Series Load Resonant High Frequency Inverter with ZCS-PDM Control Scheme for Induction-Heated Fusing Roller

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Abstract

This paper presents the two lossless auxiliary inductors-assisted voltage source type half bridge (single ended push pull: SEPP) series resonant high frequency inverter for induction heated fixing roller in copy and printing machines. The simple high-frequency inverter treated here can completely achieve stable zero current soft switching (ZCS) commutation for wide its output power regulation ranges and load variations under its constant high frequency pulse density modulation (PDM) scheme. Its transient and steady state operating principle is originally described and discussed for a constant high-frequency PDM control strategy under a stable ZCS operation commutation, together with its output effective power regulation characteristics-based on the high frequency PDM strategy. The experimental operating performances of this voltage source SEPP ZCS-PDM series resonant high frequency inverter using IGBTs are illustrated as compared with computer simulation results and experimental ones. Its power losses analysis and actual efficiency are evaluated and discussed on the basis of simulation and experimental results. The feasible effectiveness of this high frequency inverter appliance implemented here is proved from the practical point of view.

Keywords- Voltage source type series load resonant inverter, Half bridge inverter circuit topology, Lossless inductive snubbers, Zero current soft switching, Pulse density modulation ratio control, Induction heated roller in copy machine, Consumer power electronics

I. Introduction

A. Research Background

In recent years, much promising interest to a variety of global environmental-friendly technology developments has raises greatly. The Effective energy saving power utilizations relating to the office information automation (OA) and telecommunication equipments have become more and more significant.

The fixing or fusing heat roller processing a toner in a copy machine, facsimile, data recorder, pattern recognition appliance and scanner is actually required for transferring toner on printing paper from a rolling drum with a certain pressure for a copying machine as well as a high-speed laser printer. At present, the cost effective toner fixing or fusing process equipments using the radiant heat energy by the sheathed heater or the halogen lamp heater have been applied for modern office information and telecommunication appliances as facsimile, scanner, printer and copy machine. In practice, these heat energy utilization processing components usually takes 90% of all energy needed for printing device operation.

Therefore, the promising development of more effective energy-saving toner fixing process has attracted special interest for large amount of great demands with great advances of information and telecommunication technologies. Such some electric heating utilizing methods developed will lead to the improvement of the equipment in high speed and high efficiency copy machine and laser printer. On the other hand, the direct heating of the fixing roller based on induced eddy currents has attracted special interest recently as an alternative method to the conventional light energy heating fixing roller by the halogen lamp, however; only a few numbers of publications and issues on this latest development subject have been presented so far. In general, the non-contact eddy current-based induction heating drum of all types of the metals has some advantages such as safe, reliable, highly efficient, faster starting heating method, which can allow controlling temperature more simply and precisely. Therefore, this induction heating (IH) fixing roller can lead to reducing the physical size of the high efficiency printing devices and their performances enhancement. The new develop-

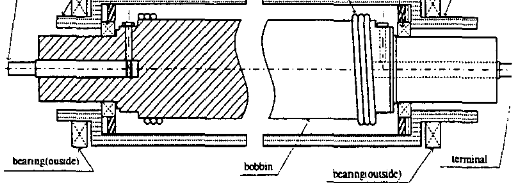


Fig.1 Sectional view of toner fixing roller in copy/printer equipment

ments of the high efficiency and high frequency power supply for the IH fixing roller in such epoch-making applications seem to be a very important and timely task from an energy saving point of view.

B. Research Objective

For industrial and consumer IH power applications in next generation, the voltage-fed high frequency inverter with series capacitor resonant tank circuitry has been widely applied so far. The general method of output power regulation in this kind of high frequency inverter is based on pulse frequency modulation (PFM) scheme of its inverter frequency. The PFM strategy implies changing the working frequency of the inverter that has essentially some drawbacks for IH applications. That is to say, the high frequency AC effective output power in case of PFM control strategy depends linearly to square root of the series load resonant inverter working frequency f_s and inverter system efficiency decreases significantly for light load in copy machine, facsimile, scanner, data recorder and printer in stand-by mode. In addition to this, when two or more inverters are assembled in a set of equipment, the actual problem of acoustic noise due to the difference operating frequency of the inverters may occurs. Furthermore, the skin effect resistance of the IH fixing roller as well as the depth of the induced eddy current penetration depend on inverter working frequency have much worse influence on the temperature distribution characteristics of the IH fixing drum roller.

