A Discrete Pulse Group Control–Based Series Resonant Inverter with Complete ZCS–Assisted Inductors for Consumer High Frequency IH Application

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Abstract— This paper presents a pulse density modulated (PDM) voltage source high frequency series load resonant soft switching inverter (SRI) for the HF induction heated fixing roller in the energy saving copy and printing machines. The proposed simple and high efficiency SRI based on PDM control operation can achieve complete zero current soft switching for wide output power regulation ranges. In this work, its transient and steady–state operating principle are described and analyzed on the basis of high frequency PDM. The operating performances as power conversion efficiency, power losses analysis and temperature rising characteristics of this SRI are demonstrated and discussed through experimental results with specific control processing. Finally, a comparative study of induction heated fixing roller and conventional halogen lamp heater are also discussed from a practical point of view.

Keywords— Series resonant inverter (SRI), Lossless snubber inductors, Pulse density modulation (PDM), Zero current soft switching (ZCS), HF Induction heating, Fixing roller, i–v characteristic fitting curve of power semiconductor device

I. INTRODUCTION

In recent years, induction heating (IH) technologies are one of the remarkable application in the power electronics area due to environmental conservation and energy saving. In the household application, the IH technologies are very important for the electric kitchen. These technologies are designed using converter circuit topology, a digital control scheme and a magnetic component. Office automation (OA) appliances also benefit from this technology. The basic circuit topologies for the IH application are the full–bridge inverter[1], the half–bridge inverter[2], the single–ended resonant inverter[3] and the active voltage clamped inverter. The half–bridge inverter topology is widely used for the IH applications because of its robustness and cost effectiveness. The soft switching techniques, zero voltage soft switching (ZVS) and zero current soft switching (ZCS) are applied to these circuit topologies to reduce switching power losses. In general, output power regulation of high frequency inverter for the IH application is based on the pulse modulation method. There are mainly three types of modulation; the pulse frequency modulation (PFM), the pulse width modulation (PWM) and the pulse density modulation (PDM)[4]. PFM is a fundamental modulation technique because it is the simplest method to operate with a single–switch inverter. The control variable is determined by the switching frequency. This is a disadvantage for home electronics and OA application because the IH load parameters basically depend on the operating frequency, therefore the PFM inverter emits a harsh sound. The noise of a PWM inverter is relatively low since the switching frequency of the high frequency inverter is constant. However, the PWM inverter is generally low power conversion efficiency with a low output power rating. On the other hand, PDM is controlled by constant frequency and constant pulse width therefore the operating condition is always constant for all output power regulation ranges.

The toner fixing process of conventional copy and printing machines is used by the radiant heat from a halogen lamp heater. It is not an effective method because of low heat response and conversion efficiency, resulting in uneven heat distribution. However, the IH technique is anticipated to overcome these disadvantages. Furthermore, the copy and printing machine operation needs the wide power regulation ranges from the standby mode to the printing mode with rated power operation. This paper discusses the PDM controlled high frequency SRI for the IH fixing roller in the energy saving copy and printing machines[5]. Its circuit operation and power regulation characteristics are presented on the basis of experimental results. In addition, its power conversion efficiency characteristics and power loss estimation are performed. Finally, comparative study of the proposed IH fixing roller and conventional halogen lamp heater are also discussed from a practical point of view.

II. INDUCTION HEATED FIXING ROLLER

A. Schematic Structure of IH Fixing Roller

The IH fixing roller in the energy saving copy and printing machines is developed as a heating method. The IH fixing roller can heat the external roller directly for melting the printing toner. Therefore, the IH fixing roller is highly efficient compared with a conventional indirect radiant heating with a halogen lamp. In addition, it is easy to control the surface temperature (160–200°C) of the IH fixing roller.

The structure of IH fixing roller is shown in Fig. 1(a). The working coil is twisted around a resin bobbin and located internally in the rolling drum as an IH fixing roller.
Fig. 1(b) illustrates the toner fixing process of IH fixing roller. It has a release layer on the surface of an iron or aluminum cylindrical heating body. A release layer is divided into two types of a hard type with a resin and a soft type with an elastic body. The soft type is used for the full color copy and printing, and the hard one is for the mono color. The heating body is made of magnetic stainless steel (SUS 410). A titanium alloy or the carbon ceramic are also used effectively.

