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A Novel and Cost-Effective Drive Circuit for Supplying a Piezoelectric Ceramic Actuator with Power-Factor-Correction and Soft-Switching Features

Chun-An Cheng , Hung-Liang Cheng , Chien-Hsuan Chang , En-Chih Chang *, Chih-Yang Tsai and Long-Fu Lan

Department of Electrical Engineering, I-Shou University, Kaohsiung City 84001, Taiwan; cacheng@isu.edu.tw (C.-A.C.); hlcheng@isu.edu.tw (H.-L.C.); chchang@isu.edu.tw (C.-H.C.); isu10701011m@cloud.isu.edu.tw (C.-Y.T.); isu11001004m@cloud.isu.edu.tw (L.-F.L.)

* Correspondence: enchihchang@isu.edu.tw; Tel.: +886-7-6577711 (ext. 6642)

Abstract: This paper proposes a novel and cost-effective drive circuit for supplying a piezoelectric ceramic actuator, which combines a dual boost AC-DC converter with a coupled inductor and a half-bridge resonant DC-AC inverter into a single-stage architecture with power-factor-correction (PFC) and soft-switching characteristics. The coupled inductor of the dual boost AC-DC converter sub-circuit is designed to work in discontinuous conduction mode (DCM), so the PFC function can be realized in the proposed drive circuit. The resonant tank of the half-bridge resonant inverter sub-circuit is designed as an inductive load, so that the two power switches in the presented drive circuit can achieve zero-voltage switching (ZVS) characteristics. A 50 W-rated prototype drive circuit providing a piezoelectric ceramic actuator has been successfully implemented in this paper. From the experimental results at 110 V input utility-line voltage, the drive circuit has the characteristics of high power factor and low input current total-harmonic-distortion factor, and two power switches have ZVS characteristics. Therefore, satisfactory outcomes from measured results prove the function of the proposed drive circuit.

Keywords: drive circuit; power-factor-correction; zero-voltage switching; piezoelectric ceramic actuator

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1. Introduction

Piezoelectric ceramic actuators generate vibrations with a frequency above 20 kHz through the piezoelectric effect and have the characteristics of high accuracy, fast response, low power consumption, miniaturization, and high-density configuration. Piezoelectric ceramic actuators are widely used in low-power ultrasonic energy conversion circuits (such as ultrasonic beauty equipment, dental scalers, and atomizers) and high-power ultrasonic energy conversion circuits (such as ultrasonic cleaning machines, ultrasonic processing machines, and ultrasonic welding machines) [1–7]. Figure 1 shows a photo of a piezoelectric ceramic actuator. The equivalent circuit model of the piezoelectric ceramic actuator is shown in Figure 2, where the voltage source v_{OUT} is the voltage output from the driving circuit to the piezoelectric ceramic actuator; the capacitance C_p is the static capacitance of the piezoelectric ceramic actuator; the resistance R_m is the mechanical equivalent resistance; L_m is the mechanical equivalent inductance, and C_m is the mechanical equivalent capacitance [8–11].

Figure 3 shows the conventional two-stage drive circuit for supplying a piezoelectric ceramic actuator applied with a DC input voltage source V_{IN-DC} [12], which consists of a front-stage DC-DC boost converter (including an inductor L_b , a power switch S_b , a diode D_b along with a DC-linked capacitor C_b), and a rear-stage DC-AC full-bridge resonant converter (including four power switches S_1 , S_2 , S_3 , and S_4 and a resonant inductor L_r) that provides rated power to the piezoelectric ceramic actuator.

Figure 1. The photo of a piezoelectric ceramic actuator.

Figure 2. The equivalent circuit model for a piezoelectric ceramic actuator.

Figure 3. The conventional two-stage drive circuit for supplying a piezoelectric ceramic actuator applied with a DC input voltage source [12].

