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IGBT Based LCL Resonant Converter for Medium Frequency Induction Melting and Heating Application

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Abstract

Induction melting and 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 paper IGBT based full bridge inverter with LCL (Inductive coupling) configuration has been designed and compared with thyristorised based parallel resonant circuit topology. 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. For the analysis, prototype of 100kW has been designed with suitable PWM control strategy. Also to attain the level of performance required for LCL load resonant topology ZVS or 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 has been described. Also the design calculations for DC link of the inverter as well as LCL resonant circuit have been described 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), Zero Voltage Switching (ZVS), Zero Current Switching (ZCS).

INTRODUCTION

The load in induction heating applications generally turns out to have a very low power factor. To compensate reactive power, the inductive load is extended to a resonant tank by adding further capacitive and sometimes inductive devices. Previous publications focus on simple series or parallel resonant circuits, often including a matching transformer, in this paper IGBT based third order resonant circuit with Inductive coupling has been discussed , The induction heating application discussed in this paper requires high active power (more than 80kW) and at the same time operates at frequencies around 500Hz. There are other induction heating applications mentioned in the literature that make similar demands on the power supply. Due to the medium frequency application, the suggested converters are mainly set up with MOSFETs. This is an economically feasible solution only for lower power requirements. The developments in IGBT-technology make it possible to build more compact and cheaper converters for this range of frequencies using IGBTs. It will be shown that for the present application, the voltage source inverter with the *LCL* resonant tank has an advantage over the current source inverter, especially when IGBTs are the chosen active devices.

Resonant circuits

Resonance circuits are combination of Inductor and capacitor, more precisely a RLC combination. Three types of resonant circuits are there and are used according to the need of applications. Series resonant circuit are used where magnification of the voltage across the work coil is required higher then o/p of the inverter., but this has an disadvantage that when it is used for higher power ratings the amount of current that flows from the inverter is same that is going to tank coil so becomes limitation for semiconductor devices used at inverter side, hence it is limited to lower power rating only. Parallel resonant circuits has an advantage that it magnify the current to work coil higher than current capability of inverter also in this circuit inverter has to carry only part of load current, so this is preferred for a medium power applications .when this resonant circuit is used for high power application what industry engineers prefer is to have to parallel inverter feeding the same tank coil, so this is also a kind of limitation for this category of resonant circuit. Third category of resonant circuit is hybrid resonance circuit, this are basically formed by adding some more inductive or capacitive components in 2nd order resonance circuit. Hence they are known as inductive coupling when added more inductance it becomes LCL resonance configuration and when added more capacitor it is known as capacitive coupling or CCL resonance configuration. Now these two types of resonant circuits are used according to the need of application or the demand of load. If load requirement is of constant current than CSI with capacitive coupling (CCL) is more preferred as CSI give constant current, where as when the load is dynamic and constant current is not required there we use VSI with inductive coupling (LCL) as the advantage of using VSI are more compared to CSI because VSI has better dynamic response, higher life, easy control as well less complexity.[1,6]

Converter topologies

With the switching times of today's high-voltage IGBTs being still quite high, 1200V IGBTs were chosen for the l00kHz application. These IGBTs can operate at a 800V dclink voltage. Therefore, a voltage boost is necessary to obtain the required voltage of maximal 3kV 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. Figure 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.[3] Neglecting parasitics and assuming ideal semiconductor switches, both inverters would at best operate with output voltage and current in phase.

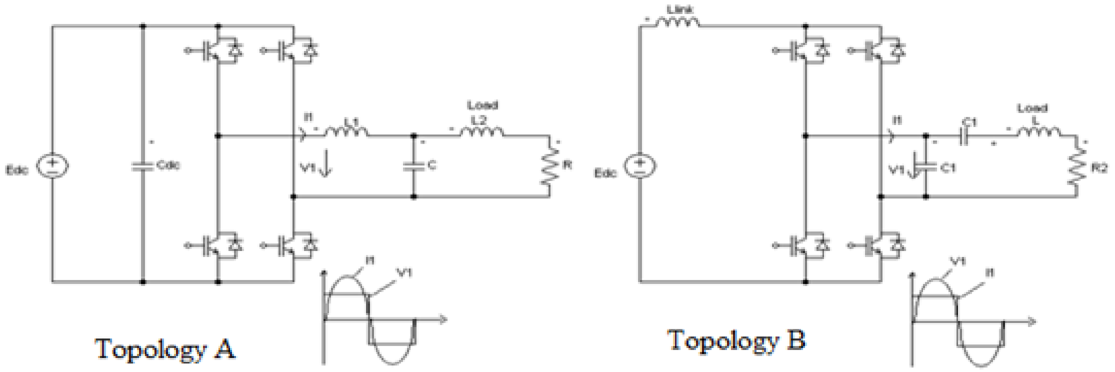


Fig. 1:- VSI with Inductive Coupling (topology A) and CSI with capacitive coupling (topology B) of the load.

