Design-Analysis and Implementation of IGBT Based LCL-Resonant Converter for Medium Frequency Induction Melting and Heating Application.

By

Swapnil Agrawal

12MEEP28

Department of Electrical Engineering

Institute of Technology

Nirma University

Ahmedabad-382481

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Major Project Report

Submitted in Partial Fulfillment of the Requirements for the Degree of

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IN

ELECTRICAL ENGINEERING

(Power Electronics, Machines and Drives)

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Certificate

This is to certify that the Major Project Report (Part-I) entitled "Design-Analysis and Implementation of IGBT Based LCL-Resonant Converter for Medium Frequency Induction Melting and Heating Application", submitted by Mr.Swapnil Agrawal (12MEEP28) towards the partial fulfillment of the requirements for Master of Technology (Electrical Engineering) in the field of Power Electronics, Machines and Drives of Nirma University is the record of work carried out by him under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

Date:

Mr. B. G. Shah
(Industrial Guide)
Vice President(Tech.),
Pioneer Furnaces Pvt. Ltd,
Anand.

Prof. P. N. Kapil
(Institute Guide)
Department of Electrical Engg.,
Institute of Technology,
Nirma University.

Head of Department
Department of Electrical Engg.,
Institute of Technology,
Nirma University

Director
Institute of Technology,
Nirma University.

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- Swapnil Agrawal

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Abstract

Induction melting heating is well-known technique used in casting foundry,metal semis product as well as in metal heat treatment plant. Recent trend is to replace thyristor used in converter with transistor like MOSFET or IGBT for better efficiency and faster switching. Various topologies have been developed in this area such as VSI CSI with series or parallel load resonant circuits. Recent developments in switching schemes and control methods have made the VSI more preferred in the application which requires output power control. In present work IGBT based full bridge inverter with LCL (Inductive coupling) configuration has been designed. Hence the price of system has also reduced,as now rectifier section is of diode which was previously thyristorised. LCL based configuration enables operation at higher voltage in order to reduce load current that flows from inverter, i.e. now inverter semiconductor devices can be chosen of lower rating as LCL tank circuit helps in boosting up of voltage and current at the load side. Also the comparative analysis with existing thyristor based converter with parallel LC tank circuit has been done. For the analysis purpose, only prototype of 1kW has been designed with suitable PWM control strategy. Also to attain the level of performance required for LCL load resonant topology ZVS ZCS of the load had been selected. This mode of soft switching is used to reduce IGBT switching losses. The circuit design had been implemented with suitable controller with control consideration. In present work the comparative study of the thyristor based converter with parallel resonant tank circuit and IGBT based inverter with third order resonance LCL configuration had been done. Also the design calculations for DC link of the inverter as well as LCL resonant circuit had been done with suitable design consideration. All design calculation data had been used for simulation purpose as well as for hardware designing and on the basis of obtained results conclusion has been drawn.

Keywords:- Voltage Source Inverter (VSI), Current Source Inverter (CSI), Pulse Width Modulation (PWM), Induction Melting & Heating, Inductive coupling (LCL).

Abbreviations

IGBT......Insulated Gate Bipolar Transistor
PWM......Pulse Width Modulation
VSI......Voltage source Inverter
CSI......Current Source Inverter
MOSFET......Metal Oxide Semiconductor Field Effect Transistor
K_p......Proportional Gain
K_I......Integral Gain
kV......Kilo volt
kVA......Kilo volt ampere
kVAR......Kilo volt ampere reactive
kW......Kilo watt
GND......Ground
PF......Power factor
AC......Alternating current
DC......Direct current
A_p......Area Product
K_g......Core Geometry
K_w......Window Utilization Factor
K_c......Crist Factor
E_L......Energy Stored in Inductor
B_m......Flux Density
A_c......Core Area
A_w......Window Area
SWG......Standard Wire Gauge
LED......Light Emitting Diodes
Op-Amp......Operational Amplifier

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Chapter 1

Introduction

The technology of 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. Induction heating is a non contact method of heating a conductive body by strong magnetic field. Most of the metals use melting as the very 1st step in producing a useful product and thereby heating is done to achieve optimum physical properties, therefore we use induction furnaces. Generally the load in induction heating applications has a very poor 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 section.

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. A penalty for power factor below and a credit for power factor above a predetermined value

b. An increasing penalty for decreasing power factor,

c. 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 observed.

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 :-

a-It magnifies the voltage across the work coil higher then o/p of the inverter.

b-Disadvantages of this circuit are it carry same current that flow through the coil.

b. Parallel resonant tank circuit :-

a-Magnify the current to work coil higher than current capability of inverter

b-Inverter has to carry part of the load current.

c. Hybrid resonant tank circuit :-

a-Magnify the current to work coil higher than current capability of inverter

b-Inverter has to carry part of the load current

c-Power factor is improved because of additional capacitor and inductor in the circuit.

1.3 Comparative Analysis of Different Resonance Circuits:-

	Series Resonance	**Parallel Resonance**	**Hybrid Resonance**
Switching losses	Moderate	High	Low
Simplicity for protection and maintenance	Very easy	Easy	Complex
ZCS or ZVS	Both	ZCS	Both
Flow of current through Inverter	Full	Part of load current	Part of load current
Higher operating Frequency	Possible	Less possible	Can be obtained
Weight	Light	Medium	Heavy
output Power	Less	Moderate	High
Efficiency	Medium	Poor	80-90 percentage
Device Cost	Higher	Lower	Moderate
Power rating of semiconductor devices	Higher	Moderate	Lowest
P.F. at all loads	Good	Poor	Better
Construction	Simple	Moderate	Complex
on load switching losses	Higher	Moderate	Lower

Chapter 2

Literature Survey and 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.

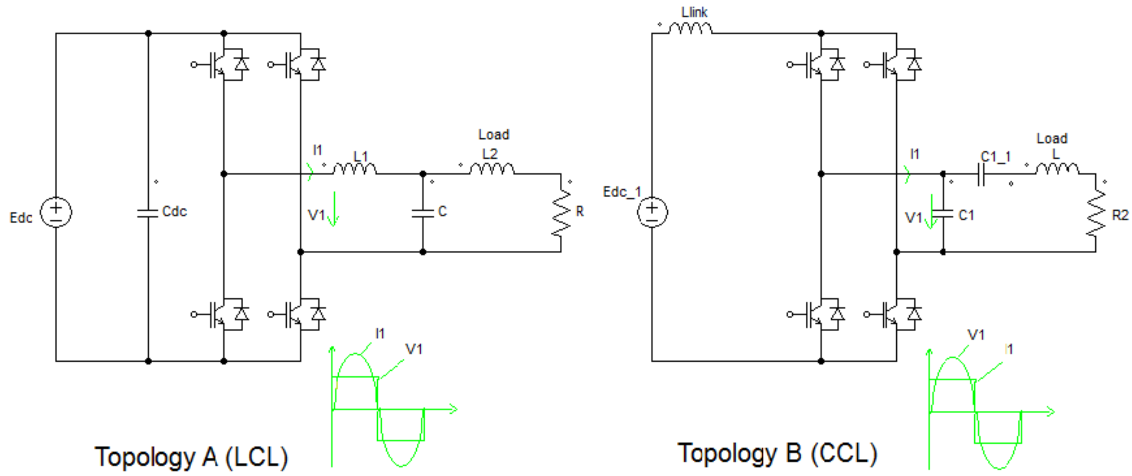

Figure 2.1: VSI with Inductive Coupling (topology A) and CSI with capacitive coupling (topology B) of the load

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.

In present work the topology which has been selected according to the industry requirement is constant load topology i.e. inductive coupling with VSI. Also the 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.

The benefit of using this topology is that at the rectifier side uncontrolled diode bridge rectifier is used, due to which control at rectifier is eliminated, hence cost

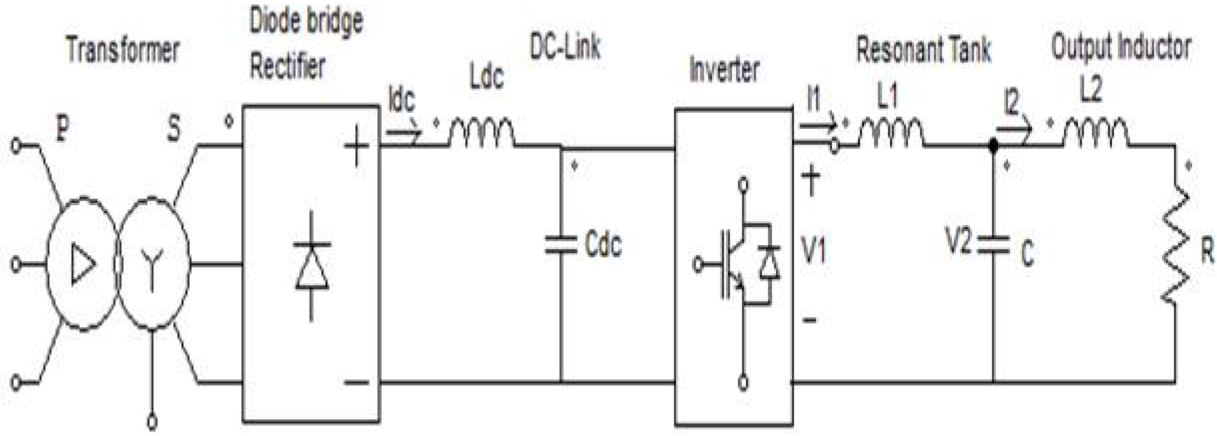

Figure 2.2: Power schematic of the IGBT based resonant inverter with LCL configuration

and control complexity has been decreases drastically. Also the control of inverter with suitable PWM control strategy makes possible to vary output power if required. Apart from this LCL resonant tank circuits operates in such a way that makes voltage as well as current high at the load coil without affecting the inverter switches rating.

2.1 Resonant Convertors:

Resonant convertors are used for reducing the switching losses and to reduce stress on device. They turn-off and turn on device at zero voltage and/or current through it. Basically two types of resonant convertors:-

a. Zero Current Switching

b. Zero Voltage Switching

a. Zero Current Switching

a-ZCS can eliminate the switching losses at turn-off and reduce the switching losses at turn-on.

b-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.

c-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

a-use in frequency conversion circuit

b-use for constant load application

c-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.

Chapter 3

DC Link Design Calculations

3.1 Calculation for value of DC Link Inductor (L_{dc}) and capacitor (C_{dc})

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.

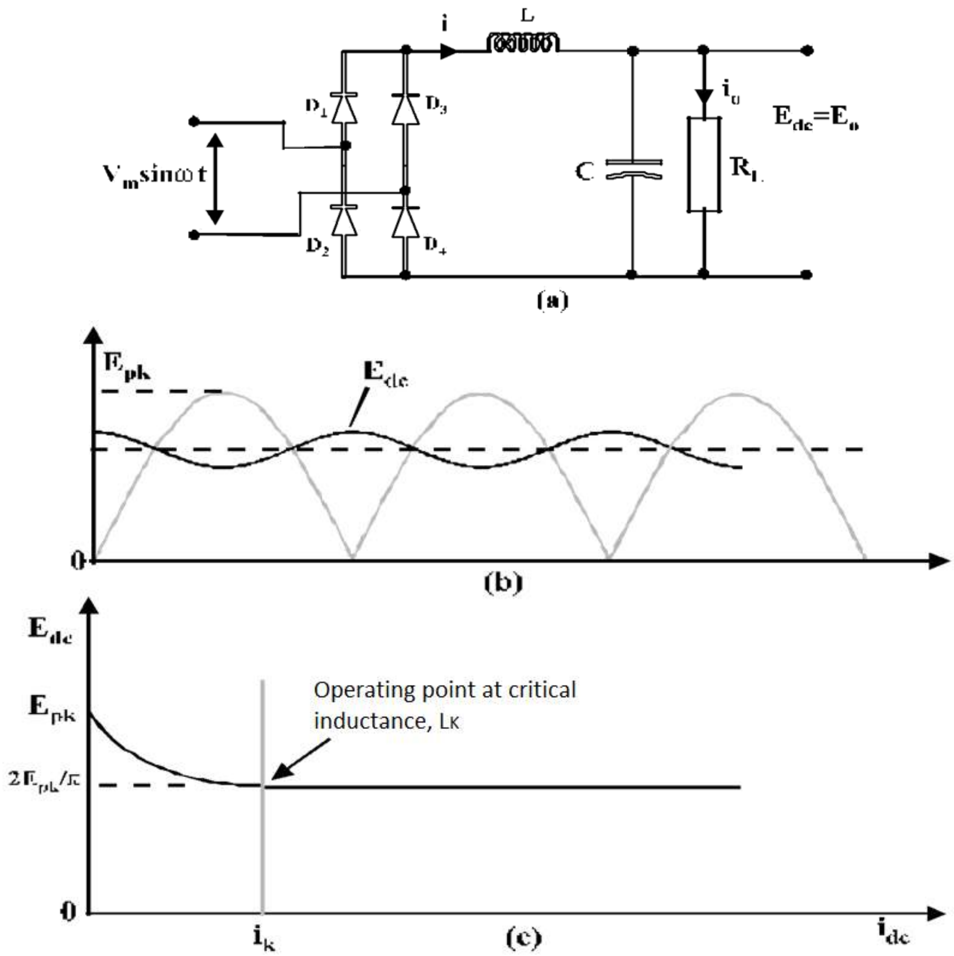

Figure 3.1: Full wave rectifier with inductor input filter (a) rectifier-LC filter circuit, output voltage waveform,(c) output voltage versus load.

