Power Factor Improvement using PWM Rectifier in Shrink Fitting

Rishabh Mhatre Komal Patil Shivani Sharma Mini Rajeev, SM IEEE

Department of Electrical Engineering, Fr. C. Rodrigues Institute of Technology, Vashi, India

***Abstract*—Induction Heating (IH) systems are a popular choice for an extensive range of applications in the automotive industry. However, the input power factor is poor in conventional IH systems, which leads to higher input current. Therefore, a single switch resonant inverter with a PWM rectifier as its input is considered in the work presented. This work validates the power factor improvement of an IH system that can be used in the automotive industry, specifically for shrink fitting. PWM rectifier is implemented in the IH system, replacing diode bridge rectifier, and it is observed that both distortion and displacement power factor are improved. In order to generate pulses for the controllable switches in the PWM rectifier, hysteresis current control method is used. Prior to this selection, various types of closed-loop current control methods were analyzed, and hysteresis current control, employing a single PI controller, is selected for the closed-loop operation. A low power level laboratory prototype is constructed and tested successfully, and results are presented in the paper.**

***Index Terms*—Harmonics, Induction Heating, Power Factor, PWM Rectifier, Resonant Inverter**

I. Introduction

Induction heating (IH) is widely used in various applications in the automotive industry. One such application is shrink-fitting, which is based on the principle of thermal expansion of metals. It is used to install or remove parts such as bearings, gears, bushings, etc., in the automotive industry [1]. In IH, the induction coil does not touch the workpiece and no combustion gases are produced. However, due to the inductive load, the displacement power factor decreases. Besides this, most IH systems use a diode rectifier or thyristor-controlled rectifier circuit for DC supply. Such circuits use a filter capacitor at the output to obtain a smooth DC bus voltage, resulting in poor input power factor and high harmonics in the input current. This increases total harmonic distortion (THD). Therefore, both displacement and distortion power factors are negatively affected. Numerous power factor correction (PFC) methods are used to mitigate these problems. Some PFC methods that can be used for induction heating include a capacitor bank, a boost converter, and a pulse width modulation (PWM) rectifier [2]. This work focuses on power factor correction using a PWM rectifier. The PWM rectifier is chosen because it has the advantage over other topologies of taking an almost sinusoidal current, consuming less reactive power. The advantages and disadvantages of different PFC methods are discussed in detail in section II. In this work, for the simulation and hardware implementation, a PWM rectifier with hysteresis control is selected. IH system with both, a diode rectifier and PWM rectifier along with a resonant inverter is implemented for low power levels. THD and power factor are compared. Rest of the paper is organized as follows. Section III outlines the methods of PFC. Section IV contains simulation results, and Section V focuses on the hardware implementation, followed by a conclusion and references.

II. Literature Survey

Various PFC methods are discussed in this section in brief.

A. Capacitor bank

Capacitor banks improve the power factor by compensating for the lagging current by creating a leading current. However, surge current taken and the poor dynamic response of this method limit the scheme. Simultaneously, this method is not capable of providing voltage regulation. Even when the line current harmonics are reduced, there is a significant phase shift in the fundamental line currents. Besides this, the switching of capacitor banks also affects the system performance. Though losses are less, the capacitor needs to be changed based on load requirements [3].

B. Boost converter

Capacitor banks improve the power factor by compensating for the lagging current by creating a leading current. However, surge current taken and the poor dynamic response of this method limit the scheme. Simultaneously, this method is not capable of providing voltage regulation. Even when the line current harmonics are reduced, there is a significant phase shift in the fundamental line currents. Besides this, the switching of capacitor banks also affects the system performance. Though losses are less, the capacitor needs to be changed based on load requirements [4]. The drawbacks of power factor correction using this method are:

- The output-to-input voltage ratio is limited.
- Current stress on switches is more in DCM.
- Stability is affected in continuous conduction mode .

C. PWM rectifier

Improving the power factor of circuits is possible by replacing the diode with controllable switches in the rectifier. Such circuits are known as PWM rectifiers. In addition to power factor improvement, they can allow the power flow to be bidirectional, as well as output DC voltage can be regulated. This is possible by controlling the width of the pulses given to these switches [5]. Control techniques researched for this study are sinusoidal pulse width modulation (SPWM) and hysteresis current control. These methods are discussed in brief.

