Improved Modification of the Closed-Loop-Controlled AC-AC Resonant Converter for Induction Heating

Kirubakaran Dhandapani and Rama Reddy Sathi

A single-switch parallel resonant converter for induction heating is implemented. The circuit consists of an input LC-filter, a bridge rectifier, and a controlled power switch. The switch operates in soft commutation mode and serves as a high frequency generator. The output power is controlled via the switching frequency. A steady state analysis of the converter operation is presented. A closed-loop circuit model is also presented, and the experimental results are compared with the simulation results.

Keywords: Electronics, AC-AC converter, resonant switching, induction heater, closed-loop control.

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I. Introduction

Static frequency converters have been extensively applied in industry as a source of medium frequency power supply for induction heating and melting installations. They are applied in all branches of the military and machine-building industries, as well as for jewelry, forge heating, domestic heating, cooking devices, and other purposes.

The ordinary circuit of an AC-AC converter for induction heating typically includes a controlled rectifier and a frequency controlled current source or a voltage source inverter. It is well known that the input rectifier does not ensure a sine wave input current and that it is characterized by low power [1]-[3]. Recently, many studies of high power factor rectifiers with a single switch have been made [4], [5]. These schemes are also characterized by a near sine wave input current. In addition, in [6]-[10], the scheme of the AC-AC converter for induction heating is described. The input circuit of the converter is constructed similarly to the input circuit in [4], [5], which also ensures a high power factor. However, the inverting circuit is constructed in the traditional mode with four controlled switches.

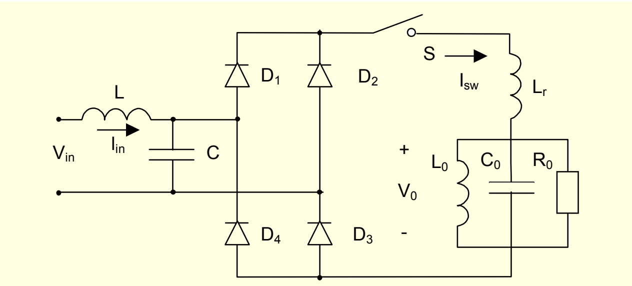

Fig. 1. Circuit diagram.

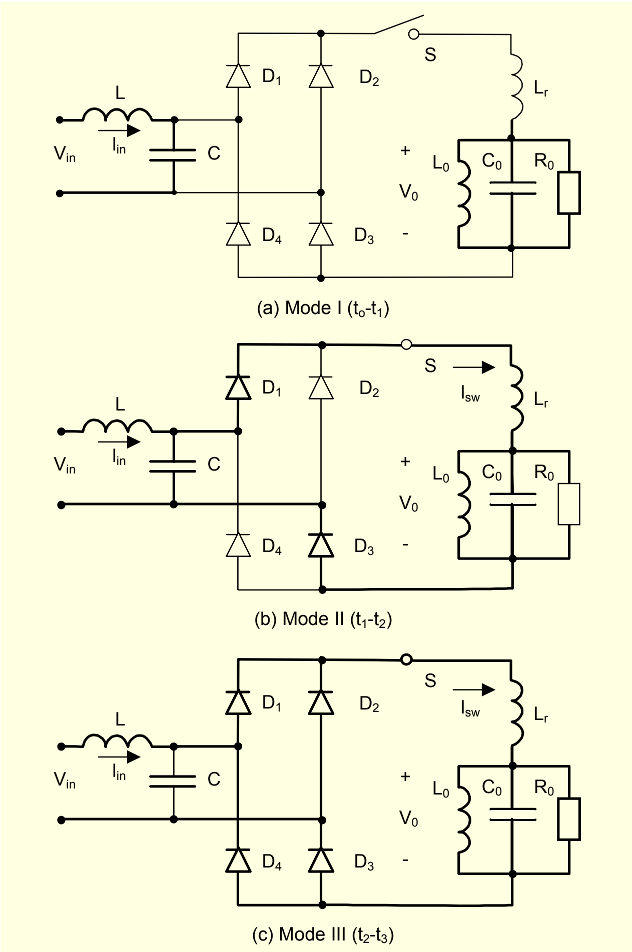

Fig. 2. Equivalent circuits.

In the scheme of the AC-AC converter shown in Fig. 1, there are two main advantages. It is characterized by a high power factor and a sine wave input current. On the other hand the inverter circuit is constructed with a single controlled switch, which serves as a high-frequency generator for induction heating. The resonant circuit in the output produces the high-frequency output required by the load.