On the other hands, various types of the zero voltage soft switching (ZVS) and zero current soft-switching (ZCS) pulse width modulated (PWM) series resonant inverters together with ZVZCS-PWM inverters have been recently discussed for consumer IH power applications. However, a constant frequency soft-switching PWM operation range of these high frequency inverters is relatively narrow. It is difficult to apply to IH fixing roller in copy machine operated under light load applications of their series load resonant inverter. There are publications relating to soft switching pulse density modulation (PDM) high-frequency inverters.

In this paper, the voltage source type half-bridge series resonant voltage-fed series load resonant inverter with two lossless inductor snubbers in series with each active switch is introduced, which can operate under a high frequency PDM-ZCS operation conditions. The high frequency power regulation characteristics of the developed high frequency series load resonant inverter which is based on a constant high frequency PDM-ZCS are presented in this paper, together with the performance evaluations of the power losses analysis or efficiency characteristics on the basis of the simulation.

II. Induction-Heated Fixing Roller

A. Schematic structure of induction-heated fixing roller

The cross sectional and physical structure of the experimental induction heated fixing roller driven actually for a load of the voltage source or current source type high-frequency series or parallel load resonant tank inverter employing MOS gate controlled power semiconductor switching devices; IGBTs is schematically shown in Fig.1. Presently, the main electric heating method for the fixing roller as light radiant heated roller in the copy and printing machines is introduced which can be heated directly by light emission from the halogen lamp. This scheme has some disadvantages such as relatively low efficiency, required maintenance, easy to temperature, non-recycle, quicker temperature response and short life. On the other hand, the fixing heat roller with an induction-heated working coil inserted inside the rolling drum made of stainless steel plate is depicted schematically in Fig.2. The titanium alloy and the carbon ceramic are effectively applied for the induction heated fixing heat roller in the copy machine and so forth.

B. Transformer circuit modeling of induction heated load

This induction heated fixing heat roller load used in this paper is modeled by using the transformer-based circuit represented in Fig.3.

This transformer circuit model is also used for the IH load circuit analysis including the high frequency inverter. R_2 is the resistance related to the high frequency dependent skin effect and current penetration depth that are based on the operating inverter frequency. In the circuit analysis of the induction heated fixing heat roller load delivering the paper, three parameters of self-inductance L_1 of cylin drically shaped working coil itself with an internal zero resistance or

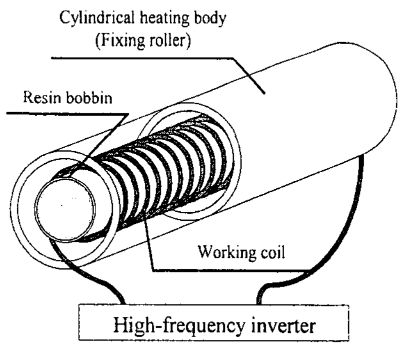


Fig.2 Induction heating fixing roller

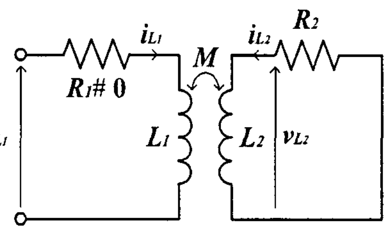


Fig.3 Transformer model of induction heating load

a slight resistance, load time constant $\tau = L_2/R_2$ and electromagnetic coupling coefficient $k = M/\sqrt{L_1L_2}$ of the transformer model are introduced on the basis of measurable variables.

