# Pulse Density Modulation Adopted Dc-Link Series Resonant Inverter for Induction Heating Application

K.K. Gopiganapathy, A. Mangaiyarkarasi

*Abstract---The aim of this paper is to simulate high efficiency IGBT series resonant inverters using pulse density modulation with open loop and closed loop control and simulation is done using the blocks of simulink in MATLAB. This convertor has advantages like reduced hardware and improved efficiency.*

*For this purpose, this project analyzes a high frequency (20 kHz) voltage-fed inverter with a series-resonant load circuit for industrial induction heating applications, which is characterized by a full bridge inverter, made of insulated-gate bipolar transistor and a power control based on pulse density modulation (PDM). Results will be verified experimentally using a prototype for induction heating applications. Simulation results will be compared with hardware results. This power control strategy allows the inverter to work close to the resonance frequency for all output-power levels. In this situation, zero-voltage switching and zero-current switching conditions are performed, and the switching losses are minimized. An additional improvement of inverter efficiency is achieved by choosing appropriate values of the modulation index. The comparative study will be made to proposed and conventional circuit. Here, the circuit is designed for heater with 230V,3.7 kw load.*

*Keywords---Pulse Density Modulation (PDM), Series Resonant Inverter (SRI), Zero Current Switching(ZCS), Zero Voltage Switching(ZVS).*

## I. INTRODUCTION

THE literature survey is made with papers which are kept for the reference. This idea was developed with skeleton of conclusion made from the paper which given in the reference. The survey done with statements and conclusions from the papers of references as given. The paper [1] has adopted series resonant inverter with PWM scheme of power control. While using PWM scheme control, the resonance in the circuit will be affected. In this paper, they have proposed the simple power-control scheme of the class-D inverter with CFVP for IH jar, which supplies a current to an IH coil. The paper [2] has adopted parallel resonant inverter with PWM control. In this case at high frequency, the size of inductor and

*K.K. Gopiganapathy, Department of Electrical and Electronics Engineering, Prathyusha Institute of Technology and Management. E-mail: kkgglife@gmail.com,*

*A. Mangaiyarkarasi, Department of Electrical and Electronics Engineering, Prathyusha Institute of Technology and Management, E-mail: mangaiavinashi@gmail.com*

capacitor is very large and the resonance can't be maintained. In order to overcome the disadvantage of PWM, the paper [3]-[4] had proposed frequency modulation to maintain resonance in the in the output. A fully digital switching frequency modulator has been designed. It has been used to reduce EMI in the A frequency band caused by resonant inverters used in induction heating appliances. The modulator has been described in VHDL which allows flexibility, reusability, and technology independence. The paper [5] uses phase shift modulation to attain regulation in the output but the resonance will be affected. These power control schemes may increases switching losses because it is impossible for switching devices to be always turned on and off at zero current. The paper [6] gives a clear idea about the PDM control with ZVS soft switching in the IGBT series resonant inverter and this paper gives results for DC link inverter topology.

The literature survey has been made with various reference paper regarding induction heating and the analyzes shows that PDM based control is a control only can operate closed to resonance frequency and base paper was justified that pulse density modulation technique is better technique with high efficiency. Here we can also achieve soft switching easily. then, the simulation is done for 3.7Kw system. Induction heating generators are resonant inverters in which the resonant tank is formed by a heating coil and a capacitor, in a series-resonant inverter (SRI) or in a parallel resonant 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 when a simple control circuit is used, so that the output power of such an inverter has to be controlled by adjusting the dc input voltage. A thyristor bridge rectifier having input inductors and a dc-link capacitor has been conventionally used as a variable dc-voltage power supply. This causes some problems in size and cost. 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. Therefore, 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 will only be possible if a low-loss power control scheme is found. This paper describes 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. 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. In fact, the inverter performs as a quasi- ZCS because the transistors are always turned off at almost zero current. The output-power control based on pulse density modulation (PDM) maintains this condition in a wide range of output power. The blanking time of the inverter transistors is designed to maintain zero-voltage switching (ZVS) mode .With this circuit, an important improvement of the inverter efficiency is expected at high-frequency working conditions.

In addition, this paper presents a study to determine the most appropriate values of the pulse density and the output current in order to obtain a further improvement of the inverter efficiency for high-frequency working conditions. Under these conditions and with fixed transistor losses, the total output power of the inverter will be increased, improving significantly the relative cost of the induction heating generators without reducing its reliability.