II. Principle of Operation

The operating principles of the circuit are illustrated in Fig. 2, and the theoretical waveforms are shown in Fig. 3. We suppose the switching frequency is much higher than the input line frequency, and in the analysis, we arbitrarily chose the time interval where $V_{in}>0$.

1. Interval T_0: $t_0<t<t_1$

The equivalent circuit is shown in Fig. 2(a). Four diodes, D_1 to D_4, and the switch S are off. In this interval, the capacitor C charges up practically linearly at a rate and a polarity corresponding to the instantaneous input voltage V_{in}.

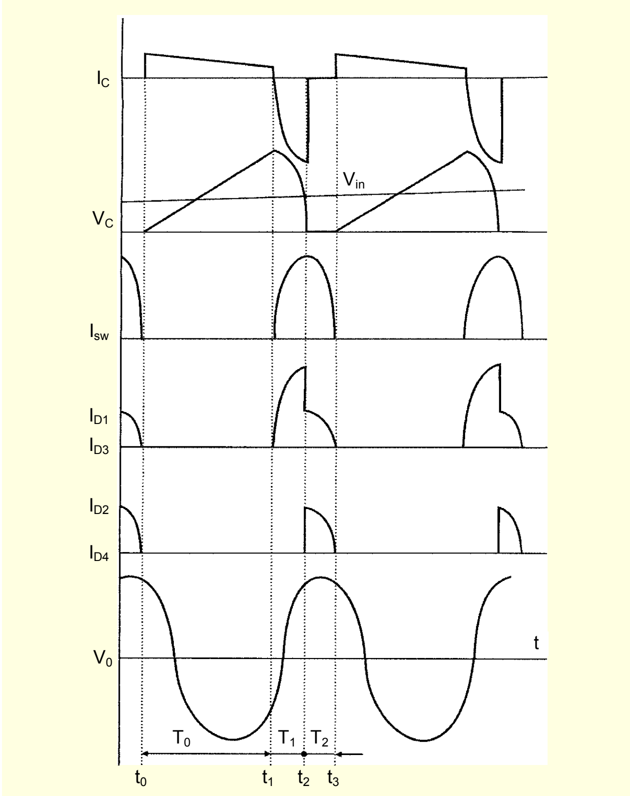
Fig. 3. Ideal switching waveforms.

2. Interval T_1: $t_1<t<t_2$

The equivalent circuit is shown in Fig. 2(b). Two diodes, D_1 and D_3, and the switch S are on. In this interval, the capacitor C discharges via the circuit C-D_1-S-L_r-load-D_3. This interval ends when the capacitor voltage reduces to zero.

3. Interval T_2: $t_2<t<t_3$

The equivalent circuit is shown in Fig. 2(c). All the diodes and the switch S are on. In this interval, the switch current flows through switch S via two parallel bridge branches. This interval ends when this switch current decreases to zero. At that moment, the switch turns off, and the process starts from the beginning.

III. Operation Analysis

Analysis of the circuit operation is based on the commonly accepted assumption that all circuit components are ideal. The approximate analytical calculations are based on two additional assumptions: that the switch current can be approximated by a semi-sinusoidal and that the load power is determined by the first harmonic of the load voltage. In this converter, the optimal