B. Transformer Circuit Model of IH load

The IH load for the high temperature applications such as heat treatment and thermal processing uses time–varying load parameters. The transformer model is used for an accurate representation of the IH load as shown in Fig. 2 for simulation analysis. The transformer model consists of the winding resistance \( R_1 \), the effective resistance \( R_2 \) by skin effect of the heating object, and self inductances \( L_1 \) and \( L_2 \). The resistance \( R_1 \) is very small enough to ignore by using a litz wire to reduce the skin effect. The resistance \( R_2 \) depends on the skin effect and current penetration depth related to the switching frequency of the high frequency inverter. The IH load parameters can be described by \( \tau \) (time constant of IH load) and \( k \) (electromagnetic coupling coefficient). \( \tau \) and \( k \) are expresses as follows.

\[
\tau = \frac{L_2}{R_2} \tag{1}
\]

\[
k = \frac{M}{\sqrt{L_1 L_2}} \tag{2}
\]

The operation of the high frequency inverter with IH load is independent from \( R_2 \) and \( L_2 \) values if the ratio of those is constant under a certain value of \( k \). The parameter \( k \) represents the degree of electromagnetic coupling with the heating body and working coil. The parameter \( L_1 \) represents a self inductance measured by primary side of the transformer model under an open circuit condition of the secondary side. The \( L_1 \) value is equal to the self–inductance of heating coil with zero conductivity of the heating object, no–load condition with a nonmagnetic heating body.

III. PDM CONTROLLED HIGH FREQUENCY ZCS SERIES LOAD RESONANT INVERTER

A. Circuit Description

Fig. 3 illustrates the PDM controlled high frequency SRI for the IH fixing roller. It consists of active power semiconductor switches \( S_1 \) and \( S_2 \), resonant capacitor \( C_r \) in series with IH load, two ZCS assisted snubber inductors \( L_{S1} \) and \( L_{S2} \) in series with \( S_1 \) and \( S_2 \), respectively.

B. Operating Principle

This high frequency inverter is controlled by PDM as shown in Fig. 4. This inverter has two mode periods; a power supplying period and an idling one. The output power is dependent on the switching pulse numbers in the PDM period. The PDM duty ratio \( D_{PDM} \) is defined as (3).

\[
D_{PDM} = \frac{T_{on}}{T_{on} + T_{off}} = \frac{T_{on}}{T_{PDM}} \tag{3}
\]
The auxiliary lossless snubber inductors \( L_{S1} \) and \( L_{S2} \) provide ZCS soft switching commutation for active power switches \( S_1 \) and \( S_2 \) in the continuous load current mode based on the overlapping current mode in \( D_{S1}–S_2 \) and \( D_{S2}–S_1 \). The ZCS range of this high frequency SRI is all the power regulating ranges. In addition, the ZCS commutation has theoretically zero tail current for the IGBTs. Therefore, the proposed SRI has extremely low switching power losses for switches \( S_1 \) and \( S_2 \). Furthermore, no power losses are consumed in the PDM scheme during the power non-injection period as compared with the SRI controlled by the other control methods such as PFM and PWM for the low output power regulation ranges.

C. Circuit Operation

Fig. 5 illustrates the circuit mode transitions of proposed SRI for the HF induction heated fixing roller. The voltage and current operating waveforms of each component are shown in Fig. 6. The operating principle in mode transitions is explained as follows.

Mode 1 The switch \( S_1 \) is in conduction mode and the output power is delivered to the IH load by the power source. The attenuated sinusoidal resonance is started through the IH load, \( C_r \) and \( L_{S1} \).

Mode 2 The current flowing through the load current \( i_L \) and the switch \( S_1 \) decreases and becomes zero at \( t = t_1 \), then the anti-parallel diode \( D_{S1} \) of switch \( S_1 \) is naturally turned on. The switch \( S_1 \) can achieve complete ZVS & ZCS hybrid soft switching commutation at turn-off transition.

Mode 3 The diode \( D_{S1} \) conducts and when the switch \( S_2 \) is turned on at \( t = t_2 \), the current flowing through diode \( D_{S1} \) begins to commutate to the switch \( S_2 \) and the current flowing through \( D_{S1} \) and \( S_2 \) are overlapped due to the lossless snubber inductor \( L_{S2} \). Therefore, the switch \( S_2 \) can achieve ZCS turn-on.

Mode 4 The current flowing through diode \( D_{S1} \) becomes zero at \( t = t_3 \) and the switch \( S_2 \) is conduction mode. The output power is delivered to the IH load by the resonant capacitor \( C_r \) and the attenuated sinusoidal resonance is started through the IH load, \( C_r \) and \( L_{S2} \).

