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Comparison of Simulation and Experimental Results of Class - D Inverter Fed Induction Heater

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Abstract: This research deals with simulation and experimentation of closed loop controlled class-D inverter fed induction heater system. This converter has reduced switching losses, stress and increased power density. The inverter system is designed and the simulation is done using Matlab. The results of simulation and experimentation are presented. The induction heater system uses embedded controller to generate driving pulses. The objective is to develop an induction heater system with minimum hardware.

Key words: Class-D inverter, closed loop control, induction heating (IH), zero voltage switching

INTRODUCTION

Induction heating is a well-known technique to produce much higher temperature such as in steel melting, brazing and surface hardening. In this system, a class D inverter is used to control the fluctuation in the input and prevent it from affecting the working of heater. 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 compared to a voltage-fed inverter topology. Common topologies of class D inverter in induction heating applications are full-bridge and half-bride inverter in low power application such as cooking and small forging systems. The half-bridge inverter is preferable due to less number of switches required. However the half-bridge inverter suffers losses at the two high frequency inductors and a risk of saturation on both inductors. The controller of class D inverter needs to maintain the operating frequency at little higher than the resonant frequency for IH system.

The requirements for the IH system are given as follows:

- High-frequency switching
- High power factor
- Wide load range
- High efficiency
- Low cost
- Reliability

A high-frequency class-D inverter has become popular and is widely used in various applications. It must be effectively selected under a high-frequency switching operation due to load specifications. In addition, one of the main advantages of the class-D inverter is low voltage across the switch, which is equal to the supply voltage. Thus, compared with other topologies (class-E quasi-resonant inverter, etc.,) for IH applications, the class-D inverter is suited for high-voltage application (Kazimierczuk, 1991). Generally, almost all IH applications use a variable-frequency scheme, Pulse-Frequency-Modulation (PFM), and pulse-amplitude modulation (PAM) to control the output power (Koertzen *et al.*, 1995; Kazimierczuk *et al.*, 1992). Between them, frequency-modulation control is the basic method that is applied against the variation of load or line frequency. However, frequency-modulation control causes many problems since the switching frequency has to be varied over a wide range to accommodate the worst combinations of load and line. Additionally, in case of operation below resonance, filter components are large because they have to be designed for the low- frequency range. In addition, it is apt to audible noise when two or more inverters are operated at the same time with different switching frequencies. Besides, the soft-switching operating area of the Zero Voltage Switching (ZVS)-PFM high-frequency inverter is relatively narrow under a PFM strategy. Keeping the constant switching frequency and controlling the output power by Pulse Width Modulation (PWM) are obvious ways to solve the problems of variable- frequency control. Therefore, class-D-inverter topologies using a PWM chopper at the input, phase-shifted PWM control, PWM technique, pulse width modulation- frequency modulation (PWM-FM) technique, current-mode control, and a variable resonant inductor or capacitor have been proposed (Izaki *et al.*, 1995; Matysik, 2006). The constant-switching- frequency operation supposes that each inverter in the applications is operating at the same frequency, making it necessary

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to control power without frequency variations, and this is highly desired for the optimum design of the output smoothing and noise filters. However, these control requirements and operating characteristics have considerable complexity due to the fixed switching frequency, which limits their performance (Bhat, 1992). In addition, if the system is operated with phase-shifted PWM control, the ZVS is not achieved at light load (Ngo, 1988; Wu *et al*., 1995). To simplify output-power control, a full-bridge Zero-Current Switching (ZCS) - Pulse-Density Modulation (PDM) class-D inverter is proposed (Fujita *et al*., 1996). The output power of the ZCS-PDM class-D inverter can be controlled by adjusting the pulse density of the square-wave voltage. When the class-D inverter operates at a fixed switching frequency that is higher than its resonant frequency, it can maintain ZVS operation in the whole load range. Thus, the switching losses and electromagnetic interference (EMI) are decreased. In addition, by adjusting the duty cycle of fixed low frequency, the output power is simply controlled in a wide load and line range. The advantages of a new power-control scheme are simple configuration and wide power-regulation range. It is easy to control the output power for wide load variation. In addition, the switches always guarantee ZVS from light to full loads, and a filter is easy to design by using the constant switching frequency. The power-control scheme and principles of the class-D inverter are explained in detail. The above literature does not deal with simulation of closed loop controlled class D inverter. This research presents simulation of closed loop class D inverter fed Induction Heater. The experimental results are compared with the simulation results.