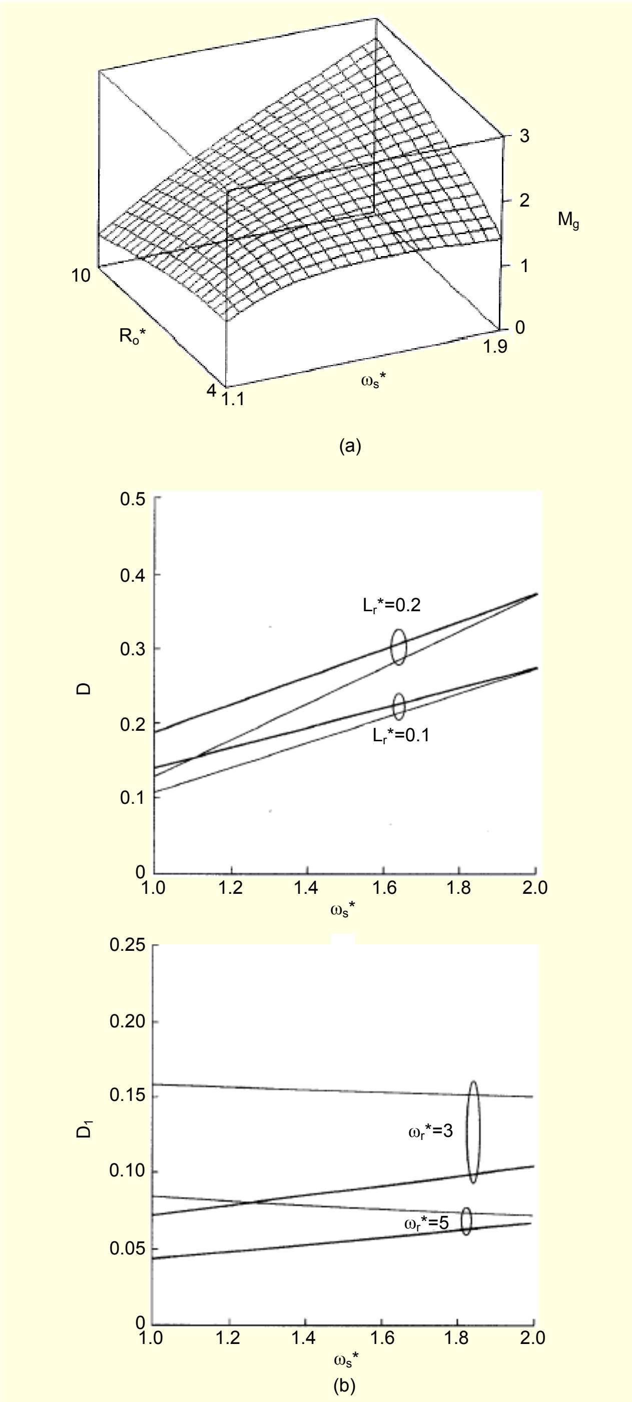

Fig. 4. (a) Factor $M_g = V_o/V_{in}$ against parameters R_o* & ω_s* and (b) duty cycle against parameters L_r* & ω_s*.

range of normalized parameters is chosen. The maximum normalized value of switch voltage is $V^*_{swmax} = V_{swmax} / V_B = 4-5$. To provide these values, it is necessary to choose the following ranges of the normalized circuit parameters:

$$L_1^* = \frac{L_r}{L_0} = 0.1-0.2; \quad \omega_r^* = \frac{1/\sqrt{L_r C}}{\omega_B} = 3-5; \quad \omega_s^* = 1.1-1.9. \quad (1)$$

The relationship between input and output voltages $M_g = V_o/V_{in}$

$$A_1 = \frac{I_{sw.max}}{I_{in}} = \frac{\pi}{D} \cdot \frac{(1-D+D_1)}{1-\cos(\pi \frac{D_1}{D})}, \quad (2)$$

$$A_2 = \frac{I_{sw1.max}}{I_{sw.max}} = \frac{2D}{\pi(1-4D^4)} \cdot \cos(2\pi D), \quad (3)$$

$$A_3 = \frac{I_{R1.max}}{I_{sw1.max}} = \frac{1}{\sqrt{1+R_0^{*2}(\omega_S^* - 1/\omega_S^*)^2}}, \quad (4)$$

$$M_g = \frac{V_{o.r.m.s}}{V_{in.r.m.s}} = \frac{\sqrt{2}}{A_1 \cdot A_2 \cdot A_3} = \sqrt{2}\,\frac{\sqrt{1+R_o^{*2}(\omega_S^* - \frac{1}{\omega_S^*})^2(1-\cos(\frac{\pi D_1}{D}))}}{1.1\pi(1-D+D_1)}. \quad (5)$$

This relationship is shown in Fig. 4(a). The values of duty cycles D_1 and D may be calculated from the plot in Fig. 4(b).

The values of duty cycles D_1 and D may also be found from the following approximate polynomial expressions:

$$\begin{aligned} D_1 &\approx (325.8 - 36.7\omega_r^* - 33.4\omega_s^* - 25.4R_0^* \\ &\quad + 2.2\omega_r^* R_0^* + 7.4R_o^*\omega_s^*)10^{-3}, \\ D &\approx (-88.3 - 445.5L_r^* - 15.5\omega_s^* + 175.1\omega_s^* \\ &\quad + 19.3R_0^* + 725L_r^*\omega_s^* - 10.3R_0^*\omega_s^*)10^{-3}. \end{aligned} \quad (6)$$

IV. Simulation Results

The circuit model of the AC-AC converter is shown in Fig. 5. Scopes are connected to measure the output voltage, driving pulses, and capacitor voltage.