## II.    INDUCTION HEATING PRINCIPLE

Many practical work pieces in induction heating applications have a cylindrical shape and are heated by being placed inside of coils with one or more turns. The magnetic field, induced in the coil when it is fed with an alternate current, causes eddy currents in the work piece, and these give rise to the heating effect. A theoretical analysis demonstrates that most of the heat, generated by eddy currents in the work piece, is concentrated in a peripheral layer of thickness $\delta$ given by $\delta = \_(\rho/\pi\mu f)$, where $\mu$ and $\rho$ are the magnetic permeability and electrical resistivity of the work piece, respectively, and $f$ is the applied frequency (skin effect). Induction heating loads (heating coil and work piece) can be modeled by means of a series combination of its equivalent resistance $R_L$ and inductance $L_L$. These parameters depend on several variables, including the shape of the heating coil, the spacing between the work piece and coil, the work piece temperature, its electrical conductivity and magnetic permeability, and the frequency.

## III.    PULSE DENSITY MODULATION

Pulse density modulation (PDM) is the power control scheme which is implemented in this project. PDM is the technique adopted to control the resonant inverter which is used to maintain the inverter in the resonance.  PDM is defined as the modulation technique which the density of the pulse will be varied with modulation index as constant.
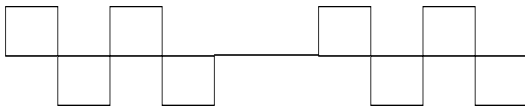


Fig 1 Pulse density modulation

## IV.    CIRCUIT DESCRIPTION AND OPERATION

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. Fig2 shows the typical system configuration of a series generator for induction heating.

The dc power supply for the inverter is a three-phase diode bridge rectifier connected to a 230-V 50-Hz power line. The working frequency is 20 kHz, the maximum RMS value of the output voltage is 230 V, and the maximum output power is 3.7 kW.

Water-cooled load is used. The output current is limited by power losses in order to ensure the inverter reliability. The values of the main components of the circuit are shown in Fig 2.

The Fig 3 shows the equivalent circuit of the voltage-fed series resonant PDM inverter and its switching modes. A conventional SRI changes between modes I and II in Fig. 3(a) and 3(b) to produce a square-wave ac voltage. In addition to modes I and II, the PDM inverter adds modes III and IV to produce a zero voltage state at its output terminals, as shown in Fig. 3(c) and 3(d). During mode III or IV, a gate turn-on signal is provided to either lower or upper leg IGBTs, respectively.



Fig.2 dc link resonant inverter

As a result, both one IGBT and the diode connected in anti parallel to the opposite IGBT remain turned on. Fig. 3 shows the principle of the PDM-based power control. $vo$ and $io$ are the output voltage and current of the inverter, respectively. The gate signals of transistor $Q1$ and $Q3$ are also represented. Signals $Q2$ and $Q4$ have been omitted since they are the complementary of $Q1$ and $Q3$, respectively.
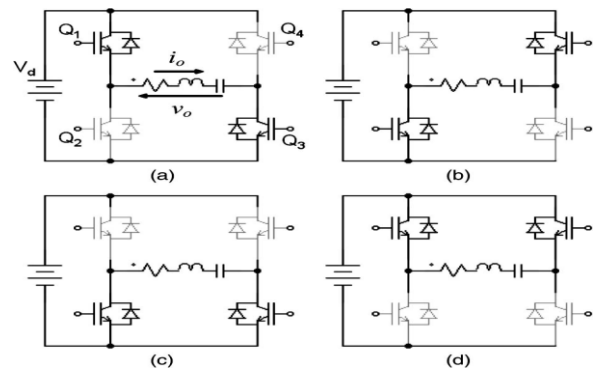


Fig.3 modes of operation

The PDM inverter repeats "run and stop" in accordance with a control sequence to adjust its rms output voltage. There are four modes of operation and they are given below The switching sequence has been summarized with the table given below irrespective of all four switches

Table .1 switching scheme of switches

| MODES OF OPERATION | GATE $Q_1$ | GATE $Q_2$ | GATE $Q_3$ | GATE $Q_4$ |
|---|---|---|---|---|
| MODE-A | 1 | 0 | 1 | 0 |
| MODE-B | 0 | 1 | 0 | 1 |
| MODE-C | 0 | 1 | 1 | 0 |
| MODE-D | 1 | 0 | 0 | 1 |

`The time constant of the envelope is $\tau$. The active output power of the series resonant PDM inverter is obtained by following the procedure explained in [14]

$$P = \frac{2}{\pi} V_d \cos\theta \frac{1}{T} \int_0^{T_{on}} i_E(t) dt \qquad (1)$$

