Improving the Efficiency of Series Resonant Inverter Using Hysteresis Current Control

D. Poorani¹, R. Rajarajan²

¹PG Scholar, Department of Electronics and Communication Engineering, Excel Engineering College, Komarapalayam.

²Assistant Professor, Department of Electronics and Communication Engineering, Excel Engineering College, Komarapalayam.

Abstract: This paper is proposed to improve the efficiency of the series resonant inverter for industrial heating applications. Resonant inverters are those operate at high frequency with reduced losses preferable for induction heating. Resonating components and switching device which are placed in series to load forms series resonant inverter. Inverter which is characterized by full bridge made up of Insulated Gate Bipolar Transistor (IGBT). Due to an induction heating the amount of controlling the power is one of the desirable things. Power control strategy is achieved by hysteresis current control which controls the output power for a wide range. Switching losses are minimized by performing zero voltage switching and zero current switching. Improvement in efficiency by choosing appropriate values of modulation index.

Keywords: Hysteresis Current Control (HCC), Induction Heating (IH), Insulated Gate Bipolar Transistor (IGBT), Phase Locked Loop (PLL) and Series Resonant Inverter (SRI).

I. INTRODUCTION

Induction heating is a process which is used to bond, harden or soften metals or other conductive materials. An electrically conductive substance requires high frequency electricity in the induction heating techniques to heat the materials [1]. In a coil which passes the high alternating current requires a high frequency electricity source and it’s also called as work coil. The current flow in this coil will generates more intense and also change the magnetic field by rapid that given in the space of work coil. The magnetic field with intense is used to place the work piece for heating. The work piece that which is conductive will flow a current in the condition of alternating magnetic field. The placement of work piece with the work coil will shows the view of an electrical transformer. Electrical energy given to the work coil is the primary one, and the secondary is work piece like single turn or short circuited [2] – [3].

This produces the large amount current to flow in the work piece. It is called as eddy currents. Induction heating generators are resonant inverters in which the resonant tank is formed by a heating coil and a capacitor. Resonant inverters are electrical inverters based on resonant current oscillation. In resonant inverters the resonant tank is formed by a heating coil and a capacitor in series or parallel. Series resonant inverters are those in which resonant components and switches are in series to the load [4]. Series resonant load are fed by voltage fed inverter. They are used to heat metals to be welded, melted, or hardened. The use of SRIs that are fed with a voltage source represents a cost-effective solution however; it does not have the ability to control the output power by itself. In order to overcome these problems, an inverter with power control by frequency or phase-shift variation is normally used to regulate the output power and, using a diode bridge
rectifier, as a dc-voltage source. These power control schemes, however, may result in an increase of switching losses and electromagnetic noise because it is impossible for switching devices to be always turned on and off at zero current. In high-frequency induction heating applications, only MOSFET inverters can be used. Nevertheless, Insulated-Gate Bipolar Transistors (IGBTs) are preferred in high-power industrial applications (availability, cost, etc.), and it is possible only if a low-loss power control scheme is applied [5] – [6]. An induction heating system of 50 kW and 150 kHz for industrial applications that use a novel low-loss control scheme. The induction system consists of a three-phase diode rectifier, a single-phase voltage-fed inverter using four IGBTs, and a series-resonant circuit with a matching transformer [9]. The working frequency is automatically adjusted close to the resonance frequency in order to allow Zero-Current Switching (ZCS) inverter operation for any load condition.

One of the methods to regulate the output power is achieved by using hysteresis current control. Hysteresis current control having advantage such as quick response, internal current limiting capability and stability. In this technique reference wave is compared with output current wave and the switching signals are applied to the inverter with the intersection of these two waves [6]. With this changes in the switching state, output voltage is controlled and current is within limit and thereby output power is controlled for a wide range. The blanking time of the inverter transistors is designed to maintain Zero-Voltage Switching (ZVS) mode. With this circuit efficiency of the inverter can be improved at high-frequency working conditions [8].

**II. SERIES RESONANT INVERTER**

Resonant inverters are electrical inverters based on resonant current oscillations. 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. To give the under damped circuit in the series resonant inverter the switching device with the resonating components are connected in series with the load [3]. The switching device with the current which falls to zero by the characteristics of the own circuit. Switching loss reduces the efficiency of the process, as more losses are generated at a higher frequency.

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 is divided into 2 methods:

(i) Zero-Voltage Switching (ZVS)
(ii) 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. Resonant inverters minimize the switching loss and provide 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.
The output-power stage consists of a single-phase voltage-source inverter using four IGBTs. The output of the inverter is connected to a series-resonant circuit with a matching transformer. The dc power supply for the inverter is a three-phase diode bridge rectifier connected to a 400-V 50-Hz power line. The switch can conduct either positive or negative current [10]. A positive or negative switch current can flow through the transistor if the transistor is ON.

![Fig 1 Circuit diagram of series resonant inverter](image)

If the transistor is OFF, the switch can conduct only a negative current, which flows through the diode. The transistors are driven by non-overlapping gating signals with a small dead time at the operating frequency $f = 1/T$. Switches are alternately ON and OFF with a duty ratio of 50% or slightly less. The dead time is the time interval when both controllable devices are off. Resistance $R$ is an AC load.

### A. Switching Mode

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 (a) Mode I (b) Mode II](image)

### III. PHASE LOCKED LOOP

Considering PLLs in IH applications, 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. Fig. 3 shows the block diagram of PLL (Phase Locked Loop).

