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Pulse Density Modulation Based Series Resonant Inverter Fed Induction Heater System

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ABSTRACT

This paper deals with implementation of a multi-output Series Resonant Inverter(SRI) for induction heating applications, which uses pulse density modulation(PDM) control for full bridge Series resonant inverters for output voltage and power control. It ensures better efficiency performances than conventional control strategies. The proposed converter can be considered as a two output extension of a full bridge inverter. This full bridge inverter can control the two outputs, simultaneously and independently, up to their rated powers, which reduces the usage of number of components as compared with conventional method. It also ensures higher utilization of switches used for its operation. A two output full bridge series resonant inverter is simulated and implemented. The Experimental results are compared with the simulation results.

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1. INTRODUCTION

Resonant inverters are now used in many applications to convert the available dc energy into ac energy such as DC-DC resonant converters, induction heating systems for industrial processes or home appliances, electronic ballasts for lighting, radio transmitters and others. The Control of output voltage or power in many resonant inverters has been obtained by varying the switching frequency, which has several disadvantages such as a wide noise spectrum which makes it difficult to control electromagnetic interference (EMI), more complex filtering of output-voltage ripple, a poor utilization of magnetic components. These problems can be eliminated with the use of a fixed- frequency or a narrow frequency range control technique.

Induction cookers are low power, maximum output induction heating system usually less than 3KW per load. An induction heating cooking appliance is basically made up of a flat-type induction coil on which the pan to be heated is placed. Between the pan and the coil an insulator (usually a ceramic glass) is placed. The heat is generated at the bottom of the pan due to eddy currents and hysteresis losses. These induced currents are caused by an alternating magnetic field generated by a medium frequency (20-100Hz) current through the coil. Pan-induction coupling is usually modeled as the series connection of an inductor and a resistor, based on the transformer analogy. The values of the equivalent inductance and resistance depend on the operating frequency and the required maximum power.

A general block diagram of an induction heating cooking appliance is shown in Figure 1. Induction cookers take the input energy from the ac mains voltage, which is rectified by a diode bridge rectifier. A bus filter is designed to allow a big voltage ripple getting a resultant power factor close to one. Then the inverter topology is used to supply the high-frequency current to the induction coil. Due to this ripple all components have to be designed for the voltage and current peak values. The commonly used inverter topologies used in induction cookers are resonant inverters, including full-bridge [1], half bridge [2], [3], [4] & [5] and single switch inverters. In this paper, Full bridge series resonant inverter topology is used for supplying the Induction Heating load.

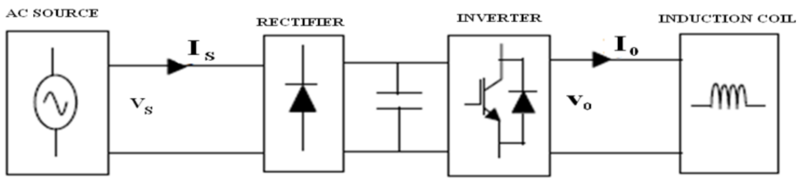

Figure 1. General block diagram of an IH cooking appliance

The objective of this paper is to define and analyze a PDM control technique for resonant inverters, so called asymmetrical voltage-cancellation (AVC) control. Previously in [6], State-Space Model has been used for switched converters for generating a two-output series resonant inverter for multi-burner induction cooking appliances. Now it is obtained by fixed frequency control [7 & 8]. Later to this in [9], an inverter is designed to give three outputs for induction heating cooking appliances, now it is designed as two output solution for induction heating cooking applications with full bridge inverter topology with fixed frequency control which reduces number of switching devices as 2n+2 instant of 4n [10].

Thus the use of multi-output inverters has clear benefits for multi-burner cookers: higher utilization of electronics, higher maximum power and it is possible to share some components of the converter. The required fixed frequency control has some additional advantages, as reducing the electromagnetic noise spectrum and avoiding the acoustic noise due to different operating frequencies which cause low-frequency interferences amplified by the pans [10].