Class D series resonant inverter: A class D inverter is generally used to energize the induction coil to generate high frequency magnetic induction.

Figure 1 shows the class D inverter system for induction heating. The class D inverter consists of two switches S_1 and S_2, a resonant capacitor C_1, inductor L_1 and an induction coil. Induction coil is represented as parallel combination of inductor L_2 and resistor R. Figure 2 represents the equivalent circuit model of the class D inverter.

The steady-state analysis of the class-D inverter is based on the following assumptions:

- All components are ideal
- The DC input voltage is constant in one switching cycle
- The effects of the parasitic capacitances of the switch are neglected
- The load current is nearly sinusoidal because loaded quality factor Q_L is high enough

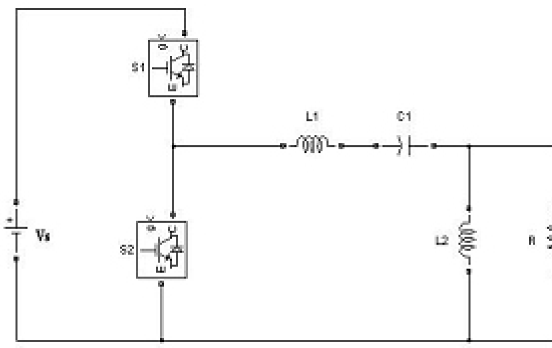

Fig. 1: Class D inverter system for IH

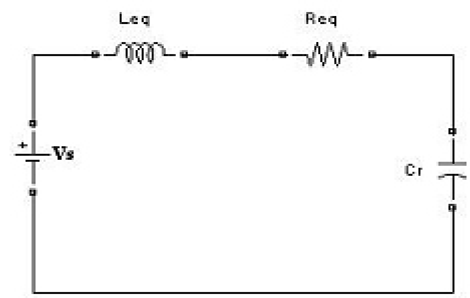

Fig. 2: Equivalent circuit

The currents in positive and negative half cycles are as follows:

$$i_1 = (V_s + V_c / \omega_r)\, e^{-\alpha t} \sin \omega_r t \qquad (1)$$

$$i_2 = (V_c / \omega_r L)\, e^{-\alpha t} \sin \omega_r t \qquad (2)$$

RESULTS

Simulation results: Class D inverter simulink circuit is shown in Fig. 3a. For induction heating class D inverter is used. This inverter converts DC input power into AC output power. This conversion is achieved by turning on and off alternately switches 1 and 2.

The voltage across the load is measured with the help of voltage measurement block and the output current is measured with the help of current measurement block and they are observed using a scope. Driving pulses given to the MOSFET are shown in Fig. 3b. Output voltage and current are shown in Fig. 3c. Both are sinusoidal due to the presence of L and C. The variation of output with the variation in the input is shown in Fig. 3d. The output voltage increases with the increase in the input voltage.

The circuit of open loop system is shown in Fig. 4a.The rectifier output voltage increases due to the step rise in input. The output voltage of the inverter is measured with the help of voltmeter and it is observed using a scope. Similarly the current through the load is

