Experimental Studies of Series-Resonant Inverters Using PDM for Induction Hardening Applications

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Abstract: This paper deals with a high-power (50 kW) high frequency (150 kHz) voltage-fed inverter with a series-resonant load circuit for industrial induction heating applications, which is characterized by a full bridge inverter made of insulated-gate bipolar transistor and a power control based on pulse density modulation (PDM). This power control strategy allows the inverter to work close to the resonance frequency for all output-power levels. In this situation, zero-voltage switching and zero-current switching conditions are performed, and the switching losses are minimized. An additional improvement of inverter efficiency is achieved by choosing appropriate values of the modulation index. The inverter system is designed and the simulation is done using Matlab. The simulation and Hardware results of are presented. Results are verified experimentally using a prototype for induction hardening applications. The induction heater system uses embedded controller to generate driving pulses. The objective is to develop an induction heater system with minimum hardware.

Keywords: Induction heating, pulse density modulation (PDM) control, series-resonant inverter (SRI).

INTRODUCTION

INDUCTION heating generators are resonant inverters in which the resonant tank is formed by a heating coil and a capacitor, in a series-resonant inverter (SRI) [1]–[3] or in a parallel resonant inverter [4]–[7]. They are used to heat metals to be welded, melted, or hardened. The use of SRIs that are fed with a voltage source represents a cost-effective solution; however, it does not have the ability to control the output power by itself when a simple control circuit is used, so that the output power of such an inverter has to be controlled by adjusting the dc input voltage. A thyristor bridge rectifier having input inductors and a dc-link capacitor has been conventionally used as a variable dc-voltage power supply. This causes some problems in size and cost. In order to overcome these problems, an inverter with power control by frequency [8], [9] or phase-shift [10]–[12] variation is normally used to regulate the output power and, using a diode bridge rectifier, as a dc-voltage source. These power control schemes, however, may result in an increase of switching losses and electromagnetic noise because it is impossible for switching devices to be always turned on and off at zero current. Therefore, in high-frequency induction heating applications, only MOSFET inverters can be used. Nevertheless, insulated-gate bipolar transistors (IGBTs) are preferred in high-power industrial applications (availability, cost, etc.), and it will only be possible if a low-loss power control scheme is found. This paper describes an induction heating system of 50 kW and 150 kHz for industrial applications that use a novel low-loss control scheme. The induction system consists of a three-phase diode rectifier, a single-phase voltage-fed inverter using four IGBTs, and a series-resonant circuit with a matching transformer. The working frequency is automatically adjusted close to the resonance frequency in order to allow zero-current switching (ZCS) inverter operation for any load condition. In fact, the inverter performs as a quasi-ZCS because the transistors are always turned off at almost zero current. The output-power control based on pulse density modulation (PDM) maintains this condition in a wide range of output power. The blanking time of the inverter transistors is designed to maintain zero-voltage switching (ZVS) mode [13], [14]. With this circuit, an important improvement of the inverter efficiency is expected at high-frequency working conditions. In addition, this paper presents a study to determine the most appropriate values of the pulse density and the output current in order to obtain a further improvement of the inverter efficiency for high-frequency working conditions. Under these conditions and with fixed transistor losses, the total output power of the inverter will be increased, improving significantly the relative cost of the induction heating generators without reducing its reliability. Many practical work pieces in induction heating applications have a cylindrical shape and are heated by being placed inside of coils with one or more turns. The magnetic field, induced in the coil when it is fed with an alternate current, causes eddy currents in the work piece, and these give rise to the heating effect. A theoretical analysis demonstrates that most of the heat, generated by eddy currents in the work piece, is concentrated in a peripheral layer of thickness δ given by δ = (ρfμ)/µ, where ρ and µ are the magnetic permeability and electrical resistivity of the work piece, respectively, and f is the applied frequency (skin effect). Induction heating loads (heating coil and work piece) can be modeled by means of a series combination of its equivalent resistance RL and inductance LL. These parameters depend on several variables, including the shape of the heating coil, the spacing between the work piece and coil, the work piece temperature, its electrical conductivity and magnetic permeability, and the frequency. work piece temperature, its work piece. 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 this inverter are high switching speed, short-circuiting protection capability, superior no-load performance because of its current-limiting DC link characteristic and low component count.

II. THE PROPOSED CONVERTER

Fig. 2 shows the typical system configuration of a series generator for induction heating. The output-power stage consists of a single-phase voltage-source inverter using four IGBTs. The output of the inverter is connected to a series-resonant circuit with a matching transformer. The dc power supply for the inverter is a three-phase diode bridge rectifier connected to a 400-V 50-Hz power line. The working frequency is 150 kHz, the maximum rms value of the output voltage is 450 V, and the maximum output power is 50 kW. Water-cooled load is used [16]. The output current is limited by power losses in order to ensure the inverter reliability.

