PAMUKKALE ÜNİVERSİTESİ MÜHENDİSLİK FAKÜLTESİ
PAMUKKALE UNIVERSITY ENGINEERING COLLEGE
MÜHENDİSLİK BİLİMLERİ DERGİSİ
JOURNAL OF ENGINEERING SCIENCES
YIL : 1999
CİLT : 5
SAYI : 1
SAYFA : 871-878

DESIGN OF A 500W RESONANT INDUCTION HEATER

Bekir Sami SAZAK
Pamukkale University, Technical Education Faculty, Department of Electrical Education, Denizli

ABSTRACT

In this paper a complete design procedure for a 500W induction heating system is given. An induction heating system basically consists of a coil and a DC/AC inverter. The use of a single switch resonant inverter, which is operated with Discontinuous Conduction Mode (DCM), allows the switching device to turn off under zero current conditions, therefore switching losses are much reduced. This inverter system transforms the DC into AC for the induction heater coil. The proposed coil design method is applicable to a load of any shape so long as the coil surrounds the workpiece. The basis of this method of coil design is the reduction of the induction heater coil and workpiece to their equivalent resistance and inductance.

Key Words : Induction heating, Coil design, Resonant inverter

500W REZONANS iNDÜKSiYON ISITICI YAPIMI

ÖZET

Bu makalede 500W'lık komple bir indüksiyon ısıtma sistemi yapımı yöntemi verilmektedir. Basit olarak bir indüksiyon ısıtma sistemi bir bobin ve bir DC/AC güç dönüştürücü içerir. Tek anahtarlı rezonans güç dönüştürücü Devam etmeyen İletkenlik Durumu'nda (DID) çalıştırılır. DID devrede kullanılan yarıiletken, anahtarların yalıtkan duruma geçerken içlerinden geçen akımın sıfır olmasını sağlar. Bu nedenle anahtarlama kayıpları çok azaltılır. Bu kaynak dönüştürücü sistemi DC'yi indüksiyon ısıtıcı bobininde kullanılmak üzere AC ye çevirir. Sunulan bobin yapım yöntemi bobinin ısıtılacak parçayı sarması şartıyla tüm parça şekilleri için geçerlidir. Bu bobin yapım yönteminin temeli, indüksiyon ısıtma sisteminde kullanılan bobin ve ısıtılacak parçanın yerine onların direnç ve indüktans eşdeğerlerinin kullanılmasıdır.

Anahtar Kelimeler : Indüksiyon ısıtıcı, Bobin yapımı, Rezonans güç dönüştürücü

1. INTRODUCTION

The technique of heating by electromagnetic induction is a well established and an invaluable tool for industries engaged in the heat treatment or hot working of metals. When a conductor is inserted into a varying magnetic field, currents are setup in the conductor by the influence of the induced voltage. Electromagnetic induction, which is the bases of all induction heating systems, was discovered by Michael Faraday in 1831. Heaviside, however, published the first article dealing with the transfer of energy from a coil to a solid core (Heaviside, 1884). Since then, induction heating has been applied successfully to a wide variety of applications as it offers significant process advantages in modern industry compared with fossil-fuel furnaces (Davies, 1979). Some of the benefits associated with the induction heating process are: short heating times, the precise control of the temperature of the workpiece, a good working environment, low space requirements, rapid availability and high energy conversion efficiency (Harvey, 1976). Consequently induction heating is widely used in industry for many applications including forming, melting, joining and hardening (Prevett, 1970; Chatterjee and Ramanarayanan, 1993). Therefore the power supply specifications and switching elements for each application are different. The use of static power supplies using solid-state devices in the induction heating industry has increased greatly over the past years and has been well investigated (Okeke, 1978; Bonert and Lavers, 1994).

For an efficient performance of an induction heating system during heating or melting operations, the design of the system must fulfill some of the following requirements:

- The system must be able to operate in any load condition. Empty, full, cold, full hot or any situation in between.
- The harmonic currents drawn from the mains supply must be low.
- The system must have sufficient tolerance to accommodate disturbances or fluctuation of the input power supply.
- Very frequent starting and stopping should be possible without any detrimental effect on the system.
- Termination of firing signals should result in an instantaneous shutdown of the system.
- Sudden changes in loaded coil impedance values must be tolerated, such as removal or insertion of the load or changes in its shape and size.

