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High-Frequency Zero Current Soft Switching Inverter with Pulse Density Modulation for Induction Heated Roller

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Abstract

This paper presents a voltage source type half-bridge series resonant high frequency (HF) inverter for induction heated fixing roller in copy machines. This high-frequency inverter works under zero current soft switching (ZCS) commutation and has wide power regulation range due to employing a pulse density modulation (PDM) scheme. Transient and steady state operating modes of the inverter are presented in this paper together with its PDM-based power regulation system. Experimental operating performances of the developed HF-ZCS inverter as well as power losses and actual efficiency are discussed and compared with computer simulation results.

Key Words : High Frequency Resonant Inverter, HF-ZCS Inverter, Induction Heated Cooker And Steamer, PDM

1. Introduction

In recent years, energy saving has become a one of the most important requirements to the office automation (OA) equipment; therefore, development of energy efficient technologies for such applications is a very important task for the near future. In such appliance as copying machines, laser printers and other devices for printing, toner fixing process consumes almost 90[%] of all electrical energy needed for operation, therefore improving of this process will lead to the overall system energy performances enhancement. At present, in printing devices toner is fixed by a rolling drum heated by the heat radiated from the halogen lamp or special sheathed heater that is a very energy inefficient process. Therefore, contact heating of the roller by induced currents has attracted an attention recently as an alternative to the light heating by the halogen lamp, however; only a small number of publications on this subject have been presented yet. At the same time, induction heating is safe, highly efficient and faster heating method that allows controlling temperature more simply and precisely, and therefore, can leading to the reducing of the printing devices size and making them more users friendly. The aim of this research is a development of the efficient power supply for induction heating (IH) system for toner fixing roller in such printing devices.

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For industrial and consumer IH applications voltage-fed inverter with series resonant load is widely applied at present. The common method of output power regulation in such inverter is pulse frequency modulation (PFM) that has some drawbacks for induction heating since implies changing of the working frequency[1]. In case of PFM effective output power depends linearly to square root of the inverter working frequency, therefore at low output power(in stand by mode) inverters efficiency is very poor.

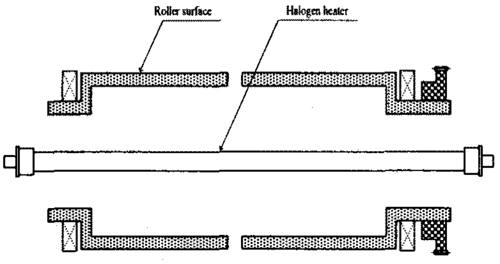
Also, the resistance of the induction heated roller and the depth of the induction eddy current penetration depend on inverter working frequency due to the skin effect that affect temperature distribution characteristics of the induction heated roller. On the other hands, various types of ZVS and ZCS pulse width modulated (PWM) series resonant inverters are also have been recently discussed for consumer IH applications. However, the soft switching PWM operation ranges of inverters are narrow and it is difficult to apply to IH roller in copy machine of light load applications[2-6].

There are also publications relating the concerning pulse density modulation (PDM) high frequency inverters with a ZVS operation[7]. The authors have already developed high frequency PDM inverter for ozone generation system and evaluated its performances previously and the PDM control strategy has been considered effective solution of the mentioned above problem for induction heating applications[8-10]. As a further development, in this paper, half-bridge series resonant voltage-fed inverter is introduced, which operates under a high frequency and ZCS operation conditions by two auxiliary inductances connected in series with the active power switches. The power regulation characteristics of the developed power conversion scheme are presented in this paper, together with the evaluations of the power losses analysis based on experiments and simulation.

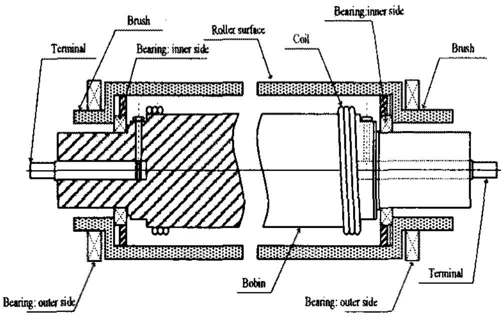
2. Induction Heated Roller and Transformer Model

2.1 Structure of Induction Heated Roller

The physical structure of the experimental induction heated roller used as a load of the developed high frequency inverter is schematically shown in Fig. 1. At present, the main heating method for the roller is heating by light emission from the halogen lamp in such structure as shown in Fig. 1 (a) In Fig. 1 (b) the same stainless steel toner fixing roller is depicted with induction heating coil inserted inside that can be represented schematically as in Fig. 2.



