REVIEW ON DIFFERENT CONTROL METHODS USED FOR INDUCTION HEATING APPLICATIONS

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ABSTRACT

Different control methods like fixed and variable -frequency operations on Series Resonant Inverter(SRI) that are used in Induction Heating applications are reviewed in this paper. The advantages of Series Resonant Inverter are being its high power density with high efficiency for wide input and output load range. The other advantages like reduced output voltage ripple with high power factor can be achieved for SRI's. In practice, SRI's operated at high frequencies (kHz to MHz) results in the increase of turn-off and gate charge losses leading to the reduction in the efficiency of Inverter. Different Control Methods implemented on SRI are reviewed for Induction Heating(IH) application in this paper. The review includes merits and demerits of these control Methods along with their applications.

Key words: Induction Heating, Series Resonant Inverters, resonant tank, soft-switching.

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1. INTRODUCTION

In Pulse-Width-Modulated (PWM) Inverters, the switches undergo switched mode operation. In this operation, the switches experience high switching stress and switching losses. This switching losses are in linear proportion to switching frequency of the system. Therefore, electromagnetic interference produced in this mode of operation is large due to high dv/dt and di/dt values. Resonant Inverters/Converters with high frequency operation have come into existence to overcome the limitations posed by PWM converters. In these systems, resonant switch is used in place of PWM switch. In this resonant switch, an LC- resonant circuit is developed such that current through the switch and voltage across the switch are enforced to pass zero crossings.^{[1],[2]} Many tank circuits that come as voltage / current-type are available in the market. These types can be determined by the resonant tank signal which transfers the

power from supply to load side. Depending on the type of application, a specific type resonant inverter is used that provides soft switching. As resonant inverters/converters are operated at high frequency, there will be a reduction in component size..

High frequency Resonant Inverters are widely used in applications like DC to AC energy conversion.^[3] Some of the applications of Induction Heating (IH) systems are found in industrial processes, domestic appliances, electronic ballasts and also in communication systems. Recently, with the advancement of power semiconductor technology, many circuit configurations and control methods with high frequency operation is preferred for high-power applications. One such application is Induction Heating (IH) that is used widely in industrial and domestic fields.^{[4]-[5]} In addition, IH system can be used as hot water producers, steam generators and for printing applications.^[6]

In high-power industrial applications insulated-gate bipolar transistors (IGBTs) are preferred because of its availability, and cost. Generally any Induction heating system comprises of a 3- ϕ diode rectifier, a 1- ϕ voltage-fed inverter, a series resonant tank circuit and a matching transformer. The operating frequency is selected closer to resonant frequency to ensure zero-current switching (ZCS) operation for all load conditions. For IH applications, many types of high frequency inverters are proposed on considering different aspects like its output power, type of control method and frequency of operation.^[7]

Figure 1 Full Bridge Series Resonant Inverter

In this paper, SRI's for IH application is considered due to its high efficiency and soft switching features. Figure 1 shows Full bridge Series Resonant Inverter circuit. In this, resonant tank is developed by a series combination of a heating coil, a capacitor and load in series with switches and supply.^{[8]-[10]} These voltage fed Inverter circuits are popular because of their cost-effectiveness in heating applications in order to heat/melt/harden the metals.^[11]. The mathematical equations for SRI can be given as

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}}$$

$$Z_c = \sqrt{\frac{L_r}{C_r}}$$

$$Q = \frac{\omega L_r}{R}$$

$$D = \frac{T_{on}}{T_s/2}$$

where f_r = resonant frequency

Z_c = characteristic impedance

Q = Quality factor

D = duty cycle

Figure 2 represents the relation between DC voltage gain and normalized switching frequency for various quality factor values for Series Resonant Inverter. This figure illustrates that the gain of the converter can be controlled by the switching frequency which changes in turn the impedance of tank circuit.

Figure 2 DC characteristics of Series Resonant converter

2. DIFFERENT CONTROL METHODS

In this section, different control methods pertaining to both variable and fixed frequency operations imposed on Series Resonant Inverters are discussed. All control methods are reviewed in the aspects of their operating principle, advantages and disadvantages. The different control methods are given underneath.

- Frequency -control
- Duty cycle -control
- Asymmetric duty cycle -control
- Asymmetric voltage cancellation -control
- Pulse density modulation -control

2.1. Frequency Control

In Frequency Control, switching frequency is varied on making either on-time or off-time as constant. In this control, the variation of f_s/f_r ratio can control the load power. Here, f_s and f_r are switching and resonant frequencies respectively. In case of melting of metals, the values of quality factor (Q) and resonant frequency (f_r) also change during heating. Therefore proper ratio of f_s/f_r is to be maintained that requires a closed loop control. Figure 3 represents the variation of output power (P_0) with the variations of quality factors for different ratios of f_s/f_r on considering SRI.

