

Automatic frequency Control Current-Source Inverter for Forging Application

Saichol Chudjuarjeen, Chayant Koumpai, and Veerapol Monyakul

Department of Electrical Engineering, King Mongkut’s University of Technology Thonburi , Bangkok, Thailand 10140
(Tel : +66-24709033; Email: saichol_70@hotmail.com)

Abstract: The paper describes an automatic frequency control current-fed inverter for forging applications. The IGBT in series with diodes as its switching devices in the inverter circuit which is of full-bridge type. The operating frequency is automatically tracked to maintain a small constant leading phase angle when load parameters change. The load voltage is controlled to protect the switches. The output power can be adjusted by varying the input current from phase controlled rectifiers which is a part of current source. The system has been operated at 15-17 kHz. The output power transferred to the load is 1,595 watts. It can heat the steel work pieces with 15 mm diameter and 120 mm long from room temperature to approximately 1100 ° C within 20 seconds with 0.97 leading power factor on the input side.

Keywords: Induction heating, current-fed inverter, resonant frequency tracking, forging application, parallel resonant inverter, current source, full-bridge inverter.

1. INTRODUCTION

The principles of induction heating are used in various applications such as brazing, surface hardening, forming and annealing. Each application uses different appropriate frequency. In forging application frequency depends on work-pieces geometry and skin depth requirement [1-3]. A large number of topologies has been developed in this area. Among them, current-fed and voltage-fed inverters are most commonly used [4]. The advantages of current fed inverter are short-circuit protection capability and superior no-load performance because of its current-limiting dc link characteristic. Voltage-fed or Current-fed inverter for induction heating applications have employed many switches such as MOSFET, SIT, SCR. Also in recent year, induction heating system using IGBT, which has the advantage of low conduction loss, high speed switching time and very little gate drive power. Due to the switches which used in the current fed inverter have to block bipolar voltage therefore diodes are used to connect in series with each IGBT in order to block reverse voltage [5].

When a work-piece is inserted into an induction coil, variation of induction heating load parameters can affect resonant frequency resulting in reduction of load power. Therefore, it is necessary to track operating frequency in order to obtain high power factor.

This paper describes the IGBT full-bridge current-fed inverter for forging application. The operating frequency is automatically adjusted to maintain constant leading phase angle when parameters of induction heating load are varied. The output power can be controlled by input current setting. The load voltage is controlled to protect the IGBT.

2. PRINCIPLES OF INDUCTION HEATING

In the heating of some work-pieces, it is required high purity. The induction heating method is the suitable method for such applications due to the non-contact between the induction coil and the work-pieces. They are heated by being placed inside an induction coil. The magnetic field, induced in the coil when energized, causes eddy currents in the work-pieces and increases the heating effect. The basic concepts are similar to the well known transformer theory, but modified to a single-turn short-circuited secondary winding. An equivalent circuit of the induction coil and work-piece is shown in Fig. 1.

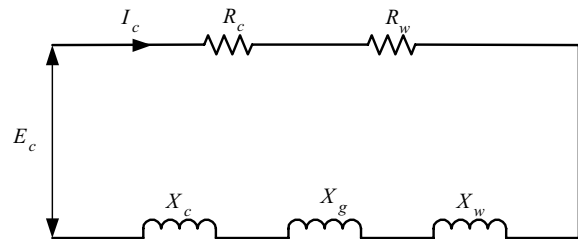


Fig 1. The equivalent circuit of induction coil and work-piece [3]

Whence

$$Z = (R_w + R_c) + j(X_g + X_w + X_c) \tag{1}$$

Where

Work resistance, $R_w = K(\mu_p A_w)$ ohms $\tag{2}$

Coil resistance, $R_c = K\left(\frac{k_r \pi l_c \delta_c}{2}\right)$ ohms $\tag{3}$