III. PDM Controlled High Frequency ZCS Series Load Resonant Inverter

A. System description

The overall high frequency power conversion system composed of the voltage-fed half bridge series load resonant ZCS-PDM controlled high frequency inverter using IGBTs is depicted in Fig.4. E_d is a DC voltage applied to the voltage source-fed high frequency inverter via single phase capacitor input type diode full bridge rectification of 200V/60Hz utility AC power source grid. The single phase PFC converter with boost chopper can be conveniently used in place of diode rectifier. For cost effective appliance design, a diode rectifier with non-smoothing filter is connected in the input side of high frequency ZCS-PDM inverter. This high frequency inverter consists of the active power switches Q_1 and Q_2 the reverse conducting switches due to the power semiconductor switches (IGBTs); SW_1 and SW_2 with antiparallel diodes; D_1 and D_2; C_r as a tuned resonant capacitor in series with IH load. L_{s1} and L_{s2} as an auxiliary ZCS-assisted inductive lossless snubbers connected in series with Q_1 and Q_2 and the induction heated fixing heat drum roller represented by the transformer circuit modeling. In this high frequency series load resonant inverter circuit, the active power switches Q_1 and Q_2 can operate completely under ZCS principle and its high frequency AC power regulation based on a variable pulse frequency modulation for both turn-on and turn-off mode zero current soft switching commutations. The effective AC output power of the high frequency inverter in Fig.4 can be newly regulated by a constant high frequency PDM control strategy on the basis of the pulse group modulation principle in Fig.5. The IH load surrounded by the dotted line is the transformer model parameters represented by the circuit parameters; four unmeasurable values (L_1, L_2, k, R_2) or two measurable values (L_1, $k = M/\sqrt{L_1L_2}$, $\tau = L_2/R_2$) of the IH load comprised of the cylindrical working coil and induction heated fixing roller load displayed in Fig.2.

B. Circuits configuration

Since the geometric placement of the induction heated fixing roller with working coil inserted inside its drum gives loose coupling coefficient $k < 1$ for the induction heating, the magnetic coupling coefficient between the fixed working coil and rolling drum load is relatively poor because of large air gap. The high frequency series load resonant inverter circuit topology with series capacitor compensated resonant load tank with C_r is introduced in Fig.4. The DC

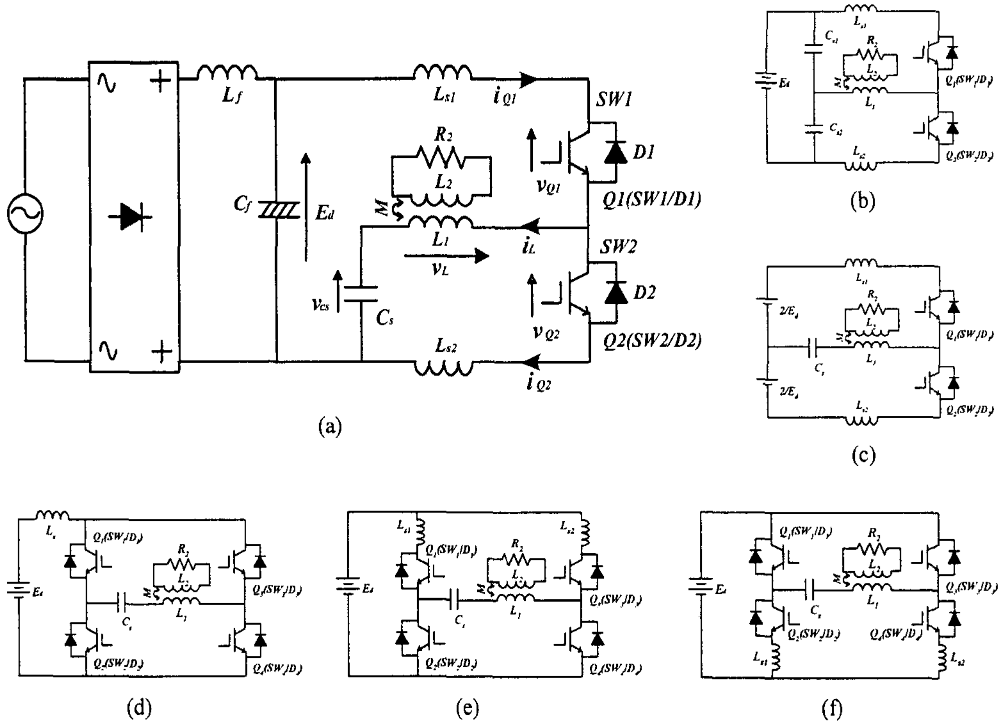


Fig.4 Voltage source SEPP ZCS-PDM high frequency inverter system for induction heated fixing roller

bus line ports of high frequency inverter is connected to the single phase diode rectifier with DC smoothing low pass filter; L_f & C_f.