3.2 CRITICAL INDUCTANCE, L_K

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 180 degree . 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 $2E_pk/\pi * R_L$ must be equal to or greater than the predominantly second harmonic component $4Epk/(3\pi * 2 * \omega_s * L_k)$, from which one obtains the condition that Lk should be equal to or greater than $(R_L/3 * \omega_s)$. The general equation for critical inductance in single and polyphase rectifiers is then:-

$L_{dccritical} \geq 2R_L/p(p^2 - 1)\omega$

Where p= no. pulse of output voltage

ω = source frequency

R_L=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, L_k 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

V_s=550 volt

F=50 Hz

$f_{ripple} = 50 * 6 = 300Hz$

$P_{output} = 100kW$

$I_{dcmin} = P_{output}/(1.35 * V_s)$

$I_{dcmin} = (100 * 1000)/(1.35 * 500) = 134.68A$

f_{of}= frequency of oscillation that has to be less than 50Hz

taking $f_{of} = 30hz$

Steps 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

$L_{dccritical} = V_{ripple}/[2\pi * f_{ripple} * I_{DCmin}] = 0.000965664H$

As $L_{dcactual} > L_{dccritical}$

Taking L actual as= 0.006

II. To find C_{dc}

$C_{dc} = 1/[4 * L_{DCactual} * f_{of}^2 * \pi^2]$

$= 4.55\mu$

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.

Chapter 4

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 no 4.1. 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.

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.

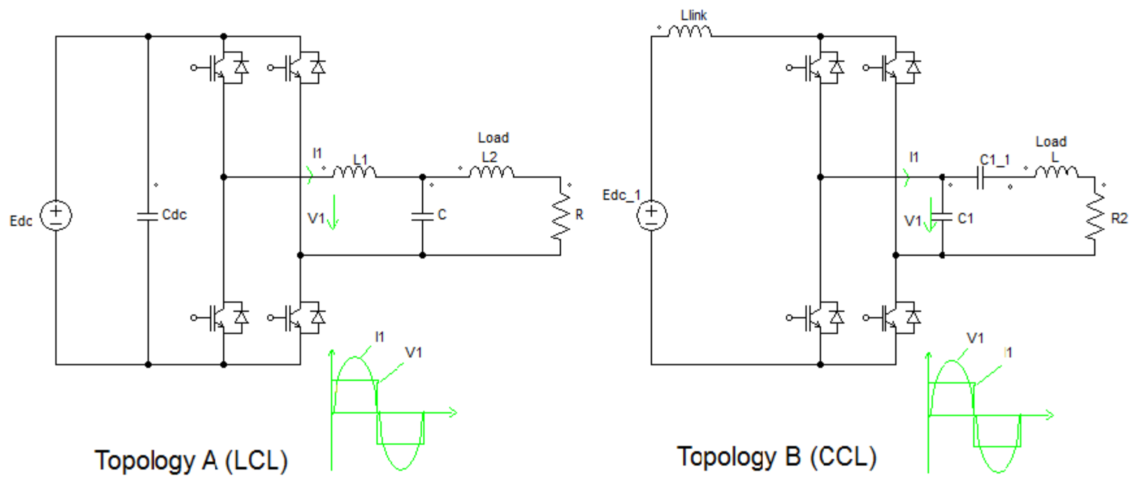

Figure 4.1: VSI with Inductive Coupling (topology A) and CSI with capacitive coupling (topology B) of the load

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 therefore 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 ω_{01} and ω_{02}.

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: $Z \rightarrow 0$

$\omega_{01} = 1/[\sqrt{C * L_1 * L_2}/(L_1 + L_2)]$.....................(4.1)

$Z \rightarrow \infty$

$\omega_{02} = 1/[\sqrt{C * L_2}]$...................(4.2)

The LCL resonant tank is supplied by a voltage source inverter. It operates at the resonant frequency defined by the complex input impedance Z$\rightarrow$ 0.

The resonant circuit works at the frequency set by the input impedance Z$\rightarrow \infty$.

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:

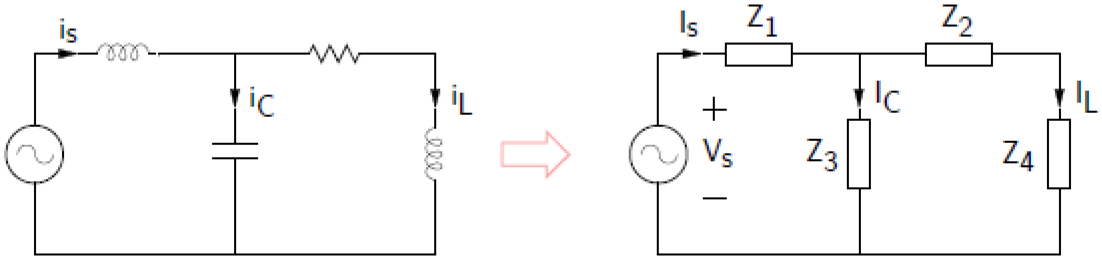

Figure 4.2: equivalent resonant-tank circuit

Here,

Z_1=$j\omega_{L_1}$ (Reactance Of Resonant Inductor)...............(4.3)

Z_2=$j\omega_{L_2}$ (Reactance Of Load Coil Inductor)................(4.4)

Z_3=$1/(j\omega * c)$ (Reactance Of Resonant Capacitor)...............(4.5)

z_4=R (Resistance Of Load Coil)............................(4.6)

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

a. 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.

   $z' = z_4 + z_2$.....................(4.7)

   $z' = R + j\omega * L_2$...............(4.8)

b. The resultant impedance of load coil and impedance of capacitor are calculated with parallel impedance calculation principal.

$Z" = z'||z_3$...............(4.9)

$Z" = ((1/j\omega * C) * (R + j\omega * l_2))/(R + (j\omega * L_2) + (1/j\omega * c))$...........(4.91)

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

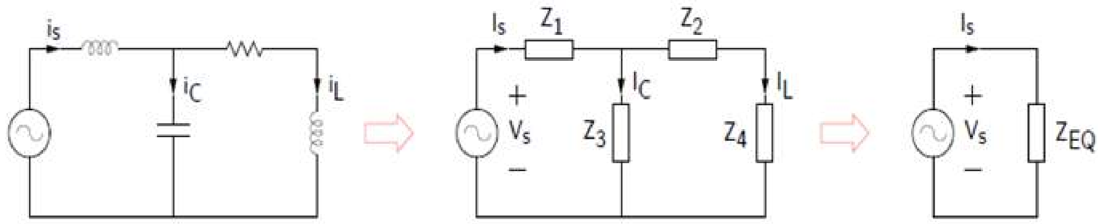

Figure 4.3: total system equivalent impedance.

After the calculating the resultant impedance the total equivalent impedance is the series connection of two impedances. $Z_{eq} = Z" + Z_1$................(4.92)

$Z_{eq} = j\omega * L_1 + ((1/j\omega * C) * (R + j\omega * l_2))/(R + (j\omega * L_2) + (1/j\omega * c))$..(4.93)

$Z_{eq} = j\omega * L_1 + (R + j\omega * L_2)/(1 - \omega^2 * C * L2 + J\omega * RC)$....(4.94)

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}.

$R_{eq} = R/((1 - \omega^2 * c * L_2)^2 + (R\omega * C)^2)$...(4.95)

And also equivalent reactance,

$X_{eq} = \omega * L_1 + (j\omega * L_2 - c * \omega^3 * L_2^2 - \omega * R^2 * c/(1 - \omega^2 * c * L_2)^2 + (RC\omega)^2)$..(4.96)

With help of these equations we can find out the correct and economical values of our circuit components. The required steps are given below:-

Step:1

$\omega = 2 * \pi * f$

$\omega = 2 * \pi * 500$

$\omega = 3140$ rad/sec

Step:2

$Req = V_{dc}^2/P_{output}$

$Req = 5.5\Omega$

Step:3

Device Current Ratio,$a =$I$_2$ $/I_1$

$a = 5.925$

$L_1 = a * L_2$

$L_1 = 0.00302\mu$

Step:4

$C = (L_1 + L_2)/[\omega^2 * L_1 * L_2]$ F

$C = 233\mu F$

Step:5

$X_{eq} = 0.8\Omega$

Chapter 5

Comparative Analysis of SCR & 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.

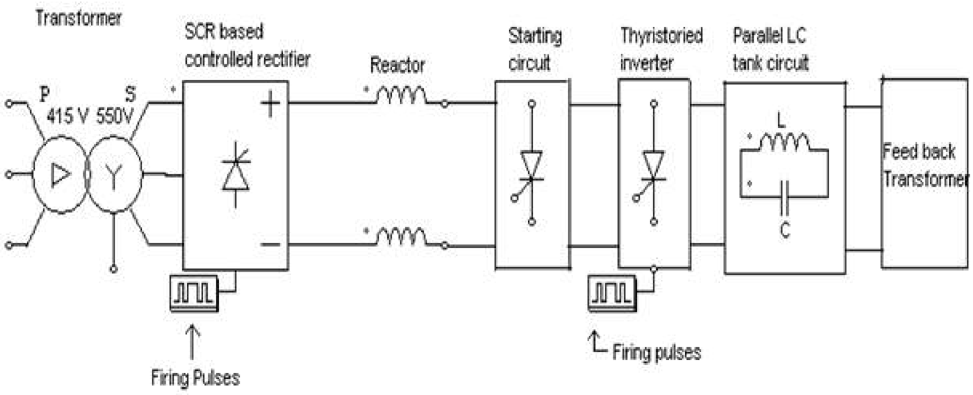

Figure 5.1: Power schematic of thyristorised based parallel resonance circuit configuration

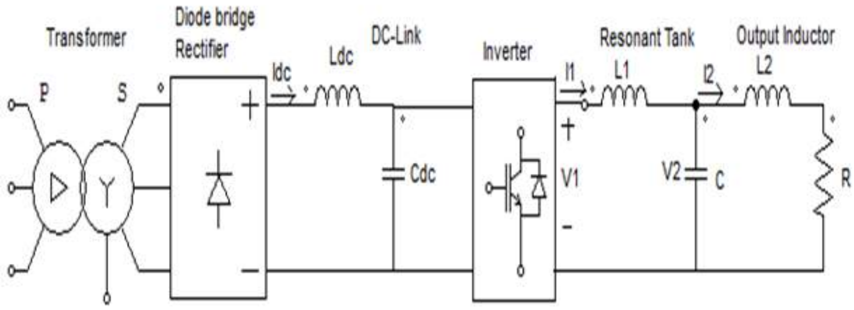

Figure 5.2: IGBT based LCL resonance inverter.

IGBT based LCL resonance Inverter	**Thyristorised based Parallel LC resonance Inverter**
Front end rectifier is diode bridge rectifier	Here rectifier is controlled rectifier thyristorised
Inverter id IGBT based	Inverter is thyristor 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
Small size	Large, due to requirement of gate drivers both side

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 [1].