Figure 4 shows the conventional two-stage drive circuit for supplying a piezoelectric ceramic actuator applied with a AC input voltage source v_{AC} and without power-factor-correction (PFC) [13,14], which consists of a front-stage AC-DC full-bridge rectifier (including four diodes D_{R1} , D_{R2} , D_{R3} , and D_{R4} along with a DC-linked capacitor C_{DC}) and a rear-stage DC-AC full-bridge resonant converter (including four power switches S_1 , S_2 , S_3 ,

and S_4 ; four diodes D_1 , D_2 , D_3 , and D_4 ; and a resonant inductor L_r) that provides rated power to the piezoelectric ceramic actuator.

Figure 4. The conventional two-stage drive circuit for supplying a piezoelectric ceramic actuator applied with an AC input voltage source without PFC [13,14].

The traditional driving circuit that supplies power to the piezoelectric ceramic actuator requires more power switches, and the switching loss and conduction loss generated by the power switches are relatively large, which will affect the overall efficiency of the circuit. In response to these challenges, this paper presents a novel and cost-effective drive circuit for providing a piezoelectric ceramic actuator with PFC and soft-switching functions, which integrates a dual boost converter with a coupled inductor and a half-bridge resonant inverter. Descriptions of the operational modes and design equations along with experimental results of the proposed drive circuit are demonstrated in what follows.

2. The Proposed Drive Circuit for Supplying a Piezoelectric Ceramic Actuator

2.1. Introduction of Proposed Drive Circuit

Figure 5 shows the proposed drive circuit with PFC, which integrates a dual boost converter with a coupled inductor and a half-bridge resonant inverter, for supplying a piezoelectric ceramic actuator. The dual boost converter with a coupled-inductor sub-circuit, which is followed by an input AC voltage v_{AC} and a filter (L_f and C_f), consists of two diodes (D_1 and D_2), a coupled-inductor (L_{B1} and L_{B2}), two power switches (S_1 and S_2), and two DC-linked capacitors (C_{DC1} and C_{DC2}). The half-bridge resonant inverter sub-circuit includes two switches (S_1 and S_2), two DC-linked capacitors (C_{DC1} and C_{DC2}), and a resonant inductor (L_r) along with the piezoelectric ceramic actuator. In addition, the coupled-inductor (L_{B1} and L_{B2}) is designed to be operated in discontinuous-conduction mode (DCM) in order to accomplish input-current shaping.

Figure 5. The proposed drive circuit for supplying a piezoelectric ceramic actuator with PFC.

Table 1 shows comparisons between the conventional two-stage drive circuits in References [12–14] and the proposed single-stage one for the piezoelectric ceramic actuator. It can be seen that the proposed drive circuit has the characteristics of power-factor-correction and soft switching and requires fewer power switches than in References [12–14], so it can be a cost-effective alternative version for supplying a piezoelectric ceramic actuator.

Table 1. Comparisons between the conventional drive circuits and the proposed version for a piezoelectric ceramic actuator.

Item	Conventional Two-Stage Drive Circuit [12]	Conventional Two-Stage Drive Circuit [13,14]	Proposed Single-Stage Drive Circuit
Number of Required Power Switches	5	4	2
Number of Required Diodes	1	8	2
Number of Required Capacitors	1	1	3
Number of Required Magnetic Components	2	1	3
Input Voltage Source Suitable for the Application	DC Voltage	AC Voltage	AC Voltage
Function of Power-Factor-Correction	Not Available	No	Yes
Soft-Switching of Power Switches	Not All Switches	Yes (All Switches)	Yes (All Switches)

2.2. Analysis of Operational Modes

When analyzing the operational modes of the piezoelectric ceramic actuator drive circuit, the assumptions made for some circuit components are as follows:

- The control signals of the power switches S_1 and S_2 are in a complementary state, and the essential diodes and parasitic capacitances on the power switches are considered.
- The two coupled inductors L_{B1} and L_{B2} in the drive circuit are designed to operate in discontinuous-conduction Mode (DCM).
- The equivalent resistance of diodes D_1 and D_2 and the forward bias voltage drop are ignored in the analysis.
- The remaining circuit components are assumed to be ideal.

