Article

Design of a Modified-Bridge Circuit with a Master-Slave Input Supply Mechanism for Ozone-Driven System Applications

Te-Chun Hung , Tsong-Shing Lee , Kuan-Chieh Huang and Yu-Hsiang Chen

Department of Electrical Engineering, Southern Taiwan University of Science and Technology,
Tainan 710301, Taiwan; tchung@stust.edu.tw (T.-C.H.); kchuang07@stust.edu.tw (K.-C.H.);
9a520002@stust.edu.tw (Y.-H.C.)

* Correspondence: tslee@stust.edu.tw

Abstract: This study proposes a design of a modified-bridge circuit with a master–slave input supply mechanism for ozone-driven system applications. Because the single-source supply design is becoming the mainstream choice in the existing ozone-driven systems, the input supply reliability of the ozone-driven system is crucial. Therefore, this proposed design involves a modified-bridge circuit combined with inductors and transistors, which can be augmented with the energy storage device as a backup source to improve the reliability of the input supply for the ozone-driven system. In addition, considering that the original source directly connected to *DC BUS* can re-charge the energy storage device, the energy recycling operation mode is designed in this proposed system to extend the duration of the energy storage device, which improves the supply reliability of the ozone-driven system further. To validate this proposed system, both model formulation and hardware realization are assessed through different test scenarios. Experimental outcomes of these tests confirm the practicality of the proposed design.

Keywords: master–slave input supply mechanism; ozone-driven system applications; single-source supply

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1. Introduction

Ozone technologies have seen wide application in various fields, such as agriculture, sterilization [1–3], water purification [4–6], portable air cleaners [7,8], and surface cleaning [9,10]. In ozone technology applications, signals with both high-voltage and high-frequency features must be generated to achieve proper electrical discharge in the ozone chip. Therefore, a suitable driving circuit or system circuit design is crucial. In some studies, advanced components with a high-frequency capacity have been used to build the ozone load driving resonant circuit [11–14]. In addition, resonant circuit designs such as LCC type or hybrid type have been adopted, due to the high voltage-gain property, to generate a high-voltage signal in a high-frequency range [15–18]. The existing ozone-driven systems are most often designed with a single input port. If a fault occurs in the power source during operation, the ozone-driven system must stop working and wait for power recovery, which significantly affects the ozone quality. Adopting designs using a single power source inevitably impairs the operational reliability of the ozone-driven system in the above application fields. To improve the reliability of the input source, connecting directly the energy storage devices to the ozone-driven system may seem to be a quick fix. However, there are issues that remain to be resolved to achieve the voltage balance between the energy storage device and the input power source.

To solve the voltage balance problem, energy storage devices are often integrated with the main input power for better power quality. Therefore, we believe that adopting a dual-input port structure in the construction of ozone-driven systems will provide a viable solution. In [19], Saleh et al. connected the multi-level converter to the energy storage devices to drive the DBD plasma load adopting multi-level switching architecture

and using multiple DC converters, which provide multiple input ports for connecting energy storage devices to overcome the problem resulting from the single power source. In addition, some studies have proposed a multi-input converter with a special control strategy to extend the input amount when connecting to energy storage devices. For example, the integration of energy storage devices and supercapacitors provides the energy for reducing the numbers of DC converters through a novel multiple-input converter [20]. Furthermore, a triple-input converter is designed for three kinds of power sources, adopting an interleaved full-bridge converter that integrates each power source to improve the supply reliability [21]. The above studies have proposed novel architectures to integrate two or more power sources and achieve encouraging results. Next, because the energy storage device is adopted as another source, the re-charging function of the energy storage device is also essential. Therefore, some studies have discussed bi-directional power transmission. For instance, an isolated converter with a bi-directional power transmission is proposed for a two-power-source input and power control in [22]. In addition, these studies have discussed the interleaved buck/boost converter with zero-voltage switching control for some bi-directional converter designs [23,24]. Furthermore, to obtain a high voltage gain with high efficiency to drive the ozone chip, some resonant circuits have been proposed [15–18]. Such a circuit consists of magnetic inductors to reach the resonance while satisfying the requirement of soft switching. Yet, the characteristics of this resonant circuit were easily affected under the bi-directional power transmission since its architecture was asymmetrically connected. Therefore, some studies have adopted the symmetrical resonant circuit for the bi-directional power transmission to achieve the stabilization of the bi-directional power transmission [25–27]. The aforementioned methods reveal that encouraging results were observed, yet each of them came with some inherent demerits in the ozone-driven applications. Moreover, considering that the ozone-driven system is usually applied to a cleansing function, the reliability of the ozone-driven system will affect directly the cleansing quality. Ozone-driven systems, which have been applied widely, are costly. Therefore, substituting the novel ozone-driven equipment for the traditional one is a difficult mission. As mentioned above, considering the replacement issues, the design of the extra-installing circuit is an excellent choice, which lets the original ozone-driven system continuously provide a stable voltage by increasing the reliability of the power supply in order to maintain a stable ozone generator. To clearly understand the relationship between each aforementioned reference and the corresponding study subject, the features of the above references are as listed in Table 1.

In this paper, a modified-bridge circuit is proposed for the ozone-driven system, which modifies a bridge circuit with inductors isolated to provide dual-input ports. Here, the master source and the slave source are connected to different input ports to independently provide the energy while maintaining the source status of each port. In addition, a symmetrical resonant tank is adopted and designed for the bi-directional power transmission, letting the resonant property of the bi-directional power transmission be similar. Once the original source is connected directly to *DC BUS*, the energy can be re-charged to the slave source through the proposed system. Thus, delivering or re-charging the energy storage device becomes much easier by the proposed system and the discharging time of the energy-storage device is also improved. Moreover, through the voltage of each port being regulated by the controller, different operation modes can be selected by simple frequency modulation. The features of this proposed system are listed as follows:

- (1) The proposed modified-bridge circuit accomplished in this paper emphasizes the benefits of using two input power sources that are supplying coordinately to improve the supplied reliability and reduce the component cost for the ozone-driven system.
- (2) The proposed system can be extra-installed in the original ozone-driven system, which means that it is not necessary to replace the original one, keeping the ozone quality and reducing the replacement cost.

- (3) The resonant circuit design is of a symmetrical type, which achieves a similar resonant property under the bi-directional power transmission. Difficult control and a complicated algorithm are unnecessary to enhance the stability of the proposed system.
- (4) The voltage status of each port can be detected through the control system operation mode setting by judging whether the energy is being provided through *DC BUS* or re-charged to the slave source (energy storage device).

The rest of this article is organized as follows: Section 2 introduces operations of the proposed system, Section 3 discusses the parameter design and analysis of the symmetrical resonant circuit, Section 4 describes the control mechanism analysis, Section 5 reports the experimental results, and Section 6 presents the conclusion.

Table 1. References of feature analysis and the corresponding subjects.