(a) Light heated roller using halogen lamp



(b) Induction heated roller

Fig. 1. Sectional View of Toner Fixing Roller

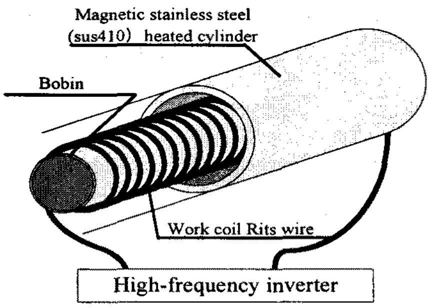


Fig. 2. Induction Heating Roller

2.2 Equivalent Transformer Model of Induction Heating Load

The equivalent electrical model of the IH load can be represented as a transformer shown in Fig. 3. Here L_1 is a self inductance of the working coil, which is defined by the high frequency magnetic flux caused by inverters current, R_2 is a frequency dependent resistance of the roller caused by the skin effect. The inductance of the transformers second side and mutual inductance are defined as L_2 and M, respectively.

If the internal resistance of the working coil is neglected, circuit equations can be derived as;

$$\begin{cases} j\omega L_1 I_{L1} + j\omega M I_{L2} = V_{L1} \\ j\omega M I_{L1} + (j\omega L_2 + R_2) I_{L2} = 0 \end{cases} \tag{1}$$

After simple transformations, equation (2) can be obtained.

$$\frac{V_{L1}}{I_{L1}} = \frac{\omega^2 M^2 R_2}{R_2^2 + \omega^2 L_2^2} + j\omega \frac{L_1 R_2^2 + \omega^2 L_2 (L_1 L_2 - M^2)}{R_2^2 + \omega^2 L_2^2} \tag{2}$$

If the first term of equations (2) is considered as R_a and the factor of the second jω is represented as L_a, then L_a and R_a can be given by;

$$\begin{cases} R_a = \dfrac{\omega^2 M^2 R_2}{R_2^2 + \omega^2 L_2^2} \\ L_a = L_1 - \dfrac{\omega^2 L_2 M^2}{R_2^2 + \omega^2 L_2^2} \end{cases} \tag{3}$$

As a result, the transformer model of the induction heating load shown in Fig. 3 can be represented by R_a-L_a parameters that can be measured experimentally.

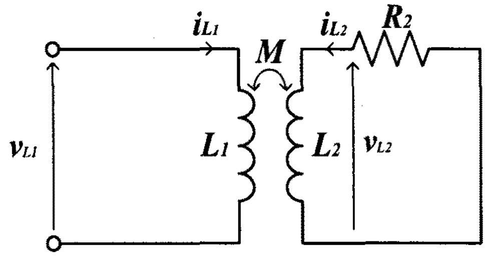


Fig. 3. Transformer Model of Induction Heating Load

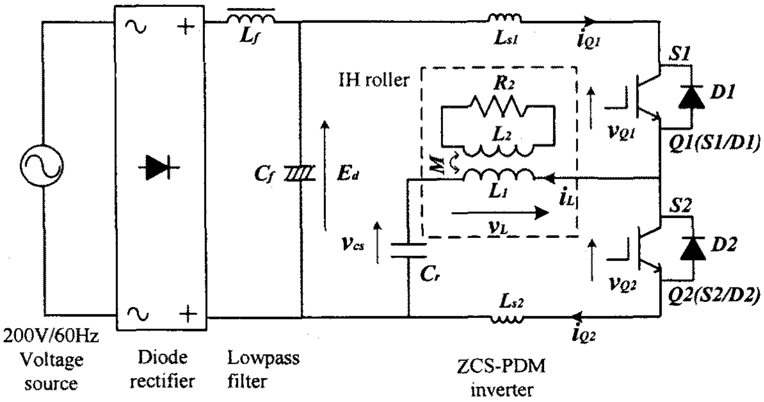


Fig. 4. High Frequency ZCS-PDM Inverter System

For the load shown in Fig. 2, such parameters as transformers electromagnetic mutual coupling coefficient k and time constant of the IH load τ can be defined as;

$$\begin{cases} k = \dfrac{M}{\sqrt{L_1 L_2}} \\ \tau = \dfrac{L_2}{R_2} \end{cases} \tag{4}$$

If time constant τ of the IH load is constant, the circuit behavior of the IH load is the same for any value L_2 and R_2. Therefore, it is better to represent the IH load by using new parameters L_1, k and τ defined as (4) rather than using the circuit parameters of the equivalent transformer circuit depicted in Fig. 3, where L_1 is measurable and L_2, M and R_2 cannot be measured. If k and τ from (4) are represented by measurable parameters R_a, L_a and L_1, it become simple to analyze the operation of the inverter circuit with the IH load.

