Zero Voltage Soft Switching PWM High-Frequency Inverter with Active Inductor Snubber for Induction Heated Roller in New Type Copy Machine

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Abstract - This paper presents a novel version of an active voltage clamped ZVS-PWM high frequency inverter using $IGBT_S$ for electromagnetic induction eddy current-based rolling drum heating in new generation copy and printing machines in consumer business use. The operating principle of this inverter circuit and unique features are described herein. Its constant frequency duty cycle (asymmetrical PWM) controlled voltage source quasi-resonant soft switching high frequency inverter employing $IGBT_S$ is proposed, which is capable of achieving stable and efficient zero voltage soft switching commutation over a widely specified power regulation range from full power to low power. The operating performances in a steady state of this inverter is discussed and evaluated on basis of simulation and experimental results as an induction heated roller in new generation copy machine.

Keywords : Soft switching high frequency inverter, Asymmetrical PWM, Fixed frequency operation, Additional series resonant snubber, Eddy-current-based heating roller, Active voltage clamped, Copy machine for office automation and information

I. Introduction

With innovative advances of discrete MOS gate controlled power semiconductor devices such as $MOFET_S$, $IGBT_S$, MCT_S, CSTBT and HiGT which are designed for high-frequency switching control and their related hybrid drive IC modules and LSI control devices, there have been practical developments of cost-effective appliances for high-frequency induction eddy current based heating applications used widely in the fields of consumer power applications. At present, the voltage-fed type, the current-fed resonant inverter circuit topologies using load resonance, transformer resonance and quasi-resonance have been newly developed for induction heating applications in industry and consumer power processing fields. In addition, some various types of voltage-fed load resonant and voltage-fed quasi-resonant inverters composed of single-ended, single-ended push-pull, center tapped push pull, half bridge, full bridge and boost half bridge circuit topologies have been introduced so far for some particular high-frequency power applications. The voltage source single ended resonant soft switching inverter circuits are widely used from the advantages of downsizing, low-cost, low-noise, high performance and high efficiency. But, in commercial 200V utility AC power supply required for high power consumer applications, the peak voltage applied for power semiconductor switching device (IGBT) of conventional single-ended voltage-fed quasi-resonant inverter using a single IGBT ranges from about 1.2kV-1.7kV, so this simple and cost effective single ended quasi-resonant pulse modulated inverter does not put into the practical use for 200V utility grid AC power line. Besides, the beat frequency-based acoustic irritating interference sound cause in multi-burner electromagnetic heated ranges and composite heating appliances of electromagnetic heated ranges and microwave oven because the control system of this simple inverter is based on PFM scheme. Furthermore, the penetration depth of induction heater might be varied in PFM control approach due to a single ended high frequency inverter. There are some practical problems to be solved in this inverter circuit topology. However, it is possible to solve this significant problem by newly improved circuit topology. In recent years, the researches and developments of the improved high frequency soft switching inverter with an additional switched capacitor composed of voltage clamping capacitor and auxiliary active power switch have attracted special interest for high frequency inverter applications. The peak voltage of power semiconductor device used in 200V commercial utility AC power source for the voltage clamped single ended quasi-resonant inverter with an active voltage clamping switched capacitor is able to be actively suppressed below about 900V, and the constant frequency duty cycle (asymmetrical PWM) control scheme can be introduced by adding an active power switch and an active voltage clamp capacitor to the voltage source single-ended quasi-resonant ZVS-PFM high frequency inverter using $IGBT_S$. In this topology, the significant problem is able to be solved effectively. This paper introduces active voltage clamped ZVS high frequency inverter with the duty cycle mode asymmetrical PWM control function which corresponds to 200V commercial power source for the induction heating roller drum used for new generation copy and print machine. The operation principle of this inverter is clarified on the basis of the simulation and experiment results, and the power regulation characteristics in the steady state operation of this inverter are described and evaluated with illustrative data.

In addition, the improved high frequency soft switching inverter circuit with the active inductor snubber is discussed in order to implement complete zero voltage soft switching under the low power regulation setting. The active inductor snubber type inverter circuit connected in parallel with the work coil is evaluated as compared with the previously proposed high frequency inverter.

