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Design Analysis and Simulation of Resonant Inverter for Induction Heating Process

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Abstract: A power electronic inverter is developed for a high-frequency induction heating application. The application requires high power for induction melting process of the electric furnace. This power-frequency product represents a significant challenge for today's power semiconductor technology. Voltage source and current source inverters both using ZCS and ZVS are analyzed and compared. To attain the level of performance required, different resonant topologies will compare and analyze.

Keywords:Induction heating ,High frequency ,Power supply, Resonant Inverter, Simulation

I. INTRODUCTION

The technology of the Induction Heating has been developed many decades ago with different topologies of the resonant converters with different tank coil resonance circuits like series resonance circuit , parallel resonance circuits and third order resonance circuits i.e. inductor coupling and Capacitive coupling known as LCL resonance coupling and CCL resonance coupling respectively.

Generally the load in induction heating applications generally has a very low power factor. To improve the power factor at utility side, a resonant circuit consisting of capacitor and inductor is been added before the tank coil to compensate reactive power. Till date most of the research has been carried out on series and parallel resonant circuits, but in case of LCL resonance inverter it has various advantages over the above mentioned resonance circuits that has been discussed in this paper.

***1.1 Problem Identification*:**

The main concern in the field of Induction heating and melting is very low power factor which is due to more inductive nature of the furnace which causes lagging power factor and because of which following causes are observed in industries:-

- A penalty for power factor below and a credit for power factor above a predetermined value.
- An increasing penalty for decreasing power factor,
- A charge on monthly KVAR Hours, KVA demand: A straight charge is made for the maximum value of KVA used during the month. Included in this charge is a charge for KVAR since KVAR increase the amount of KVA.

Second major problem is with the type of circuit configuration, i.e. series resonance configuration and most popular parallel resonance configuration because of which poor efficiency, higher switching losses and very low power factor is been observed.[ref.2]

In case of thyristorised based converters for induction furnace both rectifier as well as inverters is SCR based because of which both side switching losses occurs therefore control required is both side and at inverter side starting circuit is required due to all these reasons circuit becomes more bulkier, complex and expensive.

1.2 Resonance Circuits:

a. Series resonance

b.Parallel resonance

c.Hybrid Resonance (i.e. combination of series and parallel resonance)

a. Series resonant tank circuit:-

It magnifies the voltage across the work coil higher then o/p of the inverter. Disadvantages of this circuit are it carry same current that flow through the coil.

b. Parallel resonant tank circuit:-

Magnify the current to work coil higher than current capability of inverter Inverter has to carry part of the load current.

c. Hybrid Resonance tank circuit:-

Magnify the current to work coil higher than current capability of inverter Inverter has to carry part of the load current Power factor is improved because of additional capacitor and inductor in the circuit.

1.3 Resonant Convertors:

- Resonant convertors are use to reduce the switching losses & reduce stress on device.

- They turn-off & on device at zero voltage & or current.[Ref.]

- Basically two types of resonant convertors

a. Zero current switching

b. Zero voltage switching

a. Zero current switching:-

- ZCS can eliminate the switching losses at turn-off and reduce the switching losses at turn-on.
- ZCS is particularly effective in reducing switching losses for power devices (such as IGBT, MOSFET or any other controlled switch) with large tail current in the turn-off process.
- By the nature of resonant tank and ZCS, the peak switch current is much higher than that in a square wave. In addition, a high voltage becomes established across the switch in the off- state after the resonant oscillation. When switch on the capacitor will be discharged through the switch causing significant power loss at high frequency and high voltage.

b. Zero voltage switching :-

- use in frequency conversion circuit
- use for constant load application
- ZVS is more prefers over ZCS at high switching frequency, due to internal capacitance associated with switch.
- For both ZCS and ZVS, the output voltage control can be achieved by varying the frequency. ZCS operates with a constant on-time control, whereas ZVS operates with a constant off-time constant.