1) SPWM technique : SPWM method is a method of PWM where a sinusoidal wave is compared with a triangular wave. By adjusting the width of the pulses, the output can be modulated, as shown in Fig.1 [6].

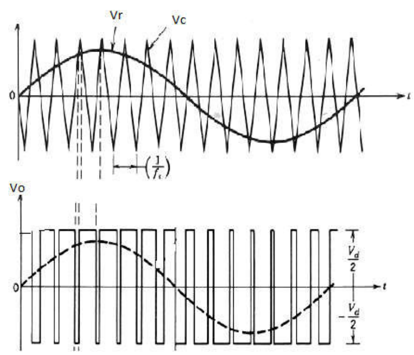

Fig. 1. PWM generation using SPWM technique [7]

2) Hysteresis control: Hysteresis current control is a method where the measured current is compared to the reference current on an instantaneous basis. Switching pulses are produced by comparing the current error against a predefined band called the hysteresis band. In the hysteresis modulator, the current error signal is compared with the hysteresis band. When the error crosses the upper boundary, the switch is turned off, and when the error crosses the lower boundary, the switch is turned on. The process continues by turning on and off the switch [8].

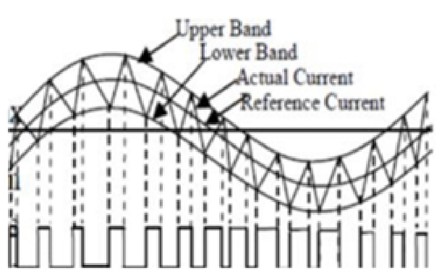

Fig. 2. PWM pulse generation by Hysteresis control [6]

The smaller the hysteresis band width, the lesser will be the peak-to-peak ripple but higher the switching frequency. Hysteresis current control is one of the fastest and easiest control methods to implement. Additionally, THD can be reduced below 5% by tuning the controller accurately. Based on the above-mentioned discussions on the control methods, a PWM rectifier with hysteresis control is selected for this work. Fig.3 depicts the block diagram of the IH system replacing the diode rectifier with a PWM rectifier. The remaining part of the block diagram corresponds to the IH system commonly used [9].

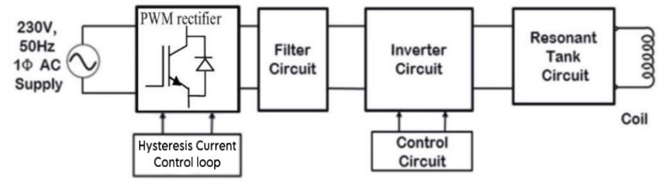

Fig. 3. Block Diagram of Induction Heating with PWM rectifier

A detailed circuit diagram corresponding to the block diagram of Fig.3 is given in Fig.4. The circuit in Fig.4 was simulated and implemented in hardware, and results are presented in Sections III and IV, respectively.

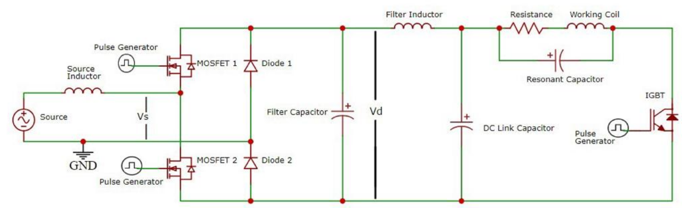

Fig. 4. Circuit diagram of IH system with PWM rectifier

III. SIMULATION METHODOLOGY

Simulation methodology of induction heating system with different rectifier topologies is presented in this section. The circuit simulation was carried out on MATLAB Simulink. A simulation was carried out for the diode bridge rectifier as well as the PWM rectifier in an induction heating system, and the results were compared based on THD and power factor. The parameters used for the simulation are given in Table I.