The pulse density modulation controlled high frequency series resonant inverter operation under ZCS commutation can be divided into two modes; continuous load current operating mode and discontinuous load current operating mode, in which the working frequency f_s of the high frequency inverter in Fig.4 is smaller than series resonant frequency $f_r \; 1/2\Sigma\sqrt{L_d C_r}$ determined by the series resonant tank load. Although ZCS commutation mode can be provided for the discontinuous current operation without two auxiliary inductive snubbers in series with Q_1 and Q_2, extremely high peak currents across the active power switches and high peak voltage on the resonant series compensated capacitor become serious problem in actual for large output power setting of this high frequency inverter.

Thus, the series load resonant inverter treated here is designed so as to operate in continuous load resonant current mode that provides the soft commutation operation in ZCS and ZVS at the turn-off mode transitions. As for turn-on mode transition, hard switching commutation for Q_1 and Q_2 could occur if no modifications due to the lossless inductive snubber topologies are made. Therefore, two extremely small inductor snubbers are connected in series with the active power switches Q_1 and Q_2 that provide complete ZCS condition for turn-on commutation. Thus, because of the lossless inductive snubbers, the soft switching commutation can be achieved both for the turn-on and turn-off mode transitions. Furthermore, since the power losses caused by tail current and fall current of MOS gate controlled bipolar mode power semiconductor switches like IGBTs during turn-off period is likely to disappear in the circuit topology that can operate under the principle of ZCS, the proposed ZCS-PDM series resonant inverter is rather preferable as load resonant ZVS inverter scheme.

C. Pulse density modulation controlled power regulation

As shown in Fig.5, the high frequency AC power regulation can be achieved by varying the pulse density modulation under time ratio during T_{on} period, when the AC output power is injected into the induction heated load and a period T_{off}, on the other hand, when the AC output power is non-injected into the induction heated load. With the changing the PDM time ratio, the applied pulse density

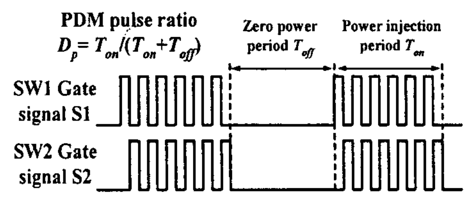


Fig.5 Principle of PDM control

ratio is taking place while the working frequency of the high frequency inverter is kept constant under a condition of zero current soft switching transition commutation.

The auxiliary inductive snubbers; L_{s1} and L_{s2} ($L_{s1}= L_{s2}=L_s$) in series with the active switches provide ZCS commutation operation for Q_1 and Q_2 in the continuous load current mode which is based on the overlapping current in (SW_1, D_2) and (SW_2, D_1).

TABLE I

DESIGN SPECIFICATIONS AND CIRCUIT PARAMETERS

Quantity	Symbol	Value
Input DC voltage	E_d	280V
Series resonant capacitance	C_r	0.49μF
ZCS inductive snubber value	L_s	12.0μH
Self inductance of work coil	L_1	90.0μH
Time constant of the load	τ	9.23μsec
Electro Magnetic coupling co-efficient	k	0.48
IGBT(TO-3P)	V_{CE}	600V
	I_C	75A
Antiparallel diode (TO-3P)	V_{RM}	600V
	I_0	30A