II. New Induction Heating Application

II.I Induction Heating Load Technology

The induction heating of conductive metal and semiconductor materials is based on non-contact direct heating using the electromagnetic eddy current induction principle. Figure1 shows a basic principle of electromagnetic induction heated cooking appliances with a pancake type spiral planer coil as litz wire-based working coil for generating high frequency magnetic flux. The pancake type working coil (see Fig.1) connected the quasi-resonant zero voltage soft switching high frequency inverter using $IGBT_S$ generates high frequency magnetic flux. And then, high-frequency magnetic field produced from the working coil makes eddy current in the bottom portion of vessel or pan. As a result, in principle, the bottom portion of this vessel is able to be directly heated on the basis of Joule's law. The Joule's heat is to be specified by resistivity of the vessel material due to eddy current heating. The electromagnetic eddy-current induction heating has excellent unique features such as rapid heating, clean, local part heating and safety. In this paper, induction heating roller drum load composed of litz wire based cylindrical type work coil and cylindrical heating element depicted in Fig.2 is newly used for a load of the inverter.

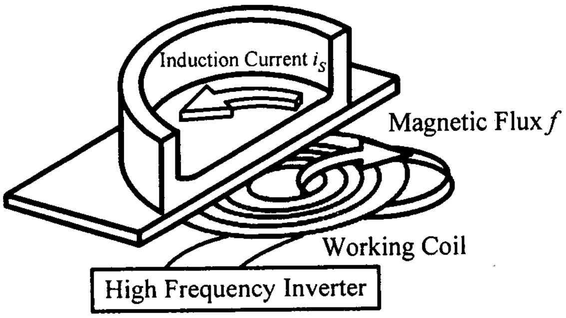


Fig.1. Induction heating principle

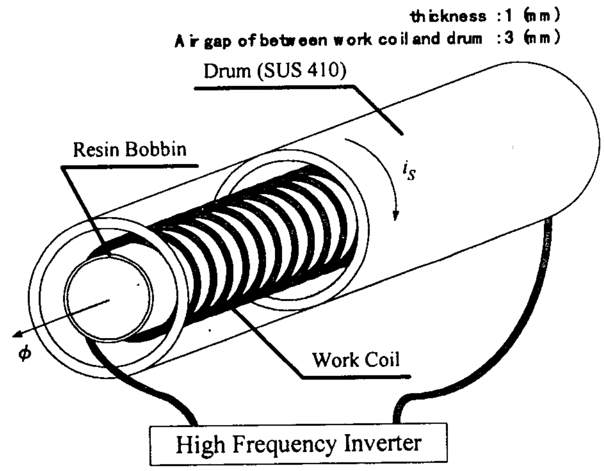


Fig.2. Induction heating roller with working coil

II.II Circuit Modeling Induction Heating Roller

This induction heating roller load is modeled by using transformer-based circuit shown in Fig.3. This lumped transformer circuit model is also used for the load analysis including the inverter. R_2 is the resistance related to the high frequency dependent skin effect which is based on the operating inverter frequency. However, it is possible to consider that the lumped resistance parameter R_2 is almost constant because this high frequency inverter operates under constant frequency duty cycle based PWM control scheme. In the circuit analysis of the induction heated load, three parameters of self-inductance L_l of working coil itself with an internal zero resistance, load time constant $\tau(= L_2 / R_2)$ and electromagnetic coupling coefficient $k(= M / \sqrt{L_1 L_2})$ of the transformer model are introduced as new variables. Practical approach to measure these parameters are described.

Figure4 shows the structure of heating roller load as a load of this high frequency inverter. In the copy and print machine, toner image adheres to decalcomania paper in the unstable condition, after decalcomania paper separates from the photoreceptor. This toner image is dried by the fixing equipment in which the heating roller consists of the working coil and the fixing roller, and toner image becomes an eternal image. At present, the fixing equipment widely spreads from the low speed to high-speed copy machine and color copy machine for industrial use is heat fixing system, and also halogen lamp system in Fig.4-(a) is introduced in conventional copy machine. The induction