TABLE I
SIMULATION PARAMETERS

Sr no	Parameter	Value
1	Supply voltage (peak)	50V
2	Source inductor	5 mH
3	Filter capacitor	2200 µF
4	Filter inductor	700 µH
5	DC Link capacitor	3.3 µF
6	Working coil	119.36 µH
7	Resistance	20 ohms
8	Resonant capacitor	30 nF

A. Induction Heating with Diode Bridge Rectifier

Fig.5 shows the simulation model of an IH system with a diode bridge rectifier. A DC link capacitor of 3.3 µF is used to aid the inverter operation. A working coil is connected in parallel with the resonant capacitor of 30 nF. An IGBT is used as a single switching device for the conversion of DC, obtained from diode bridge rectifier, to high-frequency AC. The frequency of pulses given to the gate terminal of IGBT is 50 kHz, with a fixed duty cycle of 50%.

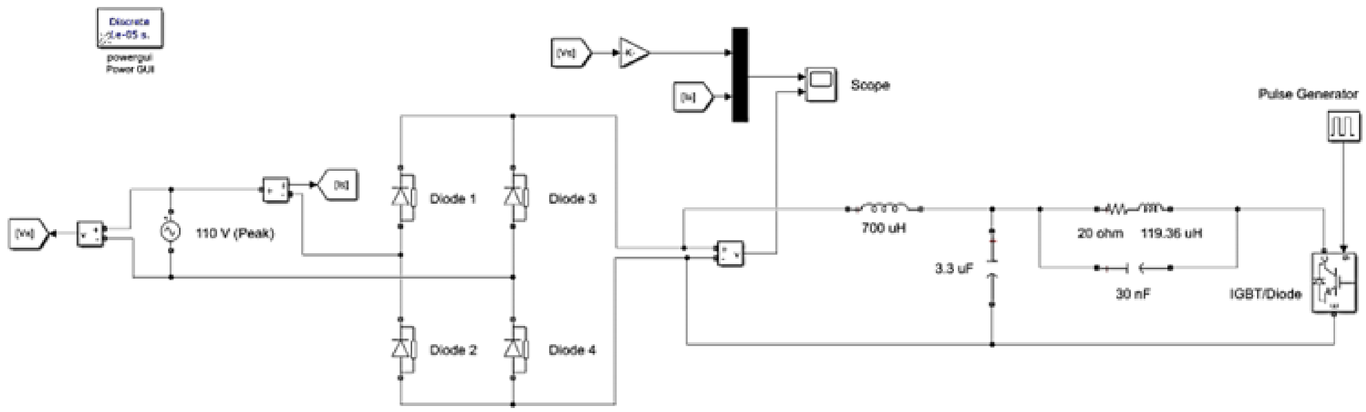

Fig. 5. IH system with diode bridge rectifier

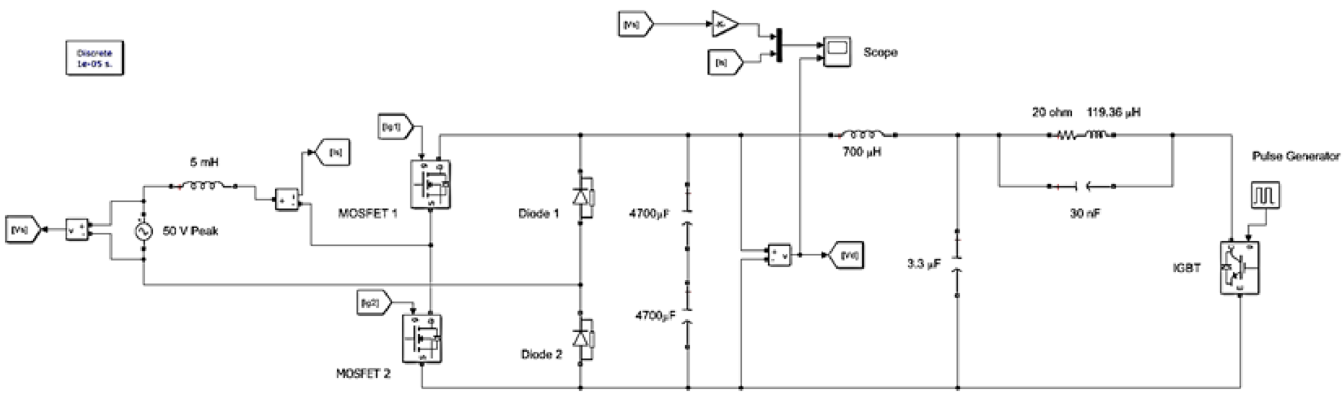

Fig. 6. IH system with PWM rectifier

B. Induction Heating with PWM Rectifier

Fig.6 shows a simulation model of a PWM rectifier connected to an induction heating system. This rectifier is connected to the resonant inverter.