Chapter 6

Simulation Results

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

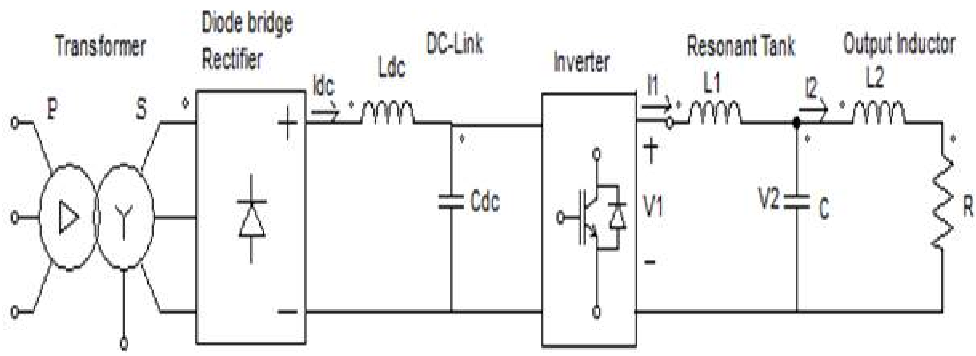

Figure 6.1: - shows the logical power schematic of IGBT based LCL resonant inverter with uncontrolled rectifier

On the basis of the input values following output has been obtained:- Given data is:-

3 ph. source voltage=415 v

Transformer output= 550 v

Required total output power rating= 100kW

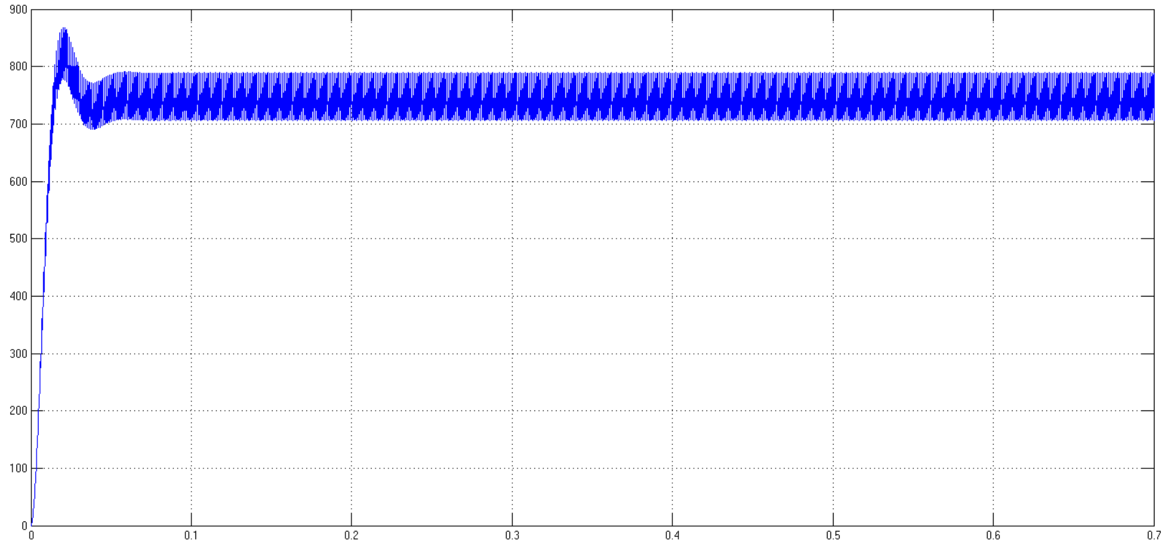

Figure 6.2: X-axis=Time(sec.),Y-axis= Voltage, Output voltage of DC link filter

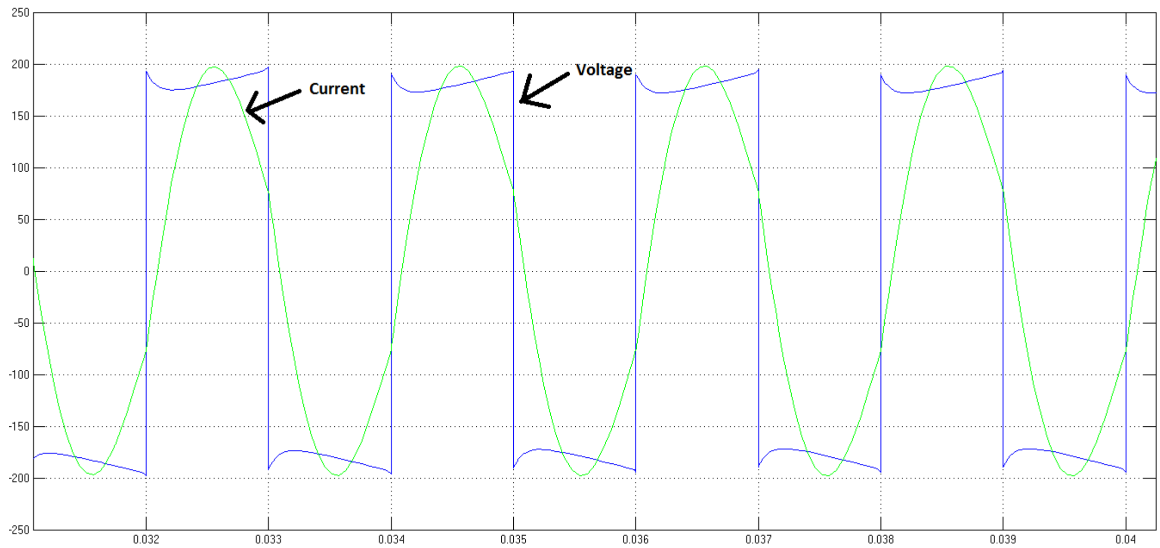

Figure 6.3: X-axis= Time (sec.), Y-axis= voltage, output voltage and current of the inverter

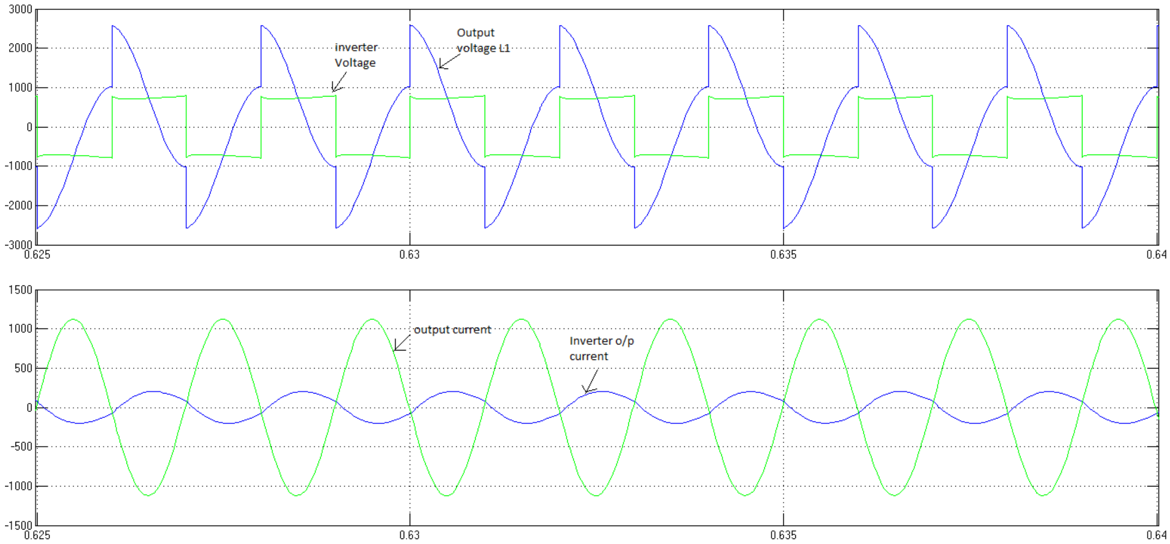

Figure 6.4: X-axis=Time(sec),Y-axis=1 voltage,2-current, output voltage and current across the inductor L1

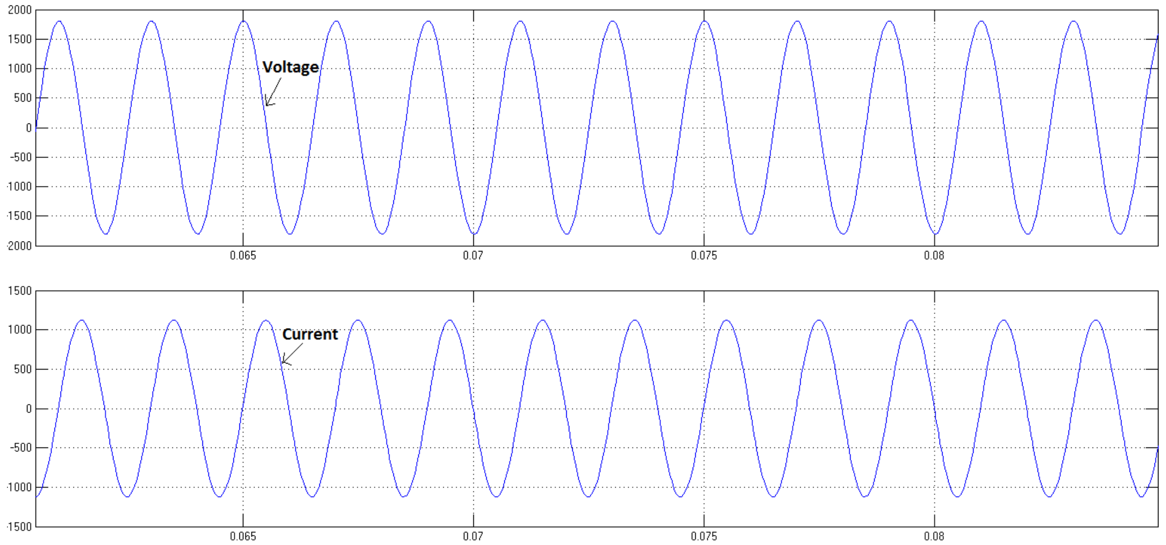

Figure 6.5: X-axis=Time(sec),Y-axis=1-Voltage,2-Current, shows the total output voltage current across the tank coil

Chapter 7

Design of Close Loop Control Circuitry

7.1 Close Loop Control Requirement

Why close loop control?

There are a number of variables which can seriously affect the heating and melting process. By determining the process fluctuations, it will ultimately be possible to improve the production process. To do this, closed loop controlled processes potentially constitute an important tool for the reduction of defects, reduction of rework and a better quality of final products. The basic need of close loop control for induction furnaces are:-

- To get desired system output w.r.t current and voltage at various loading conditions
- To optimize or reduce energy consumption
- To increase reliability and life of the system
- To protect load from instantaneous high power
- To improve product quality.

7.2 Inverter control

The control of the switching instants with a frequency of 500Hz is possible with simple PI controller. As output power can be controlled with the help of inverter only, because front end converter is uncontrolled rectifier. So by varying the pulse width output power can be controlled. The pulse width should be varied in such a way so that it can cater the instantaneous power requirement at load side.

Although the basic fact for the induction furnaces form industrial experts is that, furnace operate at the full load (full power) almost 80 percent of the total working time. So more concern is on to get perfect output in the range of 75 percent of full load to 110 percent of full load. The block diagram showed in fig.7.1 shows block diagram, in which how control gate pulses are given to IGBT gate driver to drive inverter.

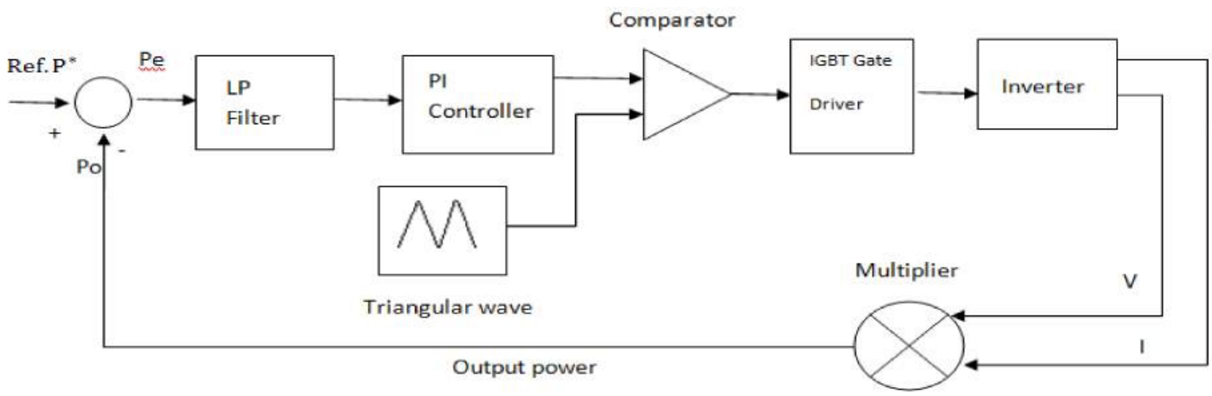

Figure 7.1: Block diagram for close loop control of inverter

The output power of the inverter is achieved by sensing current and voltage and then multiplying them to get power now this power is actual power of the system. To get desired output power, the actual power is compared with the reference power (i.e. desired power) now the error generated at the point will be Pe (error in power) this error is now processed through PI controller, PI Controller is tuned with proper integral (KI) as well as proportional gain (Kp). Than the output of the PI controller is compared with high frequency triangular wave to generate gate pulse now this gate pulses are given to the IGBT gate driver and finally inverter operates with desired voltage and current requirement at the load side.