3. ZCS-PDM High Frequency Inverter

3.1 System Description

The overall system including newly developed ZCS-PDM high frequency inverter is depicted in Fig. 4. Ed is a DC voltage applied to the inverter after diode rectification of 200[V]/60[Hz] utility power, Q_1 and Q_2 are switching blocks composed of the power semiconductor switches (IGBTs) S_1, S_2 and antiparallel diodes D_1, D_2; Cr is a series resonant capacitor; L_{S1}, L_{S2} are an auxiliary inductive snubbers connected in series with S_1 and S_2. In this circuit the switches Q_1, Q_2 operate completely under ZCS conditions for both turn-on and turn-off transitions. The circuit block surrounded by the dot line in Fig. 4 is the transformer model (L_1, k, τ) of the IH load comprised of the work coil and induction heated load displayed in Fig. 2.

3.2 Circuits Features and Operation

Magnetic coupling between coil and load is relatively poor for this circuit due to the not optimal geometric placement of the heated rolling drum and working coil. Depending on working frequency, developed inverter can operate in two modes; continuous load current operating mode, when the working frequency f_s is higher than load resonant frequency f_r and discontinuous current operating mode, when the working frequency f_s is lower. Although soft switching can be provided for the discontinuous current operation without auxiliary inductive snubbers, high peak currents on power switches and high peak voltage on the resonant capacitor become a serious problem for high output power. Therefore, developed inverter is operating in continuous load current mode that provides operation in ZCS & ZVS for turn-off transitions with no modifications. To provide soft switching for turn-on transitions too, two small inductors are connected in series with the switches Q_1 and Q_2 that delay current front and provides completely ZCS conditions. Thus, soft switching are achieved both for turn-on and turn-off transitions.

Furthermore, since the turn-off power losses caused by the tail current and fall current of power switches like IGBTs are not exist in ZCS inverter, the proposed PDM-ZCS inverter is rather preferable than ZVS schemes. As shown in Fig. 5, power regulation is carried out by varying of the time ratio between the period T_{on}, when power is supplied to the load and period T_{off}, when power is not supplied. In fact, with the changing the time ratio, the density of the applied pulses is changing; therefore, pulse density modulation control is taking place.

Since working frequency is kept constant, the depths of induction eddy current penetration and R_2 in Fig. 3 are constant. Furthermore, output power of the inverter can be regulated linearly without additional means in the wide range.

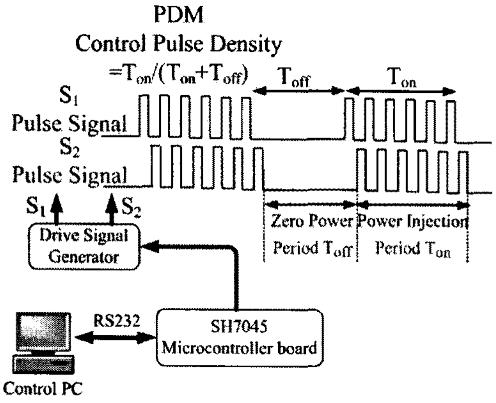


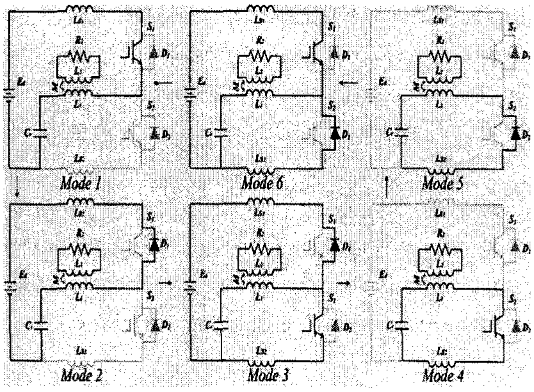
Fig. 5. Principle of PDM Control

Since completely ZCS operation for Q_1 and Q_2 is provided in whole power regulating range, the electromagnetic noise and switching losses are low. Furthermore, as compared with the inverters driven by other control methods like PFM, PWM and PAM almost no power is consumed during the period T_{off}, when no pulses are applied to the load, therefore, high inverter efficiency is observed under light load too.