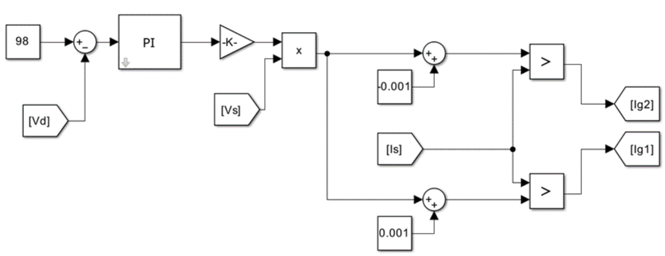

Fig. 7. Control Circuit of PWM Rectifier with IH system

Hysteresis control is implemented as shown in Fig.7. Reference of 98V is given, and Vd is the PWM rectifier output voltage shown in Fig.4.PI controller is used to reduce the error , and the output of the controller is multiplied by the source voltage (Vs), which acts as a sine template. Constants of ±0.001 are added to the reference current to form the hysteresis band.

IV. Simulation Result

Simulation Results of induction heating systems with different rectifier topologies are presented in this section. Waveforms representing different parameters like supply voltage, supply current and output Voltage are displayed along with FFT analysis.

A. Induction Heating with Diode Bridge Rectifier

From the waveforms shown in Fig.8, even though the supply current and supply voltage are in phase, the nature of the current waveform is not purely sinusoidal, and the zero crossing is distorted.

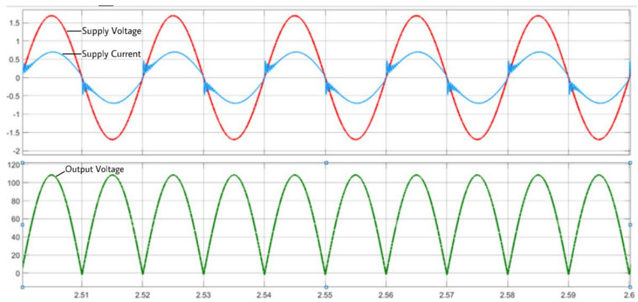

Fig. 8. Simulation result of diode bridge rectifier with IH system Supply voltage [1:65], Supply current [1:1], Output Voltage [1:1]

FFT analysis of input current is given in Fig.9, and the THD observed in the IH system with a diode bridge rectifier is 8.46%. This is above the acceptable value given by standards [10].

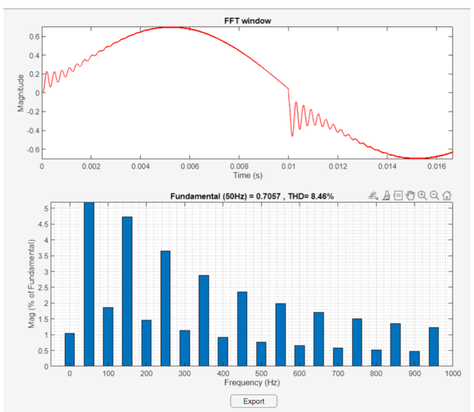

Fig. 9. FFT analysis of supply current of IH with diode rectifier

B. Induction Heating with PWM Rectifier

From the waveforms shown in Fig.10, the supply current and supply voltage are in phase with each other. Regulated output voltage is also seen in Fig.10.

