A Soft Switching Class D Current Source Inverter for Induction Heating with Ferromagnetic Load

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Abstract—A class D current source resonant inverter (CSRI) for induction heating power supplies for ferromagnetic load is proposed in this paper. The converter operates in zero-current switching mode. The switching devices are connected through the common ground and need only a single dc power supply for the gate driver circuitry. A small input inductor (500 µH) is used for shaping the line current with the aim of unity power factor operation on the line input. The operating frequency of the CSRI is automatically adjusted to maintain a small constant leading phase angle under load parameter variation. The maximum output power transferred to the load for this prototype is 1.26 kW. It can heat a 30-mm diameter and 150-mm long steel workpiece from room temperature to approximately 680ºC within 10 minutes.

Keywords: induction heating; class D current source inverter; Soft switching; parallel resonant.

I. INTRODUCTION

Induction heating is a well-known technique to produce very high temperature such as in steel melting, brazing and surface hardening. A large number of topologies have been developed in this area. Current-source and voltage-source inverters are among the most commonly used types. The advantages of current source inverter are short-circuit protection capability, superior no-load performance because of its current-limiting dc link characteristic and has a low component count compared to a voltage-fed inverter topology. Common topologies of current source inverter in induction heating applications are full-bridge and half-bridge inverter, as shown in Figs 1 and 2, respectively. In low power application such as cooking and small forging systems, the half-bridge inverter is preferable due to less number of switches required. However the half-bridge current source inverter suffers losses at the two high frequency inductors (L1 and L2) and a risk of saturation on both inductors. The controller of current source inverter needs to maintain the operating frequency at the little higher than the resonant frequency [1].

In this paper, a class D current source inverter for ferromagnetic metal load is proposed. The control method uses the phase lock loop to automatically adjust the inverter’s operating frequency to maintain a small constant leading phase angle when load parameters change. It can maintain the soft switching operation under the wide range load.

II. PARALLEL RESONANT INVERTER

Circuit Description

The parallel resonant inverter or current source inverter needs a switch that can block a bipolar voltage. Appropriate switching actions are achieved by connecting a switch and diode in series. The output voltage of the inverter is sinusoidal, in the case of low damping factor and the operating frequency is near resonant frequency. The inverter must operate at a little higher inverter frequency than a resonant frequency, in order to achieve soft-switching operation which reduces loss at IGBTs and protects spike voltage. The voltage across the switches has both positive and negative values. The positive voltage is blocked by IGBT and negative voltage is blocked by diodes.

Fig. 3 shows the parallel class D current source inverter for induction heating application. The inverter consists of two switches (S1, S2) with blocking diodes (D1, D2), a resonant capacitor (Cp), a DC inductor (LDC) and an induction coil that comprises of a series combination of resistance (Req) and coil inductance (Lcoil).

Fig. 3. A parallel class D current source inverter.
As shown in Fig. 4, four modes of operation exist within one switching cycle. The corresponding circuit topology for each mode of operation is illustrated in Fig. 5. The analysis is as follows.

1) Mode 1 \((t_0-t_1)\): While switch \(S_1\) and diode \(D_1\) are on, at \(t = t_0\), switches \(S_2\) and \(S_3\) receive positive gating signals. The negative voltage appears at the diode \(D_2\).

2) Mode 2 \((t_1-t_2)\): At \(t = t_1\), while switch \(S_1\) and diodes \(D_1\) still conducts, switch \(S_2\) and the antiparallel diode \(D_{22}\) are off, the positive output voltage switch appears at \(S_2\) and diode \(D_2\). And ZCS operation is achieved. During this mode

3) Mode 3 \((t_2-t_3)\): At \(t = t_2\), the switch \(S_1\) is turned off. Similar to that in Mode 1, and the diode \(D_1\) starts conducting positive. The negative voltage appears at the diode \(D_2\).

4) Mode 4 \((t_3-t_4)\): At \(t = t_3\), when the diodes \(D_{22}\) and \(D_1\) are off, the switch \(S_2\) and diode \(D_3\) conduct and the ZCS condition is achieved. During this mode, the output voltage \(v_o\) becomes negative.

Therefore, the one-cycle operation of the Class D current source inverter is completed. The next operating cycle continues to repeat from modes 1 to 4.

To simplify the calculation of necessary circuit parameters, the series combination of \(L_{coil}\) and \(R_{eq}\) is transferred to its equivalent parallel configuration of \(L_{coil}\) and \(R_p\) as shown in Fig. 6. The \(R_p\) is given as

\[
R_p = \frac{R_{eq}^2 + (\omega L_{coil})^2}{R_{eq}}
\]

where \(\omega\) is the system switching frequency. The total impedance \((Z_{total})\) of the resonant circuit in Fig. 6 can be expressed as,

\[
Z_{total}(j\omega) = \frac{j\omega R_p L_{coil}}{\omega^2 C_p L_{coil} R_p + j\omega L_{coil} R_p + R_p}
\]

and the resonant frequency is given as,

\[
\omega_o = \frac{1}{\sqrt{L_{coil} C_p}}
\]