7.3 Close Loop Simulation Results

Input voltage and current drawn by the system at the varying load condition. Figure

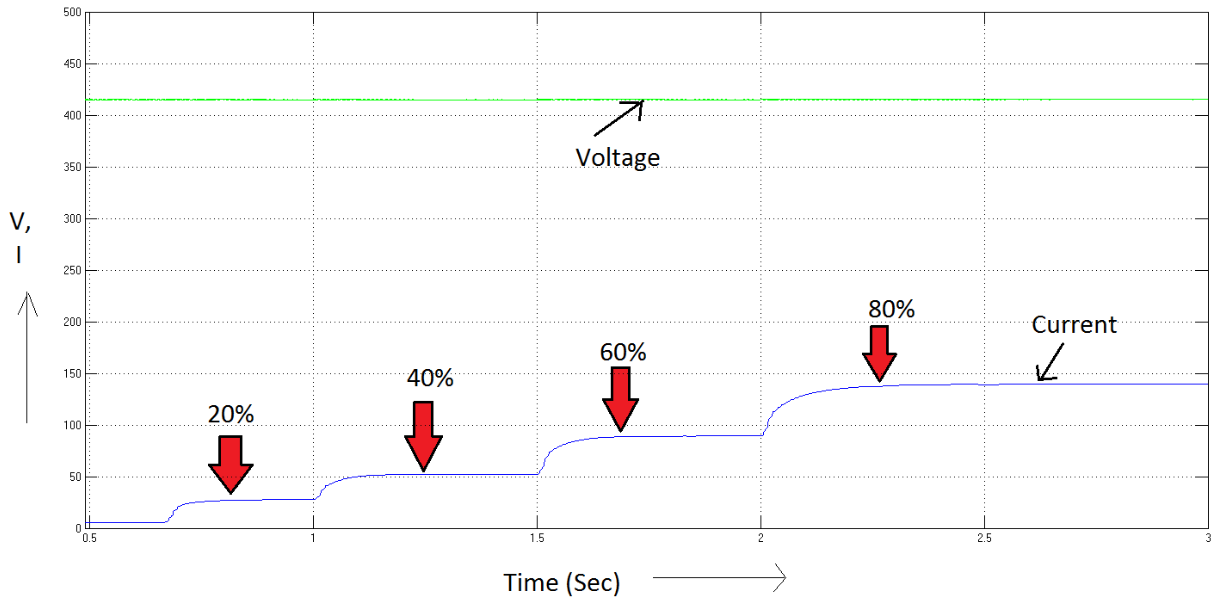

Figure 7.2: X-axis=Time(sec),Y-axis=Voltage,Current,Input voltage and current variation w.r.t load

7.3 shows change in output of PI controller with respect to variation in load power. Now in fig 7.4 the total system output(i.e. at tank coil) voltage and current with load variation is shown. And finally in figure 7.5 Input power vs inverter output power.

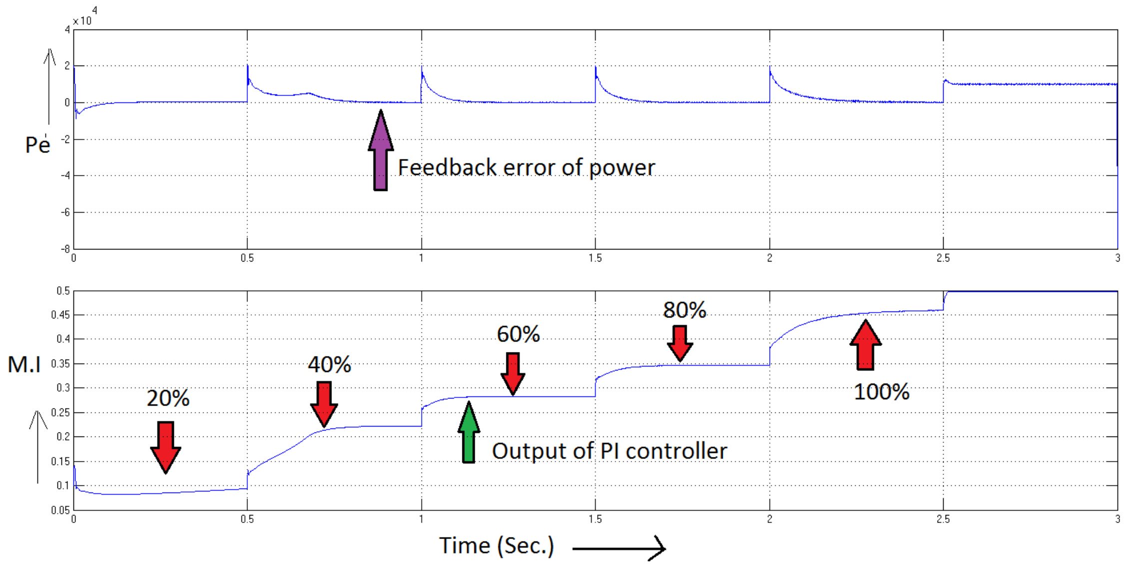

Figure 7.3: X-axis=Time(sec),Y-axis=1-Power error,2-Modulation index,Processed error of PI controller and output of PI controller

7.4 Problem Observed in Close loop System

As the load requirement is variable thereby the input power need is also variable. Incase when the system operates in underload condition the total system output wave is perfect but the inverter output voltage waveform shape is not obtaining as it is desired. i.e. the shape should be same as that of 100 percent load but it seems like for a bit more time anti parallel diode starts conduction and makes waveform distorted. The waveform which is obtained in underload condition is shown below (fig7.6) with comparison to waveform at full load(fig7.7).

Second problem is basically an advantage if we consider it in terms of circuit size and cost.that is while performing close loop simulation desired wave shape at the DC link as well as output of inverter is not obtaining following the normal technical procedure of changing the value of DC link inductor so as to get the wave shape as desired and remove spikes from the waveform. but this was not working as a solution to the problem, so finally by removing the DC link inductor the spikes from the

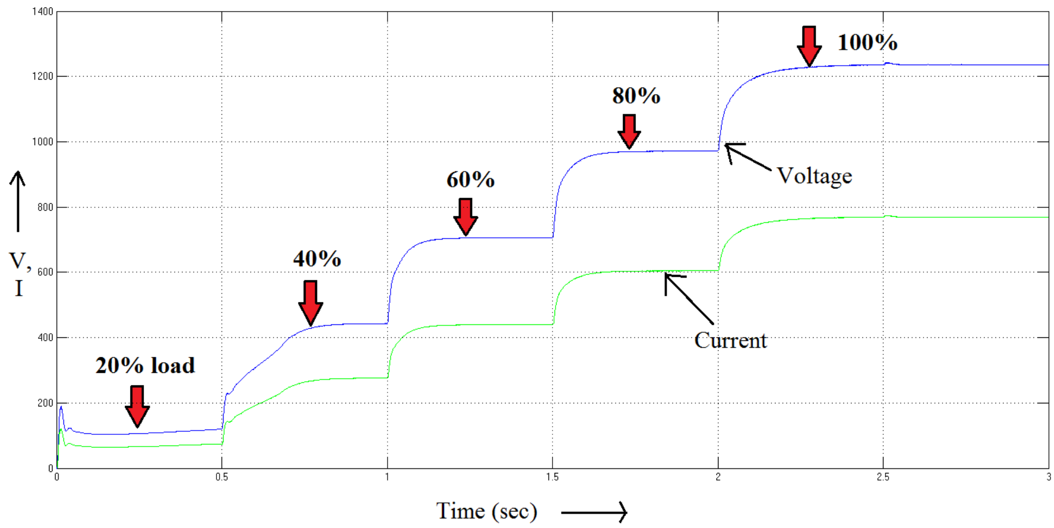

Figure 7.4: X-axis=Time(sec),Y-axis=Voltage and current,total system output w.r.t variation in load

waveform as well as desired wave shape at the output of the inverter was achieved, this way it gives the advantage to the system it will be low in cost as well as will help in compactness of the system. below figure shows the effect on wave shape with and without inductor.

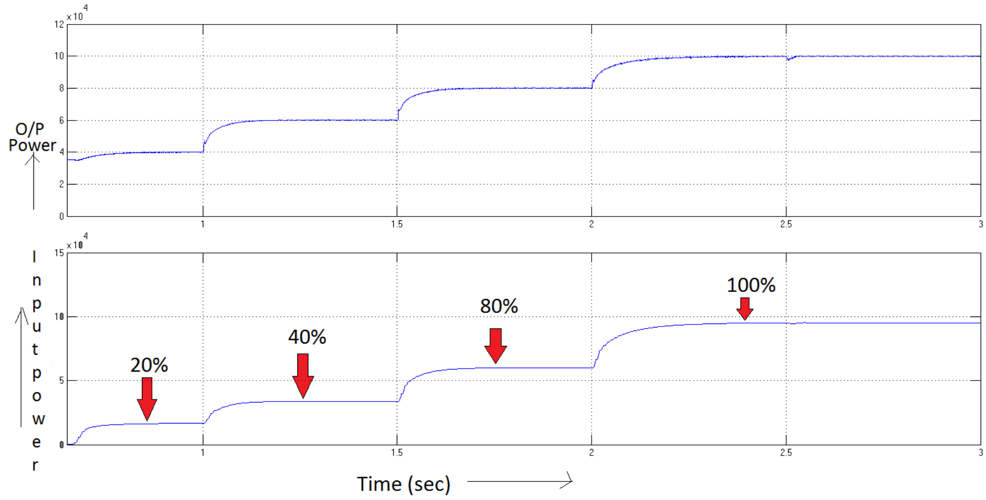

Figure 7.5: X-axis=Time(sec),Y-axis=1-output power,2-input power,variation in power w.r.t. to change in load.

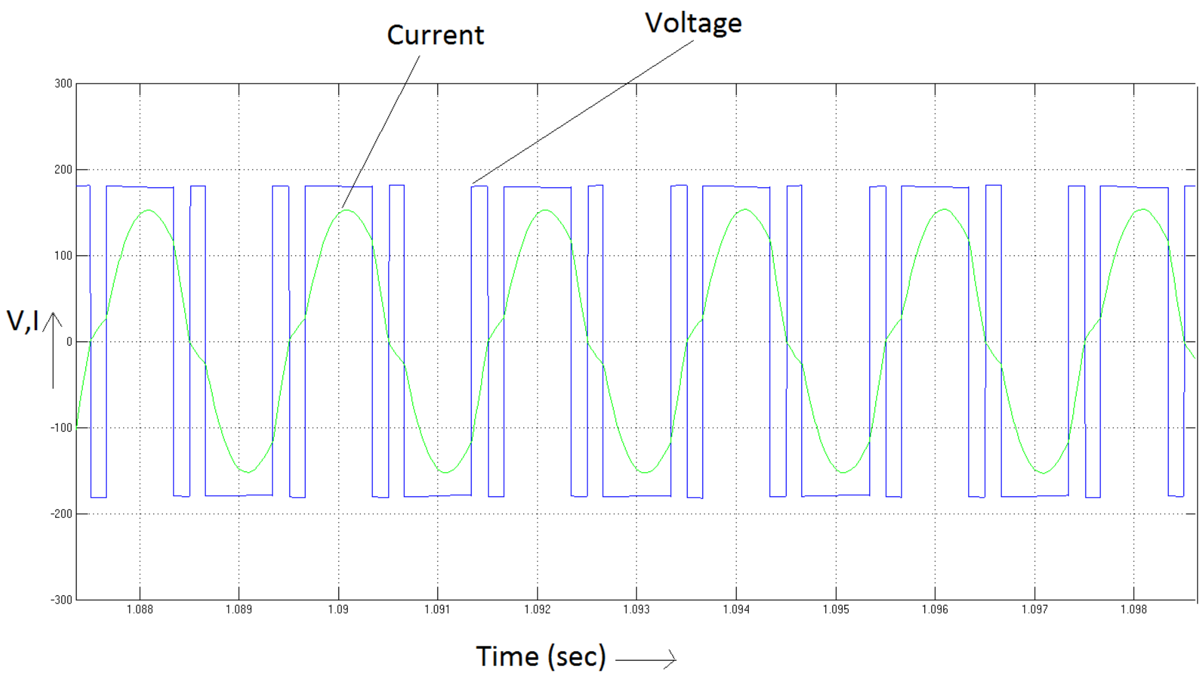

Figure 7.6: X-axis=Time(sec),Y-axis=Voltage and Current,Inverter output voltage and current at 70 percent load.

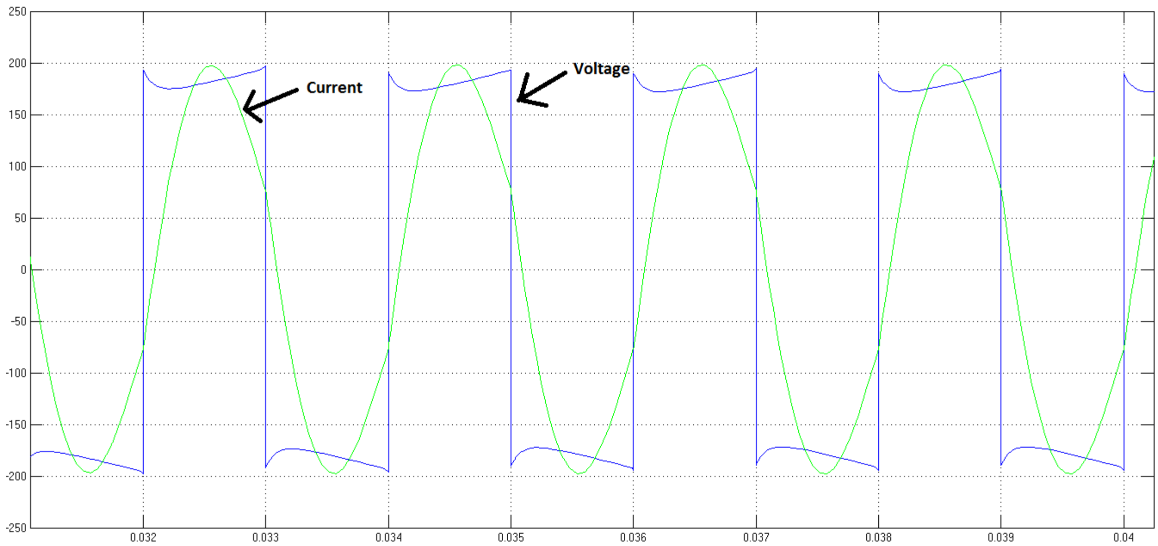

Figure 7.7: X-axis=Time(sec),Y-axis=Voltage and Current,Desired output of inverter waveform shape at each load irrespective of load variation.

