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DESIGN AND DEVELOPMENT OF VOLTAGE FED SERIES RESONANT INVERTER FOR INDUCTION HEATING APPLICATIONS

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Abstract: This paper is aimed on the design and analysis of voltage fed series resonant converters which is used for inducting heating applications. This system presents the development and design of an induction heating system, which enables optimum and economical operating over a frequency range between 20kHz and 30kHz. The induction heating system comprises of an AC-DC single phase rectifier, a DC-AC voltage fed series resonant inverter, a matching transformer and a series resonant inductive load composed of a capacitor bank and an induction coil. This capacitor bank was composed with a number of capacitors which are connected in parallel for equivalent capacitance of 2.54μF series with an induction heating coil. The induction heating system is one of the evolving heating technologies in industries, commercial and domestic applications and it provides contactless, fast, rapid and efficient heating of conductive materials taking the advantage of heat produced by eddy currents. The pulse signals to the inverter are generated by the dsPIC33F microcontroller. Initially the system will be operated at 30kHz frequency and then it gets swept until the maximum is delivered to the load. The inverter and the induction heating load will be isolated by the use of matching transformer for providing the protection against high currents evolved during heating of the load. Capacitive switching has been avoided as the system operates at a frequency higher than the resonant frequency. The workpiece which is heated should be placed in the center and contact between the workpiece and the work coil should be avoided for efficient heating. This system is employed with water cooling as a hollow copper tube was used for heating the workpiece. Finally, the workpiece was tested at a maximum power of 2kW.

***Index Terms* – Induction heating, VFSRI, Zero- Voltage Switching, Zero- Current Switching, Matching transformer.**

I. INTRODUCTION

The induction heating process takes place when an electrically conductive object is placed inside a varying magnetic field. Induction heating system is based on an electromagnetic heating system based on energy absorption from an alternating magnetic field, generated by an inductor. Induction heating process provides fast, contactless, and efficient heating of electrically conductive materials. Induction heating methods is becoming one of the efficient heating technologies in domestic, industrial, and medical applications, among other applications because of its numerous advantages when compared with other classical heating techniques such as flame heating, resistance heating, commercial heating or traditional ovens or furnaces. In IH, the heat is generated by eddy currents which are originated by a varying magnetic field that is obtained by means of a varying current circulating in an inductor. It has lot of merits compared to other heating systems such as quicker heating, faster start up, workpiece will get heated with few seconds, more energy saving which requires less operating time and higher production rates. The IH system comprises of a piece that is to be heated and the induction coil that produces the magnetic field required to generate heat. The inductor and the workpiece can have any shape and the workpiece is placed inside the coil to have a better coupling and to reduce any short circuit. Induction heating process is based on two mechanisms of energy dissipation:

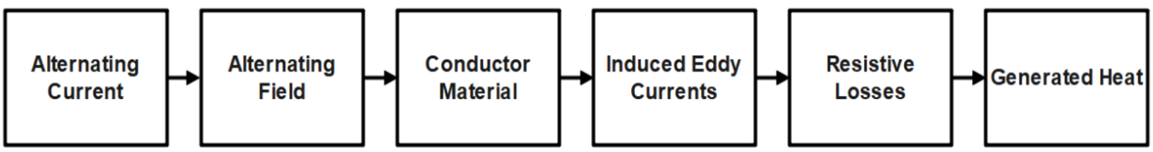

Figure 1. Induction Heating Principle

1. **Energy losses due to Joule effect**

When an alternating voltage supply is applied to an induction heating coil, an alternating current is produced in the coil. This alternating current produces an alternating magnetic field that induces voltage in the workpiece which is placed inside the induction heating coil, which opposes to the variation of magnetic field. This voltage induces eddy currents in the workpiece which have the same frequency but opposite in direction than the inverter current and these eddy currents will produce heat in the workpiece by the principle of Joule effect.

2. **Energy losses due to hysteresis**

These losses are produced by the friction between dipoles when ferromagnetic materials are magnetized in one direction and in another. They appear in ferromagnetic material below their Curie temperature where the temperature at which the workpiece becomes non-magnetic. In most of the induction heating applications, hysteresis losses represent less than the 10 % of the eddy current losses.

II. VOLTAGE FED SERIES RESONANT INVERTERS

In series resonant tanks, the inductor coil is connected in series combination with the capacitor bank represented by a single inductor and a capacitor with a reflected resistance. In such conditions, the tank will behave as a current source and the inverter is voltage fed series resonant inverter, which means that the inverter is fed from a constant voltage source. This indicates that the inverter is fed by a capacitor with a high capacitance value that sustains the voltage constant. In most of the applications the H-bridge inverter is widely used. This topology is used because allows transmitting the same power with less current for a given voltage. In voltage fed series resonant inverters, two switches of the identical inverter leg cannot be turned on at the same time, or else short circuit condition will occur. The time between the turning off of one of these switches and the turning on of the other is called dead time. In this topology, antiparallel diodes are necessary to permit inductor's current conduction when the opposite switches are turned off. There are two basic switching mechanisms with regards to soft switching: zero voltage switching (ZVS) and zero current switching (ZCS).

ZVS is associated to the turn on of the switch, that is realized with zero voltage, while ZCS is associated to the turn-off of the semiconductor, that occurs without current. That resonant frequency is the point where the maximum power is given to the workpiece, was explained in previous sections. It was also explained that, at this frequency, the commutation occurs when the current is close to zero, diminishing the commutation losses. However, in real induction heating systems it is impossible to be at perfect resonance, due to small changes in the induction heating load or because there are some inaccuracies in the control system. Therefore, during normal operation the converter is most of time slightly above or under resonance. These different commutation circumstances are studied in this section. Series resonant inverter commonly works in quasi-resonant state, which is required for setting the dead time when inverter was operating. The output voltage of the inverter is a rectangular waveform, the output current of the inverter is sinusoidal in nature, and the load frequency is the characteristic of series resonance therefore, the inverter should not be operated at no load conditions.