The operating modes and theoretical waveforms of the proposed piezoelectric ceramic driver drive circuit during the positive half-cycle of the utility-line voltage are shown in Figures 6–12, respectively. The circuit analysis and operating modes of the drive circuit during the positive half-cycle of the utility-line voltage are described and discussed in detail below.

Figure 6. Operation Mode 1 of the proposed drive circuit for the piezoelectric ceramic actuator.

Figure 7. Operation Mode 2 of the proposed drive circuit for the piezoelectric ceramic actuator.

Figure 8. Operation Mode 3 of the proposed drive circuit for the piezoelectric ceramic actuator.

Figure 9. Operation Mode 4 of the proposed drive circuit for the piezoelectric ceramic actuator.

Figure 10. Operation Mode 5 of the proposed drive circuit for the piezoelectric ceramic actuator.

Figure 11. Operation Mode 6 of the proposed drive circuit for the piezoelectric ceramic actuator.

Figure 12. Theoretical waveforms of the proposed drive circuit of the piezoelectric ceramic actuator during the positive half-cycle of the utility-line voltage.

2.2.1. Operational Mode 1 ($t_0 \leq t < t_1$)

Figure 6 shows the operational *Mode 1* of the new piezoelectric ceramic actuator drive circuit with PFC. In the previous operation mode, the essential diode of the power switch S_1 is forward-biased conduction. When the resonant inductor current i_{Lr} drops to zero, the power switch S_1 is driven on and has ZVS. The voltage source v_{AC} provides energy to the coupled inductor L_{B1} through the inductance L_f and the capacitor C_f of the filter circuit, the diode D_1 and the power switch S_1 , and the coupled inductor current i_{LB1} presents a linear increase. The DC-linked capacitor C_{DC1} charges the resonant inductor L_r through the power switch S_1 and provides energy to the piezoelectric ceramic actuator. When the power switch S_1 is turned off, the inductor current i_{LB1} rises to the maximum value. At time t_1 , *Mode 1* ends.

2.2.2. Operational Mode 2 ($t_1 \leq t < t_2$)

Figure 7 shows the operational Mode 2 of the new piezoelectric ceramic actuator drive circuit with PFC. The voltage source v_{AC} provides energy to the parasitic capacitance of the power switch S_1 through the inductance L_f and the capacitance C_f of the filter circuit, the diode D_1 , and the coupling inductor L_{B1} , and the coupling inductor current i_{LB1} begins to decrease linearly. The DC-linked capacitor C_{DC1} and the resonant inductor L_r charge the parasitic capacitance of the power switch S_1 and provide energy to the piezoelectric ceramic actuator. The parasitic capacitance of the power switch S_2 and the resonant inductance L_r provide energy to the load and provide energy for the DC-linked capacitor C_{DC2} . When the parasitic capacitance of the power switch S_2 releases energy, the voltage v_{DS2} of the power switch S_2 drops to zero, and the essential diode of the power switch S_2 is forwardly biased and turned on. At time t_2 , Mode 2 ends.

2.2.3. Operational Mode 3 ($t_2 \leq t < t_3$)

Figure 8 shows the operational Mode 3 of the new piezoelectric ceramic actuator drive circuit with PFC. The voltage source v_{AC} and the coupled inductor L_{B1} charge the DC-linked capacitors C_{DC1} and C_{DC2} through the inductance L_f and capacitor C_f of the filter circuit, the diode D_1 , and the essential diode of the power switch S_2 . At this time, the coupled inductor current i_{LB1} shows a linear decrease. The resonant inductor L_r charges the DC-linked capacitor C_{DC2} through the essential diode of the power switch S_2 and provides energy to the piezoelectric ceramic actuator. When the coupled inductor current i_{LB1} and the resonant inductor current i_{Lr} drop to zero, Mode 3 ends.

2.2.4. Operational Mode 4 ($t_3 \leq t < t_4$)

Figure 9 shows the operational Mode 4 of the new piezoelectric ceramic actuator drive circuit with PFC. When the coupled inductor current i_{LB1} drops to zero, the power switch S_2 is driven to turn on and has a ZVS characteristic. The DC-linked capacitor C_{DC2} charges the resonant inductor L_r through the power switch S_2 and provides energy to the piezoelectric ceramic actuator. When the power switch S_2 is turned off, Mode 4 ends.