Gap reactance, $X_g = K(A_g)$ ohms $\tag{4}$

Work reactance, $X_w = K(\mu_r q A_w)$ ohms $\tag{5}$

Coil reactance, $X_c = K\left(\frac{k_r \pi l_c \delta_c}{2}\right)$ ohms $\tag{6}$

$$K = 2\pi f \mu_0 \left[\frac{N_c^2}{l_c}\right] \text{ ohms per square metre. } \tag{7}$$

where

μ_r is the relative permeability

A_w is the cross section area of work-piece

A_g is the area of gap

k_r is the coil correction factor that ranging from 1-1.5

N_c is the number turn of induction coil

l_c is the length of gap

d_c is the diameters of induction coil

(p and q are function for a solid cylinder)

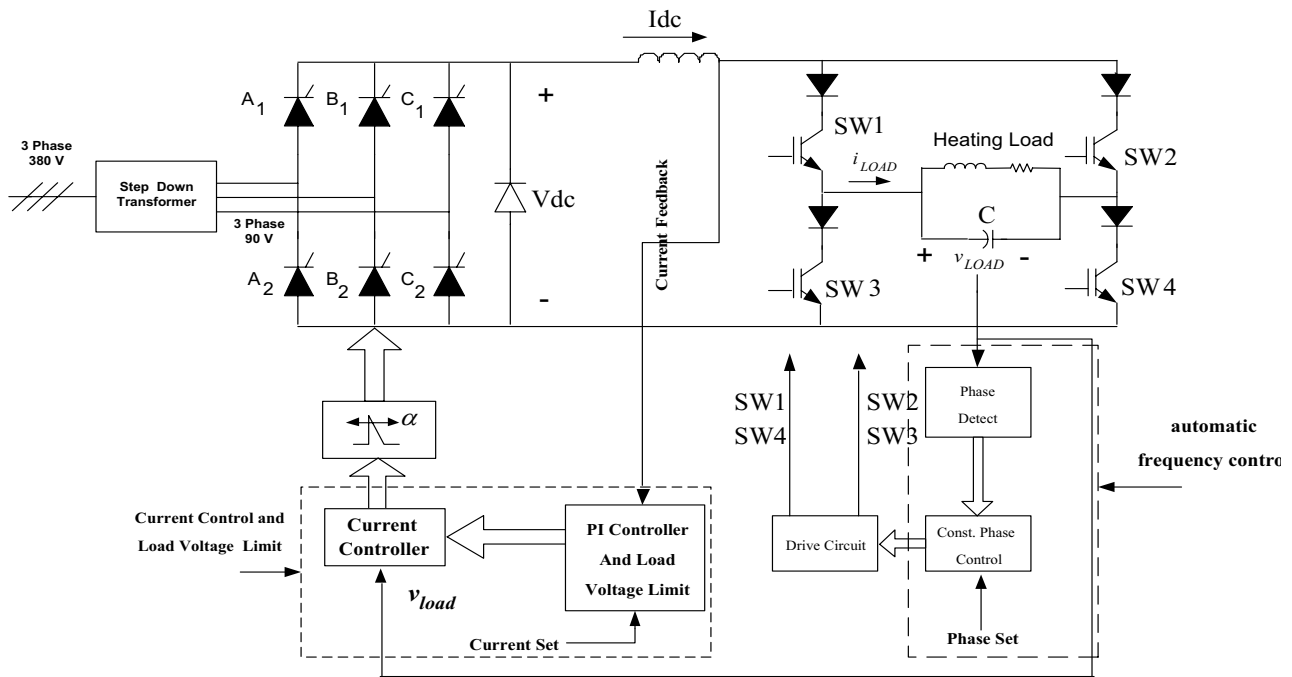


Fig. 2 Structure of the induction forging system

As shown in fig. 1 and above equations. The parameters of induction heating load (induction coil and work-piece) depend on several variables including the shape of the heating coil, the space between the work-piece and coil, their electrical conductivities and magnetic permeabilities, and the frequency[1],[3].

3. CIRCUIT DESCRIPTION AND OPERATION

The structure of the induction forging system is shown in Fig.2 It consists of a step down transformer, three-phase controlled rectifier, single-phase full-bridge IGBT inverter, an induction heating load (induction coil and work-piece), or automatic frequency control, a close loop current control and load voltage limit.