The AC-AC converter fed induction heater system was simulated using Matlab Simulink. Switching pulses are shown

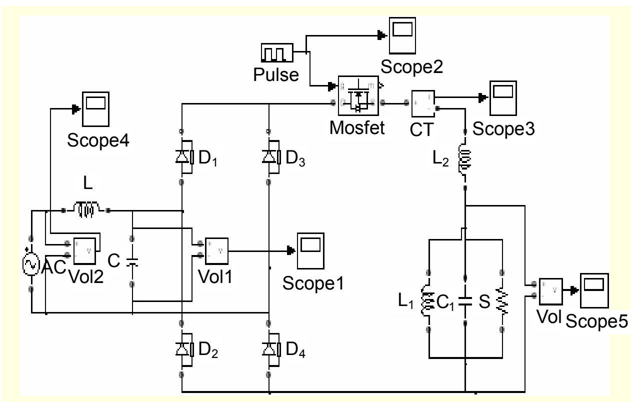

Fig. 5. Diagram of the open-loop circuit.

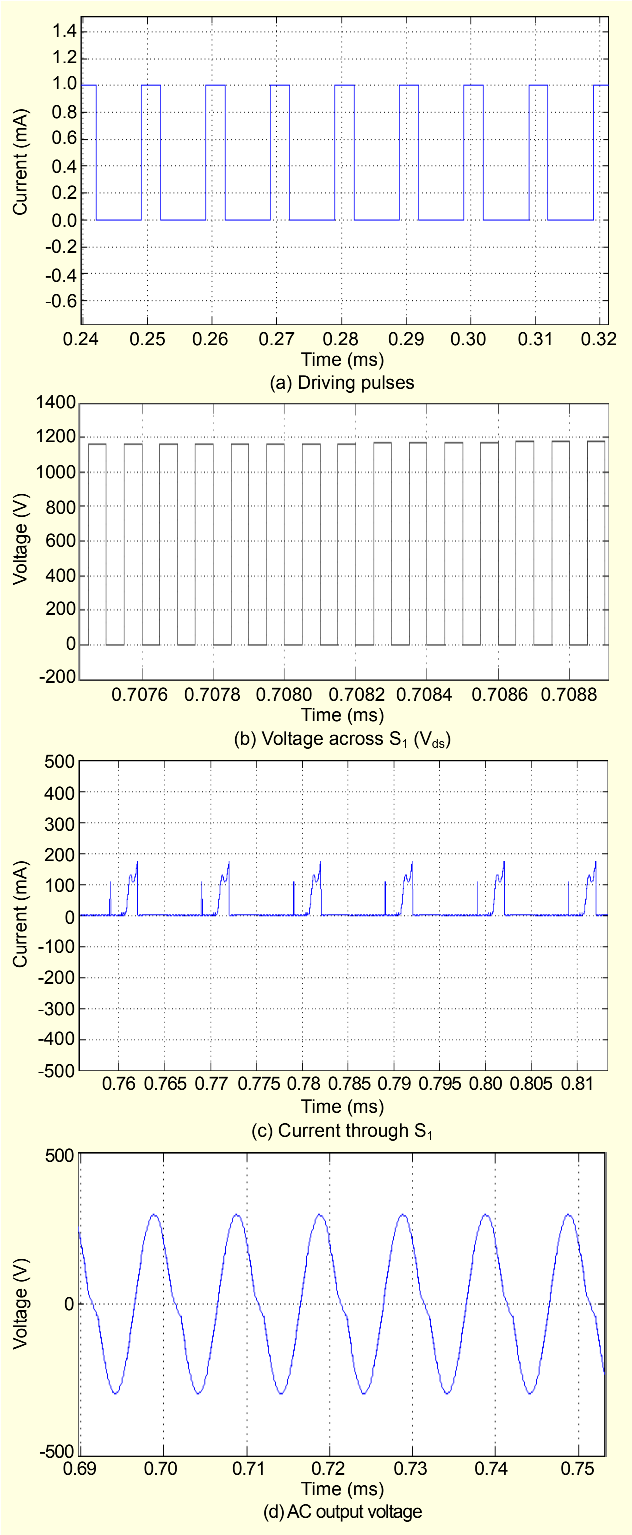

Fig. 6. AC-AC converter fed induction heater system simulation results.

in Fig 6(a). The switching frequency was 33 kHz. Voltage and current waveforms of the switch are shown in Figs. 6(b) and (c), respectively. Output of the converter is shown in Fig. 6(d).

Table 1. Performance comparison.