II. SELECTION OF TOPOLOGY

Till date most of the research has been carried out in the field of different topology in terms of selection of type of rectifier- Thyristor based, GTO, diode or IGBT, in case of Inverter whether CSI or VSI with thyristor or GTO or MOSFET or IGBT ,and resonance circuits like series, parallel, hybrid(CCL or LCL). Every configuration has its own merits and demerits in terms of different technical aspects like size, losses, efficiency, control complexity etc.

For given application with proper strategy, if a topology is selected than many of the disadvantages will be diminished. For eg.If the source voltage is variable and load requirement is also variable than a topology with rectifier as thyristor or GTO or any other controllable switch can be used whereas if the load is constant than using diode at rectifier side is better option. In case of inverter where we require constant current we go for CSI, whereas if the load metal is variable because of which the inductance of the coil changes due to which current varies, There VSI is more suitable.

For the selection of resonance circuit series and parallel resonance circuits has their own drawback like in series resonance for higher kW rating the current which passes through the tank coil comes from the inverter this has drawback that switch may not be available or capable of handling this huge power. Whereas in case of parallel resonance inverter has to carry part of load current apart from this advantage the disadvantage of this topology is very poor P.F. and low efficiency.

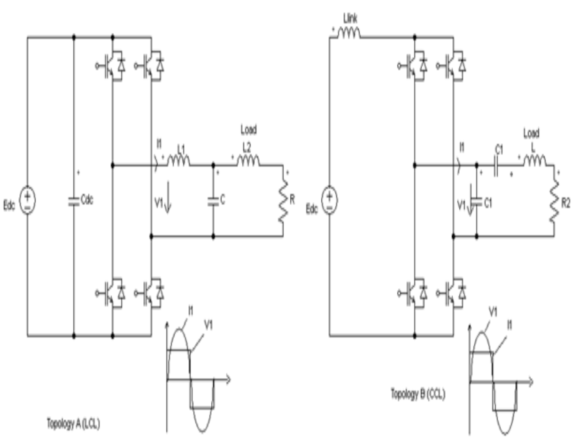

Fig. 2.1- VSI with Inductive Coupling (topology A) and CSI with capacitive coupling (topology B) of the load

Hybrid resonance circuits have advantage form above two topologies firstly, if we use LCL load resonant tank circuit than inverter has to carry only part of load current as well as we need not to worry about the rating of switch this third order resonant circuit has advantage that voltage boost up is done with primary inductance (L1) and P.F. is corrected by capacitor. And where the high current and constant current is required we go for CCL configuration with CSI. Figure 2.1shows the two topologies.

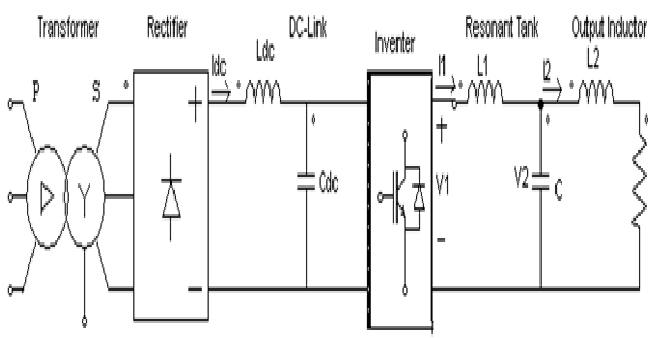

Fig.2.2- Power schematic of the IGBT based resonant inverter with LCL configuration

In present work the topology which has been selected according to the industry requirement is constant load topology i.e. inductive coupling with VSI. As load is constant so topology selected is Diode Bridge rectifier and IGBT based inverter with LCL resonance configuration. Fig 2.2 Shows power schematic of the circuit.

III. DC LINK DESIGN CALCULATION

3.1 Calculation for value of DC Link Inductor (Ldc) and Capacitor (Cdc):-

To provide lower output ripple, especially from high-power and polyphase rectifiers an inductor is placed between the rectifier and the capacitor filter. Since current cannot change instantaneously in the inductor, inrush currents at turn-on are also reduced.