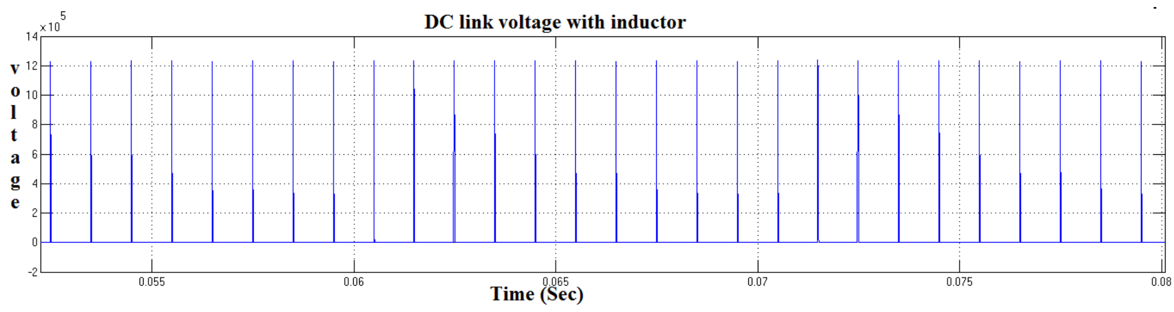

Figure 7.8: X-axis=Time(sec),Y-axis=Voltage,DC link voltage with inductor.

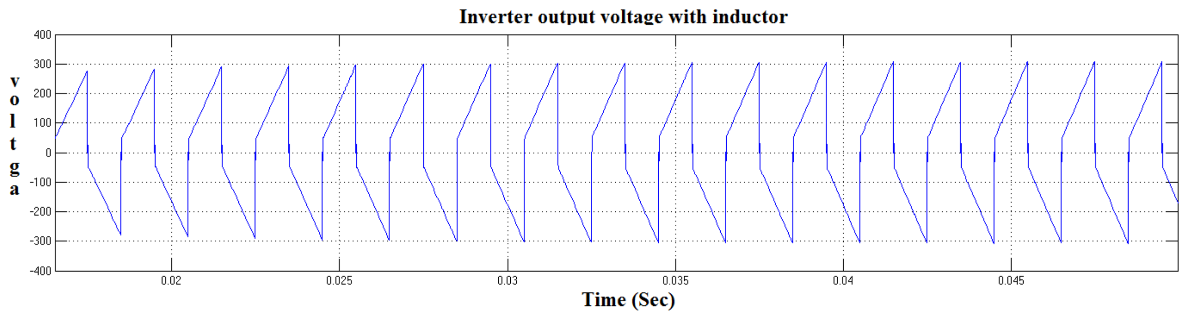

Figure 7.9: X-axis=Time(sec),Y-axis=Voltage,inverter output voltage with inductor.

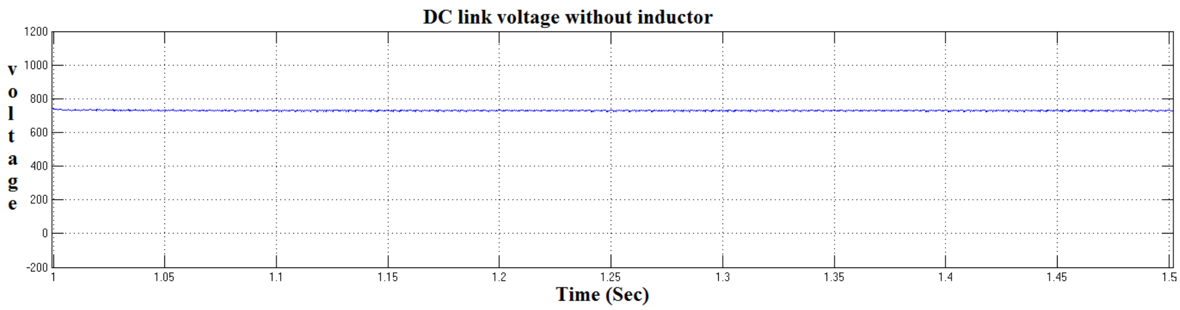

Figure 7.10: X-axis=Time(sec),Y-axis=Voltage,DC link voltage without inductor.

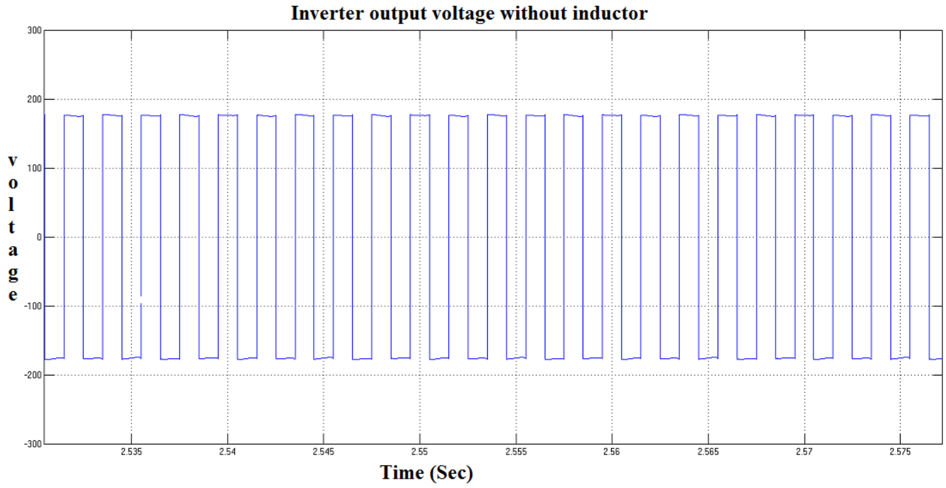

Figure 7.11: X-axis=Time(sec),Y-axis=Voltage,inverter output voltage without inductor.

Chapter 8

Design and Analysis on 1 kW LCL Resonant Inverter

For the experimental purpose a prototype of 1kW has been designed and as of now simulated in open loop. The design calculation for DC link(chapter 3) as well as LCL (chapter 4) is done in same way that of 100 kW system. Parameters for the design of 1 kW system are.

a. Three phase step down transformer=440/50 V, 2200 VA, 50Hz

b. Three phase diode bridge rectifier

c. $L_{dc} = 2$ mH

d. $C_{dc} = 5$ mF

e. single phase inverter

f. $L_1 = 4$ mH

g. $C_{ac} = 58\mu_F$

h. $L_2 = 3$ mH

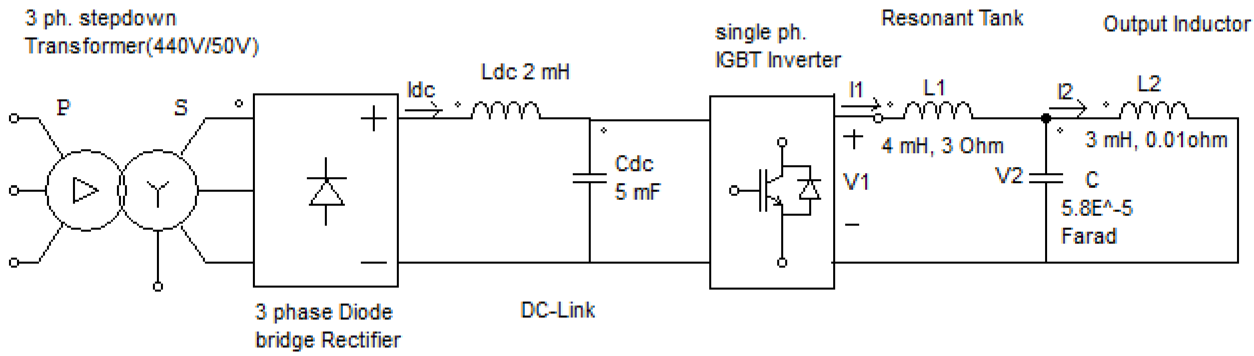

Figure 8.1: shows the power schematic of 1kW system with components rating

8.1 LC Filter Design Calculation

Given data

V_s=50 volt

F=50 Hz

$f_{ripple} = 50 * 6 = 300Hz$

$P_{output} = 1kW$

$I_{dcmin} = P_{output}/(1.35 * V_s)$

$I_{dcmin} = (100 * 1000)/(1.35 * 500) = 14.81A$

f_{of}= frequency of oscillation that has to be less than 50Hz

taking $f_{of} = 30hz$

Steps 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

$L_{dccritical} = V_{ripple}/[2\pi * f_{ripple} * I_{DCmin}] = 0.000798066H$

As $L_{dcactual} > L_{dccritical}$

Taking L actual as= 2mH

II. To find C_{dc}

$C_{dc} = 1/[4 * L_{DCactual} * f_{of}^2 * \pi^2]$

$= 5\mu$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. Similarly for LCL circuit design same steps are to be followed to get values of L1 and C.

8.2 Simulation Results Of 1kW System

Dc link output voltage and current

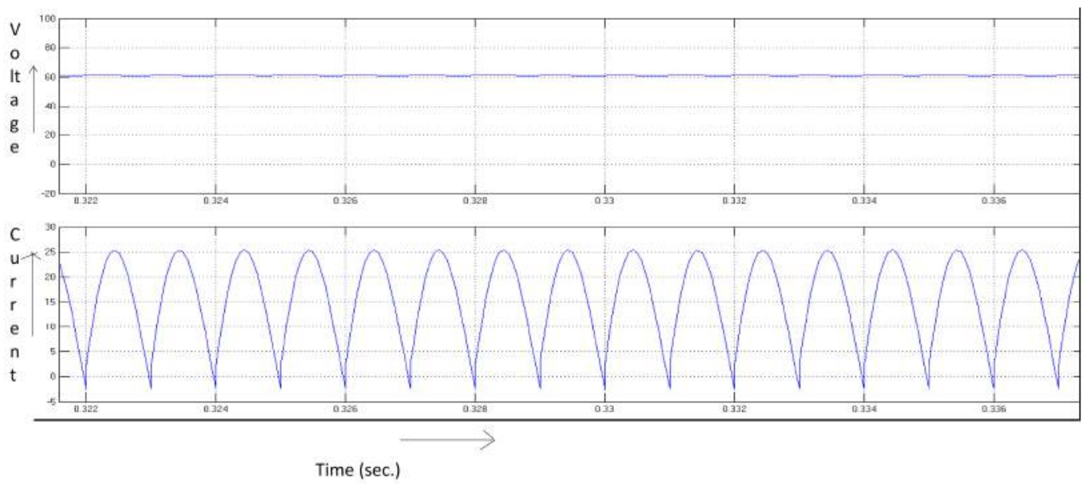

Figure 8.2: X-axis=Time(sec),Y-axis=1-Voltage,2-Current,DC link voltage and current

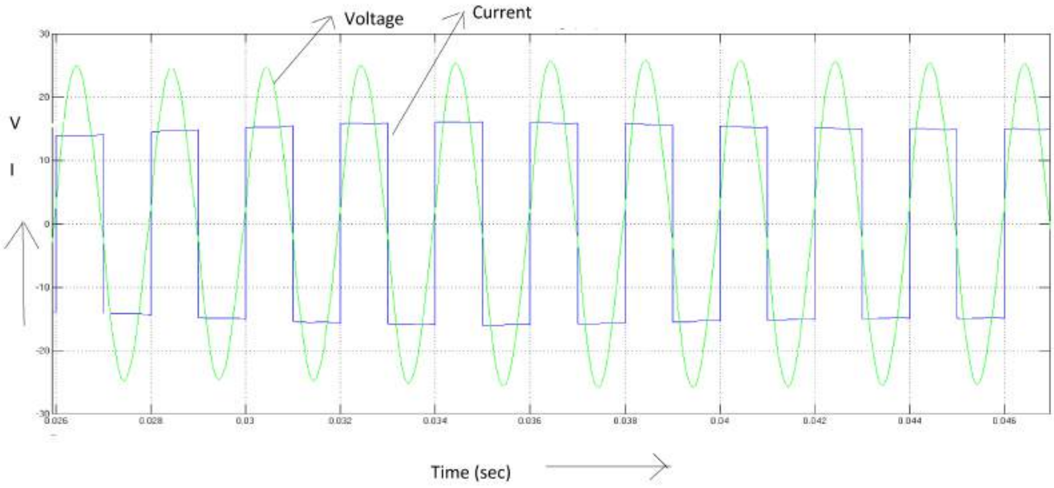

Figure 8.3: X-axis=Time(sec),Y-axis=Voltage and Current,inverter output voltage and current at 1kW