Input voltage (V)	Output voltage (V)		Efficiency (%)	
	Conventional converter	Single switch converter	Conventional converter	Single switch converter
180	129.6	152.4	71.6	84.4
200	144.1	169.4	72	84.7
220	158.2	186.4	72	84.7
240	173	203.5	72.1	84.8

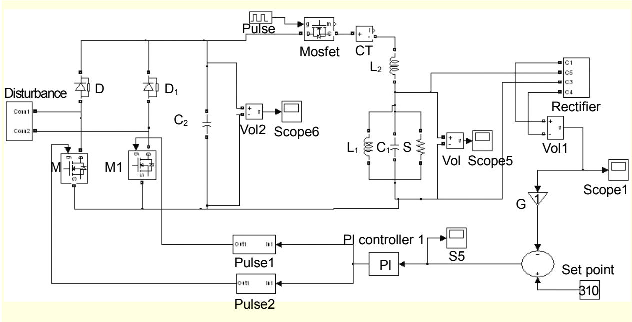

Fig. 7. Diagram of the closed-loop controlled AC-AC converter.

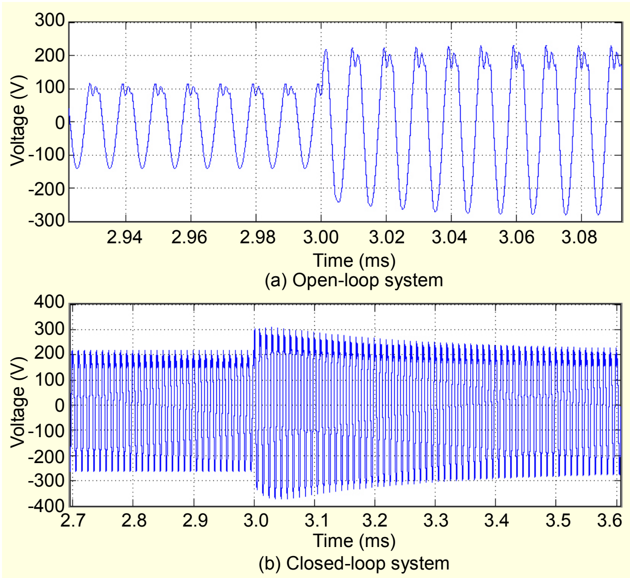

Fig. 8. Output voltages of the open-loop and closed-loop systems.

A comparison of the performance of a conventional AC-AC converter and the single switch AC-AC converter is presented in Table 1. The results confirm that the single switch converter achieves better performance efficiency than any other converter.

The closed-loop circuit model of the AC-AC converter is shown in Fig. 7. Scopes and displays are connected to measure output voltage. A disturbance is introduced at the input by using two switches. The output voltage is sensed and it is

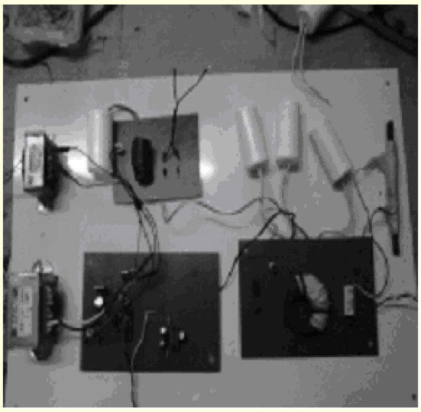

Fig. 9. Hardware layout.

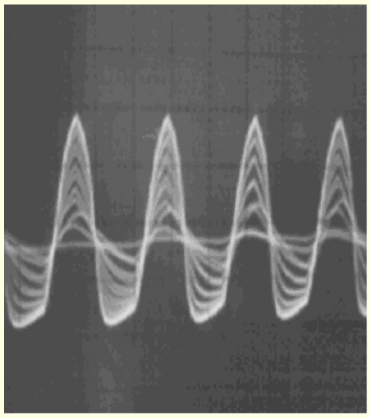

Fig. 10. Oscillogram output voltage.

compared with the reference voltage. The error signal is sent to the controller. The output of the PI controller controls the dependent source. The response of the open-loop system is shown in Fig. 8(a).

The output voltage of closed-loop system is shown in Fig. 8(b). The disturbance is applied at 0.3 secs. The settling time is 0.32 secs. The control circuit takes proper action to reduce the amplitude to the set value. Thus, the closed-loop system reduces the steady state error.

