Analysis of Series Resonant Inverter using Hysteresis Current Control

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***ABSTRACT* - The main objective of this paper is to analyze a series resonant inverter for industrial induction heating application. It is a process used for heat conductive materials, bond, harden, and soften metals. Resonant inverters which operate at high frequency preferable for induction heating. Series resonant inverters which is made up of Insulated Gate Bipolar Transistor (IGBT). Power control is obtained by Hysteresis Current Control (HCC). Soft switching techniques is performed which minimizes switching losses.**

Keywords: Induction Heating, Series Resonant Inverter, Hysteresis Current Control, Phase Locked Loop.

I. Introduction

Induction heating is used to heat conductive materials. Induction heating requires high frequency electricity to heat materials that are electrically conductive. Inrush of current is feed to the coil using high frequency electricity which is known as the work coil. When current is fed to this coil it generates a very forceful and quickly changing magnetic field in the space within the work coil. The work piece to be heated is placed within intense alternating magnetic field. The alternating magnetic field induces a current flow in the conductive work piece and it gets heated. The work coil and the work piece together can be considered of as an electrical transformer. Work coil is considered as primary in which electrical energy is feed in, and the work piece is like a single turn secondary that is short-circuited. This short circuited work piece induces inrush of currents to flow which is called eddy currents. When the AC current enters a coil, a magnetic field is formed around the coil, calculated according to Ampere's Law:

$$\int Hdi = Ni = f \qquad 1$$

$$\emptyset = \mu HA \qquad 2$$

Basic principle behind the process is Faraday's Law, the current generated on the surface of a conductive object has an inverse relationship with the current on the inducting circuit. The current on the surface of the object generates an eddy current, calculated as:

$$E\frac{d\lambda}{dt} = N\frac{d\emptyset}{dt} \qquad 3$$

As a result, the electric energy caused by the induced current and eddy current is converted to heat energy:

$$\mathrm{P} = \frac{E^2}{R} = i^2 R \qquad 4$$

Resonant inverters are used in induction heating in which resonant tank is formed by heating coil and capacitor. Series resonant inverters are those in which resonant components and switching devices are in series to the load. Series resonant load are fed by voltage fed inverter. It is often desirable to control the amount of power processed by an induction heating. Power control is achieved by variation of frequency [12],[14] and phase shift control[8],[24]. But by using this methods switching losses are not minimized since it is impossible to turn on and turn off the switches at zero voltage and zero current at all times. Hysteresis current control is one such technique used to control output power for a wide range by controlling switching signals applied to the inverter. Phase locked loop which is used to match switching frequency close to resonance frequency to supply maximum power to work piece.

II. Series Resonant Inverter

Induction heating generators are resonant inverters which operate at high frequency and produces maximum current at resonance which is sufficient to heat the work piece. Resonance occurs while the inductor and capacitor exchanges energy. Resonant inverters are electrical inverters based on resonant current oscillations. In series resonant inverters the resonating components and switching device are placed in series with the load to form an under damped circuit. The current through the switching devices fall to zero due to the natural characteristics of the circuit. In voltage-fed inverters, two switches of the same inverter leg cannot be turned-on at the same time, otherwise short-circuit occurs. 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, anti parallel diodes are necessary to allow inductor's current conduction when the opposite switches are turned-off. Basically semiconductor switching devices operate in Hard Switch Mode in various types of Pulse Width Modulation (PWM) DC-DC converters and DC-AC inverter. In this mode, switching devices turn on or off at specific current and specific voltage whenever switching occurs and switching losses are high. When the frequency is increased higher, greater the switching loss, which restricts the raise in frequency. Electromagnetic interference problem is also caused by switching loss because a large amount of $\frac{di}{dt}$ and $\frac{dv}{dt}$ is generated. Switching loss can be calculated as:

$$P_{sw}\frac{1}{2}V_{sw}I_{sw}f_{s(t_{on}+t_{off})} \qquad 5$$

where:

P_{sw} = switching loss [W]
V_{sw} = switching voltage [V]
I_{sw} = switching current [A]
f_s = switching frequency [kHz]
t_{on} = switch turn-on time [s]
t_{off} = switch turn-off time [s]

With increasing in switching frequency size of a transformer and filter is reduced, which helps build a smaller and lighter converter with high power density. But switching loss reduces the efficiency of the process, as more losses are generated at a higher frequency. Switching loss can be partly mitigated by connecting a snubber circuit parallel to the switching circuit. But the total amount of switching loss generated in the system remains the same. The loss avoided has been moved to the snubber circuit.

At high switching frequency, higher efficiency can be obtained by making switching device to turn on or off at the zero crossing. This technique is called "soft switching," which can be subdivided into two methods: Zero-Voltage Switching (ZVS) and Zero-Current Switching (ZCS). When the switching device voltage is set to zero right before turn on of switch, switching loss during turn on can be eliminate and this refers to ZVS. ZCS eliminates the turn-off switching loss by making current to zero in the circuit right before turning it off. Voltage and current in the switching circuit is made to zero using resonance condition which is achieved by L-C resonant circuit. This is called a "resonant converter" Topology.