No.	Features	Reference
[11]	An accurate analytical converter-level model is introduced. The model evaluates and optimizes the switching solution of a SiC MOSFET for the pulsed power converter.	
[12]	A high-power high-frequency ICP drive system that achieves high efficiency and durability is proposed. A 10 kW 4 MHz switching inverter and a novel control method are proposed for ICP with a high Q factor and highly variable impedance. The proposed phase lead sensing circuit can always guarantee ZVS operation of a high-power high-frequency switching inverter. Through the proposed system, ICP with a much higher plasma density can be safely driven.	SiC MOSFET application of the ozone-driven circuit design for increasing the component reliability
[13]	An optimized version of a gate-boosting driver circuit for SiC MOSFETs for ultrafast switching is proposed. A MOSFET turn-on time of below 2 ns is achievable at a high operating voltage and moderate current and below 3 ns for a wider range of load-current and operating voltage conditions.	
[14]	A high-voltage SiC MOSFETs module can serve as the main switch in a repetitive high-voltage nanosecond pulse generator. A series-connected MOSFETs module with only a single external gate driver requiring few components is suitable for a compact assembly. A 10 kV SiC MOSFETs module with a turn-on transition time ~10 ns is developed. A compact and high-voltage pulse generator composed of three 10 kV SiC MOSFETs module is tailored, with a typical rise time of ~40 ns and peak a voltage of ~30 kV.	
[15]	A 2.0 kW high-voltage rep-rate charging power supply based on a non-isolated inductor–capacitor–capacitor (LCC)-type resonant converter operating in continuous conduction mode is proposed. It provides a constant charging current with high control accuracy/efficiency. The design of the proposed capacitor charging power supply (CCPS) is a low-cost, simpler, compact, and efficient driver for the miniature pulsed plasma sources.	
[16]	A hybrid LLC resonant converter design is proposed. There are three modes of operation: As a full-bridge converter, as a dual-phase half-bridge LLC converter, or as a single-phase half-bridge LLC converter. Using GaN devices with a power density of 65 W/in ³ has been designed.	Different resonant architecture analysis for acquiring a higher voltage gain
[17]	A comparative half-bridge LLC resonant converter using the integrated LCLC resonant transformer is proposed. To reduce the demanded leakage inductance, a resonant capacitor can be connected in parallel to the magnetizing inductor through auxiliary winding as an LCLC resonant transformer. An integrated LCLC resonant transformer with lower leakage inductance for efficiency comparison is implemented.	

Table 1. Cont.

No.	Features	Reference
[18]	The light-load efficiency of the LLC resonant converters is an improvement. The simplified optimal trajectory control (SOTC) for burst mode can solve this issue by using an optimal switching pattern for burst-on time. The digital implementation of SOTC for burst mode and its limitation in a high-frequency LLC converter are discussed.	
[19]	Multistage and multilevel switch-mode converters are employed to construct the power supply. The proposed MSML-PEC power supply uses boost dc-dc PECs without high-frequency transformers. The removal of high-frequency transformers has improved the average efficiency and reduced the size of each dc-dc PEC. Modular, lightweight, and compact size power supply has been achieved.	
[20]	A novel multi-input converter (MIC) is proposed in this article for interfacing a battery-SC combination. The SC converter is mostly rated for the full surge power. The battery is operated in current control mode under normal loading conditions. The proposed system balances the flow of power between the load and the HESS.	Multiple input design for adding the input port to increase the supply reliability
[21]	Modeling and two controller design techniques for a triple active bridge (TAB) three-port dc-dc converter comprising the fuel cell, the battery, and the load are proposed. A new decoupling matrix-based proportional-integral controller design method reduces the design complexity and improves the system dynamic performance in comparison to similar three-port converters reported in the paper.	
[22]	A multiple-input configuration of an isolated bidirectional dual-active bridge dc-dc converter (MIBDC) is proposed for power flow control in a combinational battery storage. The proposed system can be operated in an independent source or a combinational source mode of operation to control the power transfer. It has the capability of bidirectional power flow and smoother transition. The proposed configuration can also be used with unequal voltage level sources by connecting them in series on the multi-input side.	
[23]	A ZVS interleaved buck/boost bidirectional converter using the active-clamp technique is introduced in this paper. Applying a simple auxiliary circuit comprised of an auxiliary switch, an auxiliary inductor, and a clamp capacitor, ZVS condition is achieved by the converter operating duty cycle or load condition. The converter can operate with the conventional fixed-frequency pulse-width modulation (PWM) control.	
[24]	An interleaved bi-directional buck-boost is proposed for achieving zero-voltage switching. Applying a coupled inductor with a variable coupling coefficient achieves a wide input-output voltage operating range. The variable coupled inductor significantly improves the soft-switching range and reduces the circulating energy. The gallium nitride interleaved bi-directional buck-boost converter is applied in this paper.	Bidirectional converters and symmetrical resonant circuit discussion for delivering and re-charging of energy regulation
[25]	An integrated half-bridge CLLC (IHBCLLC) resonant bidirectional dc-dc converter is proposed in various applications, including energy-storage systems. A half-bridge CLLC resonant circuit and a buck/boost circuit are integrated. The proposed converter obtains the high voltage gain by pulse-width modulation. The CLLC resonant circuit can help MOSFETs to achieve soft switching and high voltage gain.	

Table 1. Cont.

No.	Features	Reference
[26]	<p>The total power loss optimization and the magnetic design of the CLLC resonant converter based on the artificial intelligence (AI) algorithm are proposed in this paper.</p> <p>The parameters of the magnetic component and the resonant component are derived by the AI algorithm.</p> <p>The parameters of the transformer are optimized by the AI algorithm.</p> <p>A planar transformer is used for CLLC designing in this paper.</p>	
[27]	<p>The CLLC bidirectional resonant converter is discussed in this paper.</p> <p>Application fields are battery chargers and dc microgrids.</p> <p>Asymmetric parameters methodology (APM) can design gain curves for charging and discharging modes separately.</p>	

2. Operations of the Proposed System

Figure 1a shows the application illustration of the proposed system in this paper. As shown in this application illustration, the two parts are the original system and the extra-installed system. In the original system, the energy of the ozone-driven system is directly supplied by the original supply through *DC BUS* [28,29]. It is noted that the output voltage of the original supply fits the voltage of *DC BUS*. To avoid ozone-driven system malfunction when a fault occurs in the original supply, the proposed system is connected to *DC BUS*. Moreover, both sources are included in the proposed system, the low-voltage PFC source [30–33] and energy storage devices. As shown in Figure 1, when the main supply delivers the power to *DC BUS*, the main supply not only provides the energy for the ozone-driven system through *DC BUS* but also charges the energy storage device simultaneously. When the main supply fails, the energy of *DC BUS* will be supplied by the proposed system. The master and the slave sources can both provide the energy. If the master source is normal, it can provide the energy for *DC BUS* and re-charge the energy storage devices through the proposed system at the same time. If the master source provides insufficient energy and causes abnormality, the energy storage devices will provide independently the energy for *DC BUS* through the proposed system to regulate the energy of each source and maintain the input voltage for the ozone-driven system. Figure 1b shows the extra-installed system illustration of the proposed system. As shown in this block diagram, the proposed system feeds the energy to the original ozone-driven system through *DC BUS*. When the energy is provided by the master source or the slave source, the voltage signal of each port transfers to the feedback circuit, the controller, and the isolated gate driver to deliver suitable driving signals of the power transistors of the power stage and allow the output voltage of the proposed system to be stabilized. In Figure 1b, the voltage feedback of the ozone load transfers to the original ozone-driven system for stabilizing the ozone generation exciting and the proposed system does not intervene in the ozone control, which means that the proposed system can be applied to any existing ozone-driven system. The application compatibility of the proposed system is higher than any solutions.