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. The value of the complex input impedance Z of the resonant tank defines the two resonant angular frequencies $\omega_{01}$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.

Topology A (LCL) Topology B (CCL)

$$Z \rightarrow 0 \qquad \omega_{01} = \frac{1}{\sqrt{C.L_1.L_2/_{L_1+L_2}}} \qquad\qquad \omega_{01} = \frac{1}{\sqrt{L.C_2}}$$

$$Z \rightarrow \infty \qquad \omega_{02} = \frac{1}{\sqrt{C.L_2}} \qquad\qquad \omega_{02} = \frac{1}{\sqrt{L.C_1.C_2/_{C_1+C_2}}}$$

The LCL resonant tank is supplied by a voltage source inverter. It operates at the resonant frequency defined by the complex input impedance $Z \rightarrow 0$, which is the resonance point of a series resonant circuit. For the CCL-tank, the opposite statement is valid: the resonant circuit works at the frequency set by the input impedance $Z \rightarrow \infty$ and therefore at the resonance point of an equivalent parallel resonant circuit.[6]

System analysis

The entire induction heating system is shown in the block diagram of Fig. 2. On the input side, the high-frequency IGBT-inverter is connected to a thyristor rectifier via a voltage link. The inverter supplies a resonant LCLR-load with an LC-circuit coupling the output inductor to the inverter. This LC-circuit serves two purposes:

1. it provides the reactive current drawn by the output inductor and
2. it provides a significant voltage boost across the L_1 inductor.

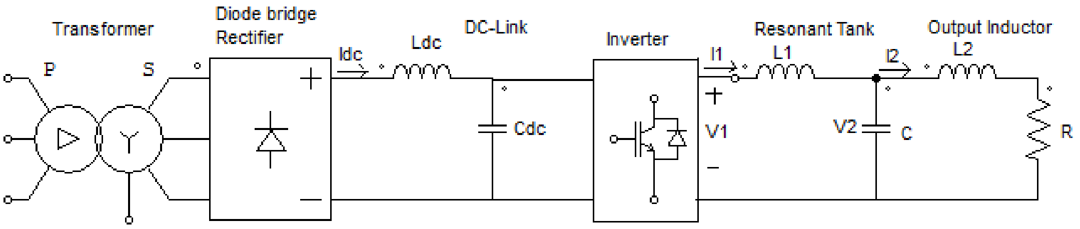


Fig. 2 Medium-frequency induction heating system with LCL resonant output

Impedance Characteristics:-

A fundamental component analysis of the resonant load gives good insight into the circuits characteristics. A very useful variable to determine the characteristics is the complex input impedance Z of the LCLR-circuit. In terms of impedance, the purpose of the inductor $L_1$is to transform the rather low impedance of the compensated output inductor (Z ≈ R ≈0.1Ω) to a more suitable value for the inverter (Z ≈ R_{eq} ≈ 5.5Ω) while working close to the resonant frequency set byL_1, L_2, C. The complex impedance Z consists of the real part.

$R_{eq}=\frac{R}{(1-\omega^2 CL_2)^2+(R\omega C)^2}$, And of imaginary part,

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

The load power and the phase demand, together with the desired resonant frequency range, fix the values of the resonant passive componentsL_1, and C. For a more exact design of the circuit it makes sense to proceed as follows.

1. Calculate the equivalent input resistanceR_{eq}, of the resonant tank for nominal power and nominal dc-link voltage.
2. Set the resonant angular frequency ω
3. With 1 and 2. Calculate the capacitance C.
4. Adjust $L_1$for $X_{eq\approx 0}$ or exactly for the desired phase lag Ø between inverter voltage and current.

Inverter control

Ultimate goal to control of power according to the need of the load, so for controlling power, inverter output current and voltage has been senses and multiplied to get actual power this is denoted as P_o, than an reference power P^* is given to the comparator where both actual and reference power are compared, error generated in power P_e is given to the Low pass filter which removes spikes from the error and then spike free error or undistorted error is given to PI controller, now this PI controller is tuned in such a way every time when the load changes it tries to achieve desired value as soon as possible and soon again makes the error zero.[2,8] The output of PI controller gets compared with high frequency triangular waveform and control signals are generated and given to gate driver of IGBT (basically the output of PI controller is a modulation index for the high frequency triangular wave) hence gating signals from gate driver is given to the inverter. This way inverter has to be controlled for the varying load condition.