3.1 Current Source and Control

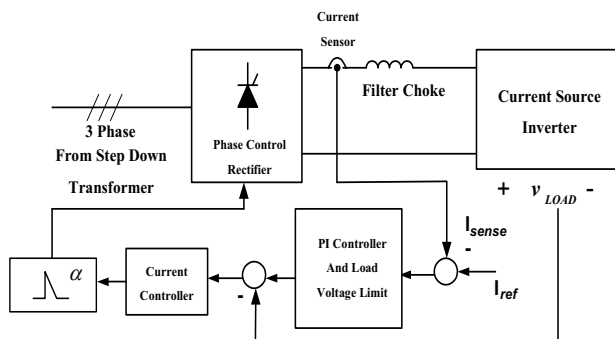


Fig. 3 Block diagram of the current control loop

The current source comprises three phase controlled rectifier and free-wheeling diode which along with filter choke produces a constant dc link current with small ripple. A close loop current control and load voltage limit are shown in fig. 3. A close loop control continuously adjusts the firing angle of the controlled rectifier to maintain a constant dc link current. The load voltage is also controlled to protect the switches.

We used TCA785 as a pulse generator which receives commands from current controller to provide constant current. The current controller employs Proportional Integral (PI) for current controller and LEM LT 100-P is used as a current sensor. Furthermore, there is a voltage controller to protect IGBT from over-voltage by comparing the output voltage with the setup value of the limit voltage circuit. Due to output of inverter is ac, thus it must be converted to dc by ideal rectifier in order to measure output voltage of the inverter.

3.2 Inverter

From fig. 2, type of inverter is used as full-bridge current source topology because: it has an inherent short-circuit protection capability and has a simple design structure, using few components. The parallel resonant inverter or current source inverter needs a switch that can block a bipolar voltage. It can make appropriate switching action by connecting a switch and diode in series. The output voltage of the inverter is sinusoidal, in the case of low Damping Factor and operating frequency is near resonant frequency. The inverter is selected to operate at a little higher inverter frequency than a resonant frequency, in order to achieve zero-current soft-switching [5] which reduces loss at IGBTs switches and protects spike voltage. The voltage across switch has both positive and negative values. The positive voltage is blocked by IGBT and negative voltage is blocked by diodes.

The switching sequence of the inverter stage is as follows:

- SW₁, and SW₄ ON
- SW₁, SW₂, SW₃, and SW₄ ON
- SW₂, and SW₃ ON
- SW₁, SW₂, SW₃, and SW₄ ON

The sequence of the gate signal fed to the gate drive circuit which is shown in Fig. 4. The overlap period when all switches are turn on, it is necessary to protect the filtering choke from the opening circuit.

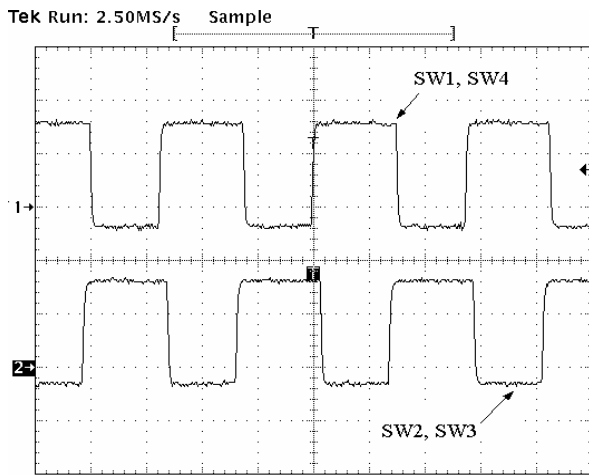


Fig. 4 Control gating signal
(V_{gate} : 10V/div, Time :20 μ s/div.)

The used IGBT's are from International rectifier and IRGPC50U devices. The type of diodes is ultra fast recovery from International rectifier and IR60HFU devices. The photo couplers TLP250 is used to drive gate of IGBTs. To drive the gate of IGBT on at voltage +15 V which is a suitable value to minimize losses. When IGBT is drive off at voltage -5 V, self-conduction due to external noise is prevented.