2.2.5. Operational Mode 5 ($t_4 \leq t < t_5$)

Figure 10 shows the operational Mode 5 of the new piezoelectric ceramic actuator drive circuit with PFC. The resonant inductor L_r and the parasitic capacitance of the power switch S_1 charge the DC-linked capacitor C_{DC1} and provide energy to the piezoelectric ceramic actuator. At the same time, the resonant inductor L_r and the DC-linked capacitor C_{DC2} charge the parasitic capacitance of the power switch S_2 and provide energy to the piezoelectric ceramic actuator. When the parasitic capacitance energy of the power switch S_1 is released and the voltage v_{DS1} of the power switch S_1 drops to zero, the essential diode of the power switch S_1 is forwardly biased and turned on. At time t_5 , Mode 5 completes.

2.2.6. Operational Mode 6 ($t_5 \leq t < t_6$)

Figure 11 shows the operational Mode 6 of the new piezoelectric ceramic actuator drive circuit with PFC. In the previous operational mode, the energy of the parasitic capacitance of the power switch S_1 is released, the voltage v_{DS1} of the power switch S_1 drops to zero, and the essential diode of the power switch S_1 is turned on in a forward bias. The voltage source v_{AC} provides energy to the coupled inductor L_{B1} through the inductance L_f and the capacitor C_f of the filter circuit and the diode D_1 , and the coupled inductor current i_{LB1} rises linearly from zero. In addition, through the essential diode of the power switch S_1 , the resonant inductor L_r and the voltage source v_{AC} provide energy to the DC-linked capacitor C_{DC1} and the piezoelectric ceramic actuator. When the resonant inductor current i_{Lr} drops to zero and the power switch S_1 is driven and turned on, Mode 6 ends and the circuit operation returns to Mode 1.

In addition, Table 2 shows states of the main power devices in each operational mode during the positive half-cycle of the utility-line voltage.

Table 2. States of the main power devices in each operational mode during the positive half-cycle of the utility-line voltage.

Main Power Devices	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Switch S_1	On	Off	Off	Off	Off	Off
Switch S_2	Off	Off	Off	On	Off	Off
Diode D_1	On	On	On	Off	Off	On
Diode D_2	Off	Off	Off	Off	Off	Off
Inductor L_{B1}	Charging	Discharging	Discharging	Discharging	Not Available	Charging
Inductor L_{B2}	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available
Inductor L_r	Charging	Discharging	Discharging	Discharging	Discharging	Charging
Capacitor C_{DC1}	Discharging	Discharging	Charging	Not Available	Discharging	Charging
Capacitor C_{DC2}	Not Available	Charging	Charging	Discharging	Discharging	Not Available

2.3. Design Equations of Key Circuit Parameters

2.3.1. Design Equation of the Coupled Inductors L_{B1} and L_{B2}

The design equation of the coupled inductors L_{B1} and L_{B2} can be represented by [15]:

$$L_{B1} = \frac{\eta v_{AC-rms}^2 D^2}{2P_O f_S} = L_{B2} \quad (1)$$

where η is the estimated efficiency of the proposed drive circuit; v_{AC-rms} is the root-mean-square (rms) value of the input utility-line voltage v_{AC} ; D and f_S are the duty ratio and switching frequency of the power switches, respectively; P_O is the output power. From the Formula (1), it can be drawn that Figure 13 shows the relationship between the coupled inductors L_{B1} and L_{B2} and the duty cycle D at different switching frequencies f_S .

Figure 13. The relationship between the coupled inductors L_{B1} and L_{B2} and the duty cycle D at different switching frequencies f_S .