A single-phase full-wave rectifier with L-C filter is shown in figure 3.1. During the peak portions of the voltage waveform, energy is stored in the inductor and during the valley portion of the voltage waveform; the energy is transferred to the capacitor and load. Referring to figure 3.1, the rectified waveform contains an average voltage component and an ac component that contains even harmonics

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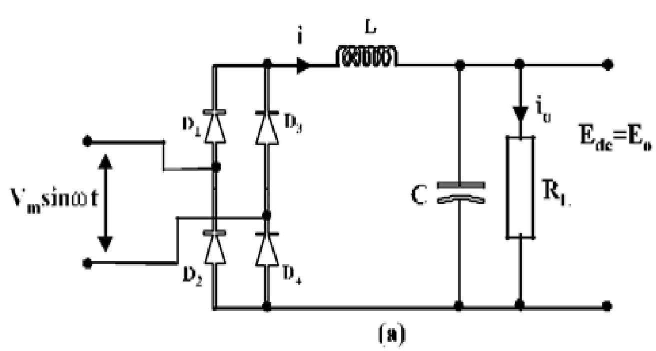


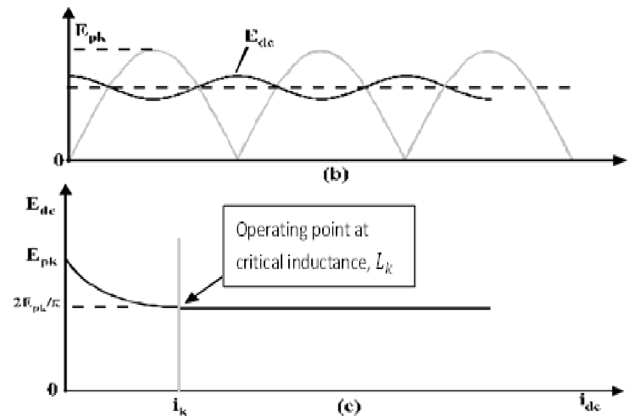


Fig. 3.1 Full wave rectifier with inductor input filter

(a) rectifier-LC filter circuit,(b) output voltage waveform,

(c) output voltage versus load.

3.2 Critical Inductance, LK:-

I. To achieve the desired voltage regulation of the filter, it is necessary to maintain continuous current flow in the inductor. When the load resistance is very large in ohmic value (approaching open circuit), the output voltage will tend to rise toward the peak input voltage, as shown in figure 3.1c. Current Ik is the value at which the inductor current becomes discontinuous and each rectifier diode conducts for less than 1800 . The inductor for such a critical current, Ik is called the critical inductance, Lk. The inductor has a dc component and an ac compo-nent of current. For the current to be continuous, the dc component 2Epk /πRL must be equal to or greater than the predominantly second harmonic component 4Epk /(3π2wsLk), from which one obtains the condition that Lk should be equal to or greater than RL / 3ws.

The general equation for critical inductance in single and polyphase rectifiers is then:

$$Ldccritical \geq \frac{2RL}{p(p^2-1)\omega s} \qquad (3.1)$$

Where p= no. pulse of output voltage

ω= source frequency

Rl=Load resistance

It can be noted from eqn.(3.1) that when the load is light ie. When RL is large, a large value of Lk is required if the ripple is not to be excessive. However, when RL decreases (as the load increases), the critical value of the inductance, Lk also reduces. This means that the series inductance should have a large value at no load and may be allowed to decrease as the load increases. Reactors whose inductance does decrease when the dc current through them increases are called "swinging chokes.