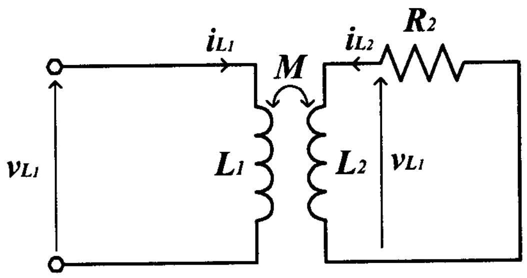
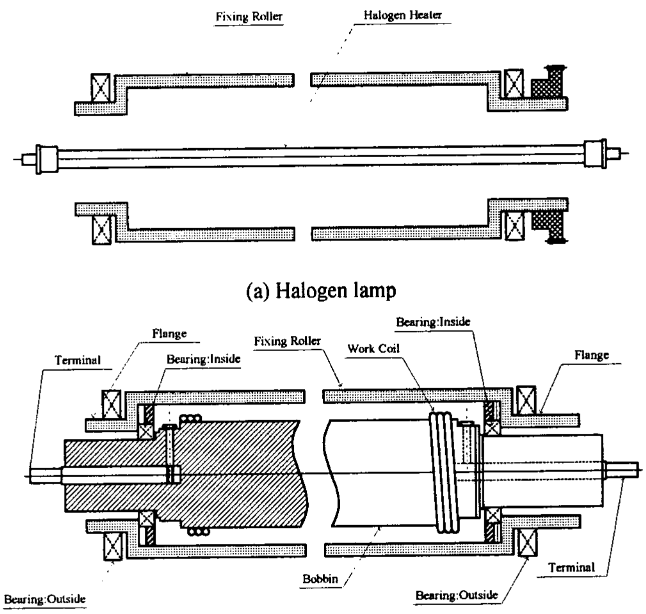


Fig.3. Transformer model of induction heating load



(b) Induction heating roller

Fig.4. Sectional view of fixing roller

heating roller drum which Fig.4-(b) demonstrates is newly adopted as induction heat fixing roller equipment.

III. Active Voltage Clamped ZVS-PWM High Frequency Inverter

III.I Circuit Description

Figure5 shows a schematic circuit diagram of the high frequency ZVS-PWM inverter using IGBT power modules. This inverter circuit is an active voltage clamp ZVS-PWM high frequency inverter topology with variable power constant frequency function used as induction heating fixing roller. The output power of this inverter can be adjusted by a constant frequency duty cycle-based asymetrical PWM control. Peak voltage stress of the main active power switch IGBT (Q_1 shown in Fig.5) can be reduced with a certain value, while ZVS operation can be realized in all the active power switches; Q_1 and Q_S. This inverter is mainly composed of the main active power switch $Q_1(SW_1/D_1)$ and the auxiliary active power switch $Q_S(SW_S/D_S)$, induction heating fixing roller, the quasi-resonant capacitor C_1 connected in parallel with the auxiliary active power switch Q_S in parallel, voltage clamped capacitor C_S (C_S>>C_1)connected in series with the auxiliary active power switch Q_S in order to clamp voltage applied to the main power switch Q_1. Induction heating load composed of working coil and induction heating fixing roller is represented by using the transformer equivalent circuit model with mutual inductances.

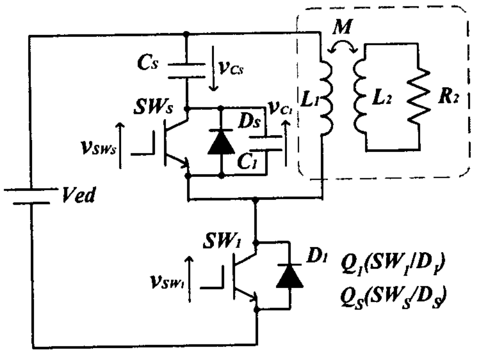


Fig.5. Active voltage clamped ZVS-PWM high frequency inverter using IGBTs

III.II Simulation and Experimental Results

Fig.6 illustrates typical steady state operation waveforms of the high frequency inverter. The design specifications and circuit parameters for simulation analysis are indicated at Table I.