With a η of 0.8, a v_{AC-rms} of 110 V, a D of 0.5, a P_O of 50 W, and a switching frequency f_S of 40 kHz, the inductances of the coupled inductors L_{B1} and L_{B2} are calculated as

$$L_{B1} = L_{B2} = \frac{\eta v_{AC-rms}^2 D^2}{2P_O f_S} = \frac{0.8 \cdot 110^2 \cdot 0.5^2}{2 \cdot 50 \cdot 40k} = 650 \mu H$$

In addition, the coupled inductors L_{B1} and L_{B2} in the prototype drive circuit are 500 μH .

2.3.2. Design Equation of the Resonant Inductor L_r

Figure 14 shows the equivalent circuit diagram of the resonant inductor combined with the piezoelectric ceramic actuator circuit model; v_{inv} and i_{inv} respectively represent the input voltage and current of the equivalent circuit; Z_{PCA} represents the equivalent circuit model of the piezoelectric ceramic actuator; Z_{in} represents the input impedance of the equivalent circuit. The output power P_O of the piezoelectric ceramic actuator is provided by the fundamental component of the input current i_{inv} of the resonant tank circuit, and the switching frequency f_s of the power switch is designed to be equal to the resonant frequency f_r of the piezoelectric ceramic actuator. In addition, at the resonance frequency of the piezoelectric ceramic actuator, the equivalent series impedance in the right branch of the Z_{PCT} resonance tank circuit is reduced to only the resistance R_m . The rms value $I_{inv1-rms}$ of the fundamental component of the current i_{inv} can be expressed as [13]

$$I_{inv1-rms} = \frac{R_m - j\left(\frac{1}{2\pi f_r C_p}\right)}{-j\left(\frac{1}{2\pi f_r C_p}\right)} \left(\sqrt{\frac{P_O}{R_m}} \right) \quad (2)$$

The input impedance Z_{in} of the equivalent circuit is expressed as

$$Z_{in} = Z_{PCA} + jZ_{Lr} = (R_1 + jX_1) + j2\pi f_r L_r \quad (3)$$

where R_1 and X_1 are the equivalent resistance and reactance of the piezoelectric ceramic actuator impedance Z_{PCA} , and they can be respectively expressed as [13]

$$R_1 = \frac{R_m}{1 + (2\pi f_r)^2 C_p^2 R_m^2} \quad (4)$$

$$X_1 = \frac{2\pi f_r C_p R_m^2}{1 + (2\pi f_r)^2 C_p^2 R_m^2} \quad (5)$$

After dividing the maximum value of the input voltage $V_{inv1-max}$ by the maximum value of the input current $\sqrt{2}I_{inv1-rms}$ of the equivalent circuit, the amplitude of the input impedance Z_{in} can be expressed as

$$|Z_{in}| = \frac{V_{inv1-max}}{\sqrt{2}I_{inv1-rms}} = \frac{8V_{DC}}{\sqrt{2}\pi I_{inv1-rms}} \quad (6)$$

where $V_{inv1-max}$ is the maximum level of the fundamental component V_{inv1} of the input voltage v_{inv} of the resonant tank circuit; V_{DC} is the voltage level of the DC-linked capacitors C_{DC1} and C_{DC2} .

By combining (3) with (6), the design formula of the resonant inductor L_r can be expressed as [13]

$$L_r = \frac{1}{2\pi f_r} \left(X_1 + \sqrt{|Z_{in}|^2 - R_1^2} \right) \quad (7)$$

With a R_m of 25 Ω , a C_p of 4000 pF, a P_O of 50 W, and a resonant frequency f_r of 40 kHz, the parameter $I_{inv1-rms}$ is calculated as

$$I_{inv1-rms} = \frac{R_m - j\left(\frac{1}{2\pi f_r C_p}\right)}{-j\left(\frac{1}{2\pi f_r C_p}\right)} \left(\sqrt{\frac{P_O}{R_m}} \right) = \frac{25 - j\left(\frac{1}{2\pi \cdot 40k \cdot 4000p}\right)}{-j\left(\frac{1}{2\pi \cdot 40k \cdot 4000p}\right)} \left(\sqrt{\frac{50}{25}} \right) = 1.414 \angle 1.432^\circ \text{ A}$$