2.1. System and Circuit Description

The architecture of the proposed system is shown in Figure 2. There are five parts: a master–slave input supply circuit, a symmetrical resonant tank, a full-bridge circuit, a control circuit, and an ozone generator. The proposed system uses a master–slave input supply circuit formed by six power transistors (Q_1 – Q_6), two inductors (L_1 and L_2), and two diodes (D_1 and D_2). D_1 and D_2 provide current paths when L_1 and L_2 release the energy in order to avoid a higher voltage spike across the two inductors, which will occur when instantaneous current variation without current freewheeling path emerges. Furthermore, two input ports are designed to let two power sources be applied to this proposed system. The inductors are applied to isolate and store the energy. To smoothly release the energy of the inductors through any path and avoid the energy being delivered to the master

source, Q_5 and Q_6 are located upside down and different as a conventional full-bridge circuit. The proposed system also includes a symmetrical resonant tank composed of two resonant inductors (L_{r1} and L_{r2}), two resonant capacitors (C_{r1} and C_{r2}), and a step-up transformer (T). In addition, the proposed system possesses a full-bridge circuit consisting of power transistors (Q_7 – Q_{10}) and an output capacitor (C_D). The proposed system not only flexibly delivers the energy to *DC BUS* for the ozone generator but also opportunely recovers the energy from *DC BUS*. First, the master power supply (**Master source**) and the energy storage device (**Slave source**) are connected to the master–slave input supply circuit. Both the output of the full-bridge circuit and the ozone generator are connected to *DC BUS*. When the original source connects directly to *DC BUS* and provides the ozone generator and the proposed system with the energy, the frequency of Q_7 – Q_{10} will be controlled to convert the energy of *DC BUS* to the voltage at high frequency, which is transferred through the symmetrical resonant tank and the transformer, and the high-frequency voltage signal is rectified and stabilized by the body diodes of Q_1 – Q_4 and capacitor C_s , respectively. Finally, the energy will be charged to the energy storage device (the slave source). When the original source fails, the energy of the ozone generator must be provided through the proposed system. The master source (V_m) delivers the energy through the master–slave input supply circuit with the high-frequency square AC voltage being converted by controlling the frequency of Q_1 – Q_6 . This high-frequency square AC voltage passes through the symmetrical resonant tank and the transformer and is rectified and stabilized by the body diodes of Q_7 – Q_{10} and capacitor C_D , respectively. Next, the energy of C_D is transferred to the ozone generator through *DC BUS*. In addition, to ensure that the energy storage device (the slave source) maintains high voltage levels for full charging, the master source provides the energy to the energy storage device by controlling the frequency of Q_1 – Q_6 . If a fault occurs in the master source, the energy will be provided by the slave source (V_s) by controlling the frequency of Q_1 – Q_6 to convert the energy of the slave source to the high-frequency square AC voltage, which was transferred through the symmetrical resonant tank and the transformer and is rectified and stabilized by the body diodes of Q_7 – Q_{10} and the capacitor C_D , respectively. Subsequently, the energy of C_D is transferred to the ozone generator through *DC BUS*.

Figure 1. Block diagram of the proposed master–slave input supply system. (a) Application illustration and (b) extra-installed system illustration.

Figure 2. Configuration of the proposed system.

To improve the input supply reliability of the ozone generator, the master–slave input supply circuit is adopted. However, when two sources are applied to provide the energy for DC BUS, the voltage of each source must be considered. Therefore, the inductors of the master–slave input supply circuit (L_1 and L_2) are applied to regulate the energy of each source in this study. Here, to design these two inductors, the duty cycles of all transistors are 50% and the boundary between continuous and discontinuous inductor current I_{Li-min} must be 0. L_1 and L_2 are as follows:

$$I_{Li} = \frac{V_s^2 i_s}{V_m (V_s / i_s)} = \frac{V_m^2}{(1-D)^2 [V_m (V_s / i_s)]} = \frac{V_m i_s}{(1-D)^2 V_s}, \quad i = 1 \text{ or } 2 \quad (1)$$

$$\Delta i_{Li} = \frac{V_m}{2L_i} T_s = \frac{(V_s - V_m)}{2L_i} T_s, \quad i = 1 \text{ or } 2 \quad (2)$$

$$I_{Li-min} = I_{Li} - 0.5 \Delta i_{Li} = \frac{4V_m i_s}{V_s} - \frac{V_m T_s}{4L_i} = 0, \quad i = 1 \text{ or } 2 \quad (3)$$

where I_{Li} is the average current of the inductor; D is the duty cycle of the power transistors; which is set up at 0.5; and T_s is the time period. From Equation (3), the minimum inductor for continuous current can be written as below:

$$L_i = \frac{0.0625 V_s}{f_s i_s}, \quad i = 1 \text{ or } 2 \quad (4)$$

From Equation (4), since the duty cycles of all transistors are about 50%, the voltage and the current of the storage device are only taken into consideration in the inductor design. If the current of the inductor is designed in the continuous mode for lower charging power of the storage device, the larger inductor must be designed; otherwise, the smaller inductor is enough in this proposed system. Table 2 shows the circuit specification of the proposed system.

Table 2. The parameters of the proposed system.

Specifications	Title 3
Master input source voltage, V_m	48 V
Slave input source voltage, V_s	40 V–54.6 V
Output voltage, V_o	400 V
Power transistors, Q_1 – Q_{10}	IXFH44N50P
Storage inductors, L_1 and L_2	1.21 mH
Capacitors of the master source and the slave source, C_m and C_s	470 μ F/100 V
Output capacitors, C_D	470 μ F/450 V
Maximum output current, I_o	2 A
Maximum output power, P_o	800 W

2.2. Operation Mode and Circuit Analysis

Since this proposed system can be applied in three operations, the circuit operations must be analyzed for each operation mode. Figures 3–5 depict the circuit operation for three operations, and Figure 6 shows their corresponding waveforms. First, the circuit operations will be analyzed for the master source supply operation, as shown in Figures 3 and 6a. The operation is described as follows:

- (1) Mode I (t_0 – t_1): As shown in Figure 3a, Q_2 and Q_6 are turned off and Q_4 and Q_5 are turned on, achieving zero-voltage switching in this mode; the energy of the master source is stored in inductor L_2 by turning on Q_4 and releasing the energy of inductor L_1 , which is stored in the energy storage device and C_s by turning on Q_5 and the diode of Q_1 . Therefore, the currents of L_1 and L_2 (i_{L1} and i_{L2}) linearly decrease and increase, respectively. At this time, since the resonant voltage v_{r1} of the primary side is a positive square wave, the resonant current i_{r1} of the primary side flowing through Q_1 and Q_4 is positive and the resonant current i_{r2} of the secondary side flows through the body diode of Q_7 and Q_{10} to transfer the energy to DC BUS with output capacitor C_D . It is noted that the current i_m of the master source has low ripples because i_{L1} and i_{L2} are interleaved to store and release energy, which can contribute to mitigating the burden of the master source supply. This operation enters the next mode until Q_4 and Q_5 are turned off.
- (2) Mode II (t_1 – t_2): In this mode, all power transistors Q_1 – Q_6 are turned off, as shown in Figure 3b. The energy of L_2 begins to be released and i_{L2} linearly decreases; thus, the energy of L_2 is stored in the energy storage device and C_s through the body diode of Q_3 and i_{r1} is freewheeling through the body diodes of Q_2 and Q_3 at the same time. When the voltage of the parasitic capacitor of Q_2 and Q_3 drops to zero, the body diodes of Q_2 and Q_3 provide a path for current freewheeling. Here, i_{L1} still decreases and i_{L2} begins to decrease. When Q_2 , Q_3 , and Q_6 are turned on, this operation enters the next mode.
- (3) Mode III (t_2 – t_3): As shown in Figure 3c, Q_2 and Q_6 are turned on and achieve zero-voltage switching in this mode. The energy of inductor L_2 is charged to the energy storage device and C_s by turning on Q_6 and the body diodes of Q_3 , and the energy of the master source is stored in inductor L_1 by turning on Q_2 . Therefore, i_{L1} and i_{L2} linearly increase and decrease, respectively. Since the resonant voltage v_{r1} of the primary side becomes a negative square wave in this time, the current i_{r1} becomes negative and flows through Q_2 and Q_3 . i_{r2} also becomes negative and flows through the body diode of Q_8 and Q_9 and transfers the energy to DC BUS with output capacitor C_D . When Q_2 and Q_6 are turned off, this operation enters the next mode.
- (4) Mode IV (t_3 – t_4): In this mode, all power transistors Q_1 – Q_6 are turned off again, as shown in Figure 3d; the energy of L_1 begins to be released; and i_{L1} linearly decreases. Thus, the energy of L_1 is stored in the energy storage device and C_s through the body diode of Q_1 . Meanwhile, i_{r1} is freewheeling through the body diodes of Q_1 and Q_4 . When the voltage of the parasitic capacitor of Q_2 and Q_3 drops to zero, the body diodes of Q_1 and Q_4 provide a path for current freewheeling. Here, i_{L1} begins to

decrease and i_{L2} continues to decrease. When Q_4 and Q_5 are turned on again and the circuit returns to Mode I, the aforementioned mode of operation continues.

Figure 3. Operation of the proposed system for the master source supply. (a) Mode I (t_0-t_1), (b) Mode II (t_1-t_2), (c) Mode III (t_2-t_3), and (d) Mode IV (t_3-t_4).

Figure 4. Operation of the proposed system for the slave source supply. (a) Mode I (t_0-t_1), (b) Mode II (t_1-t_2), (c) Mode III (t_2-t_3), and (d) Mode IV (t_3-t_4).

Figure 5. Operation of the proposed system when the energy is provided from DC BUS. (a) Mode I (t_0-t_1), (b) Mode II (t_1-t_2), (c) Mode III (t_2-t_3), and (d) Mode IV (t_3-t_4).

Figure 6. Waveforms of the proposed system for (a) the master source supply, (b) the slave source supply, and (c) the energy provided from DC BUS.

When the master source cannot normally provide the energy, the slave source provides the energy for the proposed system. Next, the circuit operations will be analyzed for the slave source supply operation, as shown in Figures 4 and 6b, with this operation described as follows:

- (1) Mode I (t_0 – t_1): As shown in Figure 4a, Q_2 and Q_3 are turned off, Q_1 and Q_4 are turned on, and the zero-voltage switching of Q_1 and Q_4 is achieved in this mode. Because Q_5 and Q_6 are always turned off in this mode, if there are surplus energies in these inductors (L_1 and L_2), i_{L1} and i_{L2} must be freewheeling through D_1 and D_2 until both i_{L1} and i_{L2} linearly decrease to zero. Since v_{r1} is a positive square wave, i_{r1} is also positive and flows through Q_1 and Q_4 . The current i_{r2} flows through the body diode of Q_7 and Q_{10} , and the energy is transferred to DC BUS with output capacitor C_D . This operation enters the next mode when Q_1 and Q_4 are turned off.
- (2) Mode II (t_1 – t_2): As shown in Figure 4b, all power transistors Q_1 – Q_6 are turned off. When the voltage of the parasitic capacitor of Q_2 and Q_3 drops to zero, the body diodes of Q_2 and Q_3 provide a path for current freewheeling. i_{r1} is still positive and freewheeling through the body diodes of Q_2 and Q_3 . i_{L1} and i_{L2} are still freewheeling through D_1 and D_2 if there are surplus energies in L_1 and L_2 . When Q_2 and Q_3 are turned on, this operation enters the next mode.
- (3) Mode III (t_2 – t_3): As shown in Figure 4c, because the voltage of Q_2 and Q_3 drops to zero in the last mode, Q_2 and Q_3 are turned on in this mode and zero-voltage switching of Q_2 and Q_3 is achieved. Since v_{r1} becomes a negative square wave at this time, i_{r1} becomes negative and flows through Q_2 and Q_3 ; i_{r2} also becomes negative and flows through the body diode of Q_8 and Q_9 and transfers the energy to DC BUS with output capacitor C_D . Because no load can consume the surplus energies of L_1 and L_2 , both i_{L1} and i_{L2} linearly decrease slowly through D_1 and D_2 . When Q_2 and Q_3 are turned off, this operation enters the next mode.
- (4) Mode IV (t_3 – t_4): In this mode, all power transistors Q_1 – Q_6 are turned off again, as shown in Figure 4d. When the voltage of parasitic capacitors of Q_1 and Q_4 drops to zero, the body diodes of Q_1 and Q_4 provide a path for current freewheeling. Therefore, i_{r1} is freewheeling through body diodes of Q_1 and Q_4 at this time. In addition, because no load can consume the surplus energies of L_1 and L_2 , both i_{L1} and i_{L2} linearly decrease slowly through D_1 and D_2 . When Q_1 and Q_4 are turned on again and the circuit returns to Mode I, the aforementioned modes of operation continue.