3.3 LC Filter Design Calculations

Given data Given data

$V_s = 550\ volt$

F=50 Hz

$$\text{fripple} = 50 * 6 = 300\ \text{Hz}$$

$$P_{output} = 100\ \text{kW}$$

$$I_{DCmin} = \frac{P_{output}}{1.35 * V_s}$$

$$I_{DCmin} = \frac{100 * 1000}{1.35 * 550} = 134.68\ \text{A}$$

$$= \text{frequnecy of oscillation that has to be less than } 50\text{Hz}$$

$$\text{taking } f_{of} = 30\ \text{Hz}$$

3.3Steps for Calculation for DC link filter:-

I. From section 3.2 it is clear that

$$L_{Dcactual} > L_{DCcritical}$$

equation for calculating L critical is

$$L_{DCcritical} = \frac{V_{Ripple}}{2 \times \pi \times f_{Ripple} \times I_{DC\ min}}$$

$$= 0.000965664\ \text{H} \qquad (3.2)$$

As $L_{Dcactual} > L_{DCcritical}$

Taking L actual as= 0.006

II. To find CDC

$$C_{DC} = \frac{1}{4 \times L_{Dcactual} \times f_{of}^{\,2} \times \pi^2} = 4.55\mu F$$

So from the above calculation we got the value of DC link Inductor and capacitor, in 'experiment results' the dc output has been shown with the above values.

IV. HYBRID RESONANCE CIRCUIT

With the switching times of today's high-voltage IGBTs being still quite high, 1200V IGBTs were chosen for the 500Hz application. These IGBTs can operate at a 800V dclink voltage. Therefore, a voltage boost is necessary to obtain the required voltage of maximal 1.2kV at the inductor. In addition, the voltage and current in the resonant circuit vary with different loads. Hence, voltage adaptation is often required when working with the full dc-link-voltage at rated power. To avoid a transformer, these demands result in the design of a third order resonant circuit with switchable passive devices.. Fig 2.1 shows the two feasible solutions for the inverter and the resonant circuit: a current-source inverter with capacitive coupling and a voltage source inverter with inductive coupling of the load. Neglecting parasitics and assuming ideal semiconductor switches, both inverters would at best operate with output voltage and current in phase.

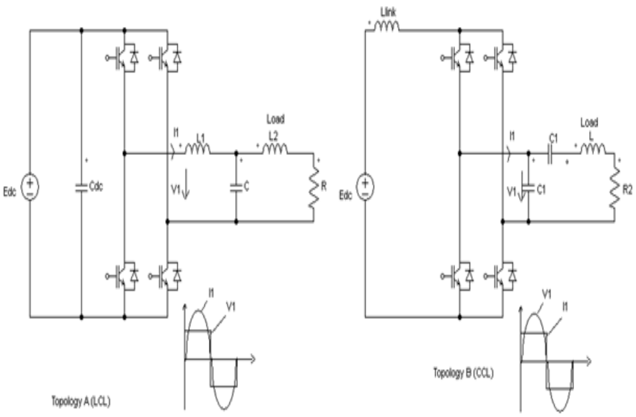


Fig. 2.1- VSI with Inductive Coupling (topology A) and CSI with capacitive coupling (topology B) of the load

The principle of duality for the series and the parallel resonant converter can be extended to the modifications of these basic circuits, topologies A and B. This includes the desired characteristics of the switching devices, the necessary dc link, the switching control and also the behavior of the circuits in case of a failure.[Ref.]

4.1 Analysis of LCL Resonance Circuit

As the nature of induction furnaces is more of inductive if we add some more inductor and capacitor in the circuit to improve power factor and to increase output power to the tank coil we can see that a part of load current only flows through the inverter giving advantage in terms of switch rating. Since inverter switches has not to carry full load current. And there for by adding an inductor and capacitor to the tank circuit we can get much higher voltage levels at the output side i.e. L1 boosts up the voltage whereas capacitor compensate the reactive power.