In case of ZCS, resonant circuit absorbs the existing inductance, which eliminates the voltage surges during turn off condition. Voltage surge during turn on of switching circuit is caused by an electric discharge of junction capacitance which cannot be avoided. This method causes switching loss ($0.5CV_2$ f). ZCS, however, is free from this defect and makes both the existing inductance and capacitance be absorbed by the resonant circuit. This eliminates the chance of causing a surge in current at turn-off (caused by inductance) or turn-on (by capacitance) conditions. ZVS enables switching with less loss, while substantially reducing the problem of EMI at high frequency.

Resonant inverters minimizes the switching loss and provides greater energy conversion efficiency to the power system, so it is widely used in a variety of industries. This is also the reason the inverter is adopted in the IH power system Topology. Fig.1. shows the typical diagram of series resonant inverter for induction heating. Three phase AC supply (400V,50HZ) is fed to rectifier. Rectifier which converts AC to DC and fed to inverter.

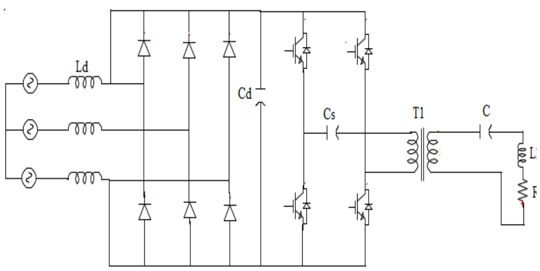

Fig.1. Circuit Diagram of Series Resonant Inverter

Inverter generates high frequency AC current which is fed to load. In order to obtain maximum power transfer from source to load impedance matching is required since the load impedance will change during the heating cycle which might necessitate retuning or rematching to the source. Output from the inverter is connected to impedance matching transformer which matches the source impedance to the load impedance and thereby transfers maximum power from source to load.

The parameters of the series-resonant circuit are defined as:

The resonant frequency:

$$\omega_o = \frac{1}{\sqrt{LC}} \qquad 6$$

L- Inductance C- Capacitance

The characteristic impedance:

$$Z_o = \omega_o L = \frac{1}{\omega_o C} \qquad 7$$

The loaded quality factor

$$Q = \frac{\omega_o L}{R} = \frac{1}{\omega_o CR} = \frac{Z_o}{R} = \frac{\sqrt{\frac{L}{C}}}{R} \qquad 8$$

Higher the Q value higher the current in the work piece.

A.SWITCHING MODES:

Series resonant inverters operate in two modes.Fig.2.shows switching modes of series resonant inverter. During mode I switches Q1 Q3 are turned on and positive voltage and current appears across the load. During mode II switches Q1 Q3 are turned off and switches Q2 Q4 are turned on and negative voltage and current appears across the load.

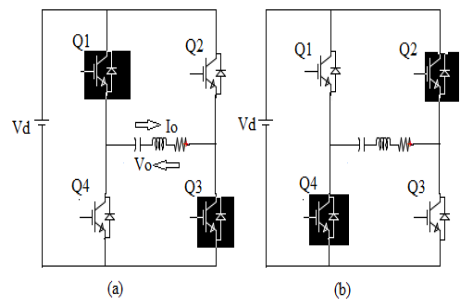

Fig.2.Switching Modes of Series Resonant Inverter

III. EXISTING TOPOLOGY:

Power control is often required for induction heating process. In existing system power control is achieved by Pulse Density Modulation (PDM). PDM is a power control technique which controls the output power by suppressing some of the pulses of the inverter. Power supplied to the load is maximum and in the other cases there are some pulses suppressed and, thus, the power supplied is lower. Compared to power control techniques like Phase shift and frequency control it has advantage that the inverter is commutating proximal to the resonant frequency and the reactive power and commutation losses are minimum. Even though PDM is advantageous compared to classical methods in terms of efficiency, it has some drawbacks that limit their widespread in industrial equipments. One of these limitations is that the power levels are not continuous, fact that can lead to a non-homogeneous heating of the work piece. In addition, the definition of the power levels supplied by the converter is not an easy task and, in case of low Q values and low power densities, the power calculation as a function of the pulse density is not obvious. Furthermore, special attention has to be taken in the DC-link design and the input inductors, to avoid voltage fluctuation and high harmonic content in the mains.

IV. PROPOSED TOPOLOGY:

Hysteresis current control is one such technique to regulate the output power for a wide range. Hysteresis mode control was introduced to the converter controller and it has been researched as a good alternative for regulating the current or voltage of a switching converter due to its fast dynamic characteristics and easy implementation. Not only the excellent loop performance it has, but also the instability can be prevented for all duty cycle since hysteretic control is basically based on the bounded operation between upper and lower trip point. It controls the switching signals applied to inverter.