The parameters R_1 and X_1 are respectively calculated as

$$R_1 = \frac{R_m}{1 + (2\pi f_r)^2 C_p^2 R_m^2} = \frac{25}{1 + (2\pi \cdot 40k)^2 \cdot (4000p)^2 \cdot 25^2} = 24.98 \Omega$$

$$X_1 = \frac{2\pi f_r C_p R_m^2}{1 + (2\pi f_r)^2 C_p^2 R_m^2} = \frac{2\pi \cdot 40k \cdot 4000p \cdot 25^2}{1 + (2\pi \cdot 40k)^2 \cdot (4000p)^2 \cdot 25^2} = 0.625 \Omega$$

With a V_{DC} of 700 V and a $I_{inv1-rms}$ of 1.414 A, the parameter $|Z_{in}|$ is calculated as

$$|Z_{in}| = \frac{V_{inv-max}}{\sqrt{2}I_{inv1-rms}} = \frac{8V_{DC}}{\sqrt{2}\pi I_{inv1-rms}} = \frac{8 \cdot 700}{\sqrt{2}\pi \cdot 1.414} = 891.4 \Omega$$

Therefore, the parameter L_r is calculated as

$$L_r = \frac{1}{2\pi f_r} \left(X_1 + \sqrt{|Z_{in}|^2 - R_1^2} \right) = \frac{1}{2\pi \cdot 40k} \left(0.625 + \sqrt{891.4^2 - 24.98^2} \right) = 3.55 \text{ mH}$$

In addition, the resonance inductor L_r in the prototype drive circuit is 3.95 mH.

Figure 14. The equivalent circuit diagram of the resonant tank circuit combined with the piezoelectric ceramic actuator circuit model.

2.3.3. Design of Input Low-Pass Filter

A low-pass filter is usually added to the AC input power terminal, which is composed of an inductor L_f and a capacitor C_f . The cut-off frequency $f_{cut-off}$ of the input low-pass filter is represented by

$$f_{cut-off} = \frac{1}{2\pi\sqrt{L_f C_f}} \quad (8)$$

In order to filter high-frequency switching noise, the design consideration of the cut-off frequency $f_{cut-off}$ of the input low-pass filter is determined as one-tenth of the switching frequency f_s . Rearranging (8), the design equation of the inductor L_f is given by

$$L_f = \frac{1}{4\pi^2 f_{cut-off}^2 C_f} \quad (9)$$

With a cut-off frequency $f_{cut-off}$ of 4 kHz and selecting a capacitor C_f of 470 nF, the inductor L_f is determined by

$$L_f = \frac{1}{4\pi^2 f_{cut-off}^2 C_f} = \frac{1}{4\pi^2 \cdot (4kHz)^2 \cdot 470n} = 3.36 \text{ mH}$$

3. Experimental Results of the Proposed Drive Circuit

In this paper, a prototype of the proposed drive circuit for supplying a 50 W-rated piezoelectric ceramic actuator has already been implemented and testified. A photograph of the proposed prototype drive circuit for supplying a piezoelectric ceramic actuator is shown in Figure 15, and the key circuit components have been indicated in the photograph. The parameters of the utilized piezoelectric ceramic actuator are shown in Table 3. In addition, the components utilized in the prototype drive circuit for the piezoelectric ceramic actuator are shown in Table 4.

Figure 15. A photograph of the proposed prototype drive circuit for supplying a piezoelectric ceramic actuator.

Table 3. Parameters of the utilized piezoelectric ceramic actuator.

Parameter	Value
Resonant Frequency f_r	40 kHz
Mechanical Equivalent Resistance R_m	25 Ω
Static Capacitance C_p	4000 pF
Rated Power P_O	50 W

Table 4. Components utilized in the prototype of the proposed drive circuit.