V. Experimental Verification

The single-switch AC-AC converter (Fig. 9) was built and tested at 230 V. The circuit parameters are R_0=60 Ω, L_0=150 μH, C_0=2.35 μF, L_r=22 μH, L_i=8.0 mH, C_{in}=0.94 μF, and the switching frequency ω_S= (62–113) ×10^3 s^{-1}. The experimental waveform of the output voltage is shown in Fig. 10. The output power control was also checked, and its dependence versus the switching frequency is shown in Fig. 11.

VI. Conclusion

An AC-AC converter circuit for induction heating was tested. Its input current is practically sinusoidal, and its power factor is close to unity. The circuit topology is very simple because it includes only one power switch. This switch operates in a soft commutation mode. The converter provides a wide-range power control. This converter has advantages including reduced hardware, reduced stresses, and high power density. A closed-loop circuit model was developed, and it was successfully used for simulation studies. The simulation and experimental results demonstrate the actual converter capability. The experimental and simulation results show good agreement.

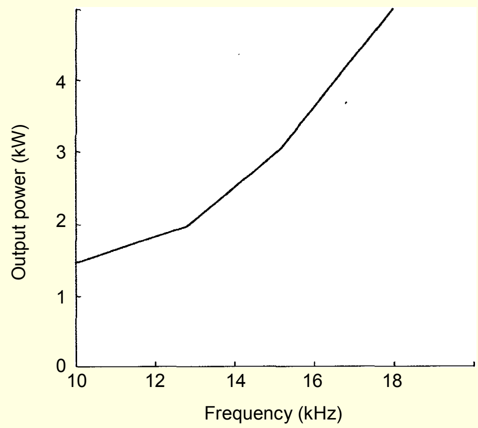

Fig. 11. Output power versus switching frequency.

References

[1] N.S. Bayindir, O. Kukrer, and M. Yakup, "DSP-Based PLL Controlled 50-100 kHz 20 kW High-Frequency Induction Heating System for Surface Hardening and Welding Applications," *IEE Proc.-Electr. Power Appl.*, vol. 150, no. 3, May 2003, pp. 365-371.

[2] A. Okuno et al., "Feasible Development of Soft-Switched SIT Inverter with Load-Adaptive Frequency-Tracking Control Scheme for Induction Heating," *IEEE Trans. Ind. Applicat.*, vol. 34, no. 4, July/Aug. 1998, pp. 713-718.

[3] H. Kifune, Y. Hatanaka, and M. Nakaoka, "Cost Effective Phase Shifted Pulse Modulation Soft Switching High Frequency Inverter for Induction Heating Applications," *IEE Proc.-Electr. Power Appl.*, vol. 151, no. 1, Jan. 2004, pp. 19-25.

[4] H. Ogiwara and M. Nakaoka, "ZCS High Frequency Inverter Using SIT for Induction Heating Applications," *IEE Proc.- Electr. Power Appl.*, vol. 150, no. 2, Mar. 2003, pp. 185-192.

[5] S.V. Mollov, M. Theodoridis, and A.J. Forsyth, "High Frequency Voltage-Fed Inverter with Phase-Shift Control for Induction

Heating," *IEE Proc.-Electr. Power Appl.*, vol. 151, no. 1, Jan. 2004, pp. 12-18.

[6] H. Ogiwara, L. Gamage, and M. Nakaoka, "Quasiresonant Soft Switching PWM Voltage-Fed High Frequency Inverter Using SIT for Induction Heating Applications," *IEE Proc.-Electr. Power Appl.*, vol. 148, no. 5, Sept. 2001, pp. 385-392.

[7] B. Singh et al., "A Review of Single-Phase Improved Power Quality AC-DC Converters," *IEEE Trans. Ind. Electron.*, vol. 50, no. 5, Oct. 2003, pp. 962-981.

[8] B. Singh et al., "A Review of Three-Phase Improved Power Quality AC-DC Converters," *IEEE Trans. Ind. Electron.*, vol. 51, no. 3, June 2004, pp. 641-660.

[9] J. Acero, R. Alonsjo, and J.M. Burdio "Modeling of Planar Spiral Inductors between Two Multilayer Media for Induction Heating Applications," *IEEE Trans. Magn.*, vol. 42, no. 11, Nov. 2006, pp. 3719-3729.

[10] B. Saha et al., "Selective Dual Duty Cycle Controlled High Frequency Inverter Using a Resonant Capacitor in Parallel with an Auxiliary Reverse Blocking Switch," *J. Power Electron.*, vol. 7, no. 2, Apr. 2007, pp. 118-123.

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