$T$ is the period of the PDM sequence; $T_{on}$ is the time where the inverter is "running"; $P_{max} = (2/\pi)V_d I_{max} \cos\theta$, where $\theta$ is the phase shift between the output voltage and the output current; $V_d$ is the dc voltage; and $I_{max}$ is the maximum amplitude of the inverter current in the case of $T_{on} = T$. If $T \_ \tau$, the output voltage and current become discontinuous waveforms, and the output power can be written as

$$\lim_{\tau \to 0} P = P_{max} \frac{T_{on}}{\tau} \qquad (2)$$

If $T \_ \tau$ (high values of the resonant load quality factor), the envelope of the output current is $\lim_{\tau \to \infty} i_E = I_{max} (T_{on}/T)$; thus, the output power is given by

$$\lim_{\tau \to \infty} P = P_{max} \frac{T_{on}}{\tau} \qquad (3)$$

The term $T_{on}/T$ is defined as modulation index or pulse density, and its value determines the output power. One differentiating characteristic of this work consists in the fact that the maximum output power of the inverter, when working at high frequencies, is obtained for modulation index values less than one, due to a major improvement in the inverter efficiency. when the IGBT are turned off ($t_{off}$) and turned on ($t_{on}$), and $t_d$ is the blanking time when all transistors are turned off. The origin of time is set at the zero crossing of the inverter current $i_o = I \sin(\omega_o t)$. In order to prevent undesirable off switching of diodes, the turn-on of transistors must occur necessarily before the zero crossing of the inverter current. This means that the switching frequency should be larger than the resonant frequency. On the other hand, the ZVS is achieved only if the $+V_d$ (or vice versa) is achieved just before of the turn-on process. To ensure this condition, the following calculations must be done [18], [19]. When an IGBT is turned off at the time $t_{off}$, the inverter output voltage $v_o$ starts to rise up from $-V_d$, as given by the following expression:

$$v_o(t) = -v_{d} + \frac{1}{c_0} \int_{-t_{off}}^{t} i_0 . dt \qquad (4)$$

Where $C_e$ is the equivalent capacitance of the inverter (output capacitance of the IGBT, snubbing capacitors, and layout). The minimum value of the time $t_{off}$ corresponds to the time on which $v_o$ reaches the value $V_d$ just at $t = 0$. It is obtained by substituting into (4) $v_o(0) = V_d$

$$t_{off\,min} = \frac{1}{\omega_0} \cos^{\wedge}-1\left(1 - \frac{2\omega_0 C_e V_d}{I}\right) \qquad (5)$$

This time is also used to define the minimum value of the blanking time $t_d$. A working frequency of 150 kHz, a maximum amplitude of inverter current of 300 A, and a dc-link voltage of $V_d = 520$ V are assumed in the design of the experimental system. The total equivalent capacitance of the inverter switches, including the snubbing capacitor and the output capacitance of the IGBT, is approximately 20 nF. Since the $t_{off}$ min obtained from (5) is 385 ns, $t_{off}$ is set up as 550 ns for the experimental system. The blanking time $t_d$ is set as 400 ns. A phase-locked loop (PLL)-based switching frequency control discussed in the following section makes the PDM inverter achieve ZVS condition.

The proposed circuit is done with closed loop implementation of the existing circuit with a PI controller. Here, the actual value is compare with the reference value and then error is generated by the comparator. The error signal is controlled by PI controller. The control signal from the controller will control the controlled rectifier. The actual value which we are comparing is dc output value
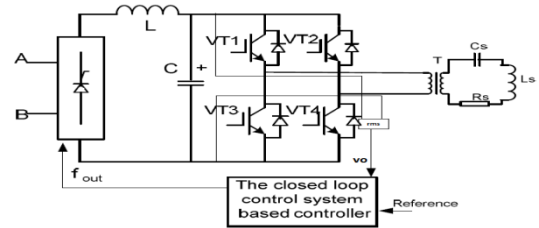


Fig 4 Proposed Circuit With Closed Loop

V. DESIGN CALCULATION

The design calculation has been made with some of the assumption as per the application in the project. The simulation developed with this assumption as followed below,