Parameter/Component	Value
Diode D_1, D_2	MUR460
Filter Inductor L_f	3.36 mH
Filter Capacitor C_f	470 nF
Coupled Inductor L_{B1}, L_{B2}	500 μ H
DC-linked Capacitor C_{DC1}, C_{DC2}	220 μ F
Power Switches S_1, S_2	W12NK90Z
Resonant Inductor L_r	3.95 mH

Figure 16a,b presents the simulated and measured inductor current i_{LB1} , and it can be seen that the current i_{LB1} is operated in DCM. Figure 17a,b shows the simulated and measured switch voltage v_{DS2} and resonant inductor current i_{Lr} . It can be seen that the inductor current i_{Lr} lags with respect to voltage v_{DS2} so that the series resonant circuit is similar to an inductive load. Figure 18a,b presents the simulated and measured switch

voltage v_{DS1} and switch current i_{DS1} ; thus, ZVS occurred on the power switch for lowering the switching losses. Figure 19a,b depicts the simulated and measured output voltage v_O and output current i_O . It can be seen from the waveform that the output voltage v_O lags the output current i_O , so the piezoelectric ceramic actuator has capacitive characteristics.

Figure 16. (a) Simulated and (b) measured inductor current i_{LB1} (1 A/div); time scale: 10 μ s/div.

Figure 17. Cont.

Figure 17. (a) Simulated and (b) measured switch voltage v_{DS2} (200 V/div) and resonant inductor current i_{Lr} (1 A/div); time scale: 10 μ s/div.

Figure 18. (a) Simulated and (b) measured switch voltage v_{DS1} (200 V/div) and switch current i_{DS1} (2 A/div); time scale: 10 μ s/div.

Figure 19. (a) Simulated and (b) measured output voltage v_O (500 V/div) and current i_O (0.5 A/div); time scale: 10 $\mu\text{s}/\text{div}$.

The simulated and measured waveforms of input utility-line voltage v_{AC} and current i_{AC} are respectively shown in Figure 20a,b, and it can be seen that PFC is achieved in the proposed drive circuit. Figure 21 shows the use of a power analyzer (Tektronix PA 4000) to measure the harmonic components of the AC input current and compare it with the IEC 61000-3-2 class C standard. From the figure, it is known that all current harmonics meet the requirements. Additionally, the measured power factor and the input utility-line current total-harmonic distortion (THD) of the proposed drive circuit are 0.8683 and 3.4927%, respectively.

Figure 20. (a) Simulated and (b) measured input utility-line voltage v_{AC} (50 V/div) and current i_{AC} (1 A/div); time scale: 5 ms/div.

Figure 21. Measured harmonics of the input utility-line current in comparison with the IEC 61000-3-2 class C standard.

4. Conclusions

This paper proposes a novel and cost-effective drive circuit, which combines a dual boost converter with a coupled inductor and a half-bridge resonant inverter, with PFC and soft-switching features for providing a piezoelectric ceramic actuator. A 50 W-rated

prototype drive circuit has been implemented and tested with an input utility-line voltage of 110 V. From the experimental results at a 110 V input utility-line voltage, the driving circuit developed in this thesis has as characteristics a high power factor (>0.86) and a low input current total-harmonic-distortion factor ($<4\%$), and two power switches possess the ZVS feature.

Author Contributions: C.-A.C. and H.-L.C. conceived and designed the circuit. C.-H.C. and E.-C.C. carried out the circuit simulations and designed the circuit parameters. C.-Y.T. and L.-F.L. carried out the prototype circuit, measured experimental results, and wrote original draft preparation with guidance from C.-A.C. E.-C.C. revised the manuscript for submission. All authors have read and agreed to the published version of the manuscript.