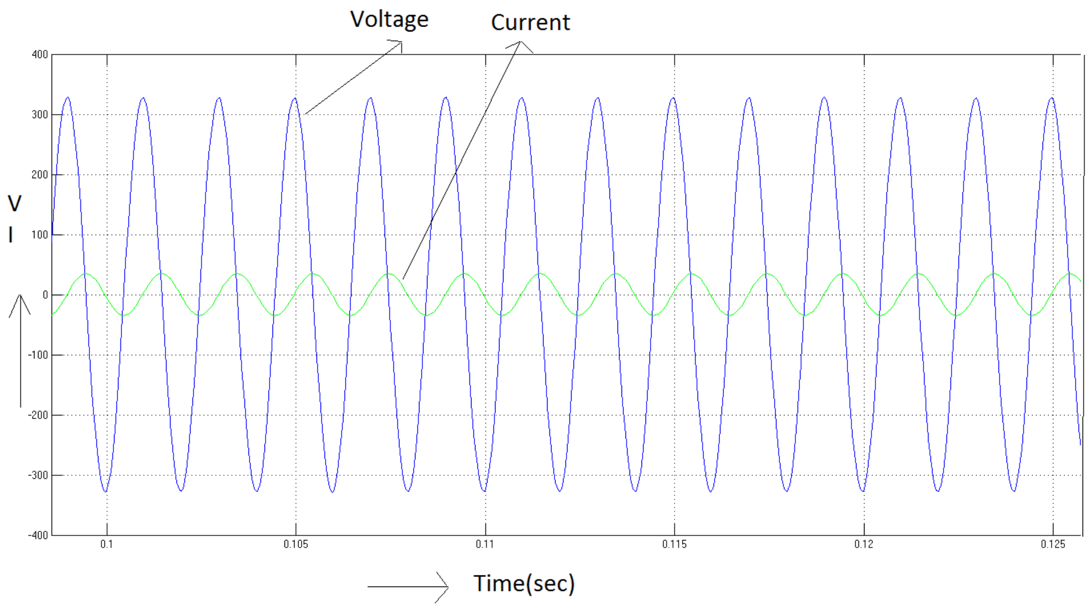

Figure 8.4: X-axis=Time(sec),Y-axis=Voltage and Current,output voltage and current at load 1kw load

Chapter 9

Hardware Design and Calculations

Since as of now open loop system is to be implemented on hardware so, for designing point of view inductor design and gate driver for IGBT are required to design, whereas for other components like three phase diode bridge rectifier, IGBT, Cdc and Cac can be obtained directly from market as per rating, and this rating can be obtained from simulation data and accordingly components has been chosen.

9.1 Inductor Design

To design the inductor the electrical and the magnetic parameters should be related to select the core, the winding gauge, the number of turns, and the air gap length. Basically inductor consists of physically of a winding and a magnetic core where in the electrical side of the inductor defines the current through the inductor, the amount of energy that the inductor requires to store, the voltage across the inductor, etc. and the core includes the magnetic and physical properties of the material like the flux density, core cross-sectional area, window area, magnetic length, permeability, etc. There are two approaches to design an inductor,

- Area Product approach (A_p)
- Core Geometry approach (K_g)

Here design has been done with area product approach and design calculations have been done with suitable assumptions.

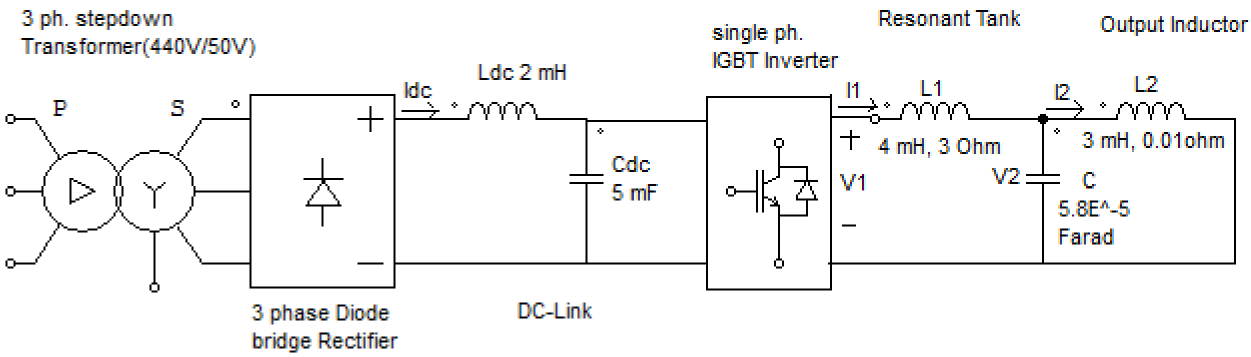

Figure 9.1: Power schematic of prototype design of LCL induction furnace

As in fig.9.1 it is clearly observable that there are three inductors which are to be designed. The first inductor is basically DC inductor and as per design there is no major difference between DC and AC inductor. In some literature it has been written that pure DC inductor does not exist, there is always some AC component of the current, which requires higher AC impedance.

9.2 Inductor Design Calculations

- Design of L_{dc}

  Area of product (A_P)

  The area product A_p should therefore be related to the energy that is stored in the core or the power that is transferred through the core.

  - Energy (E_L) that needs to be stored in the inductor in joules is

$E_L = 1/2 * L * I_m^2$

a. L = 2 mH

b. I_m is peak inductor current in amperes

$I_m = I_o + (I_L/2)$

I_o is output current, which is 18 amperes

I_L is current ripple in inductor, which is 10 percent of I_o

So, I_m= 18.9 A,

$E_L = 0.375$ J

Area of product$(A_P) = [2 * E_L/(K_w * K_c * J * B_m)]$

In which,

- K_w is the window utilization factor and has a value less than 1
  - K_c is called the crest factor for the particular current wave shape through the inductor
  - J is the current density (A/m^2)
- B_m is the maximum operating flux density in the core that corresponds to the maximum current I_m through the winding (T)

$K_c = [I_m/I_o] = 1.05$

$K_w = 0.6$ (for single winding)

$B_m = 1.5$ T

$J = 3 * 10^6 A/m^2$

$A_P = 2.64 * 10^(- 7)m^4$

We select AMCC 40 core, in which []

Net area $A_c = 3.7$ cm ^{2}

Window area $A_w = 8.4$ cm ^{2}

Area of product $A_P = 31.1$ cm ^{4}

Number of turns (N)

$N = L * I_m/B * A_c$

$= 67.55 = 70$ turns approx

Wire gauge selection $a = I_(rms)/J$

$= 6 * 10^(- 6)m^2$

$= 6mm^2$

[] select a wire gauge whose cross section area is greater than that calculated above. SWG is 10 selected $(a = 8.302(mm^2))$

- Design of L_1(Boosting Inductor)

  Area of product (A_P)

  Energy (E_L) that needs to be stored in the inductor in joules is

  $E_L = 1/2 * L * I_m^2$

  a. L = 4 mH

  b. I_m is peak inductor current in amperes

  $I_m = I_o + (I_L/2)$

  I_o is output current, which is 18 amperes

  I_L is current ripple in inductor, which is 10 percent of I_o

  So, I_m= 18.9 A,

  $E_L = 0.7144$ J

  Area of product$(A_P) = [2 * E_L/(K_w * K_c * J * B_m)]$ In which,

  - K_w is the window utilization factor and has a value less than 1
    - K_c is called the crest factor for the particular current wave shape through the inductor

    - J is the current density (A/m^2)

- B_m is the maximum operating flux density in the core that corresponds to the maximum current I_m through the winding (T)

  $K_c = [I_m/I_o] = 1.05$

  $K_w = 0.6$ (for single winding)

  $B_m = 1.5$ T

  $J = 3 * 10^6 A/m^2$

  $A_P = 5.039 * 10^(- 7)m^4$

  We select AMCC 40 core, in which []

  Net area $A_c = 5.9$ cm ^{2}

  Window area $A_w = 14$ cm ^{2}

  Area of product $A_P = 82.6$ cm ^{4}

  Number of turns (N)

  $N = L * I_m/B * A_c$

  $= 85.42 = 86$ turns approx

  Wire gauge selection $a = I_(rms)/J$

  $= 6 * 10^(- 6)m^2$

  $= 6mm^2$

  [] select a wire gauge whose cross section area is greater than that calculated above. SWG is 10 selected ($a = 8.302(mm^2)$)

- Design of L_2 (Tank coil)

  Area of product (A_P)

  Energy (E_L) that needs to be stored in the inductor in joules is

  $E_L = 1/2 * L * I_m^2$

a. L = 3 mH

b. I_m is peak inductor current in amperes

$I_m = I_o + (I_L/2)$

I_o is output current, which is 25 amperes

I_L is current ripple in inductor, which is 10 percent of I_o

So, I_m= 26.25 A,

$E_L = 1.03$ J

Area of product(A_P) = $[2 * E_L/(K_w * K_c * J * B_m)]$ In which,

- K_w is the window utilization factor and has a value less than 1
  - K_c is called the crest factor for the particular current wave shape through the inductor
  - J is the current density (A/m^2)
- B_m is the maximum operating flux density in the core that corresponds to the maximum current I_m through the winding (T)

$K_c = [I_m/I_o] = 1.05$

$K_w = 0.6$ (for single winding)

$B_m = 1.5$ T

$J = 3 * 10^6 A/m^2$

$A_P = 7.26 * 10^(- 7)m^4$

We select AMCC 100 core, in which []

Net area $A_c = 5.9$ cm ^{2}

Window area $A_w = 14$ cm ^{2}

Area of product $A_P = 82.6$ cm ^{4}

Number of turns (N)

$N = L * I_m / B * A_c$

$= 88.98 = 90$ turns approx

Wire gauge selection $a = I_(rms)/J$

$= 8.33 * 10^(- 6)m^2$

$= 8.33mm^2$

[] select a wire gauge whose cross section area is greater than that calculated above. SWG is 10 selected ($a = 10.51(mm^2)$)

So this way the design calculation of inductor has been done and then hardware implementation has to be done with above values.

9.3 Hardware Design of Inverter

9.3.1 Construction of a Single Phase Bridge Inverter

Specifications:-

a. Voltage rating 67 V_{dc} input.

b. Current rating 18.0 A.

c. Switching frequency is 500 Hz

d. Number of outputs= 2

The top and bottom devices in each leg of the inverter should be isolated.

Task:-

In meeting the above requirements it was necessary to build,

- Construction of Power Stage.
- Strong base drive circuit.

1. Construction of Power Stage:-

The total output wattage of the system is 1kW and switching frequency is 500 Hz the choice of device is an IGBT.

Selection of IGBT:-

- Considering a safety factor of three for the voltage, the voltage rating of the device should be 210 V.
- Considering a safety factor of 2 for the current, the current rating of the device should be 36 A
- The switching frequency of this IGBT should be greater than 500 Hz.

Referring to the Semikron IGBT device selection manual, SKM50GB123D IGBT module has been selected. V_{CES}= 210V, I_C =36 A. But due to the availability of SKM50GB123D (V_{CES} = 1200V, I_c = 50A) this IGBT module has been selected.

9.3.2 Design of Gate Driver Circuitry for IGBT

Gate driver circuitry is to be designed for driving (i.e. to turn on and off) any semiconductor switch. Here IGBT switch is to be derived by the gate driver, so for that control pulses is to be obtained from microcontroller, ATMEL 89C51 microcontroller has been used for this purpose and then the controlled pulses from the microcontroller has been given to gate driver circuitry (basically a optocoupler IC) than the gate driver gives optically isolated control pulses to IGBT gate. Basic block diagram of the gate driver circuitry has been shown below(figure no.9.2).

Microcontroller AT89C51:-

The AT89C51 is a low-power, high-performance CMOS 8-bit microcomputer with 4K bytes of Flash programmable and erasable read only memory (PEROM). The device is manufactured using Atmels high-density nonvolatile memory technology and is compatible with the industry standard.