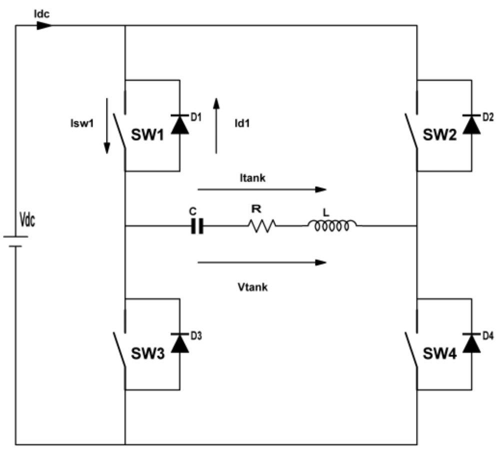

Figure 2. Voltage Fed Series Resonant Inverter

2.1. Resonant Frequency

The resonant frequency ω_r is the frequency at which the maximum module of a transfer function occurs. From the RLC equivalent circuit of a VFSRI, the subsequent equation is derived,

$$V_{tank} = V_R + V_L + V_C = RI_{tank} + L\frac{dI_{tank}}{dt} + \frac{1}{C}\int I_{tank}dt \quad (1)$$

Using Laplace Transform and with initial conditions which is equal to zero,

$$V_{tank}(s) = RI_{tank}(s) + sLI_{tank}(s) + \frac{1}{sC}I_{tank}(s) \quad (2)$$

Obtaining the following second order system with a zero

$$V_{tank}(s) = I_{tank}(s) \times \left[\frac{sCR+s^2LC+1}{sC}\right] \quad (3)$$

$$H_s(s) = \frac{I_{tank}(s)}{V_{tank}(s)} = \frac{sC}{s^2LC+sCR+1} \quad (4)$$

$$H_s(s) = sC\frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2} \quad (5)$$

$$H_s(s) = \frac{s/L}{s^2+s(\frac{R}{L})+\frac{1}{LC}} \quad (6)$$

The roots of the second order system are

$$s_1, s_2 = -\zeta\omega_n \pm j\omega_n\sqrt{1-\zeta^2} \quad (7)$$

Where ω_n is the undamped natural frequency of the resonant system and gives,

$$\omega_n^2 = \frac{1}{LC},\ \omega_n = \sqrt{\frac{1}{LC}} \tag{8}$$

ζ is the damping ratio, which is the cosine of the roots to the negative real axis of the s plan and gives,

$$\zeta = \frac{R}{2}\sqrt{\frac{C}{L}} = \frac{R}{2\omega_n L} \tag{9}$$

By converting the transfer function to the frequency domain, it becomes,

$$H_s(s)|_{s=j\omega} = \frac{j\omega C}{1-\omega^2 LC + j\omega CR} \tag{10}$$

That has the following module

$$|H_s(\omega)| = \frac{C}{\sqrt{(CR)^2 + (\omega LC - \frac{1}{\omega})^2}} \tag{11}$$

By calculating the derivative of previous equation, the next equation is obtained as,

$$\frac{d|H_s(\omega)|}{d\omega} = C\left[-\frac{1}{2}\left[(CR)^2 + (\omega LC - \frac{1}{\omega})^2\right]^{\frac{-3}{2}}\left[2\omega L^2C^2 - 2\frac{1}{\omega^3}\right]\right] \tag{12}$$

That has a zero at maximum, the resonant frequency of the circuit is given by,

$$\omega_r = \frac{1}{\sqrt{LC}} \tag{13}$$

The resonant frequency is equal to the undamped natural frequency and the transfer function at this frequency is equal to

$$H_s(\omega_r) = \frac{I_{tank}(\omega_r)}{V_{tank}(\omega_r)} = \frac{1}{R} \tag{14}$$

The tank which is comprised of a Resistance of 2Ω, an Inductance of 25 μH and a Capacitance of 2.54 μF has a unique maximum at approximately 20 kHz, corresponding to the resonant frequency. Bearing in mind that Hs(ω) is the inverse of the impedance, the impedance at resonant frequency is minimum. Therefore, if a voltage with a frequency equal to the resonant frequency feeds the RLC circuit, the current is maximum and so the heat will be generated in the workpiece.

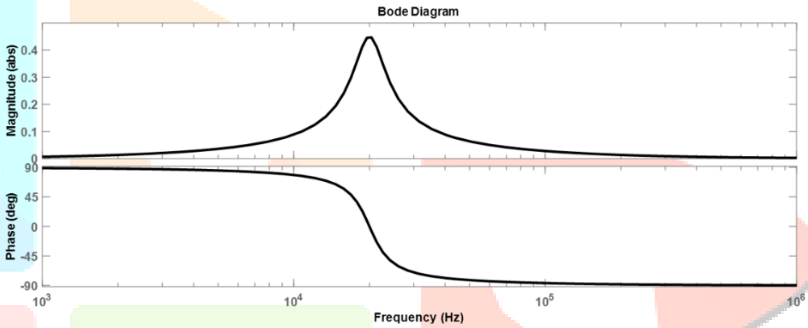

Figure 3. Bode analysis of the transfer function $H_s(\omega)$ with R = 2 Ω, L = 25 μH, C = 2.54 μF, $f_r = 20kHz$

One of the reasons of using these oscillatory circuits in induction heating applications is that they allow high currents using relatively low voltages. At resonance frequency, the impedance equals R_{eq}. Under these circumstances, the inductive and the capacitive part cancel each other and the voltage and current are in phase. Thus, the switching losses are theoretically zero because the current is close to zero during the commutation. That is the reason why induction heating converters can commutate at higher frequencies.

2.2. Commutation Analysis

The commutation process without losses is generically known as soft switching, contrarily to the conventional hard switching, where losses will occur. There are two basic switching mechanisms with regards to soft-switching: zero voltage switching (ZVS) and zero current switching (ZCS). ZVS is associated with the turn on of the switch, that is realized with zero voltage, while ZCS is associated to the turn-off of the semiconductor, that occurs without current.

At resonant frequency, the commutation occurs when the current is close to zero, diminishing the commutation losses. However, in real systems is almost impossible be at perfect resonance, due to small changes in the load or just because there are small inaccuracies in the control system. Therefore, during normal operation, the converter is most of time slightly above or under resonance. In VFSRI, to avoid short circuit of two switches, the switches from the same inverter leg cannot be conducting at the same time. The dead-time is neglected and the turn-on and off are supposed ideal, without any delay.

2.3. Commutating at Resonant Frequency (V_{dc} = 325 V, R = 2 Ω, L = 25 μH, C = 2.54 μF, $f_{sw} = f_r = 20kHz$)

In state I conduction of S_1 and S_2 will occur and in state II conduction of S_3 and S_4 will occur and in this state the conduction of diodes will never occur. In this commutation process there will no commutation losses because the switches will conduct when the current is at zero.