III. ANALYSIS OF THE PDM INVERTER

A. Switching Scheme

Fig. 3 shows the equivalent circuit of the voltage-fed series resonant PDM inverter and its switching modes. A conventional SRI changes between modes I and II in Fig. 3(a) and (b) to produce a square-wave ac voltage. In addition to modes I and II, the PDM inverter adds modes III and IV to produce a zero voltage State at its output terminals, as shown in Fig. 3(c) and (d). During mode III or IV, a gate turn-on signal is provided to either lower or upper leg IGBTs, respectively. As a result, both one IGBT and the diode connected in antiparallel to the opposite IGBT remain turned on. Fig. 3 shows the principle of the PDM-based power control. \( \nu_0 \) and \( i_0 \) are the output voltage and current of the inverter, respectively. The gate signals of transistor Q1 and Q3 are also represented. Signals Q2 and Q4 have been omitted since they are the complementary of Q1 and Q3, respectively. The PDM inverter repeats “run and stop” in accordance with a control sequence to adjust its rms output voltage.

\[ P = \frac{2}{\pi} V_d \cos \theta \frac{T_{on}}{T} \int_0^T \frac{E}{\tau} i_E(i) dt \]

\[ = P_{max} \left[ \frac{T_{on}}{T} + \frac{T}{T} \left( \frac{1 - e^{-T_{on}/T}}{1 - e^{-T/\tau}} \right) \left( e^{-T_{on}/T} - e^{-T/\tau} \right) \right]. \]

If \( T \ll \tau \) (high values of the resonant load quality factor), the envelope of the output current is \( i_E \approx \text{Imax(Ton/T)} \); thus, the output power can be written as

\[ \lim_{\tau \to 0} P = P_{max} \frac{T_{on}}{T}. \]
The term Ton/T is defined as modulation index or pulse density, and its value determines the output power. One differentiating characteristic of this work consists in the fact that the maximum output power of the inverter, when working at high frequencies, is obtained for modulation index values less than one, due to a major improvement in the inverter efficiency.

\[ \lim_{T \to 0} P = P_{\text{max}} \left( \frac{T_{\text{on}}}{T} \right)^2. \]  

Fig. 3.1. Switching pattern in PDM.

C. ZVS

Fig. 3.2. shows a detail of the voltage and current at the output of the inverter in mode I or II. The vertical dashed lines represent the times when the IGBT are turned off (toff) and turned on (ton), and td is the blanking time when all transistors are turned off. The origin of time is set at the zero crossing of the inverter current \( i_o = I \sin(\omega_o t) \). In order to prevent undesirable off switching of diodes, the turn-on of transistors must occur necessarily before the zero crossing of the inverter current. This means that the switching frequency should be larger than the resonant frequency. On the other hand, the ZVS is achieved only if the +Vd (or vice versa) is achieved just before of the turn-on process. To ensure this condition, the following calculations must be done. When an IGBT is turned off at the time toff, the inverter output voltage \( v_o \) starts to rise up from \(-Vd\), as given by the following expression:

\[ v_o(t) = -Vd + \frac{1}{C_e} \int_{-t_{\text{off}}}^{t} i_o \, dt \]

\[ = -Vd + \frac{I}{\omega_o C_e} \left( \cos \omega_o t - \cos \omega_o t_{\text{off}} \right) \]  

This time is also used to define the minimum value of the blanking time td.

A working frequency of 150 kHz, a maximum amplitude of inverter current of 300 A, and a dc-link voltage of \( Vd = 520 \) V are assumed in the design of the experimental system. The total equivalent capacitance of the inverter switches, including the snubbing capacitor and the output capacitance of the IGBT, is approximately 20 nF. Since the toff min obtained from (5) is 385 ns, toff is set up as 550 ns for the experimental system. The blanking time td is set as 400 ns. A phase-locked loop (PLL)-based switching frequency control discussed in the following section makes the PDM inverter achieve ZVS condition.

IV. SIMULATION RESULTS

The PWM inverter circuit of IGBT series-resonant inverters using pulse density modulation is shown in figure 4.3. This AC supply is converted into DC then it give as input to inverter. Then the ac is boosted by using a high frequency transformer then this boosted ac voltage is passed through load. The AC input voltage waveforms are shown in figure 4.4(a).

The switching pulses for Q1 & Q2 is shown in figure 4.4(b). The Switching pulses given to Q3 & Q4s similar that of Q1 & Q2. The gate voltage and drain to source voltage waveforms of the switches is shown in figure 4.4(c). The primary voltage waveform of the transformer is shown in figure 4.4 (d). Similarly the secondary voltage waveform of the transformer is shown in figure 4.4 (e). The output
voltage waveform of the circuit is shown in figure 4.4 (f). Then the output current waveforms of the circuit are also is shown in figure 4.4 (g). Finally the output voltage and current are shown in single scope in figure 4.4(h).

V. Hardware Results

Laboratory model is fabricated and tested. Top view of the hardware is shown in fig. 5a. The hardware consist of control board and power board. The pulses are generated using microcontroller. Dc input voltage is shown in fig 5b. Drain current waveform is shown in 5c. Driver output waveform is shown in fig 5d. Output of the Inverter is shown in Fig. 5f. Output of the Inverter is not a pure sine wave due to the resistance present in the circuit.
VI. CONCLUSION

This paper has proposed a voltage-source series-resonant PDM inverter for induction heating industrial applications. This power control strategy allows the inverter to work close to the resonance frequency for all output-power levels. In this situation, ZVS and ZCS conditions are performed, and the switching losses are minimized. Therefore, IGBT transistors can be used for an optimum design of the power stage. A 50-kW 150-kHz PDM inverter prototype with IGBT has been tested successfully in order to meet the industrial application requests. Tests made with the presented prototype using the IGBT module FZ600R12KS4. This quantitative comparison concludes that the PDM inverter would be more suitable for various induction heating applications, particularly those of high frequency when IGBT transistors are applied.

The converter using full-bridge inverter is simulated using matlab simulink. The proposed circuit is implemented using microcontroller based driver circuit. The response of micro controller based system is faster since Atmel controller operates at 12MHz. The experimental results are in line with the simulation results. This work deals with open loop system. The closed loop implementation is beyond the scope of the work. This inverter system can also be used for dielectric heating.

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