When the original source directly connects and provides the energy for DC BUS, the energy will be recovered from DC BUS to the energy storage device through the proposed system. Finally, the circuit operations will be analyzed for the energy is transferred from DC BUS, as shown in Figures 5 and 6c. Therefore, this operation is described as follows:

- (1) Mode I (t_0 – t_1): As shown in Figure 5a, because the voltage of Q_7 and Q_{10} drops to zero in the last mode, Q_7 and Q_{10} are turned on and achieve the zero-voltage switching in this mode by turning off Q_8 and Q_9 . The resonant voltage v_{r2} is a positive square wave because this voltage is converted by the switching of Q_7 and Q_{10} . The resonant current i_{r2} is positive and flowing through Q_7 and Q_{10} , and the resonant current i_{r1} that is induced by transformer T is also positive and flows through the body diode of Q_1 and Q_4 to transfer the energy to the energy storage device with capacitor C_s . This operation enters the next mode until Q_7 and Q_{10} are turned off.
- (2) Mode II (t_1 – t_2): As shown in Figure 5b, all power transistors Q_7 – Q_{10} are turned off because the voltage of the parasitic capacitor of Q_8 and Q_9 drops to zero. i_{r1} is freewheeling through the body diode of Q_8 and Q_9 . When Q_8 and Q_9 are turned on, this operation enters the next mode.
- (3) Mode III (t_2 – t_3): As shown in Figure 5c, because the voltage of Q_8 and Q_9 drops to zero in the previous mode, Q_8 and Q_9 are turned on in this mode and the zero-voltage switching of Q_8 and Q_9 is achieved. The resonant voltage v_{r2} becomes a negative square wave because this voltage is converted by switching Q_8 and Q_9 . The resonant current i_{r2} is positive and flows through Q_8 and Q_9 , and the resonant current i_{r1} that

is induced by transformer T is also positive and flows through the body diode of Q_2 and Q_3 to transfer the energy to the energy storage device with capacitor C_s . This operation enters the next mode until Q_8 and Q_9 are turned off.

- (4) Mode IV (t_3 – t_4): In this mode, all power transistors Q_7 – Q_{10} are turned off, as shown in Figure 5d, because the voltage of the parasitic capacitor of Q_7 and Q_{10} drops to zero. i_{r1} is freewheeling through the body diode of Q_7 and Q_{10} . When Q_7 and Q_{10} are turned on again, the circuit returns to Mode I for the aforementioned cycle to continue.

3. Symmetrical Resonant Circuit Analysis

To enhance the transmission efficiency, the resonant circuit and the transformer are usually applied to the power conversion. However, resonant characteristics are easily affected because the power transmission is not unidirectional. The symmetrical design of the resonant tank must be taken into consideration for reducing the variation in resonant characteristics in the different power transmission directions. The symmetrical resonant tank analysis and transformer design are described in detail in this section.

3.1. Operation Mode and Circuit Analysis

Figure 7 depicts the configuration of the symmetrical resonant tank, where L_{r1} and L_{r2} are the resonant inductors, C_{r1} and C_{r2} are the resonant capacitors, T is the transformer, and L_m is the magnetic inductor of the transformer. v_{r1} is the resonant voltage of the primary side, which is generated by the front stage circuit. v_{r2} is the resonant voltage of the secondary side, which is generated by the symmetrical resonant tank and input into the rear circuit. R_L is the equivalent load of DC BUS and V_o is the output voltage after rectification and stabilization by the rear stage circuit such as $V_{DC\ BUS}$ of Figure 2. To select the resonant capacitor, the operation frequency f_s must be defined first, and the resonant inductor can be determined from Equation (5), as follows:

$$f_s = \frac{1}{2\pi\sqrt{L_{r1}C_{r1}}} = \frac{1}{2\pi\sqrt{L_{r2}C_{r2}}} \quad (5)$$

Due to the symmetrical structure of this resonant tank, the resonant parameters of both sides can be determined from Equation (5). To ensure the symmetrical configuration of the resonant tank, the resonant parameters of the primary side L_{r1} and C_{r1} are determined first and the resonant parameters of the secondary side L_{r2} and C_{r2} are calculated by using Equation (6), as follows:

$$C_{r2} = \frac{C_{r1}}{n^2}, L_{r2} = L_{r1}n^2 \quad (6)$$

where n is the turn ratio of the transformer. When all resonant parameters are selected, the resonant characteristics must be analyzed for the different operations. The process will be explored in the next section.

Figure 7. Configuration of the symmetrical resonant tank.

3.2. Analysis of Voltage Gain and Impedance Phase

3.2.1. The Energy Is Provided by the Master or the Slave Source

Next, the analysis of voltage gain and impedance phase is described when the energy is provided from the master source or the slave source, as shown in Figure 8. As shown in Figure 8b, the equivalent circuit of Figure 8a, to consider the variation of R_L , the impedance

of the transformer is mapped to the primary side of the transformer, where L_{r2}/n^2 , n^2C_{r2} , and $8R_L/n^2\pi^2$ are the resonant parameters that mapped to the primary side from the secondary side, and these resonant parameters are in parallel connection with magnetic inductor L_m . This resonant equivalent impedance Z_{p_1} is calculated as

$$Z_{p_1}(j\omega) = \frac{-\pi j\omega^3 L_m L_{r2} C_{r2} - 8\omega^2 L_m C_{r2} R_L + n^4 \pi j\omega L_m}{-n^2 \omega^2 \pi L_m C_{r2} - \omega^2 \pi L_{r2} C_{r2} + 8j\omega C_{r2} R_L + n^4 \pi} \quad (7)$$

Figure 8. Resonant circuit for the master source or the slave source supply. (a) Configuration and (b) the equivalent circuit.

Consequently, the input impedance Z_{in_1} and the voltage gain $G_{v1}(j\omega)$ are derived below.

$$Z_{in_1}(j\omega) = \left[n^4 \pi j\omega C_{r1} \left(-\omega^2 L_m C_{r2} - \frac{\omega^2 L_{r2} C_{r2}}{n^4} + \frac{8j\omega C_{r2} R_L}{\pi n^4} + 1 \right) \right]^{-1} \times \left[\pi \omega^2 (-L_{r2} C_{r2} - n^2 L_m C_{r2} - n^4 L_m C_{r1} - n^4 L_{r1} C_{r1}) + 8j\omega C_{r2} (-\omega^2 L_m C_{r1} R_L - \omega^2 L_{r1} C_{r1} R_L + \frac{n^4 \pi}{8j\omega C_{r2}} + 8R_L) + \pi \omega^4 C_{r1} C_{r2} (L_m L_{r2} + L_{r1} L_{r2} + n^2 L_m L_{r1}) \right] \quad (8)$$

$$|G_{v1}(j\omega)| = \frac{|V_o|}{|v_{r1}(j\omega)|} = \frac{2j\omega L_m R_L \left(j\omega L_m + \frac{8R_L}{n^2\pi} + \frac{n^2}{j\omega C_{r2}} + \frac{j\omega L_{r2}}{n^2} \right)^{-1}}{n \left(j\omega L_{r1} + \frac{1}{j\omega C_{r1}} + \frac{\frac{8j\omega L_m R_L}{n^2\pi} + \frac{n^2 L_m}{C_{r2}} - \frac{\omega^2 L_{r2} L_m}{n^2}}{j\omega L_m + \frac{8R_L}{n^2\pi} + \frac{n^2}{j\omega C_{r2}} + \frac{j\omega L_{r2}}{n^2}} \right)} \quad (9)$$

Based on Equations (8) and (9), Figure 9 shows the curves of voltage gain and input impedance under different load conditions. When load variation occurs, the system frequency is adjusted to maintain the voltage gain, as shown in Figure 9a. Since the voltage gain is larger than unity, the operating frequency must be adjusted to meet the requirements of the system output. Then, as depicted in Figure 9b, where the phase of input impedance is larger than zero on the right-hand side of resonant frequency, it means that the condition of zero-voltage switching is achieved. Therefore, the operating frequency will be larger than the resonant frequency ($f_n > 1$).