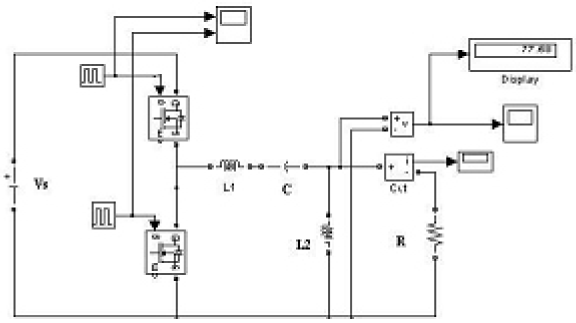

Fig. 3a: Circuit diagram

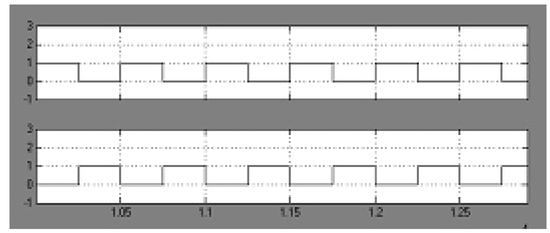

Fig. 3b: Driving pulses

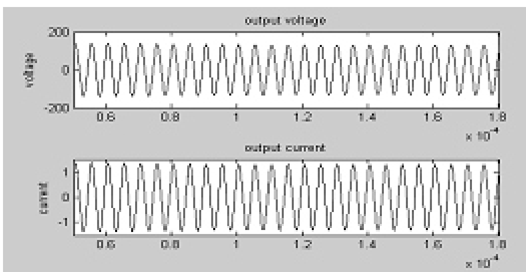

Fig. 3c: Output voltage and current

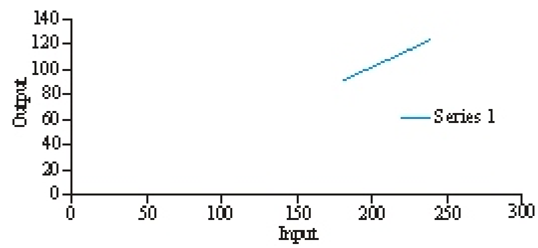

Fig. 3d: Variation of Output

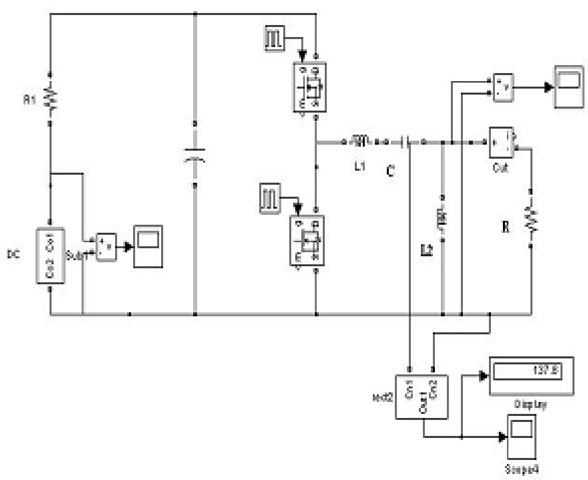

Fig. 4a: Circuit diagram of open loop system

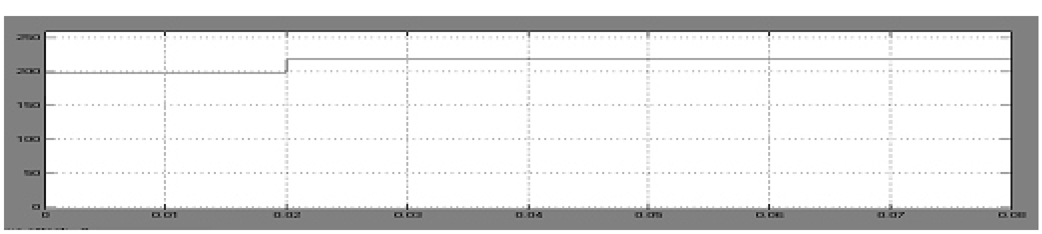

Fig. 4b: Input voltage with disturbance

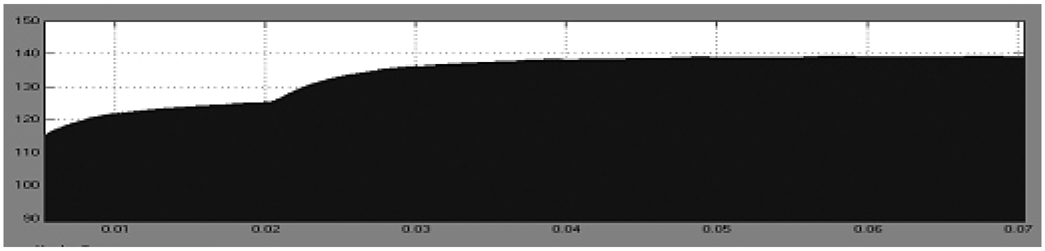