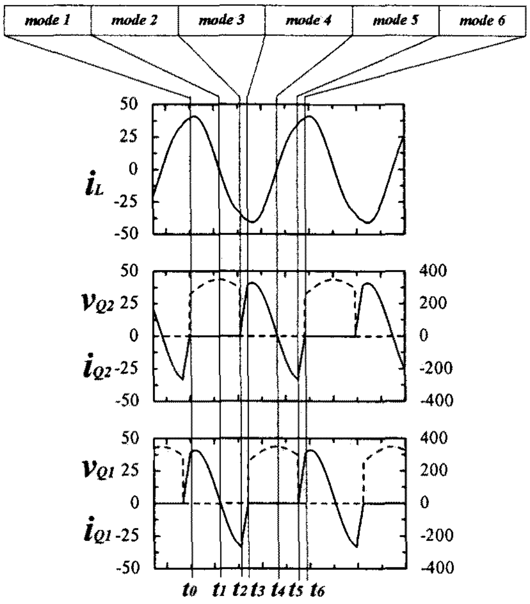
The operation modes of the inverter circuit shown in Fig. 4 for the power injection period are illustrated in Fig. 6.

▶ Mode 1(power consumption and resonance mode)

At $t=t_0$ and S_1 start conducting, series resonance is taking place in the circuit composed of IH roller Z(L_1, k, τ) and C_r, L_{S1}. Damped sinusoidal oscillating current is flowing in the working coil.



(a) Mode transitions and equivalent circuit



(b) Voltages and currents waveforms in steady state

Fig. 6. Inverter Equivalent Circuits and Steady-State Operation Waveforms

▶ Mode 2(power regeneration and resonance mode)

At $t=t_1$, i_L crosses zero and diode D_1 starts conducting. ZVS & ZCS turn-off conditions are provided by switching off the S_1 during conducting period of D_1.

▶ Mode 3(power consumption and current

overlapping mode)

S_2 is turned on during the conducting period of D_1, and current of D_1 is transferred to S_2. *di/dt* in S_2 is reduced and ZCS turn-on condition is provided by inductive snubber L_{S2}.

▶ Mode 4, 5 and 6

The operations during these modes are similar to the operations in the modes 1, 2, 3. After mode 6 the circuit cyclically repeats operations in the same order.

4. Experimental Results and Their Evaluations

4.1 Simulation and Experimental Results

The circuit parameters of the ZCS-PDM high frequency inverter using IGBTs are summarized in Table 1. The auxiliary inductance L_S is adjusted to 12[μH] to provide switch peak voltage 350[V] that includes some tolerance to the limit reference parameters of the chosen IGBTs. In this case, switch current stress di/dt_{max} becomes 12.5[A/μs] and current overlapping time t_u becomes 3.8[μs].

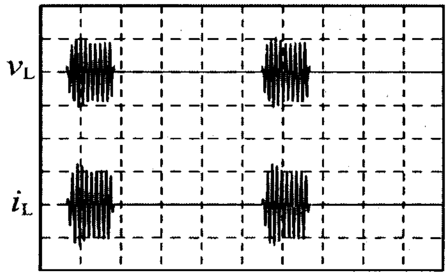
Table 1. Design specifications and circuit parameters

Item	Unit	Value
Input DC voltage	Ed	280[V]
Series resonant capacitance	Cr	0.49[μF]
ZCS inductive snubber value	Ls	12.0[μH]
Self inductance of work coil	L_1	90.0[μH]
Time constant of the load	τ	9.23[μ]
Magnetic value	κ	0.48
IGBT(TO-3P)	V_{CE}	600[V]
	I_C	75[A]
Antiparallel diode(TO-3P)	V_{RM}	600[V]
	I_0	30[A]

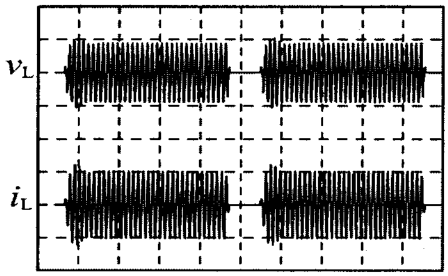
In the developed high frequency inverter we used IGBTs (Mitsubishi Electric CT75AM-12) with soft recovery diodes (Origin electric US30P) as anti-parallel diodes. For pulse density ratio D_P=0.2 and 0.8, the simulation waveforms of current i_L and voltage v_L are shown in Fig. 7 and experimental waveforms are represented in Fig. 8.