3.2.2. The Energy Is Provided from DC BUS

In this section, the study discusses the scenario in which the energy is provided by DC BUS. As seen from Figure 10a, which presents the equivalent circuit of energy reversal, the residual load power of DC BUS is first converted to an AC squared signal and then delivered to the resonant circuit. As shown in Figure 10b, to consider the variation in R_s , the impedance of the transformer is mapped to the primary side of the transformer, where C_{r1}/n^2 , n^2L_{r1} , and $8R_s/n^2\pi^2$ are the resonant parameters that mapped to the secondary side from the primary side, and these resonant parameters are in parallel connection with magnetic inductor L_m . This resonant equivalent impedance Z_{p_2} is calculated as

$$Z_{p_2}(j\omega) = \frac{(-n^4 \omega^2 L_{r1} C_{r1} + n^4 8j\omega C_{r1} R_s + 1) n^2 \pi j\omega L_m}{-n^4 \omega^2 \pi L_{r1} C_{r1} - n^4 \omega^2 \pi L_m C_{r1} + 8n^4 j\omega C_{r1} R_s + \pi} \quad (10)$$

Figure 9. The plots of voltage gain and phase angle when the energy is provided by the master source or the slave source. (a) The voltage gain and (b) the input impedance.

Figure 10. Resonant circuit when the energy is provided from DC BUS. (a) Configuration and (b) the equivalent circuit.

Given Equation (10), the transfer function of voltage gain $G_{v2}(j\omega)$ and input impedance $Z_{in_2}(j\omega)$ when the energy is provided from DC BUS are then derived as follows:

$$Z_{in_2}(j\omega) = \left[(-n^4 \pi j \omega^3 C_{r1} C_{r2}) (L_{r1} + L_m) + (j\omega C_{r2}) (\pi + 8n^4 j \omega C_{r1} R_s) \right]^{-1} \times \left\{ \pi + (\omega^4 n^4 \pi C_{r1} C_{r2}) (L_m L_{r2} + n^2 L_m L_{r1} + L_{r1} L_{r2}) - \omega^2 [\pi C_{r2} (L_{r2} + L_m) + n^4 \pi C_{r1} (L_{r1} + L_m) + 8j\omega C_{r1} C_{r2} R_s (n^6 L_m + L_{r2})] + 8n^4 j \omega C_{r1} R_s \right\} \quad (11)$$

$$|G_{v2}(j\omega)| = \frac{|V_s|}{|v_{r2}(j\omega)|} = \frac{2j\omega L_m R_s \left(n^2 j \omega L_m + \frac{8R_s}{n^2 \pi} + \frac{n^{-2}}{j\omega C_{r1}} + n^2 j \omega L_{r1} \right)^{-1}}{j\omega L_{r2} + \frac{1}{j\omega C_{r2}} + \frac{\frac{8j\omega L_m R_s}{\pi} + \frac{L_m}{C_{r1}} - n^4 \omega^2 L_{r1} L_m}{n^2 j \omega L_m + \frac{8R_s}{n^2 \pi} + \frac{n^{-2}}{j\omega C_{r1}} + n^2 j \omega L_{r1}}} \quad (12)$$

Next, Figure 11 shows the simulation results of transfer gain $G_{v2}(j\omega)$ and input impedance $Z_{in_2}(j\omega)$ under load variations. In Figure 11a, since the voltage gain is lower than 1, this means that the voltage steps down in this operation mode. Figure 11b shows the curve of the phase angle for input impedance. To achieve zero-voltage switching and considering that the intended resonant property requires inductance, the operating frequency must be larger than the resonant frequency ($f_n > 1$). Let the phase angle of impedance be higher than 0 degrees. When the parameters of the resonant tank are selected based on the above consideration, the parameters of the resonant tank of the proposed system are shown in Table 3.

Figure 11. The plots of voltage gain and phase angle when the energy is provided from DC BUS (a) voltage gain and (b) input impedance.

Table 3. Parameters of the symmetrical resonant circuit.

Items	Values
Resonant frequency	55 kHz
Resonant inductor of the primary side (L_{r1})	124.8 μ H
Resonant capacitor of the primary side (C_{r1})	67.1 nF
Magnetic inductor (L_m)	2.75 mH
Resonant inductor of the secondary side (L_{r2})	2.034 mH
Resonant capacitor of the secondary side (C_{r2})	4.12 nF

4. Control Mechanism Analysis

Figure 12 shows the control flowchart of the proposed system, where three modes of power deliveries are studied. This flowchart starts with the initialization of frequency and each voltage reference setting. The controller begins with the acquisition of the voltage of DC BUS ($V_{DC\ BUS}$) from the feedback circuit. On comparing $V_{DC\ BUS}$ with the setting voltage of $V_{DC\ BUS}$ ($V_{DC\ BUS-ref}$), if $V_{DC\ BUS}$ is lower than or equal to $V_{DC\ BUS-ref}$, then the process goes to voltage detection of the master source (V_m). If V_m is larger than or equal to V_{m-min} , it means that the energy of the master source is sufficient. Yet, if $V_{DC\ BUS}$ is still lower than $V_{DC\ BUS-ref}$, it implies that the energy is insufficient for the ozone-driven system. Next, the controller decreases frequencies of Q_2 , Q_4 , Q_5 , and Q_6 (f_{Q2} , f_{Q4} , f_{Q5} , and f_{Q6}) to raise the voltage gain and detects repeatedly $V_{DC\ BUS}$ until $V_{DC\ BUS}$ is larger than or equal to $V_{DC\ BUS-ref}$. Subsequently, the frequencies of Q_2 , Q_4 , Q_5 , and Q_6 (f_{Q2} , f_{Q4} , f_{Q5} , and f_{Q6}) are increased to reduce the voltage gain. If $V_{DC\ BUS}$ is lower than or equal to $V_{DC\ BUS-ref}$, the process is back to detecting V_m . Conversely, the operation mode is changed. This operation mode is called the master source supply mode in the flowchart in Figure 12.