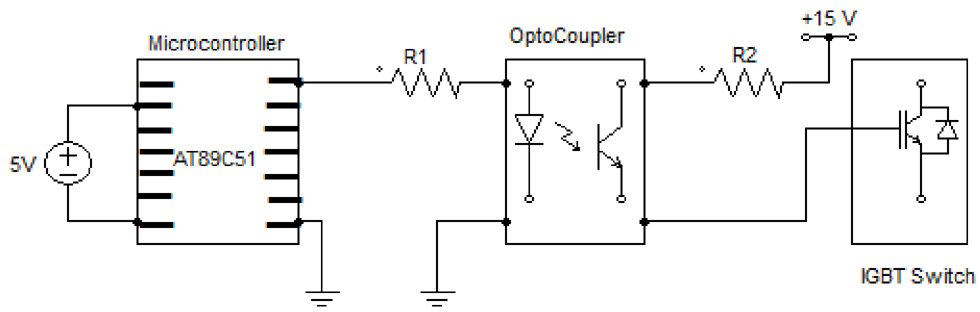

Figure 9.2: basic block diagram of gate driver circuit

MCS-51 instruction set and pin out. The on-chip Flash allows the program memory to be reprogrammed in-system or by a conventional nonvolatile memory programmer. By combining a versatile 8-bit CPU with Flash on a monolithic chip, the Atmel AT89C51 is a powerful microcomputer which provides a highly-flexible and cost-effective solution to many embedded control applications.

Optocoupler:-

Isolation between power circuit and control circuit is required in static phase converter which is provided by opto-isolator.

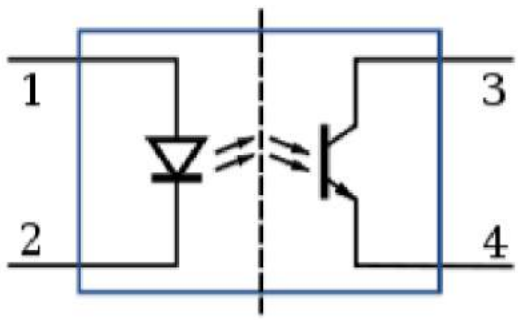

Figure 9.3: Optocoupler.

Schematic diagram of an opto-isolator is showing source of light (LED) on the left, dielectric barrier in the center and sensor (phototransistor) on the right. In electronics, an opto-isolator, also called an opto-coupler, photo-coupler, or optical isolator, is "an electronic device designed to transfer electrical signals by utilizing light waves to provide coupling with electrical isolation between its input and output".

The main purpose of an opto-isolator is "to prevent high voltages or rapidly changing voltages on one side of the circuit from damaging components or distorting transmissions on the other side". Commercially available opto-isolators withstand input-to-output voltages up to 10 kV and voltage transients with speeds up to 10 kV/s.

There are two kinds of optocouplers (a light emitting diode (LED) as an input and a phototransistor as an output) according to the type of output transistor.

1-Single transistor type

2-Darlington-transistor type

The single-transistor type optocouplers are used to perform high-speed switching (with high-speed response). The Darlington transistor type optocouplers are used to obtain a large output current by utilizing a small input current (independently of switching speeds).

Now, the threshold gate voltage is 5.5 V. But to ensure switching ON and OFF of the devices at these high frequencies, the gate voltage range is between +20V and 20V. In order to provide a sufficient gate drive current a transistor has been used before TLP250 optocoupler IC that will amplify the current to ensure turn ON of the IGBT. It should be noted that the power supply to each drive circuit should be isolated. The signals, AH, AL, BH, BL, CH, CL, DH, DL to these push pull stages is given through an opto-isolator driver IC TLP250.

Isolator driver IC TLP 250 is used.

Following reasons justify the advantages of using TLP 250.

- Input threshold voltage current If = 5 mA (max)
- Supply Voltage 10V-35 V
- Output Peak current 2 A

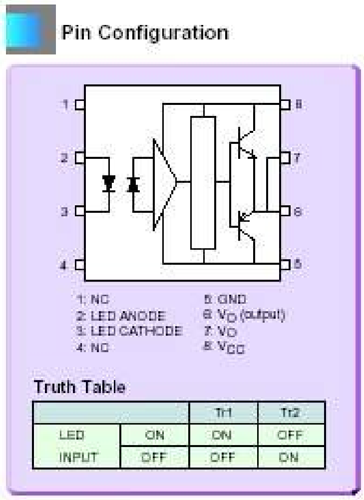

Figure 9.4: TLP 250 Opto-Isolator

- Response speed $0.5\mu_s$
- Isolation voltage 2500 Vrms

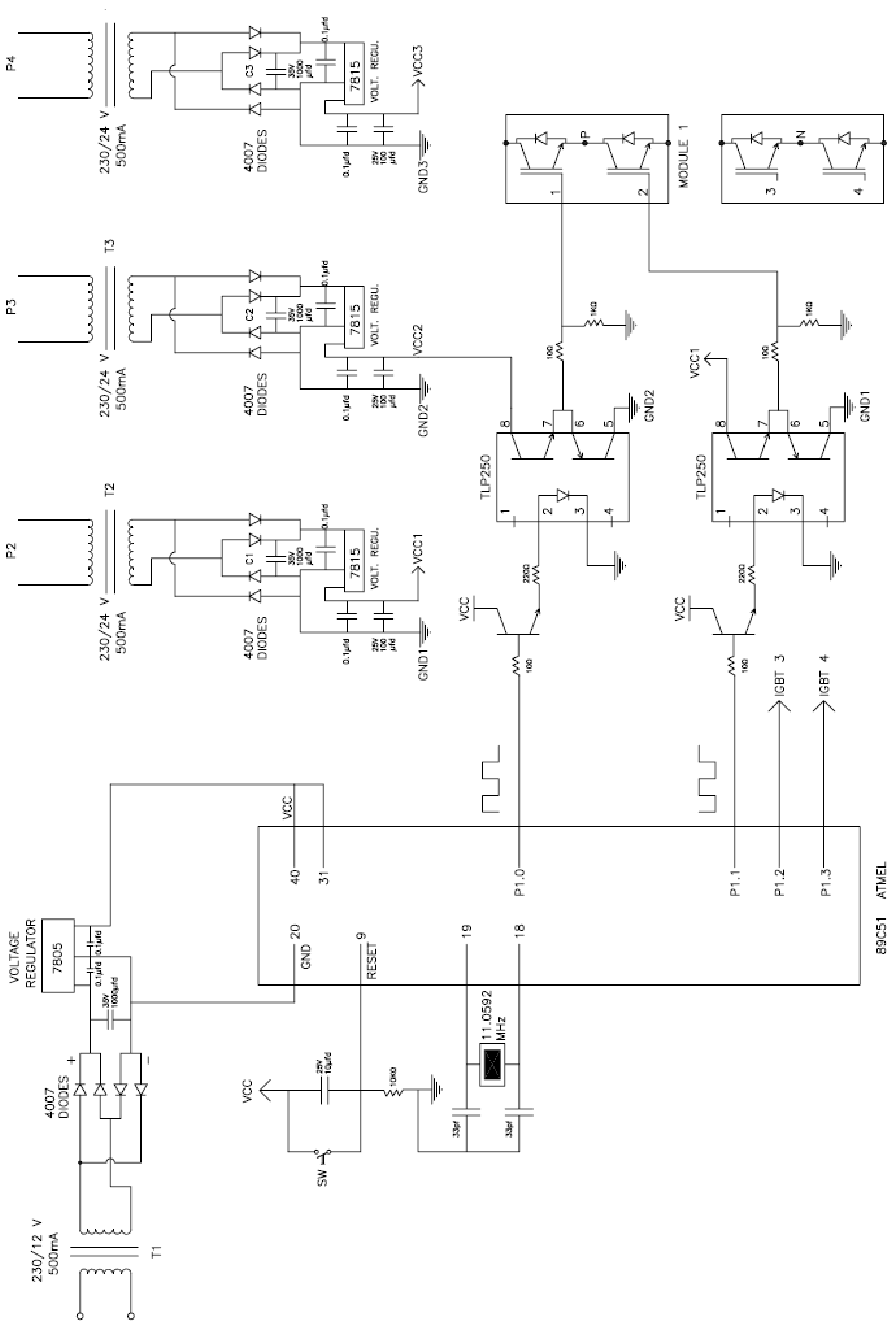

Figure 9.5: IGBT gate driver circuit diagram

Chapter 10

Hardware Circuitry and Experimental Results

Hardware design of the complete circuitry has been implemented, with the help of the design calculation suitable and specific component has been chosen for the hardware implementation. The specification of the components are as follows.

a. 3ph stepdown transformer 415 V/50 V

b. 3ph diode bridge rectifier IR- E62320

c. DC inductor 2 mH, frequency 300 Hz

d. DC Capacitor 5000 Microfarad.

e. Inverter IGBT V_{CES}=1200 V, I_C=50 A (Semikron SKM50GB123D)

f. Boosting Inductor L_1= 4 mH. 500 Hz

g. A.C. capacitor C= 58 microfarad, 415 V

h. Tank inductor L_2= 3 mH, 500 Hz

The whole hardware circuitry is shown below,

Figure 10.1: hardware setup of the LCL resonant converter

The hardware design of gate driver circuitry has been done and implemented on the IGBT based inverter, the output of gate driver (gate pulses) and inverter have been shown below.

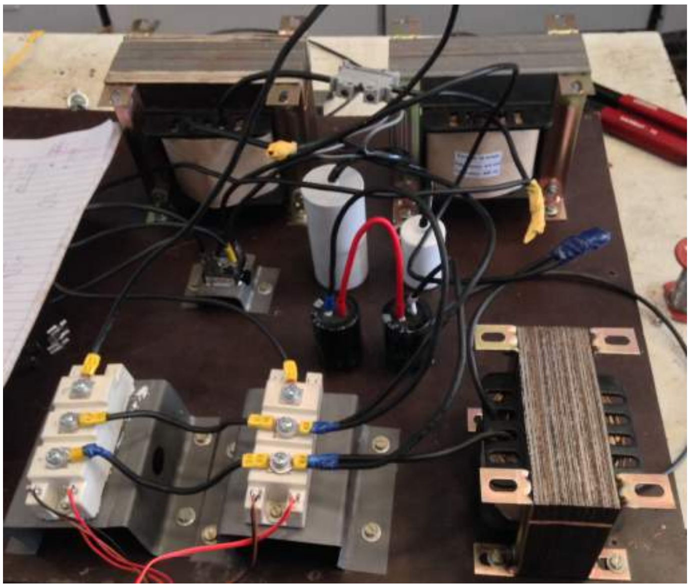

Figure 10.2: Sectional view of the Rectifier and LCL tank circuit.