Mode 5 The current flowing through the load current \( i_L \) increases, the switch \( S_1 \) decreases and becomes zero at \( t = t_4 \), then the anti-parallel diode \( D_{S2} \) of switch \( S_2 \) is naturally turned on.
turned–on. $S_2$ can achieve complete ZVS & ZCS turn–off during this mode.

**Mode 6**  The diode $D_{S_2}$ conducts and when the switch $S_1$ is turned on at $t = t_5$, the current flowing through diode $D_{S_2}$ begins to commutate to the switch $S_1$ and the current of $D_{S_2}$ and $S_1$ are overlapped due to the snubber inductor $L_{S1}$. Therefore, the switch $S_1$ can achieve ZCS turn–on.

The circuit operation repeats the mode 1–6, periodically.

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**IV. EXPERIMENTAL RESULTS**

**A. Circuit Parameters and Design Specifications**

The circuit parameters and design specifications for the PDM controlled high frequency SRI are listed in Table 1. Two auxiliary lossless snubber inductors $L_{S1}$ and $L_{S2}$ are adjusted to an appropriate value of $12 \mu H$ for the peak voltage $350 V$ of the IGBT switches. In this case, the dynamic switch current gradient $di/dt_{max}$ is $12.5 A/\mu s$ and current overlapping time is designed to $3.8 \mu s$. Fig. 7 is a view of IH fixing roller and working coil $L_1$ installed in it.

**B. Operating Waveforms**

The experimental operating waveforms of load current $i_L$ and voltage $v_L$ are illustrated in Fig. 8 for PDM ratio $D_{PDM} = 0.2$ and 0.8. From these figures, this high frequency SRI can be operated by PDM control.

Fig. 9(a) and Fig. 9(b) illustrate the voltage and current operating waveforms of the IGBTs $S_1$ and $S_2$. From these figures, all switches can achieve ZCS soft switching commutation in turn on and turn off transitions. Fig. 10(a) and Fig. 10(b) show the voltage and current waveforms of the IGBTs $S_1$ and $S_2$ at the beginning interval of the power injection. Observing these waveforms, the switches $S_1$ and $S_2$ can also operate under complete ZCS soft switching commutation for PDM control implementation.

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**TABLE I. CIRCUIT PARAMETERS AND DESIGN SPECIFICATIONS**

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input DC voltage</td>
<td>$V_{in}$</td>
<td>280 V</td>
</tr>
<tr>
<td>Resonant capacitor</td>
<td>$C_r$</td>
<td>0.49 $\mu F$</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>$f$</td>
<td>20 kHz</td>
</tr>
<tr>
<td>PDM frequency</td>
<td>$f_{PDM}$</td>
<td>400 Hz</td>
</tr>
<tr>
<td>Snubber inductor</td>
<td>$L_{S1},L_{S2}$</td>
<td>12 $\mu H$</td>
</tr>
<tr>
<td>Self inductance of working coil</td>
<td>$L_1$</td>
<td>90 $\mu H$</td>
</tr>
<tr>
<td>Time constant of IH load</td>
<td>$\tau$</td>
<td>9.23 $\mu s$</td>
</tr>
<tr>
<td>Electromagnetic coupling coefficient</td>
<td>$k$</td>
<td>0.48</td>
</tr>
<tr>
<td>IGBT (Mitsubishi, CT75AM-12)</td>
<td>$V_{CE}$</td>
<td>600 V</td>
</tr>
<tr>
<td></td>
<td>$I_C$</td>
<td>75 A</td>
</tr>
</tbody>
</table>

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(a) IH fixing roller  
(b) Working coil $L_1$

Fig. 7. Appearance of IH fixing roller and working coil.

(a) IGBT switch $S_1$  
(b) IGBT switch $S_2$

Fig. 9. Switch voltage and current waveforms at steady–state condition.
Actual Power Conversion Efficiency Characteristics

Fig. 11 illustrates power input/output and actual power conversion efficiency characteristics for proposed high frequency SRI. The output power can be linearly regulated by changing the PDM ratio $D_{PDM}$. In the printing mode, it operates at a $D_{PDM} = 1.0$. In the standby mode, it operates at a $D_{PDM} = 0.05$. The actual power conversion efficiency of this equipment can achieve 94% or more from $D_{PDM} = 0.05$ to 1.0. Therefore, this high frequency SRI can achieve high efficiency for the IH fixing roller application in the energy saving copy and printing machines.