In the literature a number of switching element have been applied to the medium-frequency induction heating system which are capable of fulfilling most of these requirements. The use of Gate Turn Off Thyristors (GTOs) or Isolated Gate Bipolar Transistors (IGBTs) as switching element gives higher operation frequency and good efficiency, but limited output power (Malesani and Tenti, 1987; Ying and Heumann, 1994). Although the cost per ampere is higher than the cost per ampere for the high frequency thyristor, it is also possible to design in the 10kHz to 25kHz frequency range using high frequency Darlington Transistor modules as the switching devices (Mauch, 1986; Dede, 1991).

Over the past 20 years, however, the thyristor inverter has become the primary source of medium frequency power for induction heating applications, replacing the motor-alternator set. It has been extensively applied for the frequency ranges between 1kHz and 10 kHz (Chudnovsky et all., 1996), because of its high current handling capability.

The advantage of the proposed single switch resonant inverter topology is that turn OFF of the thyristor takes place at zero current and therefore reduces the switching losses in the power devices. An additional advantage of the proposed inverter topology is that it requires a small number of components and is of lower cost compared with other alternative topologies.

2. PRINCIPLE OF OPERATION

A circuit diagram of the proposed single switch resonant inverter, which provides AC current through the induction heater coil, is given in Figure 1. This AC current flowing in the turns of the induction coil creates an alternating electromagnetic field for the workpiece.

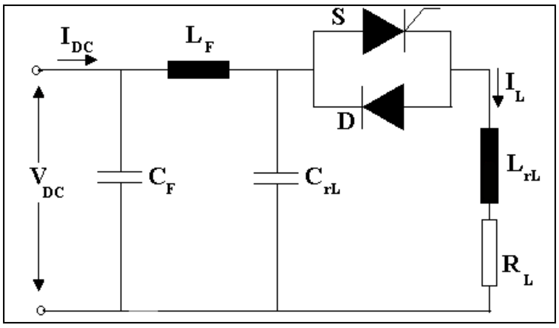

Figure 1. Circuit diagram of the proposed induction heating system

Figure 2 shows the waveforms of the proposed single switch resonant inverter. Each switching cycle is divided into three different modes. Their associated equivalent circuits are shown in Figure 3.

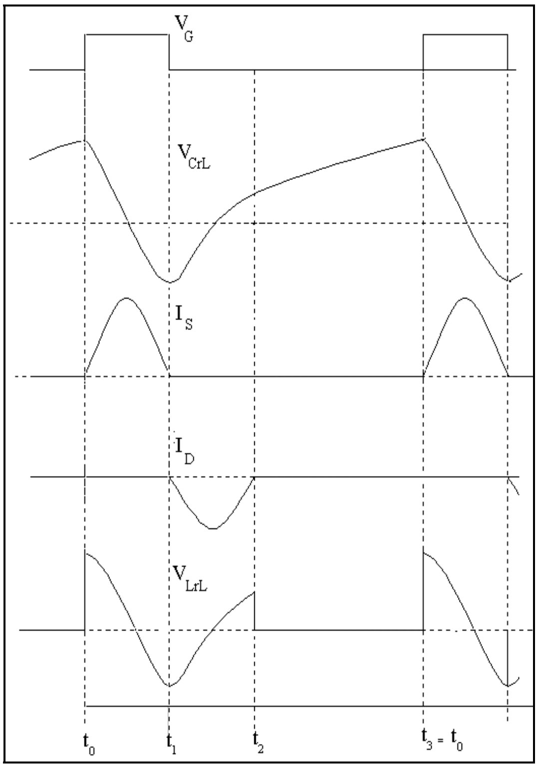

Figure 2. Operational waveforms for the single switch resonant inverter. (V_{GS}-Gate pulse of the thyristor, V_{CrL}-Voltage across the load resonant capacitor, I_S-Thyristor current, I_D-Diode current, V_{LrL}-Load voltage)