In this technique reference wave is compared with Carrier wave and the switching signals are applied to the inverter with the intersection of these two waves. When this intersected wave reaches the upper band, switches S1 and S3 are turn on. When this reaches the lower band, switches S2 and S4 are turn on. With this changes in the switching state, output voltage is controlled and current is within the hysteresis band and thereby the output power is regulated for a wide range of heating cycle.

A. Analysis of Hysteresis Current Control

Hysteresis current control is a closed loop control technique in which the output current of the inverter is made to track the command current *I and maintain the error within the hysteresis band (δ) . In the fig 3 when the error current $i_e = i^* - i$ crosses the error band, inverters are switched to bring the output current within the error band. When the output current exceeds the upper band, it is brought back to within the band (δ) by turning on the lower switch and turning off the upper switch. As a result, the voltage across the load changes from V_{dc} to 0 and the current decreases. Similarly when the output current goes below the lower band, the load is connected to V_{dc} by turning OFF the lower switch and turning ON the upper switch. As a result, the output voltage across the load changes from 0 to V_{dc} and the output current starts to build up. An optimal value of δ must be chosen to maintain a balance between the output current ripple and the switching losses and thereby eliminate particular harmonics.

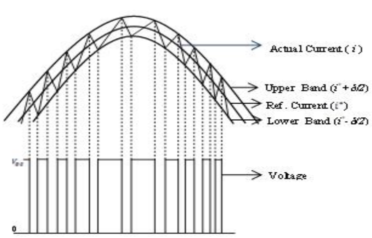

Fig 3. Hysteresis Band

Output power is calculated as:

$$P_{out} = V_{eff} I_{eff} \cos\theta \qquad 9$$

Effective inverter voltage is given as:

$$V_{eff} = \left(\frac{Ton}{T}\right) V_{effmax} \qquad 10$$

V_{effmax} is maximum rms value of output voltage.

Effective inverter current is given by

$$I_{eff} = \frac{P_{out}}{(V_{eff}\cos\theta)} = \frac{Ton}{T} I_{effmax} \qquad 11$$

To supply maximum power to the work piece operating frequency is match close to resonance frequency since at resonance frequency current is maximum. PLL systems are used to control the phase-shift between two electric variables and reach the resonant frequency. It consists of a phase detector, a low-pass filter, and a Voltage Controlled Oscillator (VCO).The phase detector produces a signal that is proportional to the phase-shift between the two input signals. Then, this signal is filtered through a low-pass filter, obtaining a DC voltage that is proportional to the phase-shift. VCO generates an AC signal whose frequency is proportional to its DC input voltage, the output of the VCO is connected with the input of the phase detector and the VCO adjusts the frequency until the output signal is matched to the input signal. PLL adjust the operating frequency until the phase shift between output current and voltage is zero since in case of voltage fed series resonant inverter the voltage and current phase-shift is close to zero at resonant frequency.

V. SIMULATION RESULTS

Series resonant inverter with hysteresis current control is analyzed and simulated using MATLAB. Sufficient Current is generated which is used to heat the work piece with the load resistance of 1ohm. Inverter switching frequency is made close to resonance frequency to get the current response at maximum. Fig 4 and fig 5 shows the output voltage and output current at the work piece.

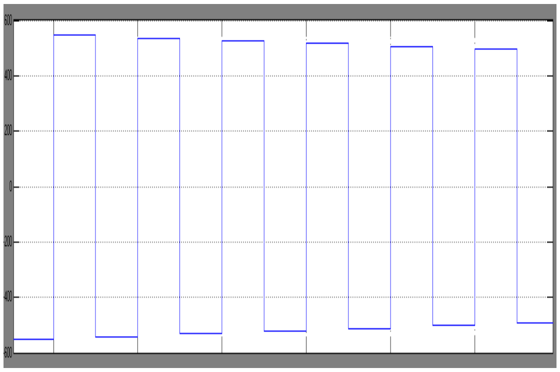

Fig .4 Output Voltage

Inverter output voltage at the work piece is 500V with load resistance of 1*Ω*.

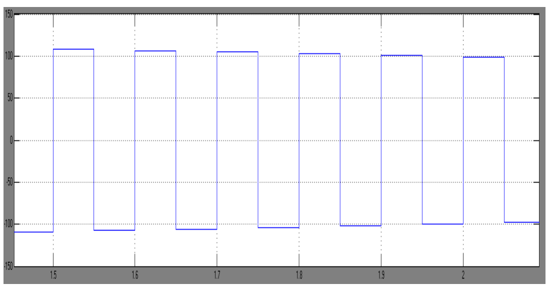

Fig .5 Output Current

Inverter output current at the work piece is 100A which is sufficient to heat the work piece with the frequency 1kHZ.

VI CONCLUSION

This paper has analyzed a series resonant inverter for induction heating application. Power control is done by hysteresis current control and provides good response for wide range. Soft switching techniques are performed which minimized switching losses. Phase locked loop which matches switching frequency to resonant frequency in order to achieve the maximum response at resonance. Thus the series resonant inverter with hysteresis current control provides best response for industrial induction heating.

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