A synthesis method proposed for switched converters is applied here as a tool for generating the new inverter. In addition to this it also employs fixed frequency control technique [11], [12] & [13] in particular PDM control. Semiconductor switches with high switching speed is normally preferred in Induction Heating (IH) applications. The IGBT switches were used in [14], which provides minimum on-state conduction losses, higher efficiency than the high voltage MOSFET switches. And a series resonant inverter with MOSFET switches was proposed to enhance the cooling arrangements and the power conversion efficiency in [15]. The multi output full bridge inverter topologies were discussed for controlling the output power by using Asymmetrical voltage cancellation (AVC) or asymmetrical Pulse Width Modulation (APWM) in [16 & 17]. Behaviour of a high frequency Parallel Quasi Resonant Inverter fitted Induction Heater with different switching frequencies are presented in [18].

The above literature doesn't deal with embedded implementation of multi output series resonant inverter system. This work deals with modeling, simulation and implementation of multi output series resonant inverter. The paper is organized as follows. In section II the operation of proposed topology of two output series resonant inverter with PDM control is presented. In section III, simulation results of a two-output series resonant inverter are presented. In section IV, Results and discussions of proposed work is presented. Experimental results of a prototype are presented in section V. Finally, the conclusions of the work are provided in section VI.

2. PROPOSED SERIES RESONANT INVERTER TOPOLOGY

One of the most popular resonant inverters is the full-bridge series resonant inverter shown in Figure 2. The basic specifications for the converter synthesis: a two-output series resonant inverter, with variable output power and a fixed frequency control. Two inductive loads should be supplied separately, up to their rated output powers, without losing the mentioned benefits of fixed frequency control strategies. And a soft-switching operation is employed for obtaining better efficiency performance.

The operation of the full bridge topology is divided into 5 modes per cycle, which uses Pulse Density Modulation control with fixed frequency operation.

Mode 1 : Re-generative mode

In this mode the energy stored in load circuit is returned back to the DC source via freewheeling diodes D1, D4 for load 1 and D1, D6 for load 2. The output voltage is $+v_{dc}$ and direction of resonant current flows from load to source. The current flows till the stored energy is returned to the source.

Mode 2 : Power Mode

In this mode the resonant load gets energy from the DC source via switches Q1, Q4 for load 1 & Q1, Q6 for load 2. The output voltage is $+v_{dc}$ and direction of resonant current flows from source to load.

Mode 3 : Freewheeling mode

In this mode the energy does not transfer to any sides. The direction of resonant current is from source to load through the freewheeling diodes D3,Q1 for load 1 and D5,Q1 for load 2, the output voltage is zero during this mode.

Mode 4 : Re-generative mode

In this mode the energy stored in load circuit is returned back to the DC source via freewheeling diodes D2, D3 for load 1 and D2,D5 for load 2. The output voltage is $-v_{dc}$ and direction of resonant current flows from source to load. The current flows till the stored energy is returned to the source.

Mode 5 : Power Mode

In this mode the resonant load gets energy from the DC source via switches Q2,Q3 for load 1 & Q2,Q5 for load 2. The output voltage is $-v_{dc}$ and direction of resonant current flows from load to source.