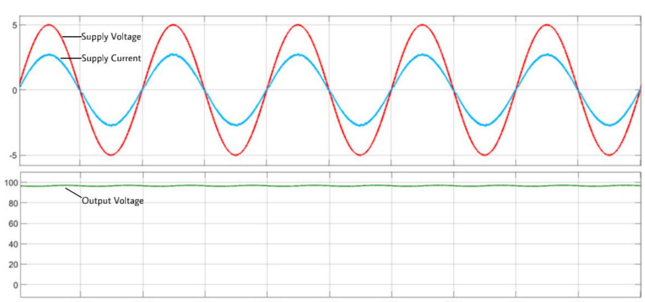

Fig. 10. Simulation result of PWM rectifier with IH system, Supply voltage[1:10], Supply current [1:1], Output Voltage [1:1]

THD observed in the IH system with the PWM rectifier is 2.07%. In the case of the Diode bridge rectifier, THD was observed to be 8.46%. In the case of the PWM rectifier, the THD can be seen as 2.07%, which is acceptable according to IEEE standards. Regulated output voltage is also obtained using a PWM rectifier.

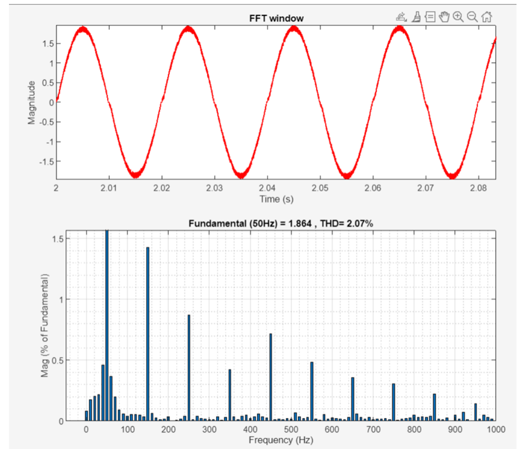

Fig. 11. FFT analysis of supply current of IH with PWM rectifier

V. HARDWARE IMPLEMENTATION

Hardware implementation of PWM rectifier followed by resonant inverter and its results are discussed in this section. The hardware model of the IH system using a diode bridge rectifier was compared with that of a PWM rectifier based on power factor and THD.

A. Hardware implementation with diode rectifier

The hardware prototype was made on a PCB using the electronic components needed to develop the induction heating power supply circuit. The hardware part comprises a power circuit and a control circuit. The power circuit consists of an implementation of a selected topology, which includes a rectifier, a resonant circuit, and an inverter circuit. The switch-control circuit consists of driver IC HCPL3120, which has an in-built opto-coupler to isolate the control circuit and power circuit. An isolation transformer at the input side is used to isolate grounds.

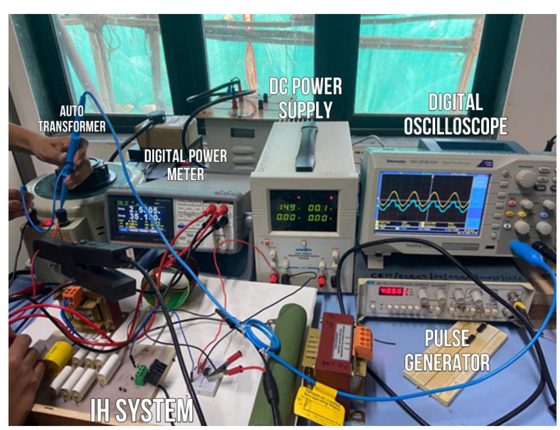

Fig. 12. Hardware setup for IH with diode bridge rectifier

Fig.12 shows the entire hardware setup. THD and power factor of the system were measured using a digital power meter, as shown in Fig.13.

Fig. 13. Power meter reading for IH using Diode Bridge Rectifier

B. Hardware implementation with PWM rectifier

Testing of the hardware was carried out by replacing the diode bridge rectifier with a PWM rectifier. In the PWM rectifier, we have used two MOSFETs along with two Gate driver circuits, which are used to amplify the pulses given to the MOSFETs. Pulses are generated, as shown in Fig.14 using logic gates.

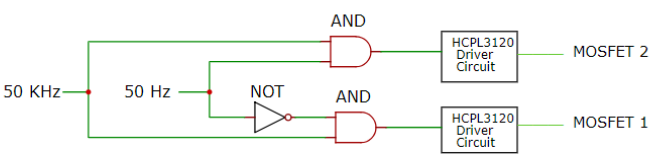

Fig. 14. To generate pulses for MOSFETs

Table II shows the list of components and parameters used in hardware implementation. Two capacitors of 4700 µF are connected in series. Fig.15 shows the hardware setup of PWM rectifier, and Fig.16 depicts the entire IH system. Design of IH components like coil, capacitor, etc. are given [9] and therefore not included in this paper.