In this case, the commutation occurs when the current is crossing zero. Observing SW1 and its antiparallel diode, the current is flowing through SW1 half of the cycle and the diode is never conducting. Under these conditions there are two possible states. In state I, the switches SW1 and SW4 will conduct and in state II, the switches SW2 and SW3 will conduct. Considering losses, there are no commutation losses because switches commutate when the current is zero. This is the ideal situation with regards to switching losses, but the probability of being at perfect resonance is low.

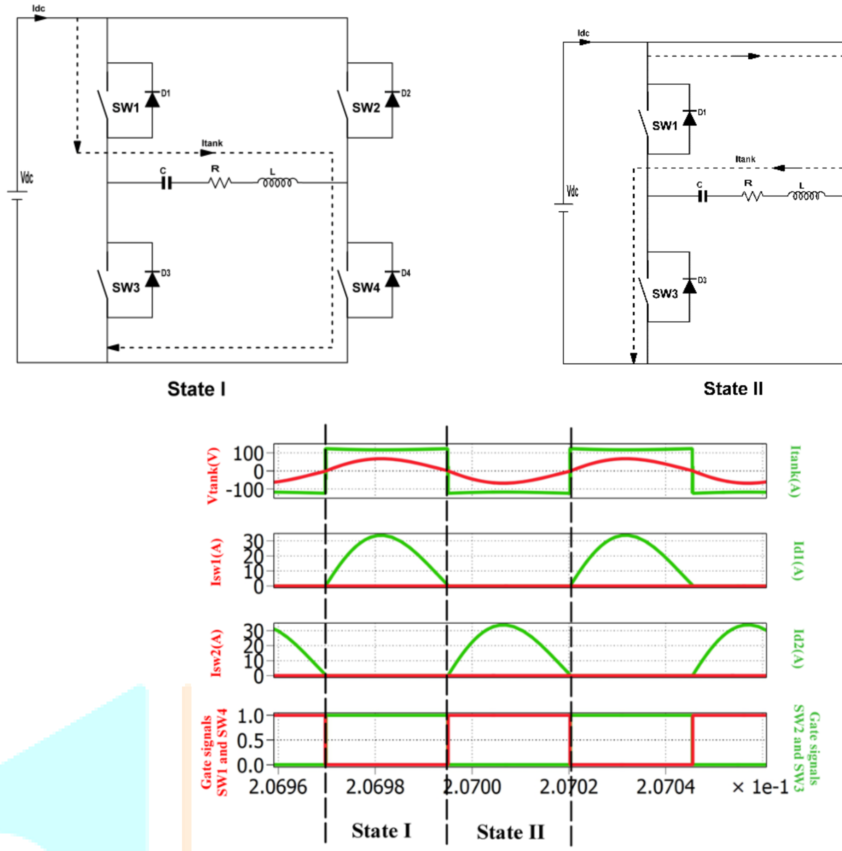

Figure 4. Modes of Operation and Output waveforms for commutating at resonant frequency