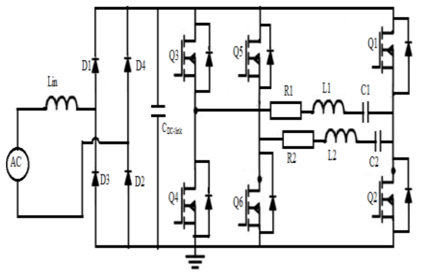

Figure 2. Two-output series resonant inverter for PDM control

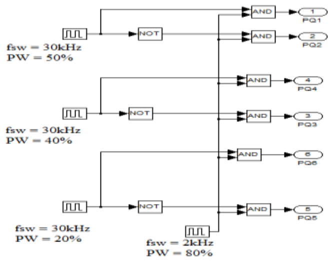

Figure 3. Pulse generation Circuit for PDM control

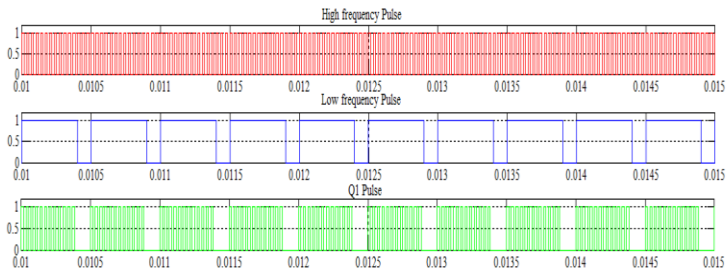

Figure 4. Typical waveforms of PDM control pulses for MOSFET 1

Figure 3 Shows the pulse generation circuit for PDM control used in multi output series resonant inverters. The pulse is generated by comparing the low frequency reference signal of 2kHZ is being compared with a high frequency carrier signal of 30kHz. The duty cycle of common leg devices are given with 50% duty, first leg devices are given with 40% duty and the second leg devices are given with 20% duty. Figure 4 shows the typical waveforms of PDM control pulsesfor MOSFET 1.

3. SIMULATION RESULTS

The inverter circuit is simulated with MATLAB-Simulink software for verifying the operating principle of the multi-output series resonant inverter topology for induction heating applications. Parameters used for simulation are given in Table 1.

Table 1. Design Parameters

Parameter Name	Values
Supply voltage, Vs	230V,50Hz, 1φ
DC link capacitance, C_{dc}	1000 e^{-6}F
Load Inductance, L	$1e^{-3}$H
Resonant Capacitor,C	$28e^{-9}$F
Load Resistance, R	9.5 Ω
Switching Frequency, F_s	30kHz
Duty Cycle of common leg, D_C	50%
Duty cycle of first leg, D_1	40%
Duty Cycle of second leg, D_2	20%

The Simulink model of full-bridge Series Resonant Inverter circuit is shown in Figure 5a which is modeled using RLC branches and MOSFET's. PDM Pulses for common leg, first leg and second leg switches are shown in Figs. 5b, 5c & 5d. The output currents of load 1 & 2 are shown in Figs. 5e & 5f. The voltage across loads 1 & 2 are shown in Figs. 5g & 5h. The variation of output power with respect to the load resistance is shown in Figure 5i. The variation of output power with respect to switching frequency is given in Figure 5j. The variation of output power with respect to the duty cycle is given in Figure 5k. The variation of output power with respect to duty cycle & load resistance is shown in Figure 5l. The variation of output power with respect to switching frequency and load resistance is shown in Figure 5m. The output power increases when the input voltage is increased.