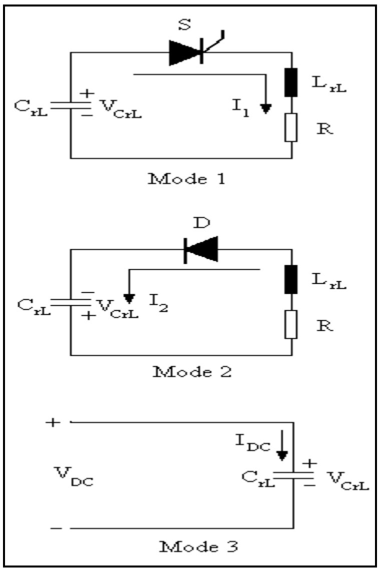

Figure 3. Equivalent modes of operation

During Mode 1, a resonant pulse of current, which flows through the load, rises from zero to a maximum value and falls to zero again at $t = t_1$ the switch is self comutated. However, the resonant oscillation continues through diode D in the reverse direction until the current falls again zero at $t = t_2$ (Mode 2). During the time interval between t_2 and t_3 the resonance capacitor is charged by the DC supply voltage (Mode 3).

The proposed single switch resonant inverter is operated under DCM by setting the switching frequency to half of the resonant frequency (Sazak, 1997). The switching frequency can be changed by changing the frequency of the thyristor gate pulses. Figure 4 shows the turn OFF switch voltage V_S and current waveform I_{S1} of the proposed inverter. It can be seen that the switch is turned OFF at zero current, therefore, turn OFF power losses are negligible. As a result of this, the proposed single switch resonant inverter has higher efficiency compare with the non-resonant inverter systems.

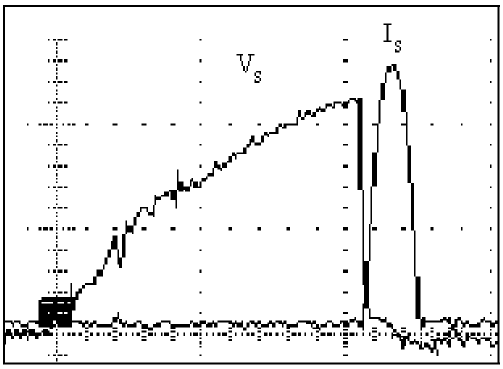

Figure 4. Switch voltage V_S and current I_S waveforms during turn-off

3. DESIGN PROCEDURE FOR THE PROPOSED INDUCTION HEATER

Power circuit of the proposed Single Switch Resonant Inverter basically consists of a resonant capacitor and a resonant inductor. A steel workpiece is placed inside the coil. A thyristor is used as the switching element mainly because of their high current handling capability. The electrical efficiency of an induction heater is defined as the ratio of the power dissipated as heat in the workpiece to the total input power. Thus, it depends on the magnitude and distribution of the current induced in the workpiece, and on the losses generated in the magnetizing winding. The highest efficiency is obtained when the electrical resistivity of the workpiece is large compared to that of the coil conductors. In order to minimize the resistivity and losses in an induction coil, water cooled high-conductivity copper is normally used. The design procedure for this part of the system has been carried out to satisfy the specifications given in Table 1.

Table 1. Design Target Specifications of the Single Switch Resonant Inverter

Inverter parameters	
Output power	$P = 500$ W
Dc input voltage	$U_{DC} = 200$ V
Resonant frequency	$f = 1000$ Hz
Power Factor of the Coil	$PF = 0.3$ lagging
Max. Switching frequency	$f_{sw} = 500$ Hz
Workpiece parameters	=
Cylindrical load diameter	$d_w = 60$ mm
Working piece length	$l_w = 100$ mm
Relative permeability of steel	$\mu_r = 10$
Resistivity of steel	$\rho_{20} = 0.2\ \mu\Omega m$
Temperature coefficient of resistivity	$\alpha_{20} = 0.00572K^{-1}$
Permeability of free space	$\mu_0 = 4\pi\ 10^{-7}$
Coil parameters	=
Coil diameter	$d_C = 110$ mm
Coil length	$l_C = 150$ mm
Resistivity of copper	$\rho_{20} = 0.017\ \mu\Omega m$
Temperature coefficient of resistivity	$\alpha_{20} = 0.004K^{-1}$

Having defined circuit parameters, other parameters have been calculated by using equivalent electrical circuit coil-design method.