2.4. Capacitive Switching (V_{dc} = 325 V, R = 2 Ω, L = 25 µH, C = 2.54 µF, $f_{sw} = 18kHz, f_r = 20kHz$)

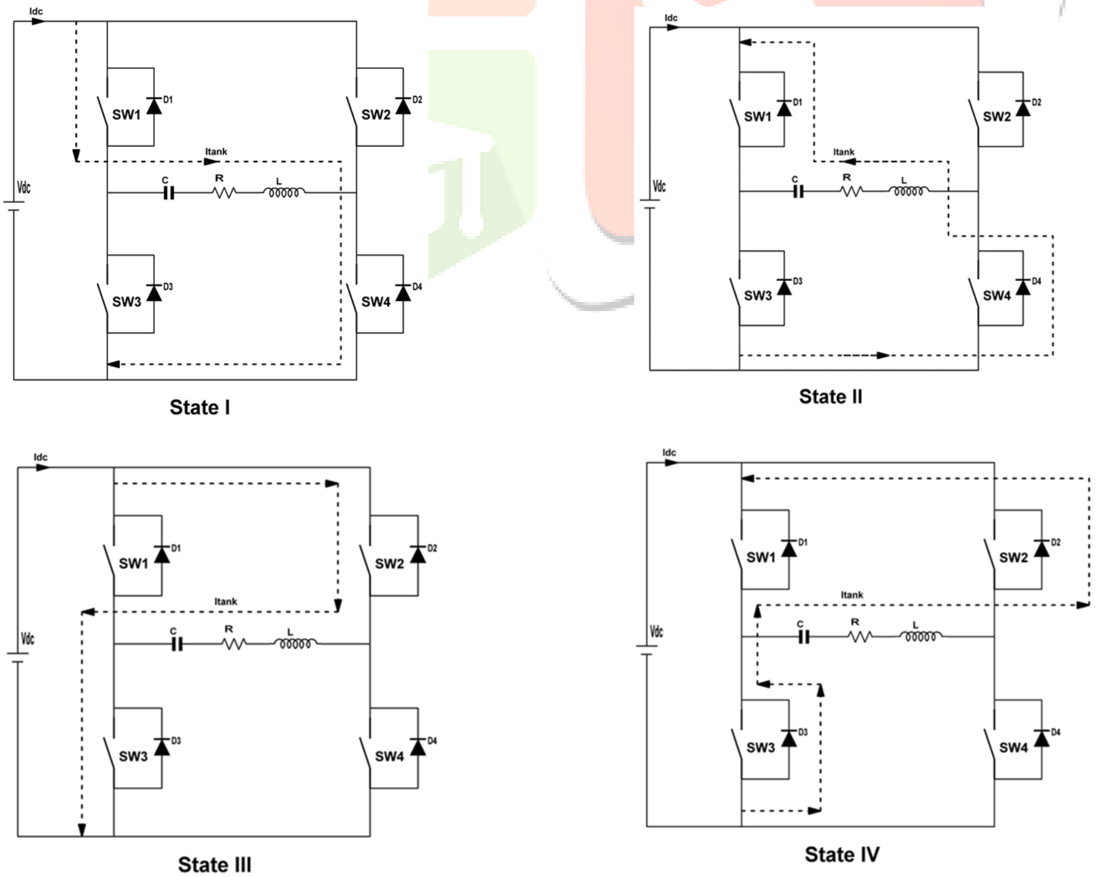

Figure 5. Sequence of events commutating below resonant frequency

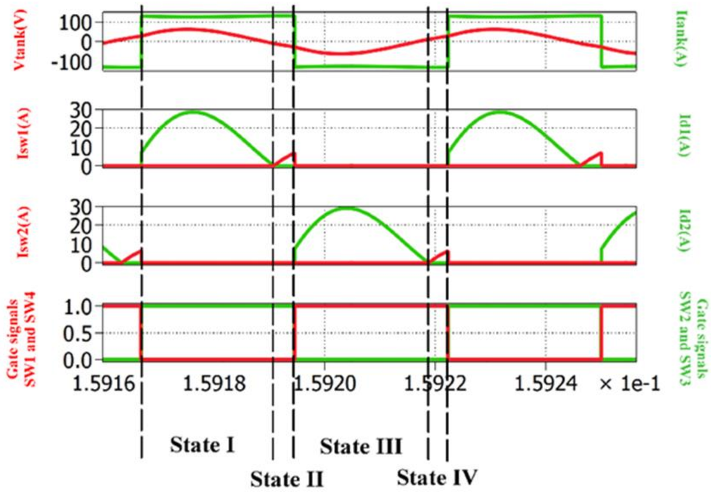

Figure 6. Output waveforms for commutating below resonant frequency

In state I current will be flowing the switches S_1 and S_2 and in state II the diodes D_1 and D_2 will be forward biased while the switches S_1 and S_2 will be in conduction state and the current in the tank circuit will change its polarity during this state of operation. In state III with zero current switching the switches S_1 and S_2 will be turned off as the current will be commutated to the antiparallel diodes. In state IV there will be hard turn on of the switches S_3 and S_4 causing the hard turn off of the diodes D_1 and D_2. The states V and VI will be similar to the states II and III but the conduction will take place with opposite switches and diodes.
In this commutation, the turn off of the diodes and turn on of the switches will be hard, but the turn on of diodes and the turn off of switches will be soft. One of the problems derived from diodes' hard turn off is that large recovery currents can create voltage spikes. This causes an increase of electromagnetic interferences, losses and in the worst case, the destruction of semiconductors. Thus, capacitive switching has to be avoided if possible.

2.5. Inductive Switching (V_{dc} = 325 V, R = 2 Ω, L = 25 µH, C = 2.54 µF, $f_{sw} = 23kHz, f_r = 20kHz$)

In state I the current is flowing through the switches S_1 and S_2 and in state II there will be hard turn off of the switches S_1 and S_2 which will further cause the hard turn on of the diodes D_3 and D_4. In state III with zero voltage switching the switches S_3 and S_4 will be turned on and in state IV the current will be flowing through S_3 and S_4 while the diodes D_3 and D_4 are blocked with zero current switching. The states V and VI will be similar to the states II and III but the conduction will take place with opposite switches and diodes.

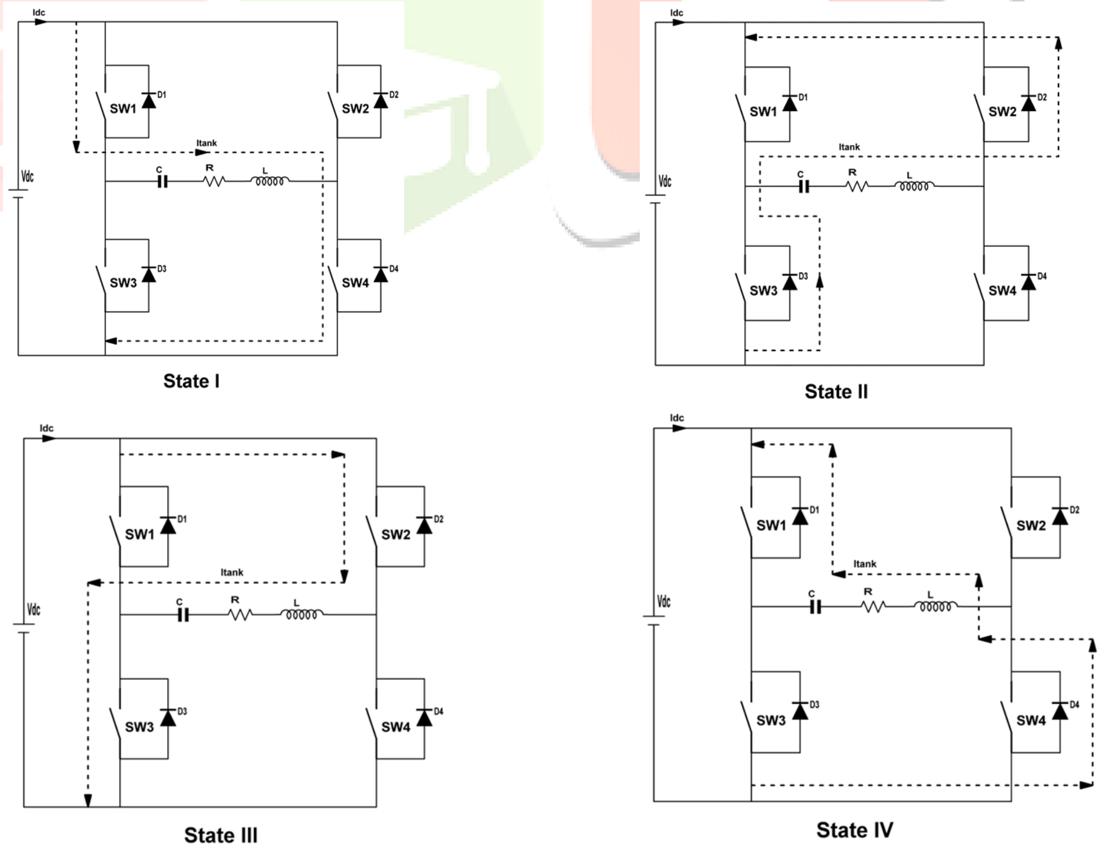

Figure 7. Sequence of events commutating above resonant frequency

In inductive switching, the commutation and the voltage's zero crossing occur before the current's zero crossing. Under these circumstances, the current lags the voltage and this type of commutation is known as inductive switching. Similarly, to capacitive switching, D1 is forward-biased. But, in this situation, D1 conducts after the commutation process and before the change of polarity of current in the resonant tank. The value of i_{tank} is also slightly lower than in case of switching at resonant frequency, but the difference is not noticeable. Observing the sequence of events, the current is flowing through SW1 and SW4 in State I. Then, the switches SW1 and SW4 are turned off hardly, causing the hard turn on of D2 and D3 in State II. Then, the switches SW2 and SW3 are turned on with ZVS because the current is flowing through their antiparallel diodes in State III.