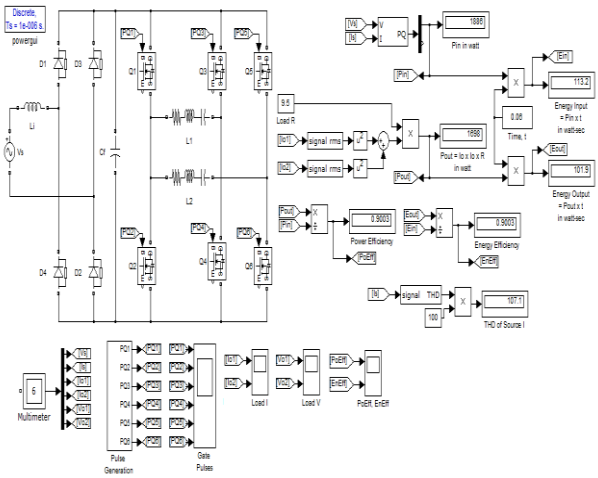

Figure 5a. Series resonant Inverter Circuit with PDM control for IH application

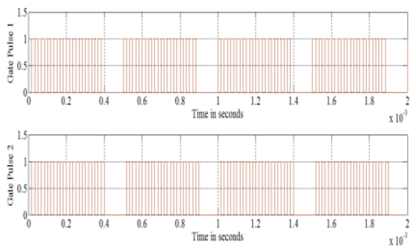

Figure 5b. Pulses for Common leg

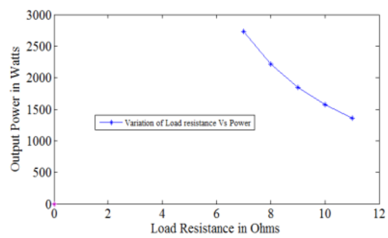

Figure 5g. Variation of Pout with Load resistance

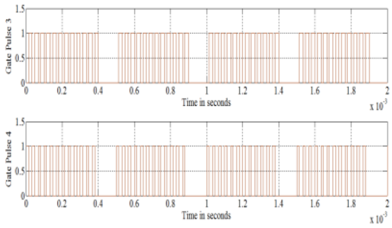

Figure 5c. Pulses for first leg

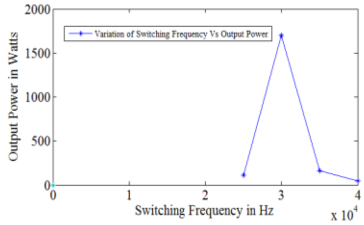

Figure 5h. Variation of Pout with f_{SW}

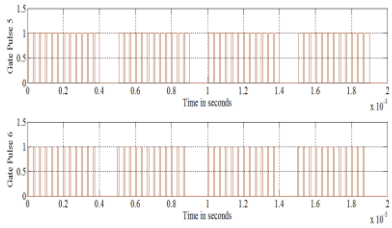

Figure 5d. Pulses for second leg

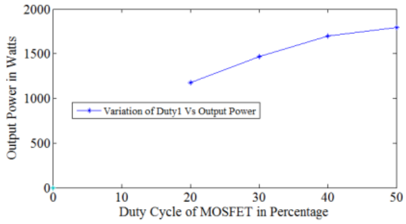

Figure 5i. Variation of Pout with Duty Cycle

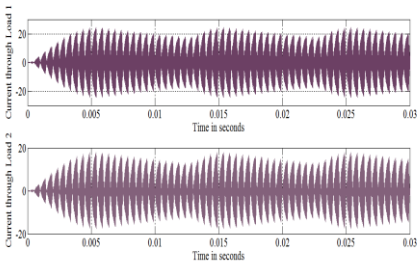

Figure 5e. Output current through load current 1 & 2

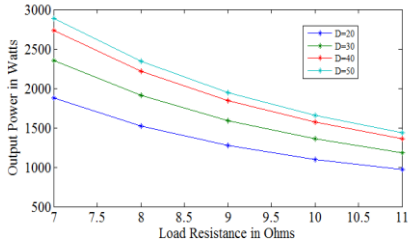

Figure 5j. Variation of Pout Vs Duty and R_L

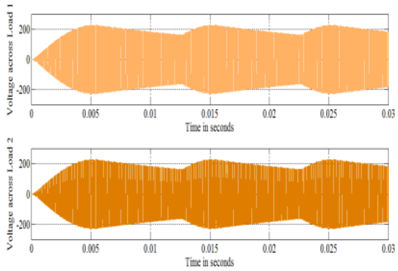

Figure 5f. Voltage across load 1 & 2

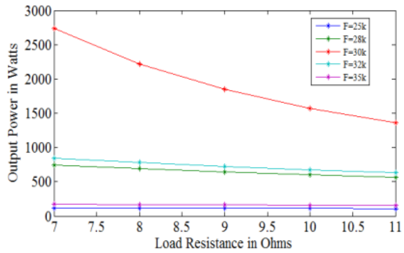

Figure 5k. Variation Pout Vs Fsw &R_L

The performance parameters of full bridge series resonant inverter fed induction heating system are calculated by using the following formulae.