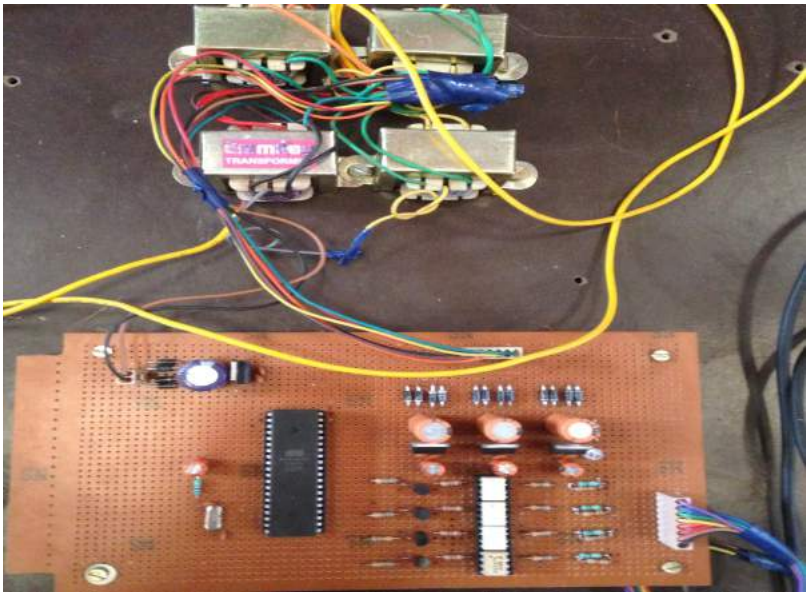

Figure 10.3: Gate driver hardware circuitry

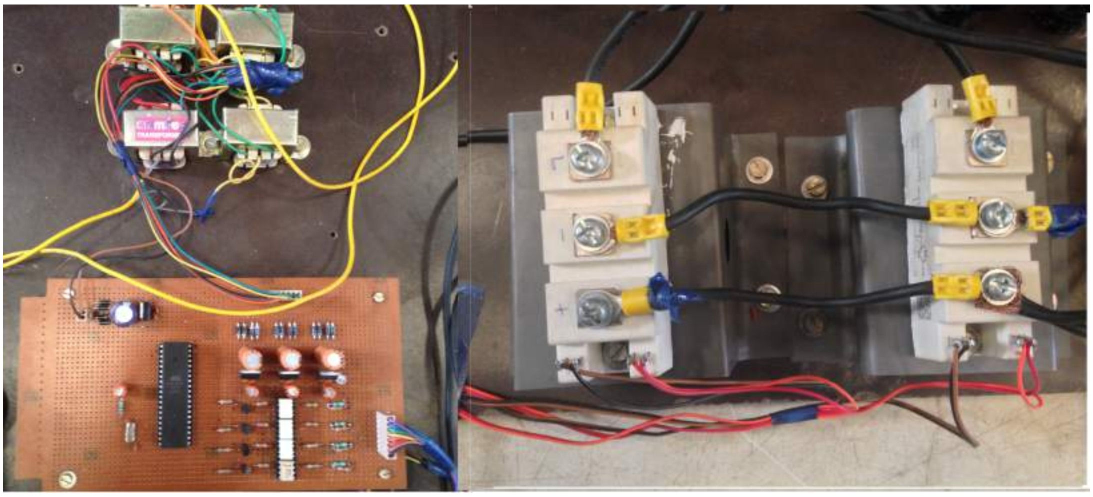

Figure 10.4: shows the hardware circuit of single phase inverter

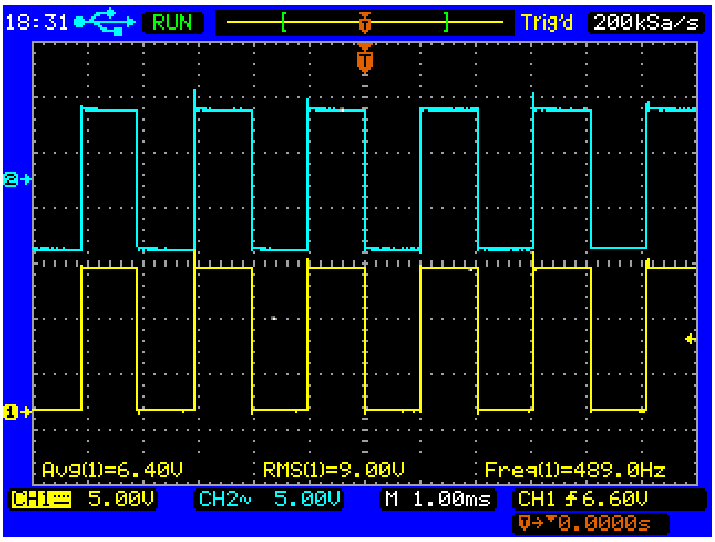

Figure 10.5: gate driver output for IGBT AH and BL

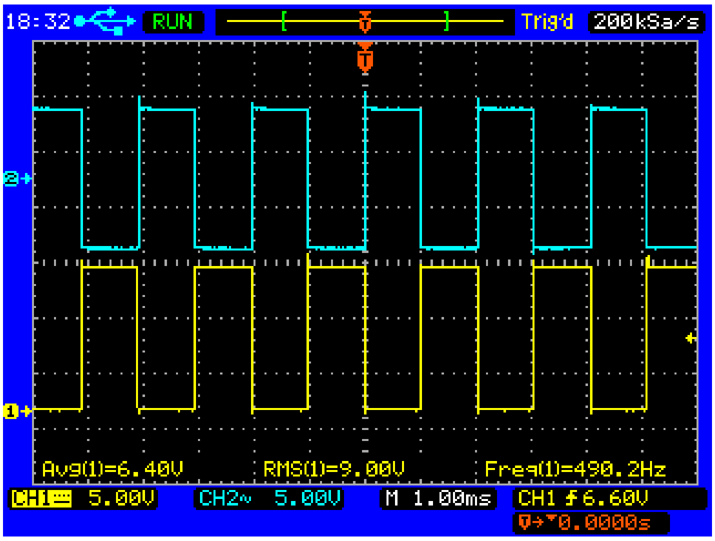

Figure 10.6: gate driver output for IGBT AH and AL

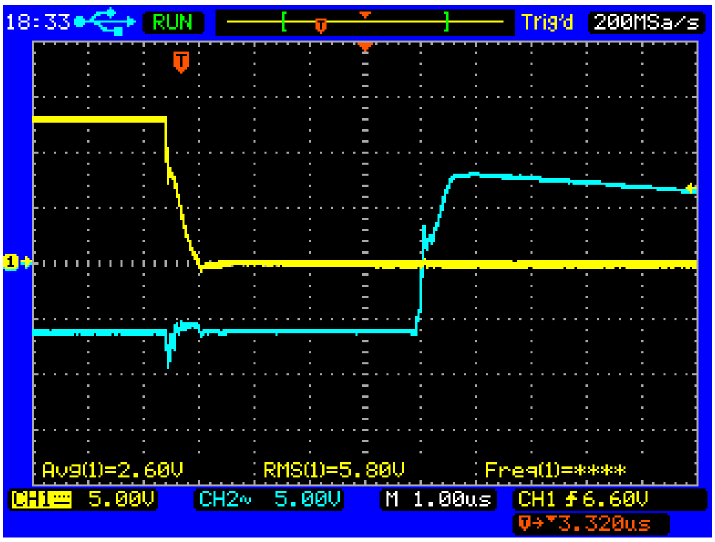

Figure 10.7: Dead band of 4 microsecond between two complimentary gating signal

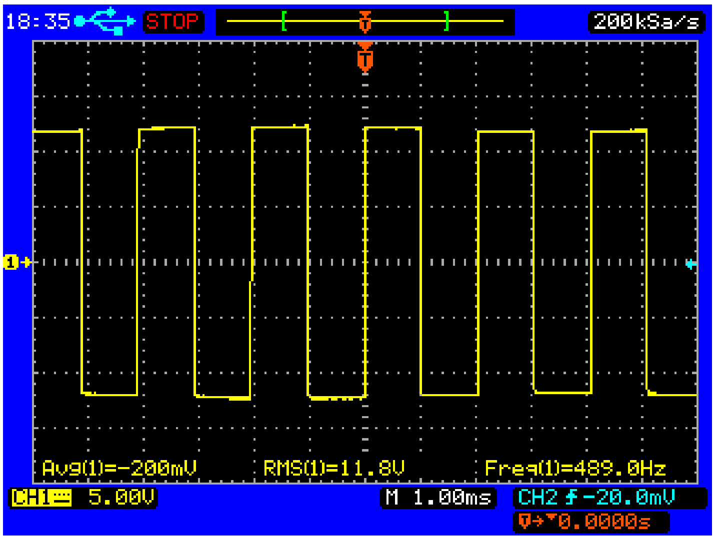

Figure 10.8: inverter output voltage with R load.

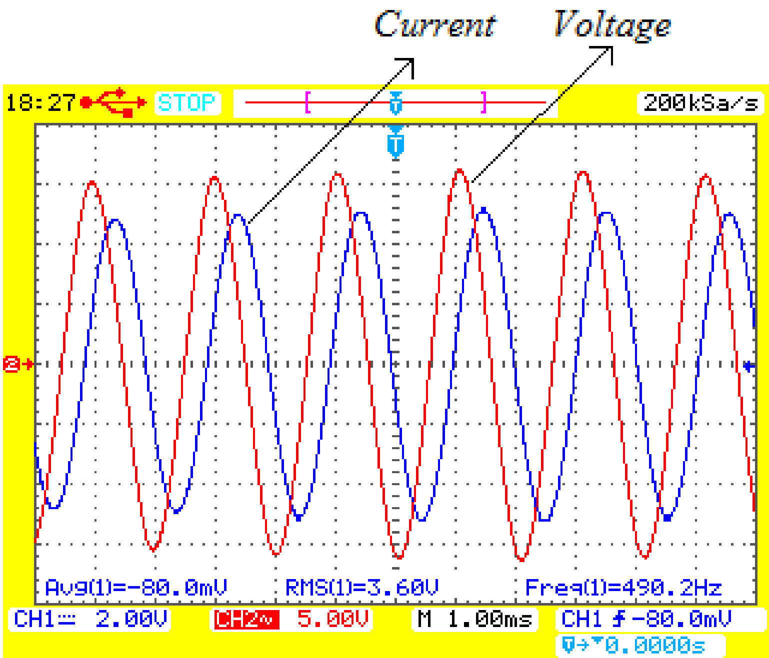

Figure 10.9: final output voltage and current at tank coil side when supplied voltage at Primary=83V, Sec.=10V and i/p current=0.7Amp and output voltage is 19V and Current is 1.5 amp.

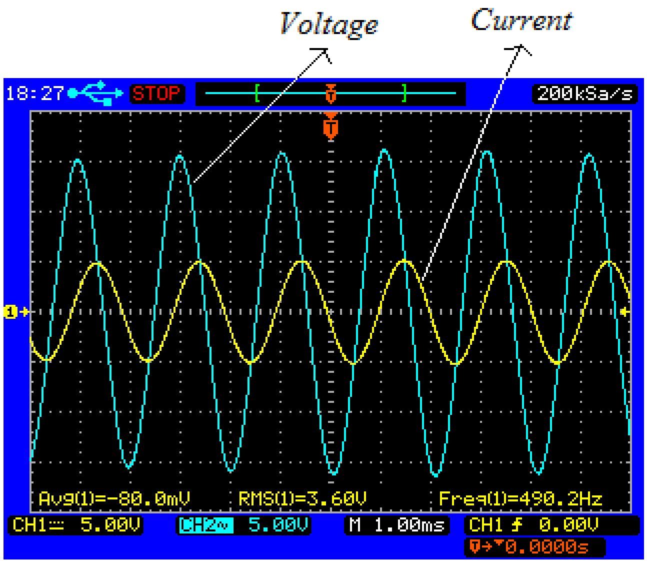

Figure 10.10: final output voltage and current at tank coil side when supplied voltage at Primary=83V, Sec.=10V and i/p current=0.7Amp and output voltage is 19V and Current is 1.5 amp.

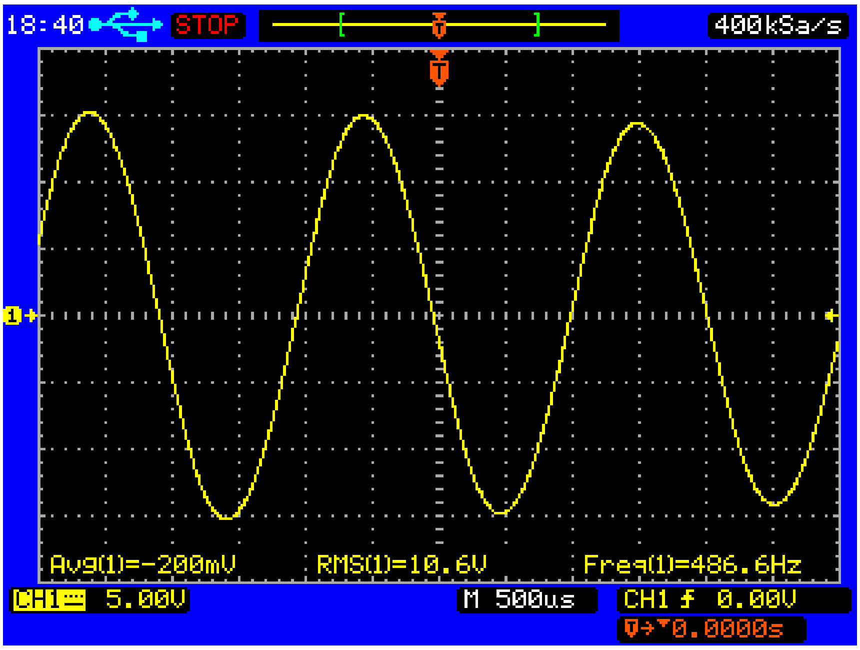

Figure 10.11: final output voltage at tank coil side when supplied voltage is 50V and i/p current=3.3 Amp and output voltage is 106V rms and Current is 8.7 Amp.

Chapter 11

Conclusion and Future Work

11.1 Conclusion

From all the analysis and comparison discussed it is concluded that, all constrains should be approximately satisfy for the desired output of the system, hence desired output is obtained. Also selection of topology has been done while keeping all the technical aspects in the mind regarding size, complexity, cost and availability of product.

From the simulation results it is verified that we are getting desired output voltage ripple from the DC-link as well as the behaviour of LCL tank circuit is also verified from fig.6.4 that after inverter voltage,the voltage is boosted up by inductor L_1 and current has been also increased by an appropriate amount with the help of C at the load side that too without affecting the inverter switches rating.Hence behaviour of LCL is observable by this study.

Close loop system results has been also verified that as the load of the system is variable or by changing load online power can cater according to load requirement,the ultimate conclusion from close loop is that with increase or decrease in the load the input power to the tank coil from the inverter so adjusts itself in such a way that only minimum amount of power is to be taken by the supply.

Simulation results of the 1kW system is same as that of 100kW system hence the output of the both are verified and hardware implementation of the inverter has been shown in chapter 10 wherein output of gate driver is perfect as well as desired wave shape of inverter output with R load is also obtained.

When inverter circuitry was subjected to the LCL tank circuit as a load than from experimental results it has been verified that all the design calculation as well as the desired output of the system is achived, also form the final output results it is verified that at the tank coil side we get higher voltage and current i.e. power compare to input power, the obtained output voltage and current is at least twice of supplied voltage and current. Hence the overall stress on semiconductor devices has been reduced and we are getting expected output of the circuit, therefore the concept of LCL resonant circuit for induction furnace has been justified experimentally.

11.2 Future Work

a. Closeloop control circuitry for hardware with specific controller can be implemented.

Chapter 12

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