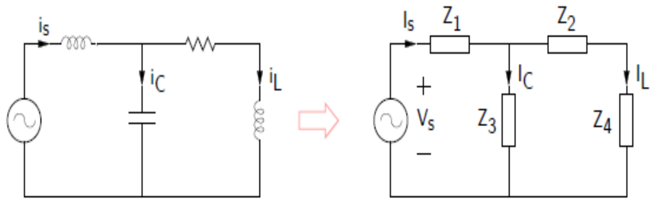
The value of the complex input impedance Z of the resonant tank defines the two resonant angular frequencies and .They can be found by calculating those frequencies which result in either infinite or zero input impedance. The following equations show the results of this analysis:

$$Z \rightarrow 0 \qquad \omega_{01} = \frac{1}{\sqrt{C.L_{1}L_{2} / (L_{1+L_2})}}$$

Z →∞ $\omega_{02} = \frac{1}{\sqrt{C.L_2}}$

The LCL resonant tank is supplied by a voltage source inverter. It operates at the resonant frequency defined by the complex input impedance Z →0 the resonant circuit works at the frequency set by the input impedance Z →∞ and therefore at the resonance point of an equivalent parallel resonant circuit.

Analysis of resonant-tank impedance, equivalent resistance and equivalent reactance can be done as given below:



Here,

- Z1= j**ω**L1(Reactance Of Resonant Inductor)
- Z2= j**ω**L2(Reactance Of Load Coil Inductor)
- Z3= 1/j**ω**c (Reactance Of Resonant Capacitor)
- Z4= R (Resistance Of Load Coil)

Now we can solve our circuit by series and parallel impedance calculation method which is also derived as under:

1. Load coil inductor and resister are in series so we can say that the equivalent impedance of these elements is the sum of individual impedance.

   Z'=Z4+Z2

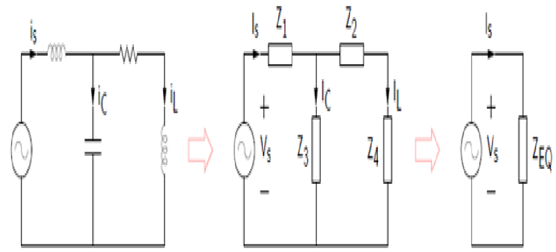
   Z'=R+j**ω**L2

2. In the next step the resultant impedance of load coil and impedance of capacitor are calculated with parallel impedance calculation principal.

   $$Z'' = Z' \parallel Z_3$$

   $$Z'' = \frac{\left(\frac{1}{j\omega C}\right)\times(R+j\omega L_2)}{R+j\omega L_2+\frac{1}{j\omega C}}$$

3. Now, our system can be represented as equivalent impedance as below:



After the calculating the resultant impedance the total equivalent impedance is the series connection of two impedances.

$$Z_{eq} = Z'' + Z_1$$

$$Z_{eq} = j\omega L_1 + \frac{\left(\frac{1}{j\omega C}\right)\times(R+j\omega L_2)}{R+j\omega L_2+\frac{1}{j\omega C}}$$

$$Z_{eq} = j\omega L_1 + \frac{\left(\frac{1}{j\omega C}\right)\times(R+j\omega L_2)}{\frac{1}{j\omega C}\times(1+jR\omega C-\omega^2 CL_2)}$$

$$Z_{eq} = j\omega L_1 + \frac{(R+j\omega L_2)}{(1-\omega^2 CL_2+jR\omega C)}$$

Where,

$$Z_{eq} = \sqrt{X_{eq}{}^2 + R_{eq}{}^2}$$

By solving this equation of Z_{eq} we can get the values of X_{eq} and R_{eq} .