Following the above operation, if V_m is smaller than V_{m-min} , it means that the energy of the master source is insufficient and the voltage of the slave source V_s must be detected at this time. If V_s is larger than or equal to V_{s-min} , it means that the energy of the slave source still needs to be replenished because $V_{DC\ BUS}$ is still lower than $V_{DC\ BUS-ref}$. As a result, the controller decreases the frequencies of Q_1 – Q_4 (f_{Q1} – f_{Q4}) to raise the voltage gain and then $V_{DC\ BUS}$ is detected repeatedly until $V_{DC\ BUS}$ is larger than or equal to $V_{DC\ BUS-ref}$. The controller then increases the frequencies of Q_1 – Q_4 (f_{Q1} – f_{Q4}) to reduce the voltage gain and detects V_m again. If V_m is still lower than V_{m-min} , the same operation will continue. Conversely, the operation mode is back to the master source supply mode. However, if V_s is also smaller than V_{s-min} , it means that the master source and the slave source will both fail to provide the energy and then the process goes to stop all operations. This operation mode is named the slave supply mode, as shown in Figure 12.

Figure 12. Control flowchart of the proposed system.

Finally, when the controller begins with the acquisition of $V_{DC\ BUS}$ from the feedback circuit and $V_{DC\ BUS}$ is larger than $V_{DC\ BUS-ref}$, it implies that the energy of DC BUS is generated by the original source that connects directly to DC BUS. Then, the controller detects V_s . If V_s is less than V_{s-max} , this means that the energy can be charged to the slave source (energy storage device). Next, the controller decreases frequencies of Q_7 – Q_{10} (f_{Q7} – f_{Q10}) to raise the voltage gain and detects V_s repeatedly until V_s is larger than or equal to V_{s-max} . The controller increases the frequencies of Q_7 – Q_{10} (f_{Q7} – f_{Q10}) to reduce the voltage gain and detect $V_{DC\ BUS}$ again. If $V_{DC\ BUS}$ is lower than or equal to $V_{DC\ BUS-ref}$, the process is back to detecting V_m . Conversely, the operation mode processes at the same mode. This operation mode is called the DC BUS supply mode in the flowchart in Figure 12.

5. Experimental Results

This section validates the feasibility and performance of a modified-bridge circuit with a master–slave input supply mechanism. Figure 13 shows the photograph of the hardware circuit. This proposed system can be separated into two parts. The first is the main circuit, which consists of a master–slave input supply circuit, a symmetrical resonant tank, a full-bridge circuit, a controller (MCU), and two auxiliary powers. The other is the ozone generator, which includes an ozone load, a driven circuit, an auxiliary power, and a controller. It is noted that the terminal connectors for the DC BUS of the main circuit and the ozone generator are connected, allowing the energy to be exchanged between them.

Figure 13. Hardware implementation of the proposed system.

To validate the capability of the modified-bridge circuit with a master–slave input supply mechanism, the voltages of the master power supply (V_m), the voltages of the energy storage device (V_s), the voltage and current of the resonant tank (v_r and i_r), and the output status (V_o and I_o) are discussed under different scenarios. Experimental results and corresponding waveforms are also analyzed below.

5.1. Input and Output Status

Here, the input and output validations start with different modes of testing, as shown in Figure 14. When the operation mode is the master source supply, it implies that the energy is provided solely from the master source. In Figure 14a, the voltage of the master source (V_m) is about 48 V and the voltage of the slave source (V_s) is about 30 V, which means that the voltage of the master source is ready to provide the energy and the voltage of the slave source is insufficient. In this operation mode, the voltage and the current of DC BUS ($V_{DC\,BUS}$ and $I_{DC\,BUS}$) are about 400 V and 2 A, respectively. According to this waveform in Figure 14a, when the consumption of DC BUS reaches 2 A, the master source not only provides independently the energy for the ozone generator and stabilizes $V_{DC\,BUS}$ but also charges the slave source through the proposed system. When the operation mode is the slave source supply, it means that the energy is provided from the slave source. In Figure 14b, V_m is about 30 V and V_s is about 50 V, which means that the master source cannot provide sufficient energy and the slave source must substitute for the master source. In this operation mode, when $I_{DC\,BUS}$ is about 2 A and $V_{DC\,BUS}$ is still maintained at about 400 V, it means that the slave source provides independently the energy for the ozone generator and it can stabilize $V_{DC\,BUS}$ through the proposed system. Operating in the DC BUS supply mode implies that the original source directly connects to DC BUS to supply the energy. It is noted that the slave source is an energy storage device, so the energy from DC BUS charges the slave source. In Figure 14c, $V_{DC\,BUS}$ and $I_{DC\,BUS}$ are about 420 V and 2 A, respectively, and the waveform of $I_{DC\,BUS}$ is negative, which means the energy is delivered from DC BUS because the original source directly connects to DC BUS. In addition, when $V_{DC\,BUS}$ is higher than 400 V, the energy can be provided from DC BUS to the slave source

through the proposed system. In this waveform of Figure 14c, V_s is about 40 V and V_m is 0 V, which means that the energy from DC BUS is only charged to the slave source and the master source cannot be charged, because the slave source is an energy storage device and the master source is a general power supply.

Figure 14. Experiment waveforms of the voltage of the master source supply, the voltage of the slave source supply, and the voltage and the current of DC BUS under (a) the master source supply mode, (b) the slave source supply mode, and (c) the DC BUS supply mode. (V_m : 50 V/div, V_s : 50 V/div, $V_{DC\ BUS}$: 200 V/div, $I_{DC\ BUS}$: 2 A/div, and time: 10 μs /div).

5.2. Resonant Property Verification

Here, the resonant property with the voltage and the current of the resonant circuit is verified under different operation modes, as shown in Figure 15. According to Figure 15a, the proposed system operates in the master source supply mode. The input voltage of the resonant circuit (v_{r1}) can be observed. v_{r1} is seen to lead the input and the output current (i_{r1} and i_{r2}) with a phase difference of θ_m , which means that the resonant property is exhibiting the inductive characteristics to help in the achievement of zero-voltage switching (ZVS). In Figure 15b, the proposed system is in the slave source supply mode and v_{r1} still leads i_{r1} and i_{r2} with a phase difference of θ_s , which implies that the resonant property is exhibiting the inductive characteristics to help achieve ZVS. It is noted that though the front of the proposed system is an integrating circuit design, the power transistors of the front of the proposed system can still achieve the condition of ZVS. In Figure 15c, the DC BUS supply mode is operated in the proposed system and v_{r2} also leads i_{r1} and i_{r2} with a phase difference of θ_D , which means that the inductive characteristic is exhibited in this resonant circuit even if the energy is provided from DC BUS for the output of the resonant circuit, which helps to achieve ZVS. Through the resonant property verification, the test results of the resonant property can meet the design of the resonant circuit, which can achieve the inductive property to help achieve ZVS irrespective of the supply mode under which the proposed system is operating.

Figure 15. Experiment waveforms of resonant property under (a) the master source supply mode, (b) the slave source supply mode, and (c) the DC BUS supply mode. (v_{r1} : 200 V/div, v_{r2} : 1000 V/div, i_{r1} : 20 A/div, i_{r2} : 5 A/div, and time: 10 μ s/div).