From Table 2 (Davies, 1979) recommended air gap between coil and workpiece can be found. It can be noted that the airgap between coil and workpiece depends on the required output temperature, working piece diameters and the coil frequency. For d_W = 60mm and f = 1000Hz the air gap between coil and core has been chosen as χ = 50 mm.

Table 2. Recommended Air Gaps Between Coil and Workpiece for Through-Heating Coils

Frequency	50/60Hz			1kHz		3kHz		10kHz	
Workpiece Temperature (°C)	550	850	1250	850	1250	850	1250	850	1250
Air Gap									
Work dia 0 to 60mm.	25	25	50	50	62	50	62	50	62
Work dia 60 to 125mm.	25	38	50	62	75				
Work dia 125 to 250mm.	25	38	50	75	80				

3. 1. Resistivity and Skin Depth

In the heating processes the variation of resistivity with temperature must be considered. The resistivity of metals varies with temperature. By using the design parameters given in Table 1, resistivity of steel at 750° found as (Davies, 1979);

$$\rho_{750} = \rho_{20}\left(1+\alpha_{20}\left(\theta-\theta_1\right)\right) \quad (1)$$

For the purpose of calculation and accommodate the variation in resistivity through the heating period, a representative value may be used, known as integrated resistivity ρ_m, which corresponds to the mean heating rate over the period. The required value for integrated resistivity is given by Eq. 2, which is simply the arithmetic mean of the square roots of the two extreme values (Nicholls, 1980).

Integrated resistivity of steel ρ_m is defined for the range of 20°-750° as;

$$\sqrt{\rho_m} = \frac{1}{2}\left(\sqrt{\rho_{20}} + \sqrt{\rho_{750}}\right) \quad (2)$$

A short circuit current, which is induced by the transformer action, flows in the workpiece. The current in the workpiece sets up a magnetic field, which opposes the field created by the current in the conductors, and the resultant field inside the workpiece is attenuated as the depth increases. This, in turn, affects the current distribution in the workpiece so that the current density also attenuates with depth. Current density falls off from the surface to the center of workpiece and the rate of decrease is higher at higher frequency (Ross, 1970). It is also depend on two properties of the material. These are resistivity and relative permeability of the workpiece. Skin depth δ is roughly where the current density has fallen to about 35 % of its surface value and can be found as;

$$\delta = \sqrt{\frac{2\rho m}{\mu_0 \mu_r \omega}} \quad (3)$$

where;

ω is the angular frequency.

Skin effect will operate on the coil, just as it does on the workpiece, tending to force the coil current to flow on the inner surface of the copper. Skin depth in copper coil δ_C can be calculated as follows;

$$\delta_c = \sqrt{\frac{2\rho_c}{\mu\omega}} \quad (4)$$

The dimensionless flux factors p and q depend not only on geometry but also on frequency, resistivity, and permeability. By using design parameters given in Table 1, p and q values are found as;

$$\frac{d_w}{\delta} = 16.28$$

For the ratios of $\frac{d_w}{\delta} > 8$ Eq 5 and Eq 6 can be used for defining p and q values (Davies, 1979).

$$q = \frac{2}{\frac{d_w}{\delta}} \quad (5)$$

$$p = \frac{2}{\left(1.23 + \frac{d_w}{\delta}\right)} \quad (6)$$

3. 2. Equivalent Circuit Components:

As there is a close analogy between induction heater coil and a transformer, the coil can be designed by obtaining the values of the resistance and reactances and solving the equivalent circuit. This method is first introduced by Baker (Baker, 1957).

Figure 5 shows the corresponding equivalent circuit. In this Figure :
R_C-coil resistance (Ω).
R_W-working piece resistance (Ω).

X_C-coil reactance (Ω).
X_W-working piece reactance (Ω).
X_g-air gap reactance (Ω).

Definition of each of these parameters gives the total electrical equivalent of the coil.