Table I. Design specifications and circuit parameters

Parameter	Value
Operating Frequency f	21.0 kHz
DC Voltage Source E_d	282.8 V
L_1	80.0 μH
C_1	0.2 μF
C_S	2.0 μF
Time Constant τ	6.0 μs
Electromagnetic Coupling Coefficient k	0.65

In Fig.6, the active power switches turned off with zero voltage mode transition, and turned on with zero voltage and zero current states. Figure 7 shows the input power of this inverter and resonant initial current required for achieving ZVS commutation of this inverter which operates

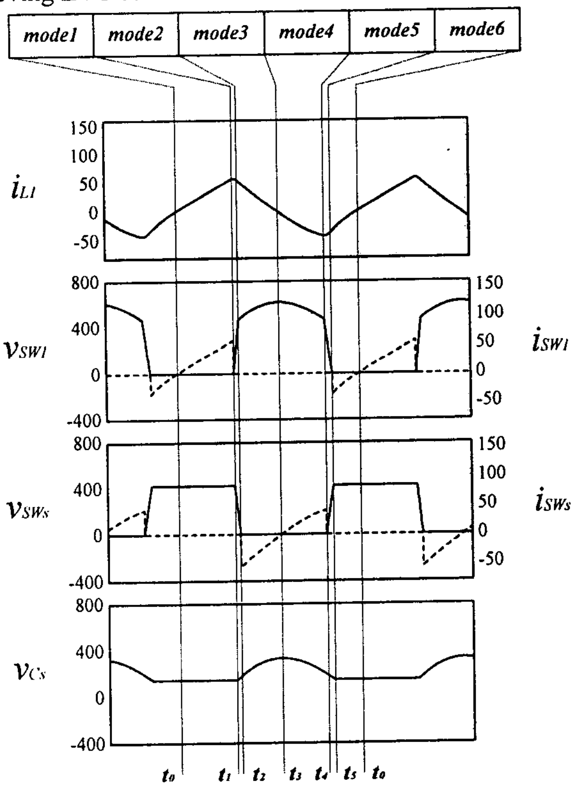
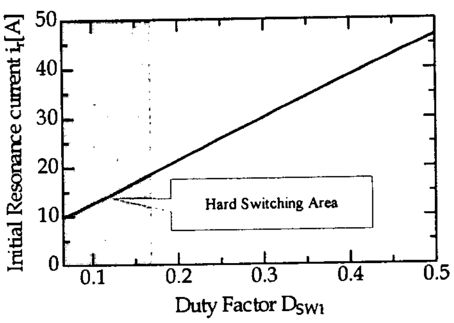
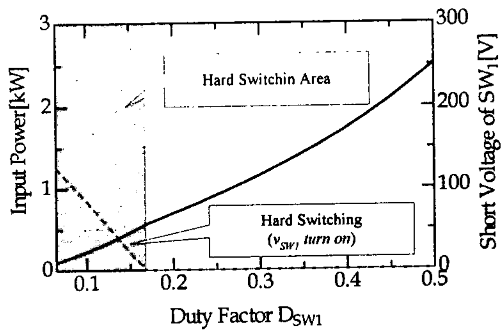


Fig.6. Operating waveforms



(a) Initial Resonance Current Characteristics



(b) Input Power Characteristics

Fig.7. Inverter Characteristics of PWM Control Scheme

under a constant frequency variable power regulation scheme. Masking area in Fig.7 is hard switching operation area of the main active power switch of the inverter in Fig.5. However, it is noted that auxiliary active power switch is the ZVS operation even in this area. When the main active power switch Q_I turns on, the hard switching mode causes under short-circuit the voltage applied to the main active power switch Q_I because of the residual voltage across the capacitor. If the voltage across the main active power switch Q_I is comparatively low in the main active power switch, it can be called the semi-ZVS operation and this masking area in Fig.7 (a)(b) is available from a practical standpoint in consumer power electronics. The hard switching operation in the main active power switch Q_I is dependent on charge and discharge operation of the resonance capacitor C_I (resultant capacitance C composed of C_I and C_S). In other words, hard switching operation in the main active power switch is decided by the current i_{LI} which flows through L_I when the auxiliary active power switch turns off. If current i_{LI} is sufficient for charge and discharge of the capacitor C_I, zero voltage soft switching is possible for the main active power switch Q_I. The current i_{LI} is defined as initial resonant current i_r in this paper. In duty cycle D≦0.17 area, the hard switching operation of the main active power switch Q_I occurs in the circuit of Fig.5 because current i_r is low.