![Fig 3 Block Diagram of Phase Locked Loop (PLL)](image)
resonant inverter the voltage and current phase-shift is close to zero at resonant frequency. A manner of detecting the resonant frequency is by calculating the phase shift between two electric variables. In case of VFSRI, the phase-shift between voltage and current is zero at resonant frequency, so one method of finding the resonant frequency is varying the frequency until the phase-shift is zero. In case of converters with LCL tanks, the base idea is the same, but with a 90 degree phase-shift between the voltage at the output of the inverter and the voltage at the capacitor. For controlling this phase-shift between two electric variables, most of IH converters use a phase-locked loop (PLL) system.

IV. HYSTERESIS CURRENT CONTROL

For controlling the converter the hysteresis current control was introduced and also it gives high speed in its dynamic characteristics and it’s easy to implement, so the research is done as a better alternative for voltage or current regulation in switching converter.

The current control is directly take care by the hysteresis current control and the technique involved in this is PMW where the implementation is simple. It provides to the system a fast and robust dynamic response, and requires a simple implementation in standard digital signal. It is based on deriving the switching signals from the comparison of current error with fixed tolerance band. To maintain the current of inverter in the hysteresis band level the switching state is considered by the controller. Hysteresis current control has series of advantages such as quick response, internal current limiting capacity and stability.

A. Hysteresis current controller - Principle

To maintain the error in the limit of hysteresis band (δ) and the command current is get tracked by the inverters output current *I where this is a instant closed loop current control method by an hysteresis current control. In the Fig.4, when the error current \( i_e = i^* - i \) crosses the error band, inverters are switched to bring the output current within the error band. By switching on the lower and upper switch we can control the output current to not get exceed the upper band and it get control in the band limit (δ) itself. This results that load gets change by the voltage from VDC to 0 and the current decreases. Similarly when the output current goes below the lower band, by switching ON the upper switch and switching OFF the lower switch, the load is connected to VDC. This results the load gets vary from 0 to VDC across the output voltage and current at the output gets build up. To be in the constant state between the output current ripple and the switching losses, the δ’s optimal value must be selected and thereby eliminate particular harmonics.

![Fig 4 Hysteresis Band](image)

B. Inverter with hysteresis current control

The basic idea of hysteresis current control is to keep the current inside the hysteresis band by changing the switching state of inverter each time current reaches boundary. In the Fig.5, the current error is used as input of the comparator and if current error is higher than the upper limit, the power switches T1 and T4 are on and T2 T3 are turned off. The opposite switching states are generated if the error is lower than the lower limit. The main task of this method of control is to force the input
current to follow the reference current in each phase.

The deviation of the currents (error current) represents the current distortion which can be calculated as:

\[ \text{distortion} = \frac{100}{I_{\text{rms}}} \sqrt{\frac{1}{T} \int i_{\text{act}} - i_{\text{ref}} \, dt} \]  

(1)

The inverter output power is given by:

\[ P_{\text{out}} = V_{\text{eff}} I_{\text{eff}} \cos \theta \]  

(2)

\[ V_{\text{eff}} = \left( \frac{T_{\text{on}}}{T} \right) V_{\text{eff,max}} \]  

(3)

Where, \( V_{\text{eff,max}} \) (maximum rms value of the output voltage).

The rms output current must be given by:

\[ I_{\text{eff}} = \frac{P_{\text{out}}}{V_{\text{eff}} \cos \theta} \right) = \frac{T_{\text{on}}}{T} I_{\text{eff,max}} \]  

(4)

Even in every output power level the inverter which works near to the resonance frequency will be seen in this power control strategy.

V. SIMULATION RESULT

In order to verify the results, the simulation is done with the help of MATLAB/SIMULINK environment.

A. Simulink model

Series resonant inverter with hysteresis current control is modeled by SIMULINK environment. In the Fig.6, Three phase AC (400V/50HZ) Supply is applied to rectifier. Rectifier which converts AC supply to single phase DC which is fed to inverter. Inverter which is made up of IGBT switches.

Inverter which is operate at high frequency and produces high current which is applied to load which generates sufficient heat to heat the work piece.

Output power is controlled using hysteresis current control for a wide range. Phase locked loop is implemented for matching switching frequency to resonant frequency thereby produces maximum response over wide range.
B. Simulated results

In the Fig.7, switching pulses to inverter switches are shown. Switching signals applied to the full bridge inverter is derived using Hysteresis Current Control (HCC) which regulates the output power for wide range. Actual current is compared with reference current based on that switching pulses are produced.

![Simulated Switching Pulses to Inverter Switches](image)

In the Fig.9, output current for inverter is shown. Series resonant inverter with hysteresis current control for induction heating application is analyzed and inverter output current for resistive load \((R_L = 100\Omega)\) is 4.5A.

![Simulated Output Current](image)

VI. CONCLUSION

This paper has proposed hysteresis current control for induction heating industrial applications. This power control strategy provides good response and output power is controlled for a wide range. Switching losses are reduced by performing zero voltage and zero current switching. The optimum power stage was designed by using IGBT Transistors in resonant inverter. For various heating cycle, Impedance matching is performed to maximize output power. Phase locked loop is implemented for matching switching frequency to resonant frequency thereby produces maximum response over wide range in order to achieve the maximum response at resonance. Thus the series resonant inverter efficiency was improved with hysteresis current control, which provides best response for industrial induction heating.

![Simulated Output Voltage](image)
REFERENCES