Power Loss Analysis

The power losses of proposed high frequency SRI are extremely low because switches $S_1$ and $S_2$ operate at ZCS turn-on and turn-off. By ZCS commutation, fall current and tail current loss of the IGBT are considered almost zero. In addition, the conduction losses of snubber inductors $L_{S1}$, $L_{S2}$ and working coil $L_1$ are negligible through use of litz wire. Therefore, the main power losses of this high frequency SRI are the conduction losses of the IGBT. The current and voltage characteristics fitting curves of the IGBT and its antiparallel diode are used for estimation of conduction power losses. The $i$–$v$ characteristics of IGBT and its antiparallel diode under constant temperature condition are shown in Fig. 12. These $i$–$v$ characteristic fitting curves are obtained from experimental results. From these results, the characteristic fitting curves can approximate quadratic function in the low forward current area and linear function in the high forward current area, which are represented in (4) and (5), respectively.

\[
\begin{align*}
    v_C &= -0.0015i_C^2 + 0.0616i_C + 0.904 & (i_C < 15A) \\
    v_C &= 0.0185i_C + 1.223 & (i_C \geq 15A) \\
    v_F &= -0.00141i_F^2 + 0.0477i_F + 0.859 & (i_F < 12A) \\
    v_F &= 0.0152i_F + 1.05 & (i_F \geq 12A)
\end{align*}
\]

(a) IGBTs for $S_1$ and $S_2$

(b) Antiparallel diodes for $D_S$ and $D_{S2}$

Fig. 10. Switch voltage and current waveforms at beginning of power injection.

Fig. 12. Current and voltage characteristics of IGBT and diode.
These equations introduce into the simulation algorithm for the semiconductor conduction power loss calculations. The conduction power losses of IGBTs and diodes can be approximately calculated by using a circuit simulation on the basis of above equations. On the other hand, the other stray power losses including switching power losses of the IGBT and reverse recovery losses of the diode can be estimated in (6) from the total power losses of this high frequency SRI on the basis of experimental results.

\[
\text{(Other stray power losses)} = (\text{Total power losses}) - (\text{Conduction power losses})
\]  

(6)

The results of power loss analysis are shown in Fig. 13. The power losses increase proportionately with PDM ratio \( D_{\text{PDM}} \). In the case of the printing mode (heavy load) at \( D_{\text{PDM}} = 1.0 \), the other stray power losses are only 20% of total power losses because of the extremely low switching power losses with ZCS soft commutation and the conduction power losses account for the rest of 80% in Fig. 13.

E. Comparative Characteristics with Halogen Lamp Heater

The rising temperature characteristics for IH fixing roller and halogen lamp heater are shown in Fig. 14. The temperature rise time for the IH fixed roller is faster than the halogen lamp heater in this graph.

Table 2 illustrates rise times to reach 185°C under the output power condition of 1200W. The IH fixing roller is approximately 9%.

<table>
<thead>
<tr>
<th>Item</th>
<th>IH fixing roller</th>
<th>Halogen lamp heater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise time to reach 185°C</td>
<td>27.9 s</td>
<td>36.1 s</td>
</tr>
<tr>
<td>Power consumption under idling mode</td>
<td>52 Wh</td>
<td>57 Wh</td>
</tr>
</tbody>
</table>

Table II. Comparative Characteristics

Fig. 13. Power loss analysis of proposed high frequency inverter.

Fig. 14. Temperature rise characteristics.

V. CONCLUSION

In this paper, has been described a PDM controlled high frequency SRI for HF induction heated fixing roller in the energy saving copy and printing machines. The steady–state SRI operation under load adaptive PDM control has been evaluated and discussed on the basis of simulation and experimental results. The proposed high frequency SRI has been operated under ZCS over wide output power regulation with PDM. In addition to these, the power conversion efficiency of this equipment could achieve 94% or more for all the output power regulation ranges from 50W to 1200W in this case. The power loss estimation has been performed on the basis of experimental i–v characteristic fitting curves for the IGBTs and its antiparallel diodes. From this calculation, the other stray power losses were only 20% of total power losses at the heavy load condition because of extremely low switching power losses with ZCS. Finally, this HF induction heated fixing roller has actually achieved a good performance as compared with conventional halogen lamp heater from the practical results. Therefore, the PDM controlled high frequency SRI was more effective for HF induction heating applications. In the future, new semiconductor devices as SiC MOSFET with SiC SBD should be evaluated for this proposed high frequency SRI.

REFERENCES