Fig. 4c: Output voltage with disturbance

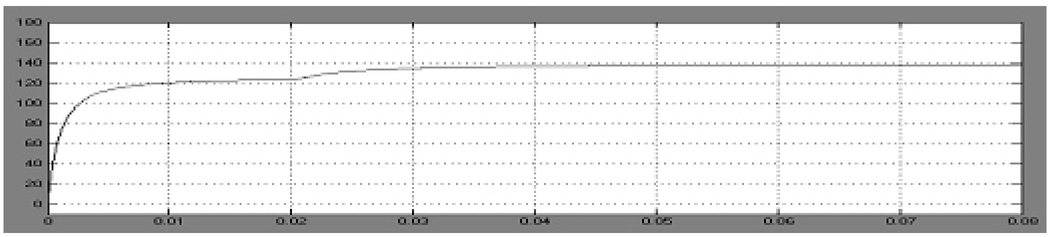

Fig. 4d: Rectifier output voltage

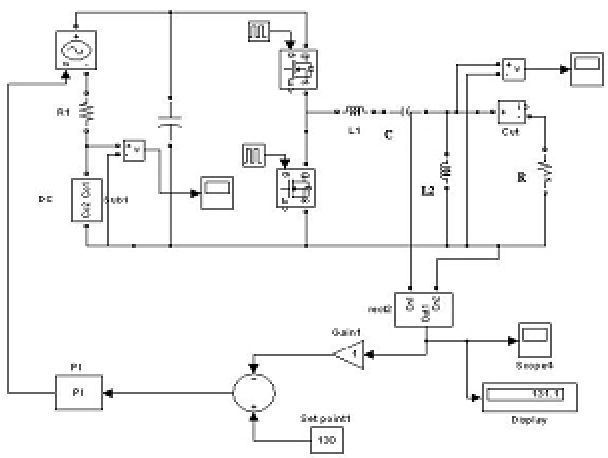

Fig. 5a: Circuit diagram of closed loop system

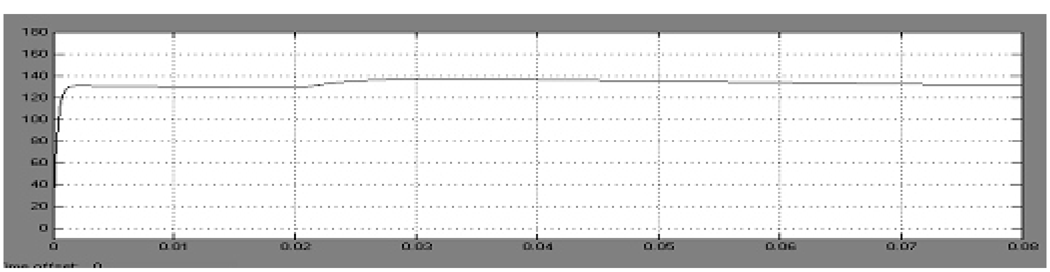

Fig. 5b: Rectifier output voltage

measured with the help of ammeter and it is observed using a scope. Input voltage and output voltage with a disturbance are shown in Fig. 4b, c, respectively. The voltage across the rectifier is shown in Fig. 4d.