Note that the inverter is designed to operate such that the switching frequency is slightly higher than the resonant frequency (i.e. \(\omega > \omega_o\)) for maximum output power. The parallel impedance at resonant frequency \((\omega_o)\) is

\[
Z_{total}(j\omega_o) = R_p
\]

and the average output power \(P\) is provided as

\[
P = \frac{v_{rms}^2}{R_p} \quad \text{or} \quad P = i_{rms}^2 \cdot R_{eq}
\]

III. EXPERIMENTAL RESULT

An experimental study is discussed in this section. The hardware prototype is created using parameters in Table I. Due to the variation of load parameters the switching frequency varies from 90.5 to 92.6 kHz. The output power is reduced from 1.2 kW to 700 W when the temperature increases. The work-piece is a metal with 35 mm in diameter and 120 mm in length. The measured signals from Figs. 7 to 12 are taken at the beginning of operation where the work-piece is at room temperature and the inverter operates at 90.5 kHz. Fig 7 shows the measured current of the switch \(S_2\) \((i_{s2})\) which is equal to \(i_i\). The fundamental component of the current is in Fig. 7 leads the output voltage \(v_o\). While each switch turns on with positive voltage which results in turn-on switching loss, the turn-off transition is dependent on the operation of the other switch which results in zero turn-off switching loss, as seen in Figs. 8 and 9.
The output voltage $v_o$ and the coil current ($i_{coil}$) waveforms are shown in Fig. 10 where the input power to the inverter is at 1260 W. As mentioned before, the input inductor is intentionally chosen to be small to improve the input power factor. The line input current and voltage waveforms are essentially in-phase as shown in Fig. 11.

### TABLE 1. SYSTEM PARAMETER

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Value at 25ºC</th>
<th>Value at 680ºC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage $v_{AC}$</td>
<td>$v_{AC}$</td>
<td>60 V_{rms}</td>
<td>60 V_{rms}</td>
</tr>
<tr>
<td>Switching Frequency $f$</td>
<td>$f$</td>
<td>90.5 kHz</td>
<td>92.6 kHz</td>
</tr>
<tr>
<td>Resonant capacitor $C_P$</td>
<td>$C_P$</td>
<td>0.88 µF</td>
<td>0.88 µF</td>
</tr>
<tr>
<td>Induction coil inductor $L_{coil}$</td>
<td>$L_{coil}$</td>
<td>3.78 µH</td>
<td>3.52 µH</td>
</tr>
<tr>
<td>Equivalent resistor $R_{eq}$</td>
<td>$R_{eq}$</td>
<td>118 mΩ</td>
<td>90 mΩ</td>
</tr>
</tbody>
</table>

Fig. 7. Current of switch $S_2 (I_{S2})$ and output voltage waveforms ($I_{S2}: 10$ A/div, $v_o: 100$ V/div and Time: 2 µs/ div.)

Fig. 8. Current ($I_{S2}$) wave form and voltage wave form ($V_{S2}$) across at the switch $S_2 (I_{S2}: 20$ A/div, $V_{S2}: 100$ V/div and Time: 2 µs/ div.)
Fig. 9. Current wave form ($I_{s1}$) and voltage wave form ($V_{s1}$) across at the switch $S_1$ ($I_{s1}$: 20 A/div, $V_{s1}$: 100 V/div and Time: $2 \mu$s / div.)

Fig. 10. Coil current wave form ($i_{coil}$) and coil voltage wave form ($v_{coil}$) ($i_{coil}$: 100 A/div, $v_{coil}$: 100 V/div and Time: $2 \mu$s / div.)

Fig. 11. Input current ($i_{in}$) and input voltage wave form ($v_{in}$) ($i_{in}$: 50 A/div, $v_{in}$: 50 V/div and Time: 5 ms / div.)

Fig. 12. Current of switch $S_2$($I_{s2}$) and output voltage wave forms ($I_{s2}$: 10 A/div, $v_{o}$: 100 V/div and Time: $2 \mu$s / div.)

Fig. 13. Current ($I_{s2}$) wave form and voltage wave form ($V_{s2}$) across at the switch $S_2$ ($I_{s2}$: 10 A/div, $V_{s2}$: 100 V/div and Time: $2 \mu$s / div.)

Fig. 14. Current wave form ($I_{s1}$) and voltage wave form ($V_{s1}$) across at the switch $S_1$ ($I_{s1}$: 10 A/div, $V_{s1}$: 100 V/div and Time: $2 \mu$s / div.)
The measurements are repeated when the work-piece temperature has reached 680 ºC. Since the inductance and series resistance decrease, the operating frequency has been increased to 92.5 kHz and the input power decreases to 720 W.

IV. CONCLUSIONS

A class D current source inverter can be used for induction heating with ferromagnetic load. The resonant frequency increases when the load parameters (\(L_{Coil}, R_{eq}\)) change. The inverter operates in the range of 90.5-92.6 kHz dependent on the load condition. The operating frequency can track the change in phase angle in order to maintain the operating frequency at slightly higher than the natural frequency when the parameters of load are varied, ensuring maximum power transfer to the load throughout the heating cycle. For future work, the current sensor of the induction coil can be used to send a control signal to a PFC converter to accurately control power by adjusting the duty cycle of the switch.

V. REFERENCES