This high frequency inverter is possible to control continuously the input power by duty cycle control strategy. However, hard switching of the main active power switch Q_I occurs in the area which input power is low. The condition of low input power is the preheating mode (the standby mode) in the copy machine so that it is necessary to complete soft switching in order to reduce power loss and electromagnetic noise by the inverter switching.

IV. Improved Quasi-Resonant High Frequency Inverter

IV.I Circuit Description

The improved circuit topology which enables zero voltage soft switching in the low input power area is actually required because there is a problem that the hard switching mode arises in low input power area. This paper presents an improved circuit topology with active inductor snubber for quasi-resonant ZVS-PWM high frequency inverter (shown in Fig.5). Figure 8 shows this improved inverter circuit topology. This improved circuit is similar to quasi-resonant high frequency ZVS-PWM inverter (shown in Fig.5). The additional active inductor snubber is connected in parallel for the working coil L_I. It is possible that the main active power switch Q_I turned on with zero voltage by adding active inductor snubber for the conventional high frequency ZVS-PWM inverter mentioned above. However, this active inductor snubber is used only area which the main active switch Q_I can not be turned on with zero voltage under duty cycle D≦0.2 in the conventional high frequency quasi-resonant inverter in terms of improvement of inverter efficiency.

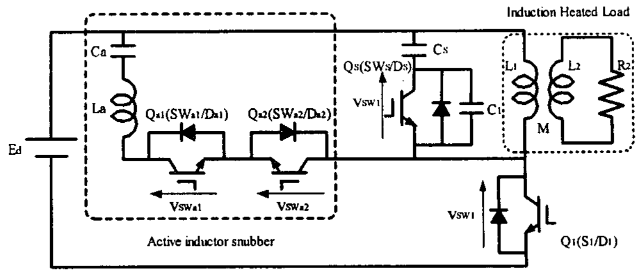


Fig.8. Active Voltage Clamped ZVS-PWM High Frequency Inverter with Sub Resonance Commutation Circuit Addition Type

IV.II Simulation and Experimental Results

Fig.9 shows steady state operation waveforms of the improved circuit topology. The parameters for the simulation analysis are shown in Table II.