3.3 Inverter Control

The work-pieces geometry, conductivity and permeability of different metals tend to change the inductance of the heating coil when inserted into it. Considering the fact that the resonant capacitance is fixed, the tank circuit is driven to its new resonant frequency by tracking the switching frequency of the inverter. The phase-locked loop integrated circuit device for load-adaptive parallel resonant frequency tracking is introduced for resonant inverter.

An automatic frequency control is shown in Fig. 5. It comprises voltage sensor at load, zero crossing detector, phase shift circuit, phase detector, VCO and PI controller. The phase-locked loop integrated circuit is applied for frequency control at a little higher inverter frequency than a resonant frequency. By using exclusive-OR gate and VCO in IC 4046 that are the phase locked IC. For current fed inverter, gate drive signal is in phase with signal of load current phase. Hence, we can use gate drive signal instead of load current pulse. Current signal was compared with voltage signal in order to detect the difference of the phase by exclusive-OR gate, which admires to use to be a phase different detector. In close loop by using IC phase locked loop, we have to convey the voltage signal passes a zero crossing detector to shift 90° of phase origin before bringing it into exclusive-OR gate. The

signal which leaves from exclusive-OR gate was filtered by RC low pass filter to get an average value of voltage. The average voltage conforms with different of phase between voltage and current at load. At that time the voltage is sent into compare with required phase set. The phase error from comparison is the input of constant phase controller to adjust voltage control oscillation in order to maintain the constant leading phase angle when parameters of heating load are varied.

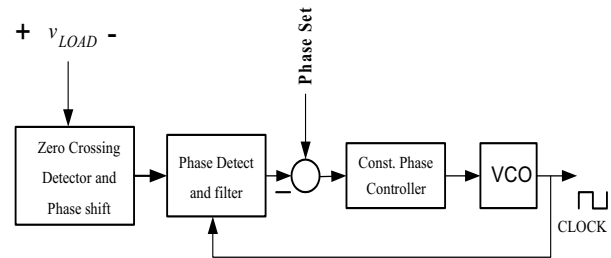


Fig. 5 Diagram of the automatic frequency control

3.4 Resonant capacitor bank

The loaded work coil has very poor power factor. It is necessary to have reactive power compensation with a capacitor bank connected in parallel to the coil. The parameters of induction heating can be modeled by means of series combination of its equivalent series resistance and reactance. Its model can be changed to be parallel circuit as shown in fig. 6

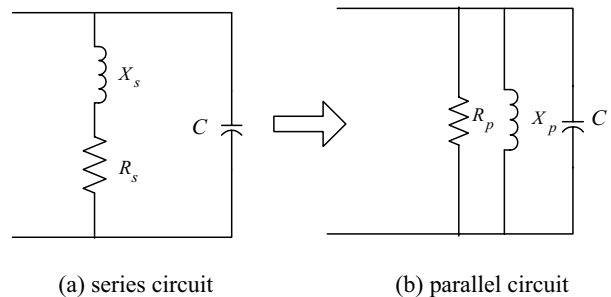


Fig. 6 Changing series circuit to parallel circuit Equivalent

The expression for the complex impedance of the parallel circuit at any frequency (f) is given by [10]

$$Z(f) = \frac{R_p}{1 + jQ_p \left(\frac{f}{f_0} - \frac{f_0}{f} \right)} \quad (8)$$

Where

R_p = Equivalent resistance of the tank circuit as seen by the source.

X_p = Equivalent reactance of the tank circuit as seen by the source.

Q_p = Quality factor of the tank circuit.

f_0 = Natural resonant frequency of the tank circuit.