Input Power, $P_{in} = VI \cos\varphi$ (1)

Output Power, $P_{out} = [I_1{}^2 + I_2{}^2] \times R$ (2)

Power Efficiency, $\eta = \frac{P_{out}}{P_{in}}$ (3)

Switching Frequency, $f_{swit} = \frac{1}{T}$ (4)

Resonant Frequency , $f_{reso} = \frac{1}{[2\pi\sqrt{LC}]}$ (5)

Total Harmonic Distortion, $THD = \frac{\sum(I_{0rms}{}^2 + I_{1rms}{}^2)^{\frac{1}{2}}}{I_{1rms}}$ (6)

The measure of harmonic presence in a non-sinusoidal periodic waveform is represented by the equation (6). Where, I_{0rms} is the root mean squared (RMS) value of any non-sinusoidal current and I_{1rms} is the root mean squared (RMS) value of the fundamental harmonic present in that current. It gives information about how close a non-sinusoidal waveform close to its fundamental in waveshape [18].

4. RESULTS AND DISCUSSIONS

In induction heating system the depth of penetration of heat is inversely proportional to the working frequency. And in general the periodicity is inversely proportional to the working frequency. Therefore the duty cycle of MOSFET is varied, to control the working frequency and the depth penetration of heat. In this paper, the proposed full bridge series resonant circuit is modelled and simulated under different switching frequencies such as 25 kHz, 30 kHz and 35 kHz respectively. The proposed circuit is designed with the resonant frequency of 30.077 kHz. Thus around the switching frequency, the switching operations ensuring less switching losses with maximum efficiency. The selection of the switching frequency a little superior to resonant frequency is generally advantageous.

When the switching frequency is at 25kHz a reduced amount of the resonant frequency, then from Figure 5h, it is shown that the switching operation do not follow the resonant conditions that produces high switching losses and hence reduces the output power and efficiency. And the THD of the source current is excessive at this switching frequency, which results non-sinusoidal nature of source current and thus the input voltage may have unnecessary harmonics. In order to filterout this unnecessary harmonics an ac filter is needed at the input side and thus increases the cost of induction heating system. In addition, this reduced switching frequency may create an unwanted perceptible noise. So, the selection of lower switching frequency normally avoided.

When the switching frequency is at 35kHz higher than the resonant frequency may produce larger THD value of the output current and it is successful for induction heating purpose, but this is also not advisable because again the switching operation do not follow the resonant conditions and hence produce high switching losses which results lower output power and efficiency as shown Figure 5h.

Table 2. Performance parameters of Full Bridge SRI with PDM control

Inverter Type	Vs (V)	Pin (W)	Pout (W)	Power Efficiency (%))	THD (%)
FB_SRI_PDM	230	1886	1698	90.03	107.1

Performance analysis plots are also plotted for full bridge series resonant inverter fed induction heating system. The result shows that output power decreases for the increase of load resistance and also decreases with decrease in duty cycle. And the maximum output power is obtained with the switching frequency of 30 kHz for all other frequencies output power is reduced because the load circuit is tuned to frequency of 30kHz. A simulation result shows that the two-output full bridge inverter topology gives an efficiency of 90.03% with the input voltage of 230V. Also the input current THD obtained is 107.1 %.

5. EXPERIMENTAL RESULTS

An experimental model of induction heating system with Series Resonant inverter has been built in order to verify the effectiveness of simulation results. Hardware module is shown in Figure 6a. Driving pulses for MOSFET's Q1 & Q2 are shown in Figure 6b. Driving pulses for Q3 & Q4 are shown in Figure 6c. Switching pulses for Q5 & Q6 are shown in Figure 6d. Voltage across load 1 is shown in Figure 6e. Voltage across load 2 is shown in Figure 6f.