5.3. Zero-Voltage Switching Verification

In this section, zero-voltage switching (ZVS) achievement is verified in the test results. Please refer to Figure 16 for an explanation. Here, the voltage and the current for the power transistors of the proposed system must be observed while power transistors turn on. In Figure 16a, when the operation mode is the master source supply, negative currents (i_{ds2} and i_{ds5}) flow through the body diodes of Q_2 and Q_5 before the voltages (v_{ds2} and v_{ds5}) become zero. When v_{ds2} and v_{ds5} become zero because Q_2 and Q_5 are turned on, i_{ds2} and i_{ds5} flow through Q_2 and Q_5 , realizing zero-voltage switching. In Figure 16b, when the operation mode is the slave source supply, the currents (i_{ds1} and i_{ds2}) are negative and flow through body diodes of Q_1 and Q_2 before Q_1 and Q_2 are turned on. Until the voltages (v_{ds1} and v_{ds2}) become zero because Q_1 and Q_2 were turned on, i_{ds1} and i_{ds2} become positive and flow through Q_1 and Q_2 to achieve ZVS. In Figure 16c, the system is operating in the DC BUS supply mode and negative currents (i_{ds7} and i_{ds8}) flow through body diodes of Q_7 and Q_8 before Q_7 and Q_8 are turned on. When the voltages (v_{ds1} and v_{ds2}) become zero since Q_7 and Q_8 are turned on, i_{ds7} and i_{ds8} become positive and flow through Q_7 and Q_8 because of ZVS. These testing results show that the power transistors can be operated under ZVS regardless of the operation mode this proposed system is operating in, implying that the switching loss can be reduced effectively.

5.4. Operation Mode Change Verification

Since there are three operation modes in this proposed system and the operation mode changes according to the voltage of each port, the operation mode change must be verified in this section. In this experiment, DC power supplies are used in each port to simulate the master source, the slave source, and the original power source, which directly connects to DC BUS. The voltage of DC power is adjusted to simulate the voltage variety of each port, to observe the operation mode change situation of the proposed system as shown in Figure 17. Figure 17a,b shows the voltage variation in each port and the driving signal when the master source supply mode changes to the slave source supply mode. In Figure 17a, the voltage of the master source gradually drops to 40 V and the driving signal of Q_5 is turned off, which means that the energy of the master source is insufficient to provide energy and the driving signals of the corresponding power transistors (Q_5 and Q_6)

must be stopped. After 20 ms, the driving signal of Q_1 is turned on and the voltage of the slave source drops a little bit, which means that the driving signals of the corresponding power transistors (Q_1 and Q_2) start to operate, letting the slave source substitute for the master source to provide the energy. In Figure 17b, there is a roughly 40 ms time difference between the voltage of the master source starting to gradually drop and the voltage of the slave source dropping a little bit. The voltage of *DC BUS* can be stabilized. Figure 17c,d shows the voltage variation in each port and the driving signal variation when the slave source supply mode switches to the master source supply mode. In Figure 17c, the voltage of the slave source drops to 36 V and the driving signal of Q_1 is turned off, which simulates the situation when the energy storage device (the slave source) is cut off and the driving signals of the corresponding power transistors (Q_1 and Q_2) are turned off. After 20 ms, the driving signal of Q_5 is turned on and the voltage of the master source drops a little bit, which means that the driving signals of corresponding power transistors (Q_5 and Q_6) start to operate and let the master source provide the energy. In Figure 17d, the voltage of *DC BUS* is still stable during operation mode change, which is about 60 ms. Finally, both the master source and the slave source cannot provide the energy and the energy is re-charged to the slave source (the energy storage device). As shown in Figure 17e, the voltage of *DC BUS* is stepped up to 420 V and the driving signal of Q_1 is turned off, which simulates that the original source directly connects to *DC BUS* and the energy will be provided through *DC BUS* from the original source. The driving signals of corresponding power transistors (Q_1 and Q_2) must be turned off. After 20 ms, the driving signal of Q_7 starts to operate and the voltage of the slave source is stepped up, which means that the driving signals of the corresponding power transistors (Q_7 – Q_{10}) start to operate to provide the energy from *DC BUS* and re-charge the energy storage device (the slave source). Through these experimental results, it can be observed that the proposed system is functioning well regardless of the operation mode.

Figure 16. Experiment waveforms of zero-voltage switching under (a) the master source supply mode, (b) the slave source supply mode, and (c) the *DC BUS* supply mode. (Time: 10 µs/div).

5.5. Comparison with the References

Finally, a comparison with the reference focuses on some indexes, such as input port amount, input voltage, used converter amount, supply coordination function, and output

voltage in this section as listed in Table 4. First, the proposed system has two input ports that connect the master source and the slave source (energy storage devices) by applying circuit integration design, which significantly improves the supply reliability. Other references have only one input port that connects a single source. If the source failure occurs, this kind of ozone-driven circuit will stop operating. It is noted that [15] has five input ports that connect five batteries to supply, yet six circuits are applied in this reference, which means complicated control and a higher circuit cost for this design. Furthermore, the supply coordination function must be discussed because the energy is provided by two sources in this paper and the proposed system has three operation modes to decide which one source delivers or re-charges, and other references have no supply coordination function because only a single source provides the energy. From the indexes of the input voltage and the output voltage, the proposed system can be extra-installed with the original ozone-driven system [11], which implies that the original system remains the same to maintain the ozone quality and minimize the system change to reduce the installation cost.

Figure 17. Experiment waveforms of (a) show the driving signal verification when the master source supply mode changes to the slave source supply mode, (b) depict the voltage of each port when the master source supply mode changes to the slave source supply mode, (c) elucidate the driving signal verification when the slave source supply mode changes to the master source supply mode, (d) show the voltage of each port when the slave source supply mode changes to the master source supply mode, and (e) show the driving signal verification when the slave source supply mode changes to the DC BUS supply mode, (V_s : 20 V/div, V_m : 20 V/div, $V_{DC\ BUS}$: 150 V/div, v_{gs_Q1} : 5 V/div, v_{gs_Q5} : 5 V/div, v_{gs_Q7} : 5 V/div, and time: 100 ms/div).

Table 4. Comparison with the references of the ozone-driven circuit.

Paper No.	Input Port Amount	Used Circuit Amount	Supply Coordination Function	Input Voltage	Output Voltage
[11]	1	1	No	400 V _{DC}	8.2 kV
[12]	1	1	No	208 V _{AC}	NA
[13]	1	1	No	1200 V _{DC}	1.6 kV
[14]	1	1	No	NA	10–30 kV
[15]	1	1	No	60 V _{DC}	20 kV
[19]	5	6	No	30 V _{DC}	1500 V
✓ The proposed system	2	1	Yes	Master: 48 V _{DC} Slave: 40–54.6 V _{DC}	400 V

6. Conclusions

This paper presents the realization of a modified-bridge circuit with a master–slave input supply mechanism for ozone-driven system applications. Through the master–slave input supply circuit, the completed circuit exhibits better reliability during different operating conditions. In this study, a symmetrical resonant circuit that achieves zero-switching conditions under each operation mode is designed. The hardware prototype is realized in the laboratory, and experiments are executed under different scenarios. The experimental results validate the practicality of the proposed system, which should be most beneficial to improve the reliability of the ozone-driven system.

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