The operating frequency is selected at 16 kHz which is the optimal point of skin depth, efficiency and power factor for induction load. From Eqs. (1) ~ (6) can calculate $X_s = 0.575 \Omega$, $L_s = 5.75 \mu\text{H}$, due to the loaded work-coil has very poor power factor (<0.1). So $R_s \ll X_s$, can be estimate $X_s = X_p$, so $L_s = L_p$ [7],[8]. We can select the capacitor which will connect with parallel induction coil for required interval by $C = 1/(\omega^2 L_p) = 17.2 \mu\text{F}$. The capacitor value is $17.5 \mu\text{F}$ which can be approximate to value and easy to provide.

4. EXPERIMENTAL RESULT

A prototype is built and tested by feeding heat to a work-piece which has diameter of 15 mm. and length of 120 mm. Induction coil is paralleled with $17.5 \mu\text{F}$, capacitor. all measured signals are taken at around 1100°C work-piece temperature.

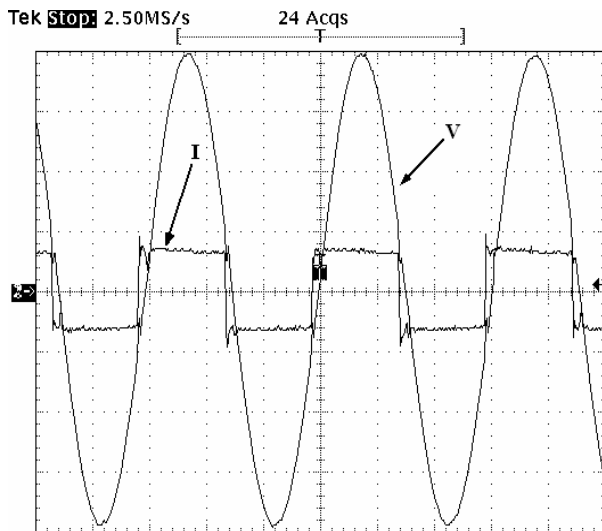


Fig. 7 The inverter output voltage and current wave forms (I : 20A/div, V : 50V/div and Time : $20 \mu\text{s/div.}$)

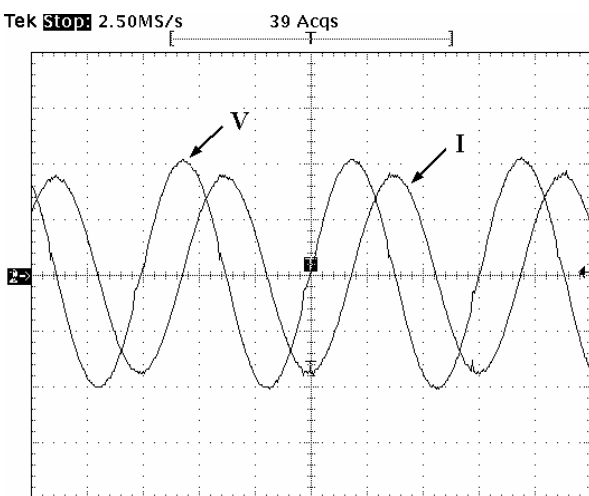


Fig. 8 The inverter load voltage and the coil current wave forms of inductor (I : 200A/div, V : 50V/div and Time : $20 \mu\text{s/div.}$)

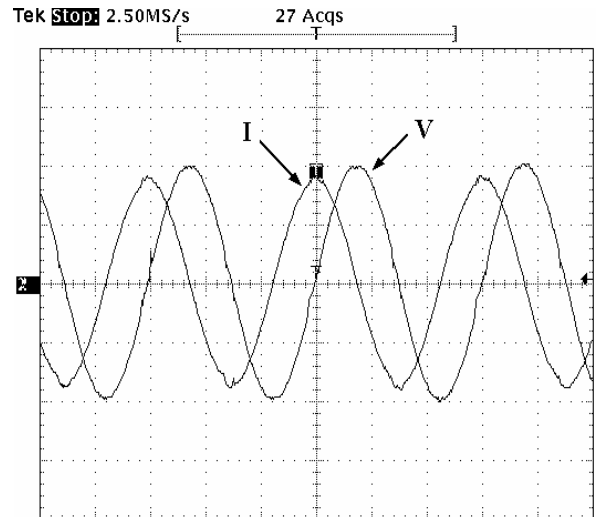


Fig. 9 The inverter load voltage and the current wave forms of capacitor (I : 200A/div, V : 100V/div and Time : $20 \mu\text{s/div.}$)