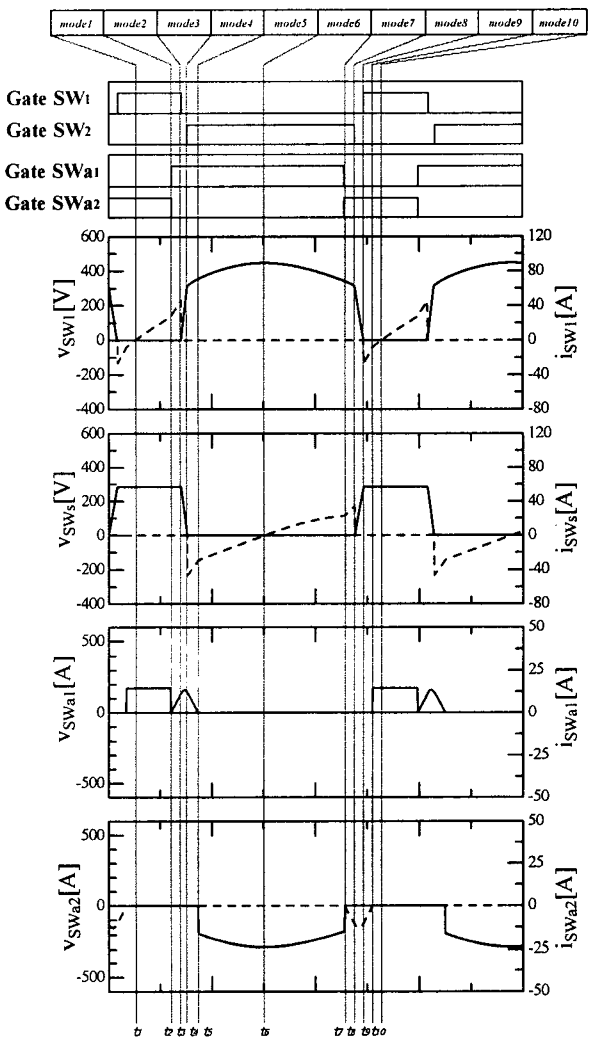


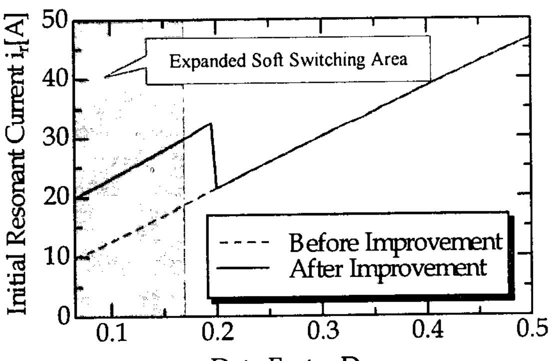
Fig.9. Steady state operation waveforms

Table II. Design specifications and circuit parameters

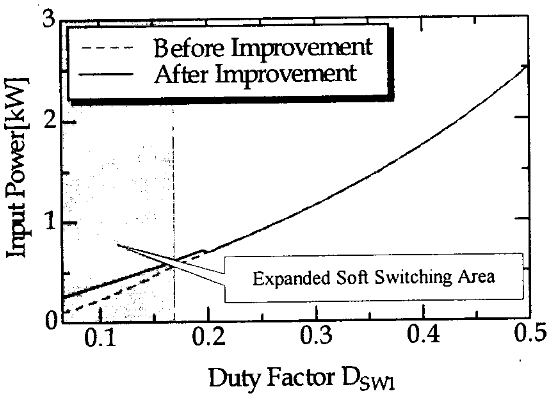
Parameter	Value
Operating Frequency f	21.0 kHz
DC Voltage Source E_d	282.8 V
L_I	80.0 μH
C_I	0.2 μF

C_S	2.0 μF
Relaxation Time τ	6.0 μS
Electromagnetic Coupling Coefficient k	0.65
L_a	30.0 μH
C_a	3.75 μH

The initial resonance current i_r is able to be increased by introducing this new high-frequency inverter topology at turning on Q_1 and Q_S so that this new inverter operates with the aid of this additional ZVS assisted circuit in order to achieve soft switching in low input power. In addition, both of the auxiliary active power switch Q_{a1} and Q_{a2} added to achieve soft switching are respectively turned on and off with zero current states, all the active power switches can be turned on with soft switching commutation of zero voltage or zero current. Figure 10 shows characteristics of initial resonance current i_r and input power P_{in}. The auxiliary active inductor snubber is effectively used only in the duty cycle≦2.0 area considered the margin for the hard switching area. In spite of adding a active inductor snubber, the input power of this high frequency inverter can be continuously controlled by duty factor adjustment. This resonance commutation circuit enables zero voltage soft switching in input power of high frequency inverter is low. In other words, the wide soft switching operation area can



(a) Initial Resonant Current Characteristics



(b) Input Power Characteristics

Fig.10. Advanced Characteristics for PWM Control Schime

be realized by this improved circuit that the active inductor snubber is added only in low input power area in which the main active power switch Q_1 can not be turned on and off with zero voltage or current states in the high frequency inverter circuit shown in Fig.5. It is possible to select the power semiconductor device IGBT of low capacity with good performance because the voltage and current of newly added active power switch are lower than those of SW_1 and SW_S.

V. Conclusions

This paper presented the improved quasi-resonant soft switching PWM high-frequency inverter with constant frequency variable power function for efficient induction heating copying machine, while operation principle of this inverter was described clearly. The steady state operation and power control characteristics and zero voltage soft switching area of high-frequency inverter were quantitatively explained graphically for duty factor control. It was possible to turn on and off with zero voltage applied to the active power switches for the low input power of high frequency inverter that additional active inductor snubber was newly added. This additional active inductor snubber was applied in duty factor≦2.0 from the efficiency improvement of this inverter. The input power of both inverters could be continuously controlled by changing duty factor, in particular, all the active power switches of high frequency inverter with active inductor snubber can turn on under zero voltage or zero current in the standby mode in which input power is specified to be low. From the above fact, the proposed soft switching inverter circuits were found to be useful for induction heating fixing in copy machine system which requires the standby mode. In the future, the analysis of efficiency, power losses and temperature characteristics of the closed loop control in induction heating fixing for copy machine should be done for the inverter treated here.

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