Enlarged waveforms for the switches Q_1 and Q_2 are shown in Fig. 9 and Fig. 10 respectively. The experimental results have good agreement with the simulation ones, therefore transformer models parameters of IH load can be considered to be valid.

From Fig. 11, the voltage and current waveforms of Q_1 and Q_2 for the beginning of the power injection period are shown. It is clear that Q_1 and Q_2 can operate under the conditions of ZCS principle during this period too, that is important, since due to the low current in the load, it is difficult to provide soft switching for this period by another method.

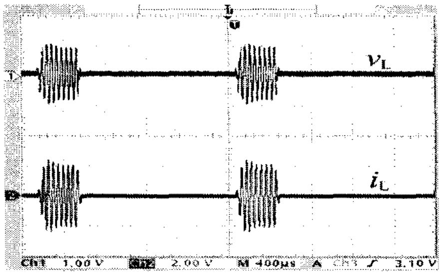


(a) D_P=0.2

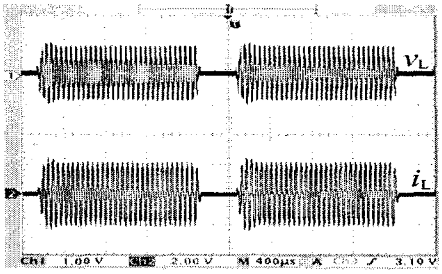


(b) D_P=0.8

Fig. 7. Simulation Waveforms of v_L and i_L (500[V/div], 40[A/div], 400[μs/div])

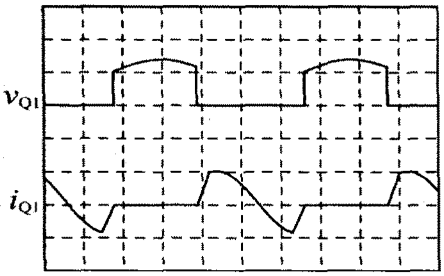


(a) D_P=0.2

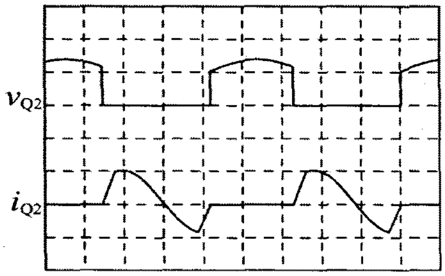


(b) D_P=0.8

Fig. 8. Experimental Waveforms of v_L and i_L (500[V/div], 40[A/div], 400[μs/div])

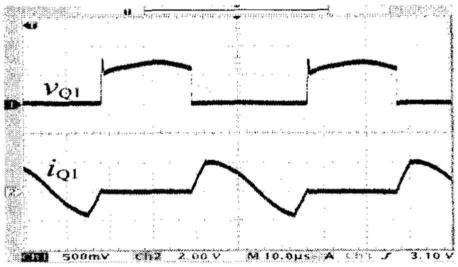


(a) Current and voltage on Q_1

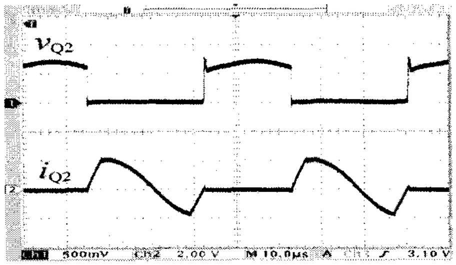


(b) Current and voltage on Q_2

Fig. 9. Simulation Waveforms of Switch Voltage and Current(250[V/div], 40[A/div], 10[μs/div])