Resonant frequency, $F_r$=20 kHz

Q-Factor of inverter, Q=1.3

Power, P=3.7 kW

Supply, V=230v

Load resistance, R=2.6Ω

From the value of resonance frequency $F_r$, quality factor $Q$ and load resistance $R$, we can determine the value of resonance capacitor $C_r$, resonance inductor $L_r$ and time period $T_r$

$$Q = (\omega Lr)/R$$
$$Lr = (RQ)/\omega.$$
$$\omega = 2\pi Fr$$

Substituting the value for above equation. We get,$L_r$=29μH

From the value of resonance frequency $F_r$ and resonance inductor $L_r$, we can find the find value of resonance capacitor $C_r$.

$$Fr = (2\pi \sqrt{LrCr}) - 1$$

Therefore the value of $C_r$=2.2μF. Then with the value of $F_r$, we can determine the value switching time period of each switches in the invertor as followed below,
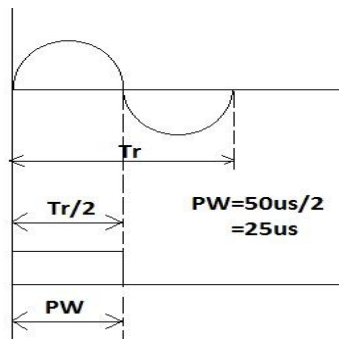
$$T_r = 1/F_r = 1/20khz = 50\mu s$$



Fig. 6 pulse width of inverter switch

## VI.    SIMULATION RESULTS

The circuits of both existing and proposed system are simulate using MATLAB-SIMULINK. Here, the SIMULINK model is created and the simulation will carried out.

The circuit of IGBT series-resonant inverters using pulse density modulation is shown in figure.2. This AC supply is converted into DC then it give as input to the inverter. Then it is boosted by using a high frequency transformer then this boosted ac voltage is passed through RLC load. The simulink model for closed loop is shown figure given below. The results achieved in with closed loop with controlled output are shown below in the figure
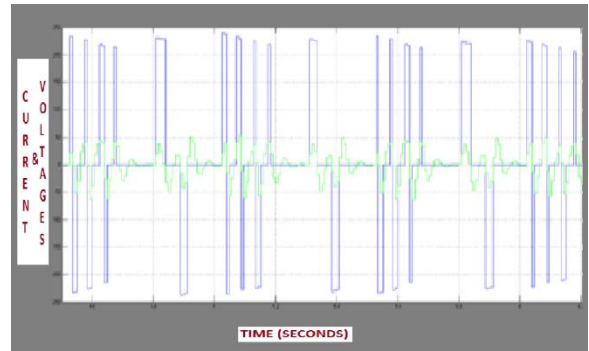


Fig.7 current and voltage waveform in open loop

The current and voltage waveform of achieved by closed loop implemented with disturbance and controlled output is shown in fig.8&9
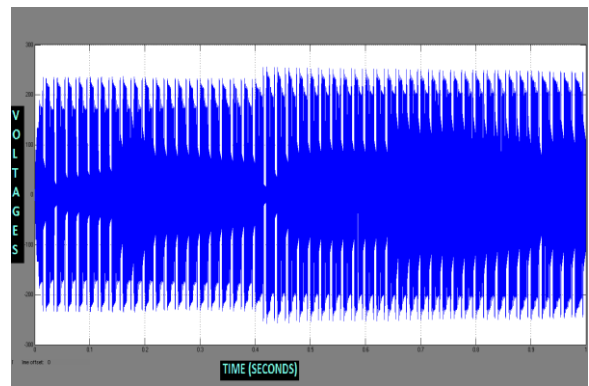


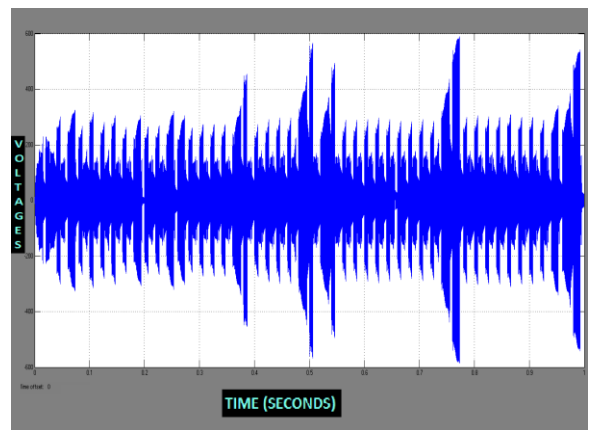Fig.8 current and voltage waveform in open loop with disturbance for 230V input