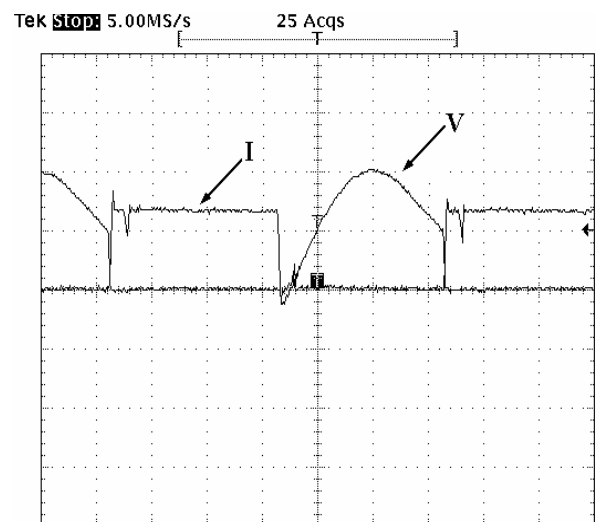


Fig. 10 The switching voltage and current waveform across IGBT (I : 10A/div, V : 100V/div and Time : $10 \mu\text{s/div.}$)

Fig. 7 shows the output sinusoidal voltage and pulse current wave forms in repetitive steady state under a full-load condition. The leading of phase angle is about 14° . Fig. 8 shows the current wave forms of inductor lags the load voltage. Fig. 9 shows the current wave forms of capacitor leads the load voltage. Fig. 10 shows the switching voltage and current waveform across IGBT at 16.8 kHz, it is obvious that zero-current soft-switching and no voltage spikes is present hence the need for any snubber circuit or voltage clamping devices was eliminated, which reduced the number of components needed for the inverting stage.

The input power is 1,757 W, leading power factor is 0.97. The power at coil is 1,595 W, so efficiency of rectifier and inverter is 90.78 %

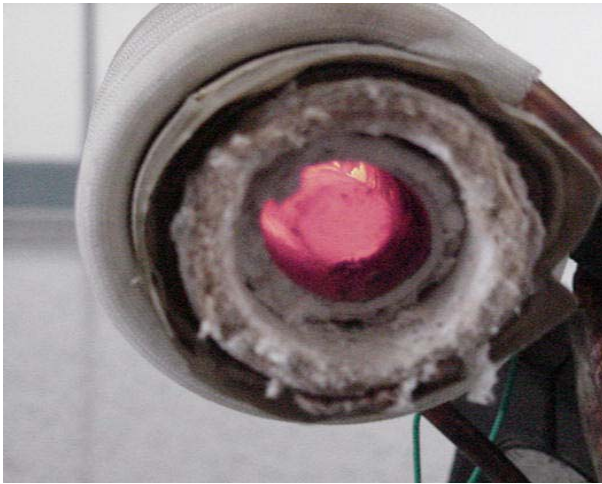


Fig. 11 A work-piece at 1100 °C

Fig. 11 shows the induction heating load. It consists of a 15-turn, water-cooled copper coil made from 5 mm hollow tube. It has refractory insulator between induction coils. The induction coil has insulator to weld with copper is used to be an electrode. The steel work-pieces are cylindrical and are placed an internal refractory test tube.

5. CONCLUSIONS

An induction forging prototype has been implemented with IGBTs. It can heat the 15-mm diameter and 120-mm long steel work-piece at room temperature to approximately 1100°C within 20 seconds. It can be operated at 15-17 kHz depend on load condition. And its operating frequency can track fast to change and to maintain lock at the little higher than the natural resonant frequency when the parameter of induction heating load are varied, ensuring maximum power transfer to the load throughout the heating cycle. Therefore the resonance locked-loop is found to be suitable for the application of the automatic frequency control of the prototype induction forging.

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