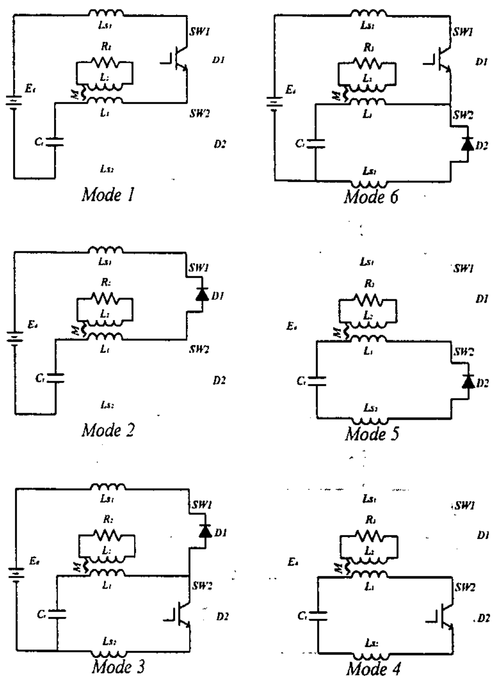


Fig.6 Mode transitions and equivalent circuits

Since a complete ZCS operation for Q_1 and Q_2 is provided over whole power regulating ranges, the high frequency leak current related electromagnetic noise and switching power losses for Q_1 and Q_2 are kept to be low. Furthermore, as compared with the series load resonant inverters driven by the other control methods of PFM, PWM and PAM for the conditions of the light induction heated load, almost no power losses in the ZCS-PDM scheme is consumed during the power non-injected period in this high frequency inverter. The switching power losses in ZCS-PDM scheme canbe reduced even in power injection mode. Therefore, the high inverter efficiency is observed for heavy and light induction heated loads.

D. Circuit operation waveforms

The soft switching commutations and equivalent circuits in the operating modes of the inverter circuit are shown in Fig.6. The voltage and current operation waveforms of the voltage source series load resonant ZCS-PDM inverter circuit shown in Fig.5 during the power injection period are illustrated in Fig.7.

The circuit parameters of the voltage source type PDM controlled high-frequency ZCS inverter using IGBTs are indicated in Table 1. Two auxiliary inductive snubbers L_s are adjusted so as to be 12ΠH to provide the switch peak voltage 350V that includes ascertain tolerance to the limited standard rating parameters of the selected IGBTs. In this case, the dynamic switch current stress di/dt_{max} becomes 12.5A/Πs and current overlapping time t_u is set to 3.8Πs.

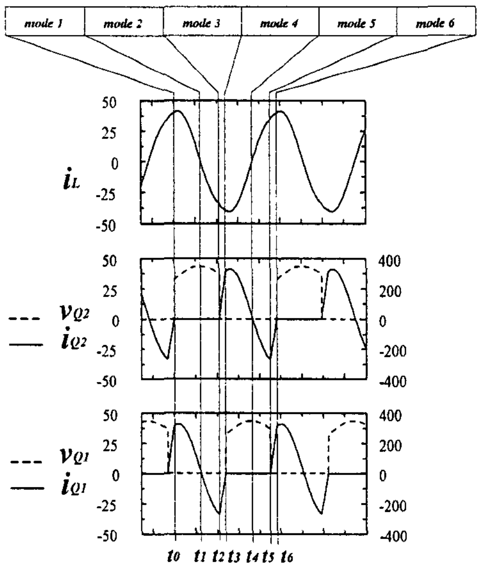
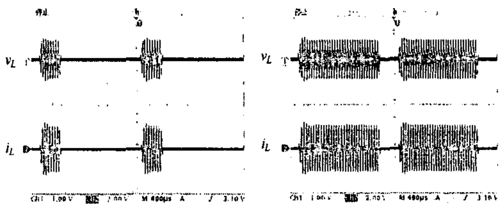


Fig.7 Voltage and current waveforms in steady state of power injection

IV. Experimental Results

The developed voltage source high-frequency series resonant ZCS-PDM inverter uses IGBTs (Mitsubishi Electric Co., Ltd., CT75AM-12) with soft recovery fast switching diodes (Origin Electric Co. Ltd, US30P) as the antiparallel fast recovery diodes. For pulse density modulation ratio D_p=0.2 and D_p=0.8 in a PDM control scheme, the measured operating waveforms of load current i_L and load voltage v_L are depicted in Fig.8. Observed voltage and current waveforms v_{Q1} & i_{Q1}, v_{Q2} & i_{Q2} for the active power switches Q_1 and Q_2 in switching arms of a voltage source type series resonant ZCS-PDM inverter are shown in Fig.9.

The validity of the transformer type circuit models parameters of the induction heated type fixing heat roller load in Fig.1 and Fig.2 is proven on the basis of these experimental results.



