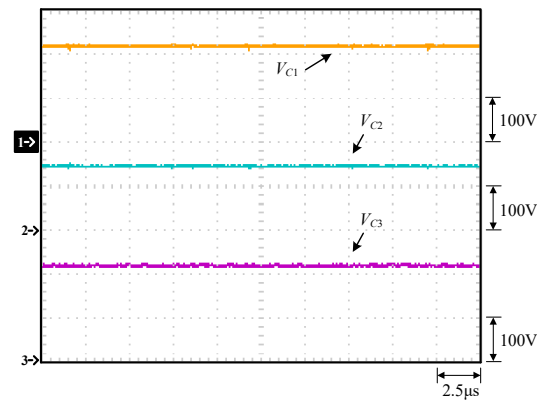


Figure 28. Measured waveforms relevant to voltages across capacitors: (1) V_{C1} ; (2) V_{C2} ; (3) V_{C3} .

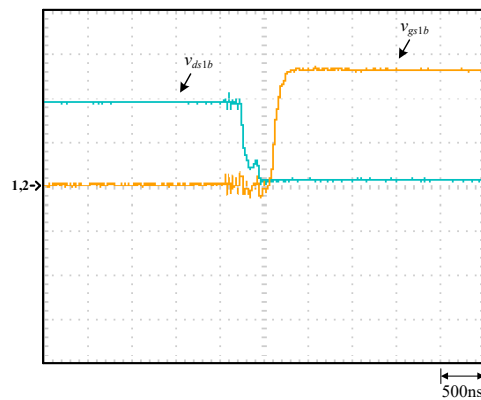


Figure 29. Zoomed-in waveforms of Figure 25 relevant to S_{1b} : (1) v_{ds1b} ; (2) v_{gs1b} .

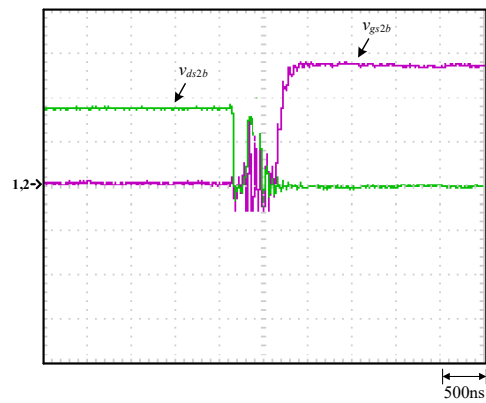


Figure 30. Zoomed-in waveforms of Figure 26 relevant to S_{2b} : (1) v_{gs2b} ; (2) v_{ds2b} .

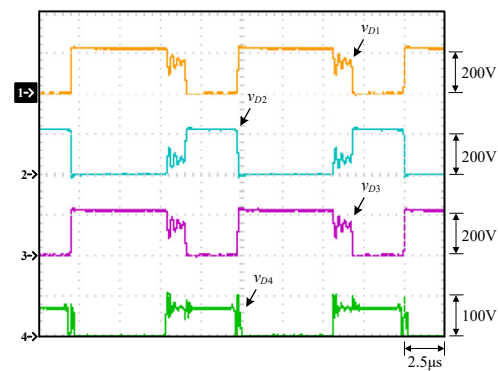


Figure 31. Measured waveforms relevant to diodes: (1) v_{D1} ; (2) v_{D2} ; (3) v_{D3} ; (4) v_{D4} .

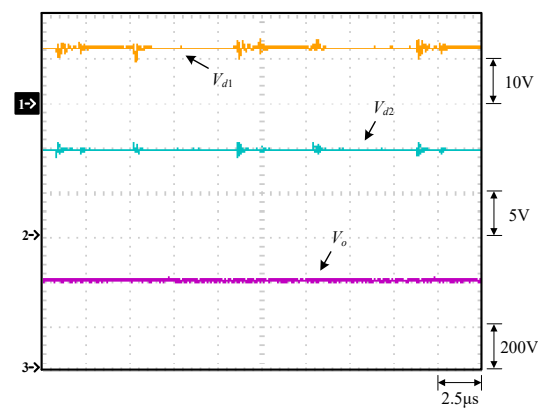


Figure 32. Measured waveforms relevant to input and output voltages: (1) V_{d1} ; (2) V_{d2} ; (3) V_o .

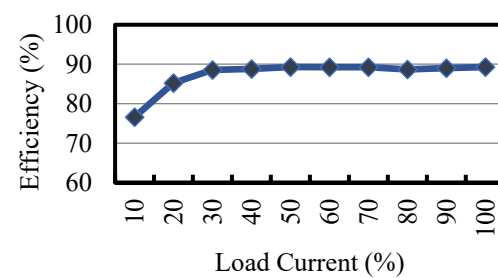


Figure 33. Curve of efficiency vs. load current.

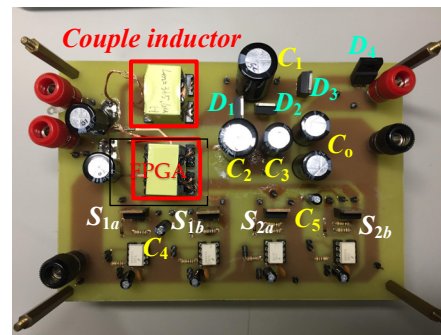


Figure 34. Photo of the experimental setup.

7. Conclusions

In this paper, the interleaved MISO circuit was applied to a thermoelectric system, where the ultrahigh voltage gain was obtained by using coupling inductors and switched capacitors. The two thermoelectric modules have individual MPPTs even although the passive current-sharing device is embedded in this circuit, and this was verified by Section 3.4. Furthermore, the active voltage clamp circuits ensure that the high-frequency oscillation is reduced, the switches are turned on with ZVS, and that the voltage stresses on the switches are low. Therefore, the rated-load efficiency is 89.27%. In addition, the number of inputs can be extended.

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