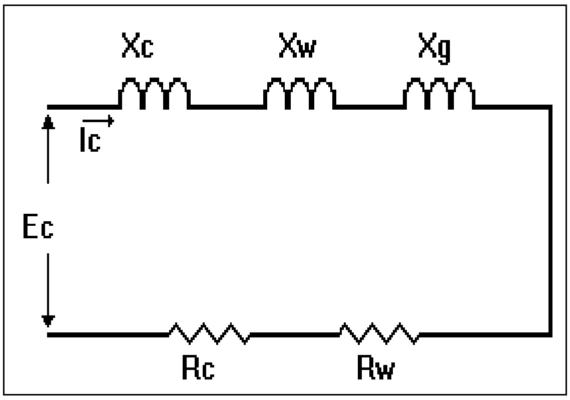

Figure 5. Electrical equivalent circuit of an induction heater coil

Resistance of workpiece R_W can be found from Eq. 7 as;

$$R_w = K(\mu_r p A_w) \quad (7)$$

where, A_W is the cross section area of the workpiece. K depends on the coil parameters and defined as;

$$K = \frac{2\pi f \mu_0 N_c^2}{l_c} \quad (8)$$

Coil resistance R_C depends on the physical parameters of the coil and given by;

$$R_c = K\left(\frac{k_r \times \pi \times d_c \times \delta_c}{2}\right) \quad (9)$$

where;

k_r - Coil correction factor, 1.5 (assumed). This factor takes into account the spacing between turns and other imperfections of a practical coil.

Coil reactance X_C is approximately equal to the coil resistance R_C. Airgap between coil and workpiece is considered as a series reactance. Reactance value of the airgap X_g is defined as:

$$\chi_g = K(A_g) \quad (10)$$

where; A_g is the cross section area of air gap.

Work piece reactance X_W is found from Eq. 11, which is similar to Eq. 7. The use of q value instead of p is the only difference between these two equations. Thus;

$$\chi_w = K(\mu_r q A_w) \quad (11)$$

The values which are obtained from Eq.12 to Eq.21 can be used to calculate the major coil properties such as efficiency, the coil power factor, number of volts per turn.

3. 3. Coil Efficiency, Power Factor, Apparent Power

The ratio of workpiece resistance R_W to total resistance is called the coil efficiency η. From Eq. 12, it can be seen that to obtain higher efficiency, coil resistance value R_C must be reduced;

$$\eta = \frac{R_w}{Rc + R_w} \quad (12)$$

The ratio of the total resistance R_{total} to impedance Z is termed as displacement factor Cosϕ and given by;

$$Cos\varphi = \frac{R_{total}}{Z} \quad (13)$$

where impedance of the induction heater Z can be found from Eq. 14 as ;

$$Z = \sqrt{(R_w + R_c)^2 + (X_w + X_c + X_g)^2} \quad (14)$$

Rearranging Eq. 13 and Eq. 14 yields;

$$Cos\varphi = \frac{R_w + R_c}{\sqrt{(R_w + R_c)^2 + (X_g + X_w + X_c)^2}} \quad (15)$$

The displacement factor is also termed the ratio of the active power P to the apparent power S as follows;

$$Cos\varphi = \frac{P}{S} \quad (16)$$

3. 4. Coil Ampere-Turns and Volts Per Turn

Coil ampere-turns $I_C N_C$ and volts per turn E_C/N_C are important coil design parameters. These parameters can be found as follows;

$$I_c N_c = \sqrt{\frac{S}{\frac{Z}{N_c^2}}} \qquad (17)$$

where;

I_C is the r. m. s values of coil current and N_C is the number of turns.

The reflected impedance per turns Z/N_C^2 is found by combining Eq. 14 and Eq.17. That is;

$$\frac{Z}{N_c^2} = K\sqrt{(R_w + R_c)^2 + (X_w + X_c + X_g)^2} \qquad (18)$$

The term E_C/N_C is known as the volts per turns figure for a coil. It is the voltage across each number of turns. The ratio is the same for each winding on the coil. Coil volt per turns of the proposed coil is found from Eq.19 as follows;

$$\frac{E_c}{N_c} = \sqrt{S \times \frac{Z}{N_c^2}} \qquad (19)$$

where, E_C is the r.m.s value of coil voltage, N_C is the number of turns, S is the apparent power of the coil.

Number of turns N_C depends on the r.m.s values of coil voltage E_C and volts per turns E_C/N_C. It is seen from Eq. 20 that the total voltage across the windings is directly proportional to its number of turns;

$$N_C = \frac{E_C}{\frac{E_C}{N_C}} \qquad (20)$$

The source of magnetic field in a coil is the ampere-turns products of the windings. When the coil is connected to the power supply, the current I_C flows through the winding and creates a magnetic field. This coil current I_C can be calculated as follows;

$$I_C = \frac{I_C N_C}{N_C} \qquad (21)$$

3. 5. Resonant Components

After defining the K parameter from Eq.8, all the reactance and resistance values can be calculated.