(a) D_p=0.2 (b) D_p=0.8

v_L:500[V/div], i_L:40[A/div], t: 400[μsec/div]

Fig.8 Experimental waveforms of v_L and i_L for PDM duty cycle

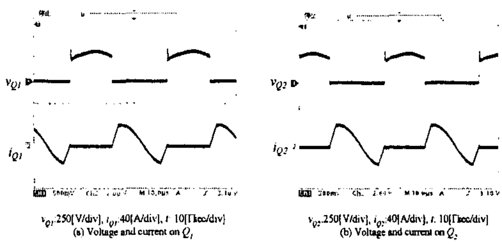


Fig.9 Experimental waveforms of switch voltage and current

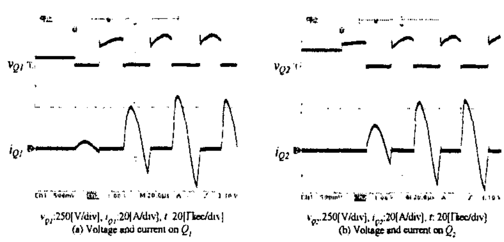


Fig.10 Experimental waveforms of switch voltage and current at the beginning of the power injection period

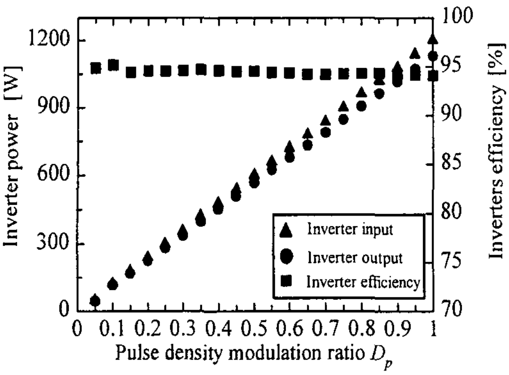


Fig.11 Power regulation characteristics in experimence

The voltage and current operating waveforms of the active power switches Q_1 and Q_2 during the beginning interval of the power injection period of PDM scheme are shown in Fig.10. It is clear that Q_1 and Q_2 can operate under a condition of ZCS principle for a PDM control implementation.

Figure 11 illustrates the pulse density modulation ratio D_p vs. output power characteristics and pulse density modulation ratio D_p vs. power conversion efficiency characteristics for voltage source type series resonant high frequency ZCS-PDM inverter in Fig.4. The high frequency AC output effective power of the high frequency inverter treated here can be regulated and linearly by changing the pulse density modulation ratio D_p. For output power regulation ranges from 5% to 100% of the maximum output power, the actual AC power conversion efficiency more than 94% can be obtained by the breadboard setup implementation. Especially, it is more important that actual efficiency more than 94% is able to be achieved even for both D_p=1.0 in copy machine printing mode and D_p=0.05 in its stand-by mode, which make the proposed voltage source series resonant ZCS-PDM controlled high-frequency inverter more effective for the induction heating type fixing heat roller applications in copy and printing machines.

V. Conclusions

In this paper, the voltage-fed high-frequency half-bridge (single ended push-pull; SEPP) type series load resonant zero current soft switching inverter topology with ZCS-assisted two auxiliary inductive snubbers has been introduced for the induction-heated fixing roller in the copy and printing machines. Its steady state inverter operation under PDM control scheme has been evaluated and discussed on the basis of simulation and experimental data.

The high frequency AC power regulating characteristics and operating performances of this simple voltage source SEPP series resonant high frequency ZCS-PDM inverter using IGBT modules in steady state operation has been qualitatively evaluated in simulation and experiment. For the power loss estimations of this high frequency inverter, the transformer type circuit model of the induction-heated fixing roller in copy and printing machines has been used from a practical point of view.

The actual high efficiency more than 94% of the series load resonant ZCS-PDM high frequency inverter for IH roller in copy and printing machines has been observed for all the output AC power regulation ranges from 50W to 1200W with stable zero current soft switching operation processing and linear output power control characteristics under a condition of ZCS commutation. The voltage source SEPP type high frequency series resonant ZCS inverter with lossless inductive snubbers, which is based on a constant frequency PDM control scheme, has provided its practical effectiveness for the stand-by mode and printing mode. Furthermore, the power losses analysis of this high frequency inverter with a high frequency PDM control scheme has been analyzed using the approximated *v-i* characteristics of IGBTs and diodes used here.

Acknowledgment

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