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References

1. Lee, J.H.; Lee, H.C.; Choi, J.H.; Park, S.J.; Nam, H.G. 10kW Industrial Ultrasonic Welder Design. In Proceedings of the 31st International Telecommunications Energy Conference, Incheon, Korea, 18–22 October 2009; pp. 1–6.
2. Tsujino, J.; Hongoh, M.; Yoshikuni, M.; Miura, H.; Ueoka, T. Welding Characteristics and Temperature Rises of Various Frequency Ultrasonic Plastic Welding. In Proceedings of the 2005 IEEE Ultrasonics Symposium, Rotterdam, The Netherlands, 18–21 September 2005; pp. 707–712.
3. Kauczor, C.; Frohliche, N. Inverter Topologies for Ultrasonic Piezoelectric Transducers with High Mechanical Q-Factor. In Proceedings of the Annual IEEE Power Electronics Specialists Conference, Aachen, Germany, 20–25 June 2004; Volume 4, pp. 2736–2741.
4. Yu, T.; Lee, H.; Lee, D.; Song, S.; Kim, D.; Park, S. Design of LC Resonant Inverter for Ultrasonic Metal Welding System. In Proceedings of the 2008 International Conference on Smart Manufacturing Application, Goyangi, Korea, 9–11 April 2008; pp. 543–548.
5. Agbossou, K.; Dion, J.-L.; Carignan, S.; Abdelkrim, M.; Cheriti, A. Class D Amplifier for a Power Piezoelectric Load. In *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*; IEEE: Piscataway, NJ, USA, 2000; Volume 47, pp. 1036–1041.
6. Ma, K.H.; Chang, W.C.; Lee, Y.C. A New Tracking Method with FPGA Chip for Ultrasonic Welding System. In Proceedings of the 2009 International Conference on Power Electronics and Drive Systems, Taipei, Taiwan, 2–5 November 2009; pp. 369–370.
7. Volosencu, C. Control System for Ultrasonic Welding Devices. In Proceedings of the IEEE International Conference on Automation, Quality and Testing, Cluj-Napoca, Romania, 22–25 May 2008; Volume 2, pp. 135–140.
8. Lian, Y.; Gao, C.; Liu, X. A hybrid driving strategy for piezoelectric actuator. In Proceedings of the 2013 International Conference on Mechatronic Sciences, Electric Engineering and Computer (MEC), Shenyang, China, 20–22 December 2013; pp. 3800–3804.
9. Cheng, L.; Kang, Y.; Chen, C. A Resonance-Frequency-Tracing Method for a Current-Fed Piezoelectric Transducer. In *IEEE Transactions on Industrial Electronics*; IEEE: Piscataway, NJ, USA, 2014; Volume 61, pp. 6031–6040.
10. Ghasemi, N.; Zare, F.; Davari, P.; Weber, P.; Langton, C.; Ghosh, A. Power electronic converters for high power ultrasound transducers. In Proceedings of the 2012 7th IEEE Conference on Industrial Electronics and Applications (ICIEA), Singapore, 18–20 July 2012; pp. 647–652.
11. Zhou, Y.; Zhou, B.; Li, S. Driving Performance Analysis of a Novel Piezoelectric Actuator. In Proceedings of the 2010 International Conference on Measuring Technology and Mechatronics Automation, Washington, DC, USA, 13–14 March 2010; pp. 34–37.
12. Lai, J.A. Two-Stage Driver for Piezoelectric Actuator. Master's Thesis, Chung Yuan Christian University, Taoyuan City, Taiwan, 2004. Available online: <https://hdl.handle.net/11296/qmkd88> (accessed on 9 October 2021).
13. Jittakort, J.; Sangswang, A.; Naetiladdanon, S.; Koompai, C.; Chudjuarjeen, S. Full Bridge Resonant Inverter Using Asymmetrical Control with Resonant-frequency Tracking for Ultrasonic Cleaning Applications. *J. Power Electron.* **2017**, *17*, 1150–1159.
14. Jittakort, J.; Sangswang, A.; Naetiladdanon, S.; Chudjuarjeen, S.; Koompai, C. LCCL Series Resonant Inverter for Ultrasonic Dispersion System with Resonant Frequency Tracking and Asymmetrical Voltage Cancellation Control. In Proceedings of the IECON 2015—41st Annual Conference of the IEEE Industrial Electronics Society, Yokohama, Japan, 9–12 November 2015.
15. Cheng, C.A.; Chang, C.H.; Cheng, H.L.; Chung, T.Y. A single-stage high-PF driver for supplying a T8-type LED lamp. In Proceedings of the International Power Electronics Conference (IPEC-Hiroshima 2014—ECCE Asia), Hiroshima, Japan, 18–21 May 2014; pp. 2523–2528.