And finally, i_{tank} changes polarity and diodes D2 and D3 are blocked with ZCS because the current starts conducting through SW2 and SW3 in State IV. In states V and VI the diodes turn-on and switches turn-off is hard, but the turn-off of diodes and the turn on of switches is soft. Considering the low probability of being at perfect resonance and the problems derived from the hard turn-off of antiparallel diodes, commutation above resonant frequency is preferrable. Under these conditions, it has to be noted that it is mandatory to use switches with unidirectional voltage capability but with bidirectional current capability, thus, using antiparallel diodes becomes necessary.

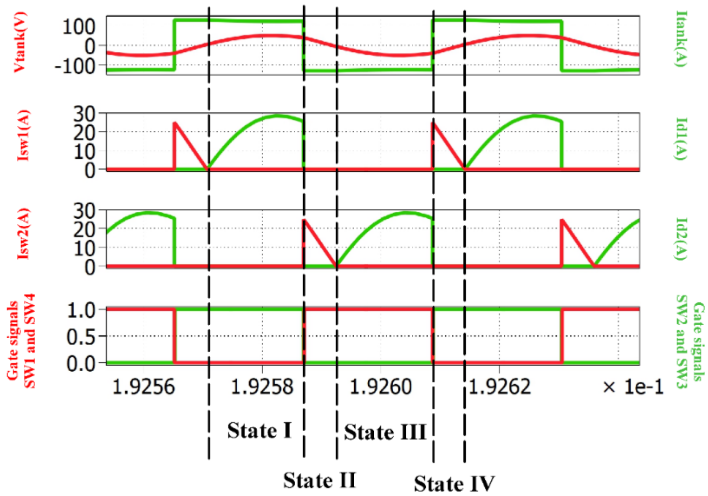

Figure 8. Output waveforms for commutating above resonant frequency

2.6. Matching Transformer

In IH, having high current values in the inductor coil is more prominent because more heat is produced in the workpiece. However, in case of VFSRI, the current in the resonant tank is the same than in the inverter. Considering that the value of the equivalent resistance is usually lower than one ohm, the voltages in the inverter are low and the currents high. From the inverter's point of view, the use of low voltages and high currents produce much more losses and voltage drop. At the beginning, this was the main limiting problem of VFSRI topology for IH converters with semiconductors and one of the reasons of CFPRI proliferation. However, nowadays, the developments in materials science and manufacturing have permitted the appearance of high-performance transformers. Nevertheless, it is worth pointing out that transformer efficiency is usually higher than 90 %. The matching transformer is used between the inverter and the resonant tank circuit to provide required inductance to the induction coil. The matching transformer is also used for transferring maximum power to the load.

2.7. Comparative Analysis Between VFSRI and CFSRI

The VFSRI is fed by a capacitor that maintains the voltage constant whereas CFSRI is fed by an inductor that maintains the current. Dead-time between switches is required to avoid short-circuit in VFSRI. Overlap time is required to avoid over-voltage in CFSRI. VFSRI needs short circuit protection. CFSRI has inherent short-circuit capability. In case of failure all the switches have to be turned-off in VFSRI. In case of failure all the switches have to be turned-on in CFSRI. Voltage-fed converters are easily found in medium power applications. Commercial protection circuits should be used in case of short-circuit for VFSRI. Current-fed converters are usually found for high power applications (>1 MW). Special protection circuits and drivers are needed in case of overvoltage for CFSRI. In a VFSRI the voltage feeding the tank is a square wave and the current is sinusoidal. In a CFSRI the current feeding the tank is a square waveform input and the voltage is sinusoidal in nature.

For VFSRI the voltage on the inductor is Q times higher than at the output of the converter, but the current in the tank is the same than in the inductor. Usually, a matching transformer is needed between the inverter and the tank. For CFSRI the current in the inductor is approximately Q times the current at the output of the converter. A matching transformer is not usually required. High voltage capacitors are sometimes needed for the tank for VFSRI. High voltage capacitors are not required but more capacitors in parallel are needed for CFSRI. In a VFSRI the switches of the inverter have to be unidirectional in voltage but should be bidirectional in current. An antiparallel diode is necessary across the switches. In a CFSRI the switches have to be unidirectional in case of current but should be bidirectional in case of voltage. A series diode is needed. The VFSRI is switching at inductive switching ($f_{sw} > f_r$). The CFSRI is switching at capacitive switching ($f_{sw} < f_r$).

III. Design of Induction Heating System

The input to the rectifier is given by a single- phase AC voltage supply of 230V. The rectifier converters AC to DC by using an input filter. The input filter consists of an LC circuit to obtain a pure DC and most of the AC interference signals will be blocked. The voltage fed series resonant inverter is fed from a capacitor which maintains the voltage constant which is suitable for induction heating applications. To avoid high current flowing through the switches in the inverter a matching transformer is employed.

The output of the inverter will be connected to the primary of a matching transformer for step down of voltage at secondary side. The secondary will be flowing through the resonant tank composing of capacitor, inductor and resistor. The resistance value will be included as a reflected resistance from the induction coil. At the load side a bank of capacitors will be connected in parallel for making the power to flow in a smoother way. The gate signals to the inverter switches will be derived from a gate driver circuit and the control signals for the gate driver will be sent by a microcontroller by programming it using Embedded C.