Figure 3 Output power Versus Quality factor for different values of f_s/f_r

The limitations of this control method are

- EMI problem
- ZVS operation is affected

2.2. Duty Cycle Control

Duty cycle control comes under fixed frequency operation where the switching frequency is kept fixed and the duty cycle is changed by changing either on or off time. This control method makes synchronization of power inverters with the system clock unlike that of frequency control method.. Figure 4 represents a Parallel Resonant Inverter circuit for IH application. [12]-[13]

Figure 4 Full Bridge Parallel Resonant Inverter

In this circuit, a matching transformer is used to for the following reasons.

- To reduce the switch voltage and current in the respective Parallel /Series Inverters.
- To change the impedance of work piece so that device ratings come under manageable levels.

Figure 5 represents the switching pulses and output voltage waveforms for SRI used for IH applications

Figure 5 Switching Pulses and Output Voltages

Figure 6 represents the relation between output power (P_0) and duty cycle for different values of quality factor by keeping f_s/f_r ratio as constant for SRI.

Figure 6 Output power Versus Duty cycle for different values of Quality factor

2.3. Asymmetric Duty Cycle Control

In Asymmetrical duty cycle control, fixed frequency is obtained by controlling the on-period of the switches. In this, the error signal is compared to a carrier signal of saw tooth to generate a sequence of pulses with a duty cycle of D . The variation of duty cycle occurs with the shape of AC waveform falling on resonant tank. This variation of duty cycle regulates the output voltage. This control method optimizes the size of magnetic components. Figure 7 represents the switching pulses and output voltage waveform of Asymmetrical duty cycle control.

Figure 7 Switching Pulses and Output Voltages for Asymmetrical duty cycle control

Figure 8 represents the relation between output power (P_0) and duty cycle for different values of quality factor by keeping f_s/f_r ratio as constant for SRI.

Figure 8 Output power Vs Duty cycle for different values of Quality factor

The advantage of this control is that the dead band between two consecutive conduction periods of switch is negligible enough that the delivery of energy to the load is quick and easy. This ensures low switching and conduction losses. The limitation of this control is the maximum frequency of operation is less than the achievable with the actual resonant circuit due to timing difficulties.

2.4. Asymmetric Voltage Cancellation Control

The Asymmetric voltage cancellation control method gives better efficiency in comparison with the conventional fixed-frequency methods in the aspects of zvs -operation and wide output power/load variations. Figure 9 represents typical waveforms of asymmetrical voltage-cancellation control method.

Figure 9 Waveforms of asymmetrical voltage cancellation -control.

For a full-bridge SRI shown in Figure 1 inverter topology, a generalized quasi-square output V_{ab} is observed in Figure 9. This V_{ab} voltage is controlled by the four control variables (α_+ , α_- , β & T_s) as indicated in Figure 9. In fixed-frequency control, switching period (T_s) is kept constant and the remaining three control variables are considered. For the basic inverter circuit shown in Figure 1, some typical waveforms like conduction sequence of switches S1-S4, quasi square output voltage (v_{ab}), and output current (i_o) of full-bridge topology are indicated in Figure 9. The dashed waveform (v_{ab1}) gives the fundamental harmonic component of v_{ab} .^{[14]-[15]}

2.5. Pulse Density Modulation Control

In Pulse Density Modulation (PDM) control, the inverter should be operated at resonant frequency and missed gate pulses should be made proportional to the load changes. PDM control gives a good selectivity of frequency over wide variations of line and load. In PDM, by suppressing some of the pulses of the inverter output power can be controlled but not the voltage.^[16] The PDM period is assumed to be an integer of switching periods and can be generated by a look up table to give required patterns. Many PDM controls uses a digital controller having a PWM cycle equals to 16 times the switching time. Figure 10 represents operating waveforms of a PDM converter.

Figure 10 Operating waveforms of a PDM converter

The advantages of PDM control are good lightload regulation and high efficiency. ZCS is ensured if the inverter is operated at resonant frequency. The limitation with PDM, are

improved transient response and smaller filter size cannot be achieved despite switching at high frequency. This happens because transient response and filter size and is limited to PDM frequency instead switching frequency of the circuit. In this control, current stress on semiconductor devices and power levels are not continuous which causes a non-homogeneous heating of work piece.

3. CONCLUSION

The review emphasizes on the usage of Series Resonant Inverter in the applications of Induction heating as it gives high power density and efficiency at high frequency of operation. Conventionally, selecting operating frequency is limitless but in practice, the applications based on resonant inverter topologies are limited as they possess some shortcomings due to their control methods. The review elaborates on different control methods like frequency -control, duty cycle -control, asymmetric duty cycle -control, asymmetric voltage cancellation -control and pulse density -control. The review includes merits and demerits of these control methods along with their applications. It is concluded based on the type of application, a proper control method can be utilized.

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