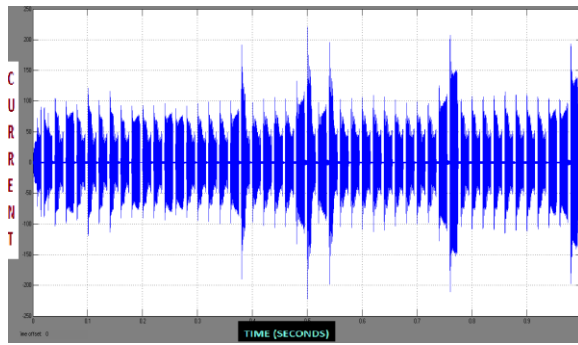Fig.9 voltage waveform in closed loop for 230V input

Fig.10 current waveform in closed loop for 230V input

Here, the output of closed loop is with harmonics disturbance and this can be permitted. Because, it is used for induction heating application. The stability and control is study with value of the waveform which is shown in fig.11.
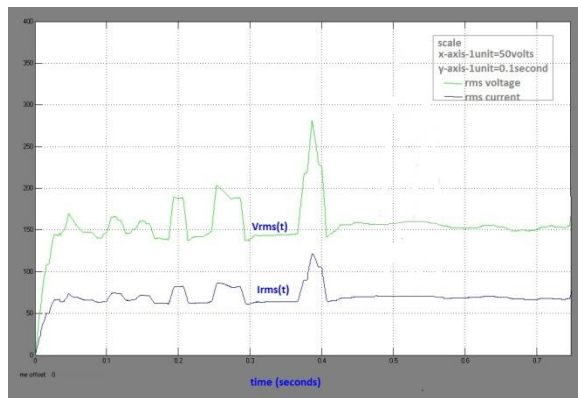


Fig.11 RMS value of current and voltage waveform in closed loop

## VII.    CONCLUSION

The DC link full-bridge resonant inverter used for induction heating is simulated using MATLAB SIMLINK. The conventional and proposed circuits are simulated. The proposed circuit is implemented with close loop using PI controller. The SIMULINK model is tested with resistive load in MATLAB and waveforms are presented.

The scope of this paper is to simulate and implement other high efficient controller for close loop system. Hence, the closed loop system is implemented in simulation. Zero voltage switching is achieved by the converter. Here this inverter will not affect the resonance condition due PDM technique.

The simulation are done for both conventional circuit and proposed circuit with SIMULINK model and the results are compared with each other. The closed loop of the proposed circuit is tested by applying some disturbance and the results are compared.

The results can be further improved by implementing higher level controller and the disturbance can be reduce further.

### REFERENCES

[1]  N.-J. Park, D.-Y. Lee and D.-S. Hyun, "A power-control scheme with constant switching frequency in class-D inverter for induction-heating jar application," *IEEE Trans. Ind. Electron.*, vol. 54, no. 3, pp. 1252–1260, Jun. 2007.

[2]  A. Shenkman, B. Axelrod, and V. Chudnovsky, "Assuring continuous input current using a smoothing reactor in a thyristor frequency converter for induction metal melting and heating applications," *IEEE Trans. Ind. Electron.*, vol. 48, no. 6, pp. 1290–1292, Dec. 2001.

[3]  K. B. Zhao, P. C. Sen, and G. Premchandran, "A thyristor inverter for medium-frequency induction heating," *IEEE Trans. Ind. Electron.*, vol. IE-31, no. 1, pp. 34–36, Feb. 1984.

[4]  L. A. Barragán, D. Navarro, J. Acero, I. Urriza, and J. M. Burdío, "FPGA implementation of a switching frequency modulation circuit for EMI reduction in resonant inverters for induction heating appliances," *IEEE Trans. Ind. Electron.*, vol. 55, no. 1, pp. 11–20, Jan. 2008.

[5]  S. Mollov, M. Theodoridis, and A. Forsyth, "High frequency voltagefed inverter with phase-shift control for induction heating," in *Proc. Inst. Elect. Eng.—Electr. Power Appl.*, Jan. 2004, vol. 151, no. 1, pp. 12–18.

[6]  V. Esteve, J. Jordan, E. J. Dede, C. Cases, J. M. Magraner, E. Sanchis-Kilders, and E. Maset, "Using pulse density modulation to improve the efficiency of IGBT inverters in induction heating applications," in *Proc. IEEE 38th PESC*, Jun. 2007, pp. 1370–1373.

[7]  V. Esteve, J. Jordán, E. J. Dede, E. Sanchis-Kilders, and E. Maset, "High energy efficiency test system for induction heating generators," in *Proc. ICREPQ*, Apr. 2006, pp. 105–106.