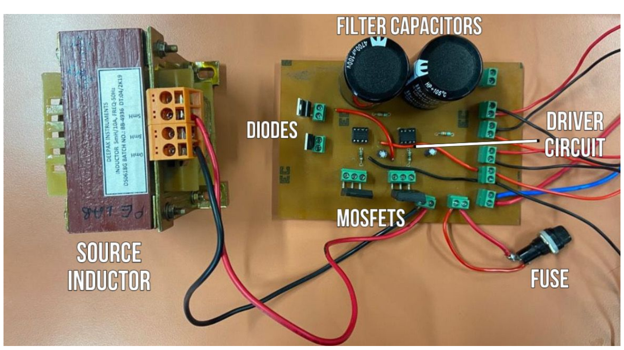

Fig. 15. Hardware setup of PWM rectifier

TABLE II
COMPONENTS USED IN IMPLEMENTATION

Sr no	Components	Specification	Quantity
1	Source inductor	5 mH	1
2	Filter capacitor	4700 µF	2
3	MOSFET	FCH47N60F	2
4	Diode	RHR15120	2
5	Fuse	6 A	1
6	Pulse gen. 1 (freq., Duty cycle)	50 Hz,50%	1
7	Pulse gen. 2 (freq., Duty cycle)	50 kHz,50%	2
8	AND gate	IC7408	1
9	NOT gate	IC7404	1
10	Gate driver	HCPL3120	3
11	Filter inductor	700 µH	1
12	DC link capacitor	3.3 µF	1
13	Working coil	119.36 µH	1
14	Resonant Capacitor	220 nF	7

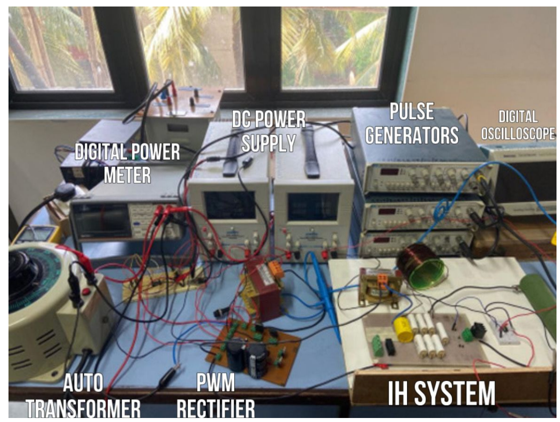

Fig. 16. Hardware setup for IH with PWM rectifier

Fig. 17. Power meter reading for IH using PWM Rectifier

Fig.17 shows THD and power factor measurement with a PWM rectifier. In the case of the diode bridge rectifier, THD was observed to be 11.86%, and the power factor was 0.74 in the prototype implemented. However, in the case of a PWM rectifier, the THD is around 5%, which is acceptable according to IEEE standards. There is also an improvement in the power factor from 0.74 to 0.95. A comparison is given in

III. The system was tested for low power levels to show the improvement in power factor and THD. The heating effect was observed on a metal piece kept inside the inductor coil. The setup can be used for shrink-fitting and other similar applications. Results of THD and power factor are compared in the hardware implementation for the same heating effect on the metal piece.

TABLE III
COMPARISON OF RECTIFIED TOPOLOGIES

Sr. No.	Topology	THD (%)	Power factor	Vs (rms)
1	Diode Rectifier	11.86	0.74	20 V
2	PWM rectifier	5.02	0.95	20 V

VI. CONCLUSION

Simulation and hardware results show that Total Harmonic Distortion (THD) is reduced by 42.32%, thereby improving the power factor when the diode rectifier is replaced by a PWM rectifier in the IH system. The power level chosen was similar to that of shrink-fitting operations in the automotive industry. However, the same system can be used for other applications as well. The implemented IH system has fewer components, including a rectifier fed from a single-phase AC source and a single switch resonant inverter that has the working coil. An aluminum rod was kept inside the working coil to check the heating effect. A comparison was observed in simulation and in prototype implementation. The IH system considered in this work is more compact and efficient as compared to conventional IH systems.

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