$$R_{eq} = \frac{R}{(1-\omega^2 CL_2)^2+(R\omega C)^2}$$

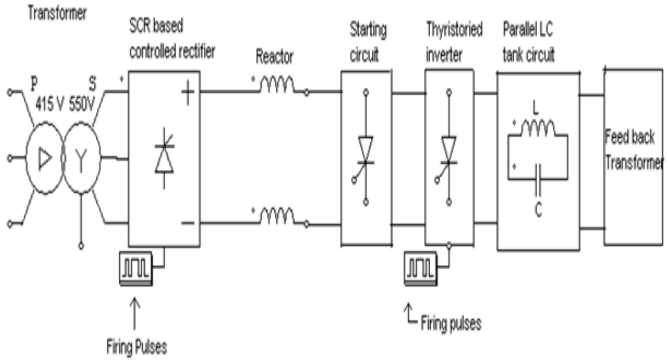
And also equivalent reactance,

$$X_{eq} = \omega L_1 + \frac{j\omega L_2-\omega^3 CL_2{}^2-\omega R^2 C}{(1-\omega^2 CL_2)^2+(R\omega C)^2}$$

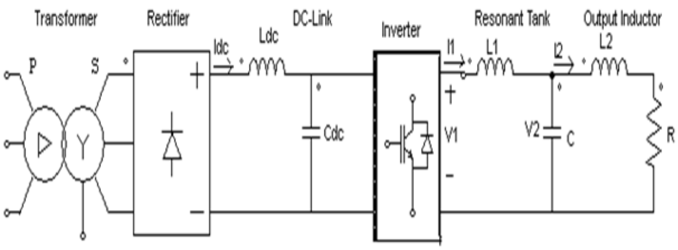
With help of these equations we can find out the correct and economical values of our circuit components.

V. COMPARATIVE ANALYSIS OF THYRISTORISED AND IGBT BASED TOPOLOGIES

Thyristorised based configuration has many drawbacks comparatively to IGBT based resonant inverter. Fig.5.1 (a) shows the power schematic of the thyristorised based resonant converter with parallel resonance circuits.



(a)



(b)

Fig. 5.1- Power schematic of (a) thyristorised based parallel resonance circuit configuration,(b) IGBT based LCL resonance inverter.

Table 5.1 Comparison of IGBT based LCL resonance inverter.Thyristorised based parallel LC resonance inverter

IGBT based LCL resonance inverter	***Thyristorised based parallel LC resonance inverter***
Front rectifier is diode bridge rectifier or uncontrolled rectifier	Here rectifier is controlled rectifier thyristorised
Inverter is IGBT based	Inverter is rectifier based
Starting circuit is not required	Starting circuit is required
Output Voltage gain is possible	Not possible
Power factor is good	Power factor is poor
Control is easy	Complex control
Good efficiency	Poor
Low Cost	Expensive

From the comparative analysis it is clear that LCL has much more benefits over the conventional converter topology that has been used since many year. As factor makes itself clears that LCL designs gives good Power factor and that was the main concern in the huge inductive loads as well as the cost has been reduced due to less capacitor as well as uncontrolled switches at rectifier side.

VI. INVERTER CONTROL

The control of the switching instants with a frequency of IOOk Hzis too high to be implemented with a DSP or a micro-controller. Hence, a control scheme based on an analog Phase Locked Loop (PLL) has been chosen. In combination with an integrator, the PLL adjusts to the desired phase angle between the output voltage and current of the inverter, and supplies the IGBT-driver stages with the switching signals.

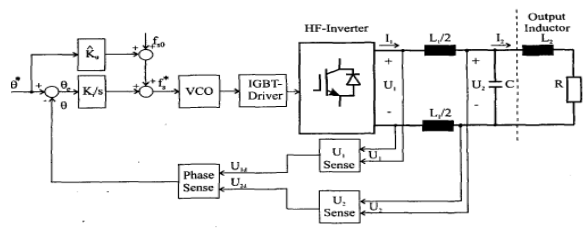
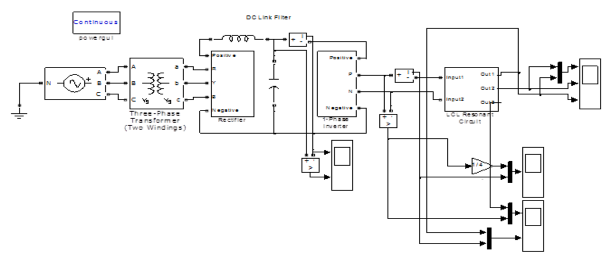


Fig. 6.1. Basic Phased Locked Loop Structure

VII. SIMULATION AND SIMULATION RESULTS

Simulation of IGBT based LCL-resonance converter has been shown below.