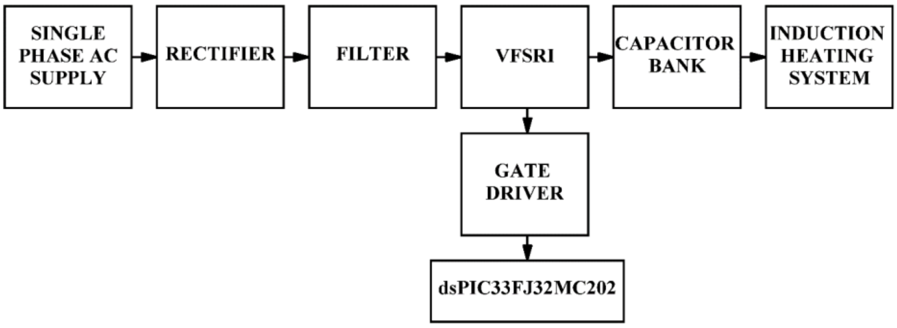

Figure 9. Block Diagram Representation

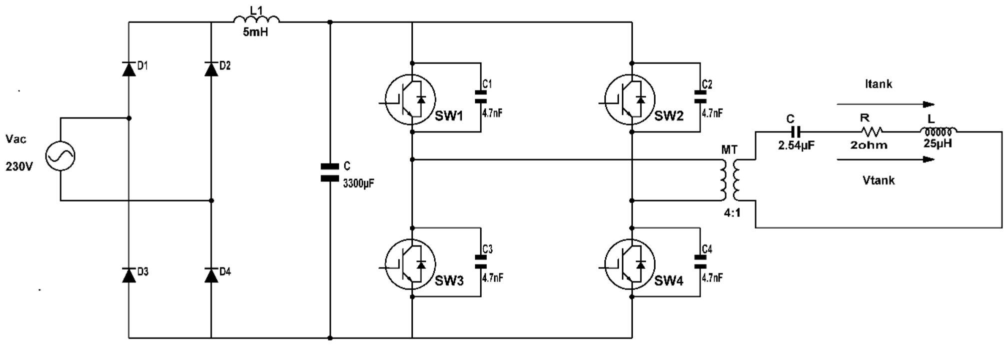

Figure 10. Schematic of IH System

The power circuit of a 2kW, 23kHz is generally classified into two sections: single phase diode rectifier with an input filter and a voltage fed series resonant inverter with an inductive load. The single-phase rectifier MDS100/16 is used for producing pure dc waveform from single phase 230V ac supply with less ripple. The purpose of LC filter is to reduce harmonics and EMI from circuits. The input filter consists of a 5mH inductor made of EE ferrite core and four capacitors connected in series and parallel combination for a capacitance value of 3300µF. A snubber circuit which is composed of 1.8kΩ resistor and 4.7nF capacitor is used for limiting the switching losses. The H-Bridge inverter will be feeding a high frequency square wave voltage waveform to the matching transformer. The matching transformer has 4:1 turns ratio made up of one pair of EE70 ferrite core. The value of the induction heating coil is chosen to be around 25mH which is made up of a hollow copper tube and a capacitor bank is connected in series with the induction coil which is composed of capacitors for equivalent capacitance value of 2.54µF. And the reflected resistance of the induction coil is estimated up to 2Ω. The control signals to the inverter switches were generated by dsPIC33FJ32MC202 microcontroller.

In induction heating system, the heat is generated by eddy currents which are originated by a varying magnetic field that is obtained by means of a varying current circulating in an inductor. To have a high varying current in the inductor an oscillatory circuit is formed by an inductor and a capacitor in series or in parallel. This oscillatory circuit also known as resonant tank, is usually fed by a converter, whose characteristics depend on the frequency, the power and the type of resonant tank. The commutation process occurring at resonant frequency allows more efficient operation in the equipment, which may be essential in high frequency applications, even though the main reason is for permitting higher currents in the inductor. One common criterion in classifying the converters according to the type of resonant tank, where the most basic topologies are based on series and parallel tanks. The converters which are related with these tanks are the current fed series resonant inverters (CFSRI) and the voltage fed parallel resonant inverters (VFPRI).

3.1. Inductor Coil Design

The circumstances that should be kept in mind when designing a coil for an induction heating system

1. The induction coil should be winded as close as possible, where the largest possible number of magnetic flux lines would intersect the workpiece at the heating point which can be used for allowing maximum energy transfer. Therefore, higher current is generated in the workpiece as the flux density is higher near the heating part

2. The coil should be designed in a way that the greatest number of flux lines in a solenoid coil are concentrated towards the center of the coil and thus providing maximum heating rate at the part to be heated.

3. The geometric center of the coil is a weak flux path where most of the flux is concentrated closer to the coil turns and decreases with distance from the turns. If a part were placed off center in a coil, the area closer to the coil turns would intersect a greater number of flux lines and thus be heated at a higher rate. The area of the part away from the copper coil experiences less coupling and would be heated at a lower rate. This effect is more noticeable in high-frequency induction heating.

4. The magnetic center of the induction coil is not essentially the geometric center and therefore, the magnetic field is weaker at the point where the leads and coil join. As the number of coils turns increases and the flux per each turn is added to the previous turns. Due to the impracticality of always centering the part in the work coil, the part should be offset slightly toward this area in static heating applications.

5. Finally, the induction coil must be designed in a manner to provide necessary actions regarding the cancellation of the magnetic field. If opposite sides of the inductor coil are way too close, the coil does not have sufficient inductance required for efficient heating.

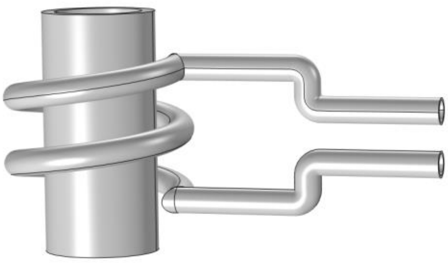

Figure 11. Induction Heating Coil Design

3.2. Induction Heating Coil Parameters
Outer Diameter: 53mm
Number of Windings: 2
Thickness of copper tube: 1mm
Hollow tube diameter: 5mm
Spacing between coil turns: 5mm

$$L = 25\mu H \ (With\ workpiece)$$
$$L = 6.3\mu H \ (Without\ workpiece)$$
$$\sqrt{C} = \frac{1}{2\pi f\sqrt{L}} = \frac{1}{2\pi \times 20 \times 10^3\sqrt{25 \times 10^{-6}}}$$
$$C = 2.54\mu F$$
$$Damping\ ratio, \zeta = \frac{R}{2}\sqrt{\frac{C}{L}} = \frac{2.22}{2}\sqrt{\frac{2.54 \times 10^{-6}}{25 \times 10^{-6}}} = 0.3$$
$$Quality\ Factor, Q = \frac{1}{2\zeta} = \frac{1}{2 \times 0.3} = 1.6$$

3.3. Hollow Cylindrical Workpiece Parameters
Material: Iron
Outer Diameter: 42.9mm
Inner Diameter: 38mm
Height: 30cm

$$Skin\ Depth, \delta = \sqrt{\frac{2\rho}{\mu\omega}} = 503\sqrt{\frac{\rho}{\mu_r f}} = 503\sqrt{\frac{9.71 \times 10^{-8}}{5000 \times 23 \times 10^3}} = 0.0146mm$$

3.4. RC SNUBBER DESIGN FOR IGBT
Snubber Capacitor:

Snubber capacitor: 4.7nF/630V

Snubber Resistor: 1.8 kΩ, 2 Watt

$$W = \frac{1}{2}CV^2 = \frac{1}{2} \times 4.7 \times 10^{-9} \times 179.27^2 = 75.52 \times 10^{-6}J$$
$$P = \frac{W}{t} = \frac{75.52 \times 10^{-6}}{0.00013} = 0.5809W$$