For the proposed system;

Total resistance, $R_{total} = 2\Omega$

Total reactance, $X_{total} = 5.7\Omega$

Total inductance value of the induction heater L_{rL} is found by using Eq. 22 as :

$$L_{rL} = \frac{X_{Ltotal}}{\omega} = 0.91\text{mH} \qquad (22)$$

The proposed inverter circuit consists of an L-C resonant circuit. Oscillating voltage and current, due to resonance, are applied to the load. In the proposed inverter circuit, the power flow to the load is controlled by the resonant circuit impedance, which in turn is controlled by the switching frequency of the thyristor f_{SW} in comparison to the resonant frequency f of the resonant circuit. To operate the inverter for given resonant frequency f=1000Hz, it is necessary to calculate the component value of the resonant capacitor C_{rL}.

Therefore, resonant frequency f;

$$f = \frac{1}{2\pi\sqrt{L_{rL} C_{rL}}} \qquad (23)$$

Rearranging Eq. 23 for the resonant capacitor value C_{rL} yields;

$$C_{rL} = \frac{1}{(2\pi f_0)^2 L_{rL}} \qquad (24)$$

$$= 27.8\mu\text{F}.$$

4. EXPERIMENTAL RESULTS

A prototype of the induction heating system has been built and tested by using a thyristor (N105HR06) and a diode (RURU8060). The results are obtained from this prototype are shown in Figure 6 to Figure 9.

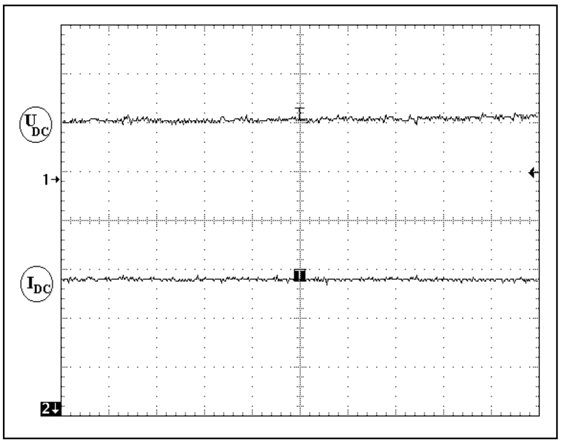

Figure 6 Measured input DC line voltage [CH1:100V, CH2:1A, T:20µS].

Figure 6 shows the applied DC line voltage. The single switch resonant inverter converts this DC input voltage to an AC voltage of specific frequency. Discontinuous conduction mode of operation of the single switch resonant inverter is achieved by setting the switching frequency to half of the resonant frequency. Measured voltage and current waveforms for the resonant capacitor C_{rL} are shown in Figure 7.

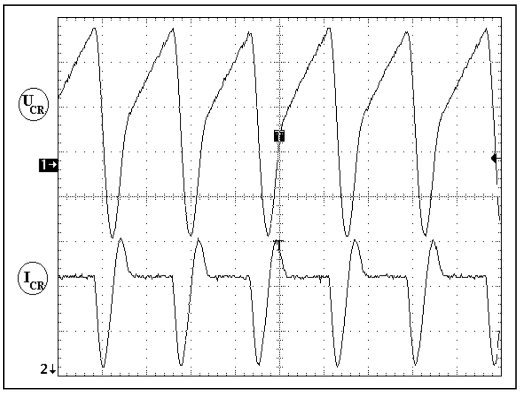

Figure 7. Measured current and voltage waveforms of the load resonant capacitor [CH1: 50V, CH2: 5A, T: 0.5 m S].

The proposed induction heating system is performed by a constant on time control system. By varying the off time of the pulses, the amount of power being converted is also varied. The advantage of the proposed method is that the Zero Current Switching is achieved for a wide range of output power.