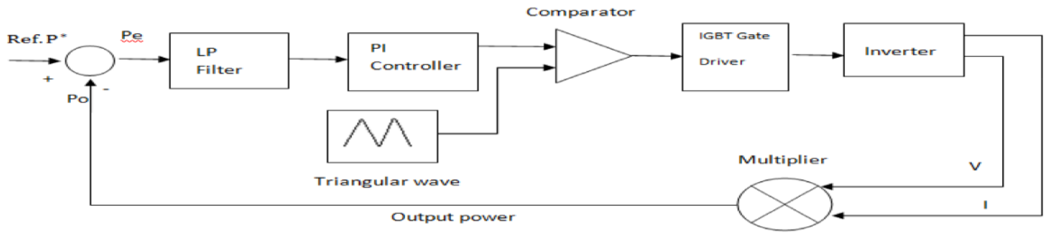
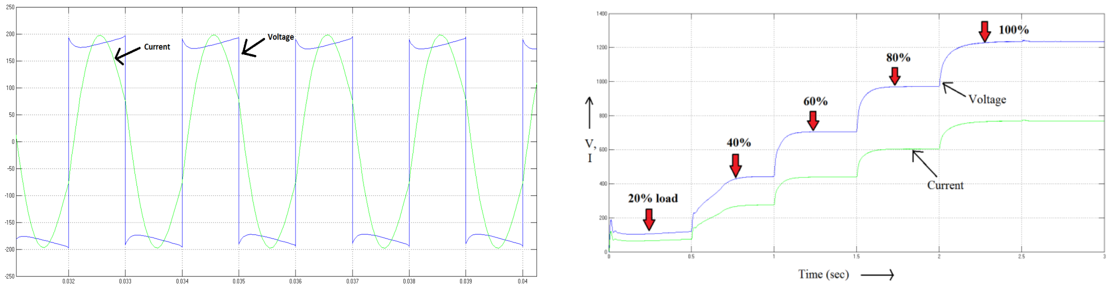


Fig.3 Inverter control of medium-frequency induction heating system with LCL resonant output.

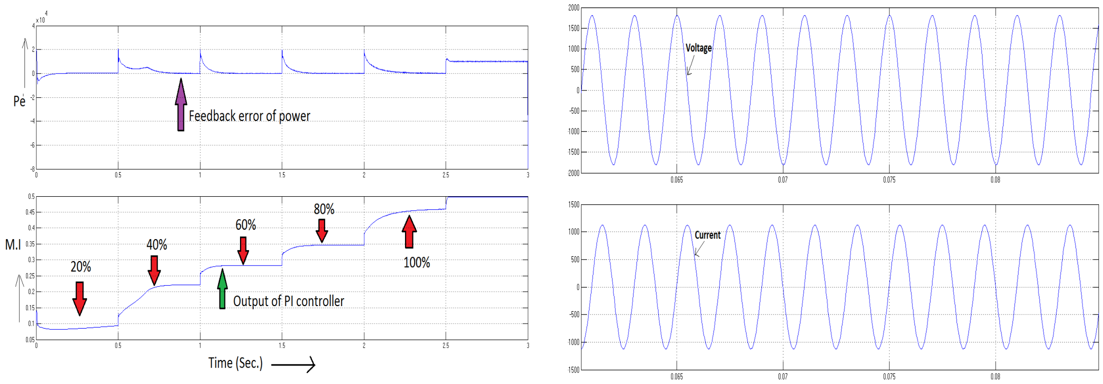
Simulation results

From above analysis and calculations a appropriate circuit has been designed in MATLAB and simulated these are the results obtained for circuit with close loop control.Fig.6 shows the output of inverter when operating at 100% load it is to be noted that for the purpose of visibility inverter output voltage has been reduced to 1/4th times of actual. Hence the wave shape obtained at the output of inverter is same that the output of VSI looks like for both current and voltage.



(a) (b)

Fig.4 (A)X-axis- Time(Sec.), Y-axis- Voltage(Square wave), Current (Sin wave),(B) variation in voltage and current at different loading condition.



(a) (b)

Fig.5 (A) feedback error and PI controller output at different loading condition,(B) total system output voltage and current at the load side I.e. at with boosted up by

Inverter control with the PI controller has been done, and hence from fig.8 (A)it is clear that every time when the load changes the PI controller soon tries to make feedback error zero and also the variation in modulation error is observable from the figure. Also from fig. 8 (B) shows the total output voltage and current of the system where the significant amount of boost-up from the inverter output can be observed without affecting inverter semiconductor devices. It can be observed that now voltage has a peak to peak value of 1800 volts and current has peak value of 1181 amp. So this way simulation results prove that LCL resonant configuration is better than other resonant configuration for particular type of application.

Summary

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 100kW active power at a frequency of 500Hz. 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 simulation results verifying the operation of the control are shown. Also the merits of chosen topology with thyristor based parallel resonant circuit have been discussed.

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