IV. Results and Discussion

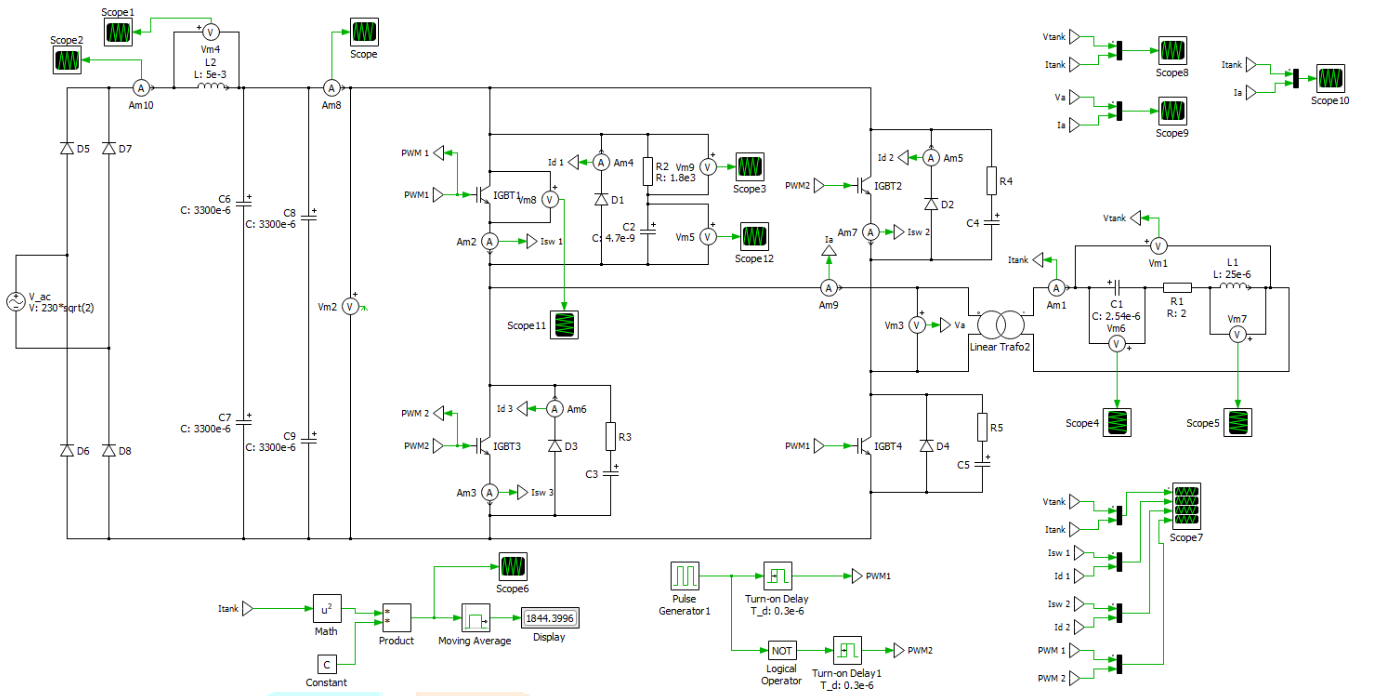

Figure 12. Simulation Diagram

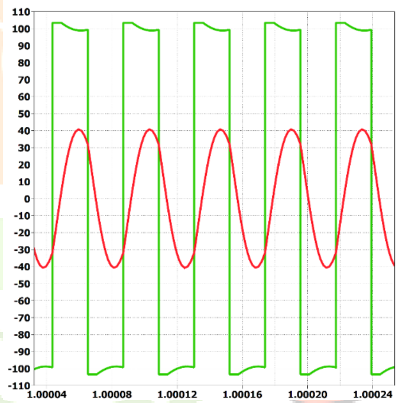

Figure 14. Matching transformer secondary voltage and current waveform at 23 kHz

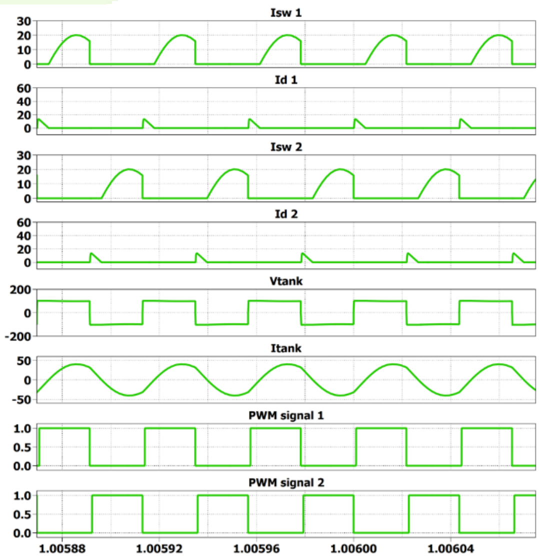

Figure 13. Simulation Results at 23kHz

The simulation for the induction heating system was carried out in Plexim software which is especially designed for power electronics applications. It facilitates the modeling and simulation of complete systems, including power sources, power converters, and loads and also it provides a wide range of tools. The simulated results can be viewed in Scope. The software also consists of built-in analysis tools and coder options which can be integrated with microcontroller with real-time C code. Using the simulation results the user can change parameters and invoke simulations or post-process output data and evaluate results.

The input voltage to the inverter will be 280V and the input current will be 7.6A. The input voltage is stepped down by the use of a matching transformer. The transformer also isolates the load from the inverter side by protecting the switches from high current. The secondary side load voltage is 70V and the load current is 30A. The system was simulated with 50% duty cycle at 23kHz and the system was analyzed at three conditions as operating at resonant frequency, operating below resonant frequency and operating above resonant frequency. The switches will turn on with a delay of $0.3\mu s$. The matching transformer is simulated with leakage inductances of 5nH in the primary side and 7nH in the secondary side. Finally, the workpiece will get heated at a power of 1.8kW.

4.1. Thermal Analysis

There are various numerical methods for modelling induction heating systems such as finite element method, boundary element method and mixed finite or boundary element method. The COMSOL Multiphysics software is used to simulate designs in both 2D or 3D model and it can be used in all fields of engineering, manufacturing and industry applications. An inductor with two windings is modelled in COMSOL Multiphysics software. By using this software, the results can be analyzed with different frequencies with more reliable results. It provides coupled interfaces integrated with partial differential equations. This software uses finite element method for modelling purposes. The material used here is iron for hollow cylindrical workpiece and copper for induction coil.