As seen in Figure 8 the proposed resonant inverter system produces nearly sinusoidal output current. Figure 9 shows the converter output power versus to the input voltage at different values of switching frequency. Variation of output power is achieved by changing the switching frequency, whilst the input voltage is maintained constant

Figure 8. Measured load voltage v_L and load current i_L [CH1:50V, CH2: 5A, T: 0.5mS]

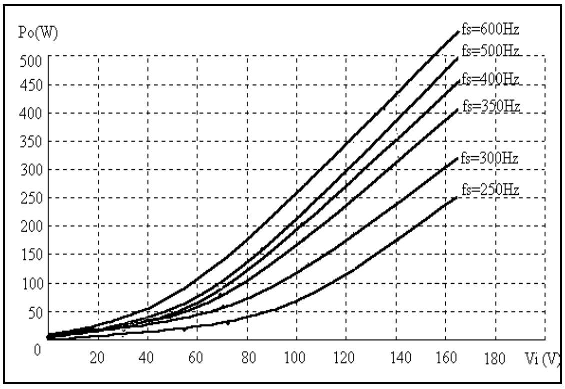

Figure 9. Output power of the induction heating system at different inverter operation frequencies.

5. CONCLUSIONS

The proposed induction heating system offers advantages including a relatively simple power circuit, high power capability, simple protection circuits and higher efficiency. Additionally, the use of Resonant Switching technique allows semiconductor devices to be operated at much higher frequencies and with reduced control requirements compared with conventional switch mode operation. The proposed coil design method is the same procedure as the reduction of a transformer to its equivalent circuit, where the various flux path are represented in term of inductance, and the losses including the load, represented as resistance. Employing switching device with a higher current handling capability can increase the output power level of the proposed inverter. Single phase configuration of the proposed system may open new areas for home cooking and heating applications by induction heaters.

6. REFERENCES

Baker, R. M. 1957. Design and Calculation of Induction Heating Coils, AIEE Trans. 57 (4), 31-40.

Bonert, R., Lavers, J. D. 1994. Simple Starting Scheme For A Parallel Resonance Inverter For Induction Heating, IEE Tr. on Power Electronics, May, 9 (3), 281-287.

Chatterjee, K., Ramanarayanan, V. 1993. A Comparative Study of Inverter Circuits for Induction Heating, Int. Power Engineering Conf., Singapore, 537-542.

Choudnovsky, V., Axelrod, B., Shenkman, A. 1996. Medium frequency combined inverter for electroheat with improved starting arrangements, IEE Proc. Electr. Power Appl., 143 (2), March, 165-171.

Davies, J. 1979. The Induction Heating Handbook, 15-23 s. McGraw-Hill Book Company (UK) Limited,

Dede, E. J. 1991. 25kW/50kHz Generator for Induction Heating IEEE Tr. on Industrial Electronics, 38 (3), 203-209.

Harvey, I. G. 1976. The Theory of Multi Layered Windings for Induction Heating and Their Application to 1MW, 50 Hz, Longitudinal Flux Billet Heater, 8. **Congress U. I. E.,** Liege, Belgium, 2 (4), 1-23.

Heaviside, O. 1884. The Induction on Currents in Cores, The Electricians, May 3, 583-587.

Malesani, L., Tenti, P. 1987. Medium-Frequency (GTO) Inverter for Induction Heating Applications, **Proc EPE Conf**., 271-276.

Mauch, K. 1986. Transistor Inverters for Medium Power Induction Heating Applications, IEEE-IAS, 555-562.

Nicholls, H. J. 1980. Induction Heating, 5 s. The Electricity Council, U. K.

Okeke, S. N. 1978. Application of Thyristor Inverters in Induction Heating and Melting, Electron and Power, 24 (3), 217-221.

Prevett, P. D. 1970. The Role of Induction Heating in HDW: A Modern Metal Joining Process, IEEE Tr. on Industry and General Applications, IGA-6 (2), March/April, 128-130.

Ross, N. V. 1970. A System For Induction Heating of large Steel Slabs, IEEE TR. on Industry and General applications, 1GA-6 (5), 449-454.

Sazak, B. S. 1997. A New Unity Power Factor Quasi-Resonant Induction Heater, Doktora Tezi, University of Glamorgan, U. K.

Ying, J., Heumann, K. 1994. Series resonant Inverter With Cycle Control For Induction Heating, Proceedings IPEMC, The First International Power Electronics and Motion Control Conf., June (1), 367-373.