7.1 Output Waveforms:-

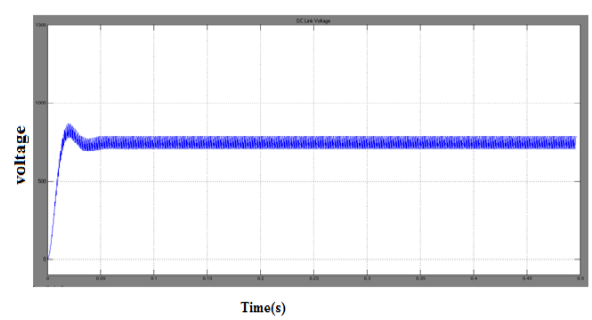


Fig:- (A) shows the output of the DC link of rectifier

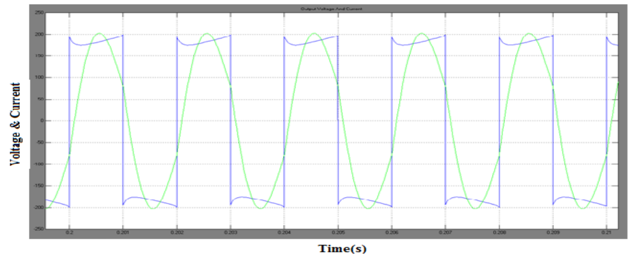


Fig.:- (B) output voltage and current of the inverter-

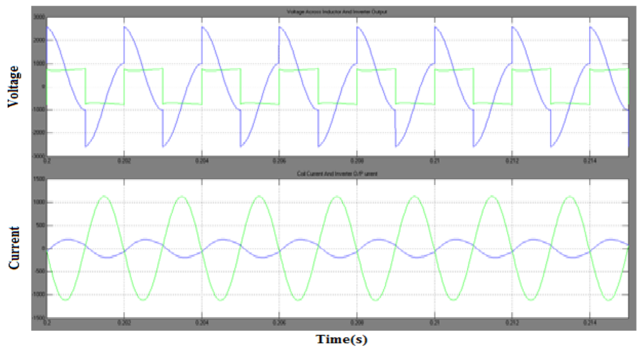


Fig.:- (C) output voltage and current across the inductor L1

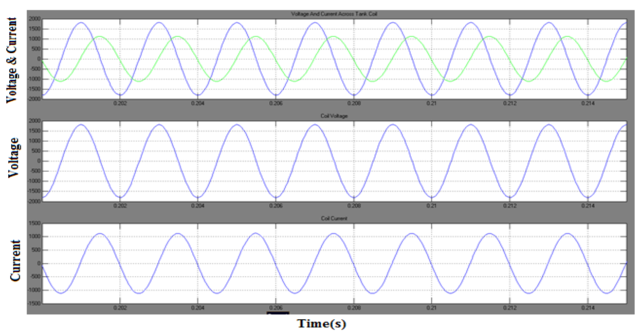


Fig.:- (D) shows the total output voltage & current across the tank coil.

VIII. CONCLUSION

In this paper, the design of an IGBT-based power supply for an induction heating system has been presented. The 'variable load is highly inductive and requires a high active power at a frequency of 1OOkHz. Based on a detailed topology investigation, a third-order LCL-resonant circuit supplied by a voltage source H-bridge-inverter is chosen. An analysis of the circuit and basic design rules are given. A control scheme allowing operation of the inverter with the lowest IGBT switching-losses is explained and the matlab simulation with uncontrolled rectifier & simulation results for 100kw power supply is shown.

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