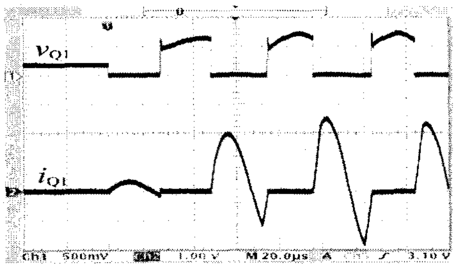


(a) Current and voltage on Q_1

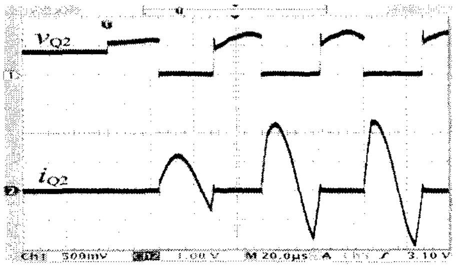


(b) Current and voltage on Q_2

Fig. 10. Experimental Waveforms of Switch Voltage and Current(250[V/div], 40[A/div], 10[μs/div])



(a) Current and voltage on Q_1



(b) Current and voltage on Q_2

Fig. 11. Experimental Waveforms of Switch Voltage and Current at the Beginning of the Power Injection Period(250[V/div], 40[A/div], 10[μs/div])

Fig. 12 illustrates the dependence of output power efficiency and output power relating to the pulse density modulation ratio. As can be seen the output power of the inverter can be regulated linearly by changing the pulse density modulation ratio. At the same time, power conversion efficiency more than 94[%] can be achieved for output power regulation ranges from 5[%] to 100[%] of the maximum output power. It is significant that power efficiency of more than 94[%] can be achieved for both D_P=1.0(printing mode) and D_P=0.05(stand-by mode), that makes the proposed ZCS-PDM high frequency inverter less power consuming comparing to the previous power sources for IH roller application in copy machines.

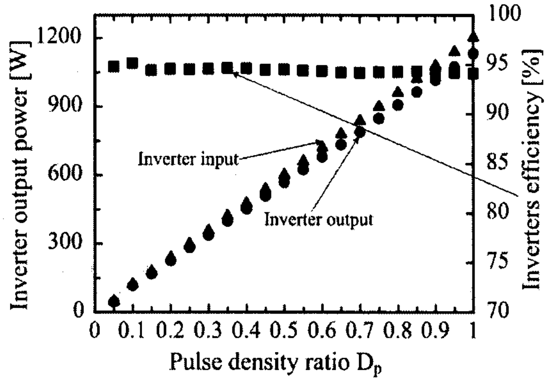


Fig. 12. Power Regulation Characteristics in Experience

In the developed inverter the turn-off signal is applied to the switch when anti-parallel diode is conducting, therefore, power losses related to the current fall and current tail of switch are very low. Main components of power losses in this inverter are conducting power losses in Q_1 and Q_2 (IGBTs and their antiparallel diodes) and the switching losses at turn-on, however, by using the inductive snubbers the later component are significantly reduced. Then using the measured in experiment inverters total power, switching losses can be calculated. The total inverter power losses are increasing linearly with pulse density ratio D_P as shown in Fig. 13. It was found that the conductive losses account for 80[%] of total losses. For the light load for stand by mode, the conductive losses of the switches account for almost all the losses in this inverter.

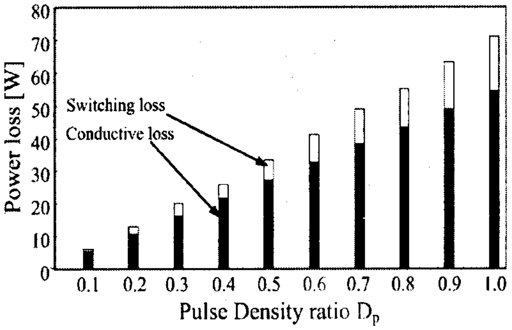


Fig. 13. Power Loss Analysis

5. Conclusion

In this paper, the voltage-fed high frequency half-bridge series load resonant inverter for IH roller in copy machine has been introduced. Due to the auxiliary inductive snubbers soft switching operation of the inverter is achieved for a wide range of output power. Power regulating characteristics and operating performances of this inverter for steady state operation has been evaluated in simulation and verified by experiment. Good agreement of the simulation and experimental results make valid the employing of the transformer model of the IH roller for the simulation.

The actual high efficiency more than 94[%] has been observed for all output power range from 50[W] to 1200[W] with stable operation and linear output power control under ZCS commutation. At the same time, due to the PDM control scheme, high efficiency of the output power has been observed in stand by mode, that is big advance, comparing to the previous models. Also, power losses analysis of this inverter has been undertaken in this paper, using the approximated v-i characteristics of IGBTs and diodes.

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