The modelled system can be studied in various frequency domains such as stationary domain and transient domain. The results can be viewed at required input times and the iteration methods can be also viewed in the solver. Various parameters like magnetic flux density, current density distributions and temperatures of both workpiece and coil at different times can be viewed. In this paper, numerical simulation of an induction heating system is demonstrated by using finite element method.

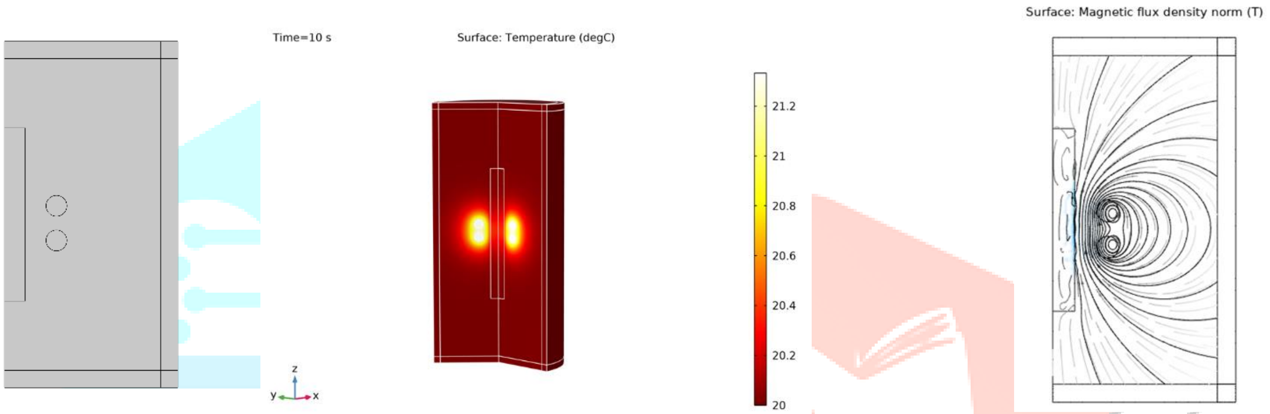

Figure 15. Thermal Approach Model

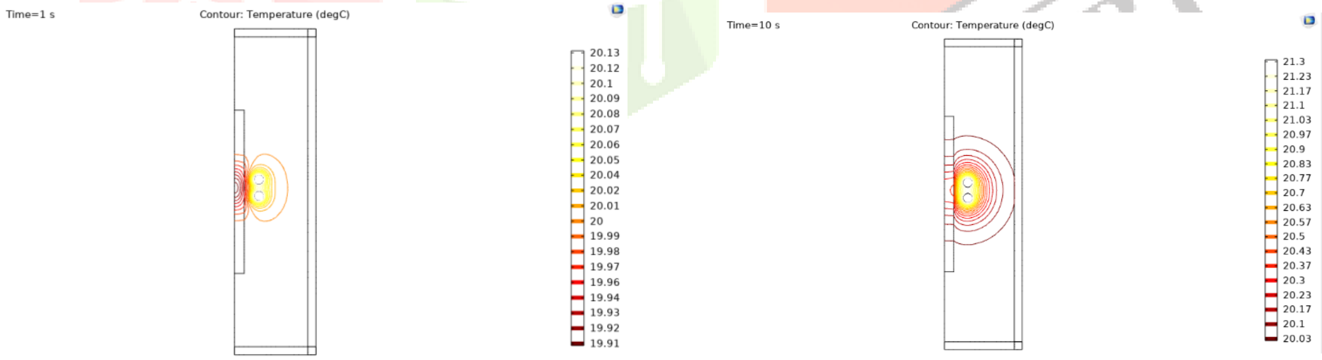

Figure 16. Electric Field Lines

4.2. Hardware Implementation

The gate driver for the inverter is made by TLP250N IC where the pulse signal is generated by dsPIC33FJ32MC202 microcontroller. The microcontroller was programmed with Embedded C code which is executed in MPLAB software. The microcontroller is debugged and programmed by using PICKIT software. dsPIC33FJ32MC202 microcontroller is used for generating PWM pulses for the IGBT devices. From the microcontroller the high pin (Pin 23) and low pin (Pin 24) are connected with one buffer and the high pin (Pin 25) and low pin (Pin 26) are connected with another buffer. ULN2003 is responsible for dissipating voltage spikes if any arising in the circuit by using the suppression diodes. It protects the microcontroller from the load side. +12V to COM point is for a flyback diode that protects the circuit from back EMF. 3.3V is extracted by using LM317 voltage regulator with an input supply of 5V. The input voltage supply to drive the gate driver is given by switched mode power supplies. The gate signals will be sent individually to the switches by using individual gate driver circuits. From MDS100/16 the dc voltage is given as input to the H-Bridge inverter. The inverter and the induction coil are isolated by using a EE70 matching transformer. Finally, the system is operated and tested under 23kHz operating frequency. It is most effective for the buffer circuit to occupy the transient voltage when IGBT is switching and it is also helpful in reducing the IGBT turn off losses and eliminate parasitic oscillations.

V. Conclusion

Thus, a 2kW high frequency induction heating system has been developed which is fed from a single-phase rectifier which operates from single phase supply. A resonant inverter topology was implemented which utilizes a series resonant tank to achieve a higher operating efficiency in an open loop manner. The proposed system has been simulated using PLECS for further implementation of hardware. The system consists of a resonant tank with R = 2 Ω, L = 25 µH, C = 2.54 µF was designed and the results have been demonstrated for different switching frequencies. dsPIC33f will be used for generating gate pulses to FGA25N120ANTD IGBT switches. For DC power supply to the voltage fed series resonant inverter a MDS100/16 three phase rectifier module has been used with an LC filter. A capacitor of high capacitance value of $3300\mu F$ has been used for maintaining the constant voltage to the inverter. A matching transformer was included in the load side for providing maximum efficient transfer of energy from input to the load for heating the workpiece. A part of thermal analysis for an induction heating system was done in COMSOL Multiphysics software and the results has been analyzed for 2kW system and for further analysis an induction heating coil with hollow cylindrical workpiece is being modelled in SolidWorks software. In order to avoid capacitive switching this system has been designed with operating frequency higher than resonant frequency.

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