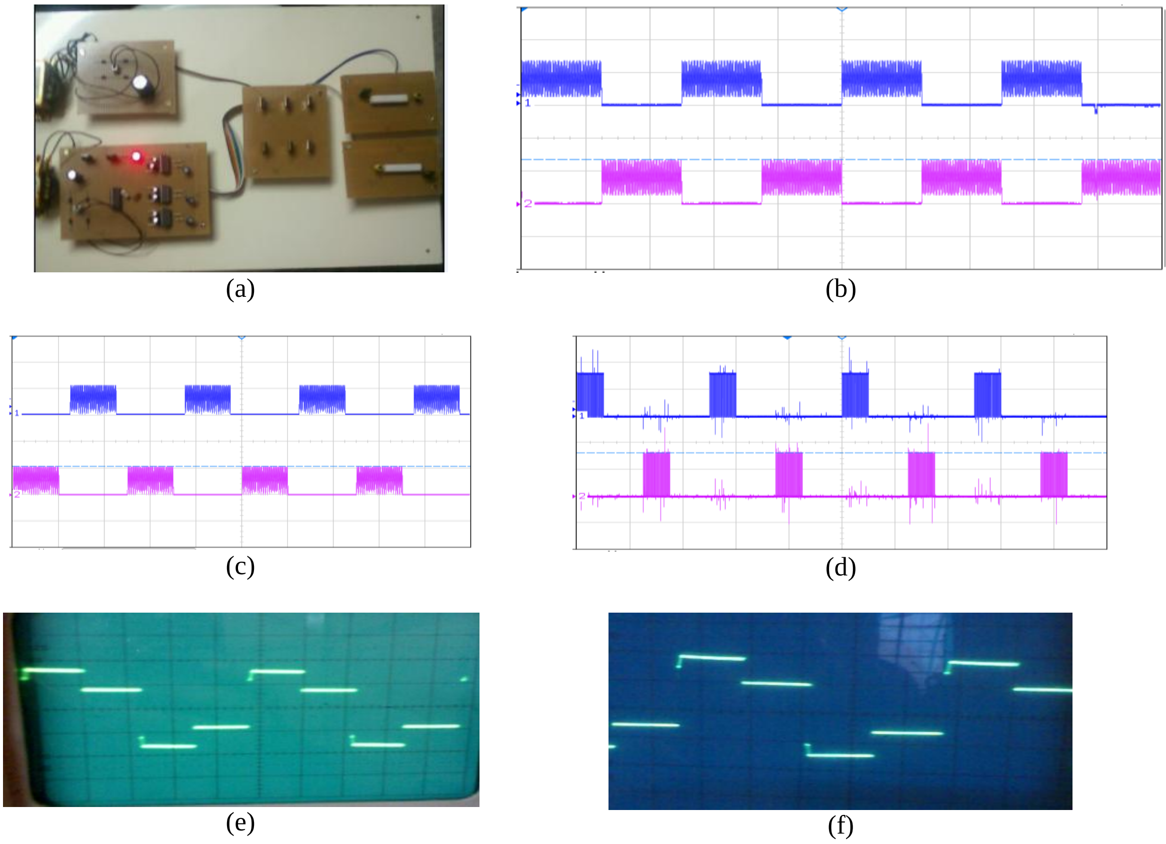

Figure 4 (a) Experimental model of series resonant inverter a) Experimental model. (b) Driving pulses for Q_1 & Q_2 (X-axis:9.5µs, Y-axis: 3V/div). (c) Driving pulses for Q_3 & Q_4 (X-axis:9.5µs, Y-axis: 3V/div). (d) Driving pulses for Q_5 & Q_6 (X-axis:9.5µs, Y-axis: 3V/div). (e) Voltage across load 1 (X-axis:5µs, Y-axis: 40V/div). (f) Voltage across load 2 (X-axis:5µs,Y-axis:40V/div)

6. CONCLUSION

Two output series resonant inverter system with Pulse Density Modulation Control is modeled using the blocks of Simulink and the results are presented. This inverter uses smaller values of L & C since it operates at high frequency. Switching losses are reduced by using resonant switching. Higher amount of heat is generated with the use of two RLC branches. Variation of output power with the variation in the duty cycle, switching frequency, load resistance are also presented. The hardware is fabricated and tested in the laboratory. The experimental results are in line with the simulation results.

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