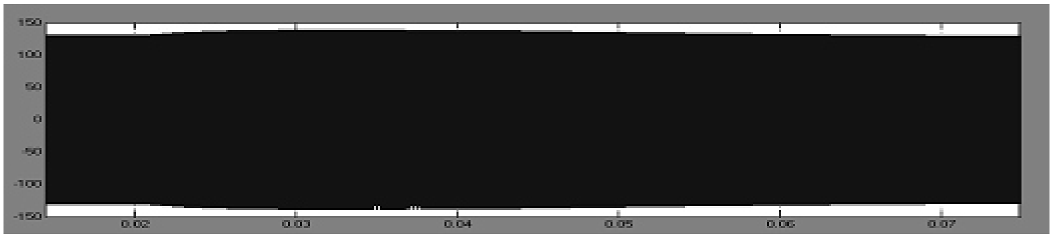

Fig. 5c: Output voltage

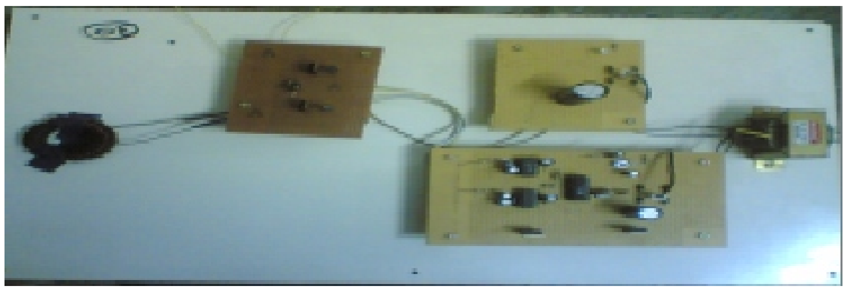

Fig. 6a: Hardware Circuit

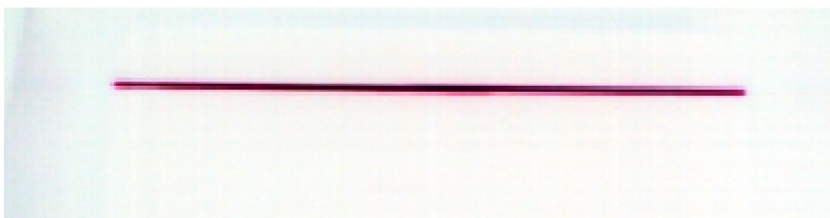

Fig. 6b: DC Input Voltage

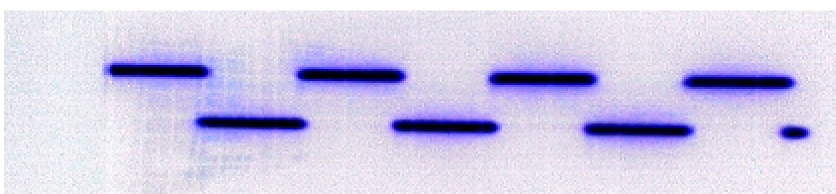

Fig. 6c: Driving Pulses

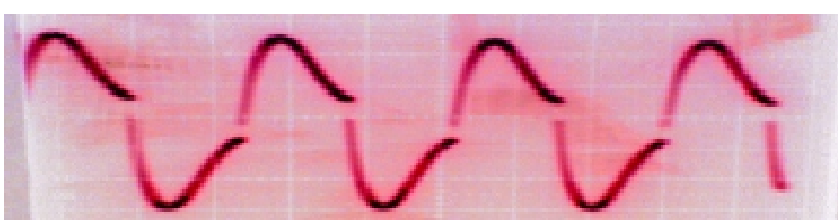

Fig. 6d: Output of class D inverter

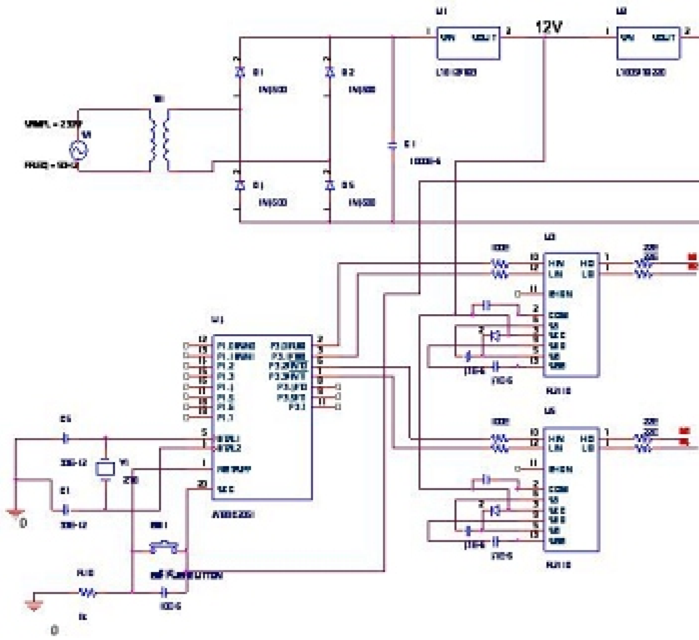

Fig. 6e: Control Circuit

In open loop system the rectifier output voltage increases and it is undesirable. This is prevented by using closed loop system. The circuit of closed loop system is shown in Fig. 5a.

In closed loop system, output voltage is given to the rectifier and the output of rectifier is given as input to the comparator. The comparator output is given to a PI controller. The output of PI controller controls two pulses given to the two switches. In closed loop system the rectifier output voltage reaches steady state value as shown in Fig. 5b. Output voltage of closed loop system is shown in Fig. 5c. It can be seen that the output reaches constant value. The steady state error in the output is reduced.

Experimental results: The hardware is fabricated and tested in the laboratory. Top view of the hardware is shown in Fig. 6a. The DC input voltage is shown in Fig. 6b. Driving pulses given to the MOSFET are shown in Fig. 6c. The output of the class D inverter is shown in Fig. 6d. The control circuit used for generating the pulses are shown in Fig. 6e. The microcontroller 89C2051 generates the pulses. The pulses are amplified using the driver IC 2110.

CONCLUSION

The class D inverter fed induction heater system is simulated and implemented. This system operates at high efficiency due to soft switching. The simulation and experimental results are presented. It is observed that the experimental results are similar to the simulation results. This system has advantages like reduced volume, reduced hardware and faster response. Volume of L and C is reduced due to high frequency operation. Hardware is reduced since it uses only two switches. Faster response is obtained by using Atmel micro controller.

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