

Study of PDM for Enhancing Performance of IGBT Series-Resonant Inverter

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Abstract - The research aims to provide a thorough understanding of a cutting-edge high-power, high-frequency voltage-fed inverter for the demands of industrial induction heating. The configuration used is full bridge inverter design, by using insulated-gate bipolar transistors (IGBTs), ensuring toughness and efficiency in operation. The inverter stands apart by power control logic, the inverter operates pulse density modulation (PDM). Unlike conventional methods, PDM ensures that the inverter operates very closely to its resonance frequency across all power levels. This approach helps the inverter work efficiently at the right frequency for different power levels. It also makes sure that switching happens smoothly without wasting energy. Zero-voltage and zero-current mean that when the inverter switches on or off, there's no voltage or current flowing. This helps reduce energy loss during switching.

Keywords: Induction Heating (IH), zero-current switching, zero-voltage switching, pulse density modulation control (PDM).

I. Introduction

The principle of induction heating was discovered by Michael Faraday in 1831. In an experiment with two coils wired around an iron core, he discovered that during the switching event of a battery connected to the first coil an opposite current flow could be measured with a galvanometer on the second coil as shown in Fig. 1 reference. He concluded that an electric current could be produced by a changing magnetic field. Faraday's Law was followed by discoveries such as Lenz's Law. This law explains that inductive current flows inverse to the direction of changes in induction magnetic movement. Different applications use resonant inverters as induction heating systems for industrial processes or home appliances, electronic ballasts for lighting, dc-dc resonant converters, and others. [2] Increasing the switching frequencies in an inverter improves the power density and the circuit performance, and makes harmonic filtering easier; the audible noise can be reduced, which is a very desirable enhancement in induction heating systems for home appliances, for instance. However, higher switching

frequencies are limited by the switching stresses on the power devices, switching losses and electromagnetic interference (EMI).[2]

Resonant dc-ac inverters are used in a number of applications to convert dc energy into ac energy [4]. Some examples include dc-dc resonant converters, induction heating systems for industrial processes or home appliances, electronic ballasts for lighting, radio transmitters, and others. The output voltage or power in many resonant inverters has been traditionally controlled by varying the switching frequency. This variable-frequency operation has several disadvantages [4] including a wide noise spectrum which makes it difficult to control electromagnetic interference (EMI), more complex filtering of the output voltage ripple, and poor utilization of magnetic components. In addition, zero-voltage-switching (ZVS) operation is normally preferred in most applications, and conventional resonant converters operate with zero voltage for the active devices when the switching frequency is above the resonant frequency [4]. High above-resonance operation imposes a low power factor loading of the inverter, resulting in large circulating currents which reduce efficiency.

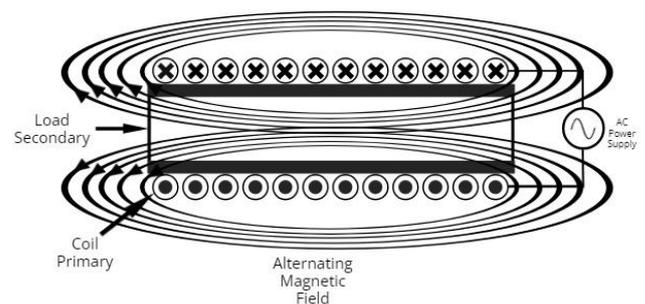


Figure 1: Concept of Induction Heating

II. Induction Heating Principle

The core theory of induction heating (IH) parallels that of a transformer. It's all about using electromagnetic forces and understanding something called the skin effect. Basic system, consisting of inductive heating coils and current, to explain electromagnetic induction and the skin effect. In its simplest form, a transformer operates with a direct relationship between the primary and secondary currents based on their turn ratio.

Losses in both primary and secondary coils occur due to their resistance, and the coupling between the two circuits is considered perfect, with no magnetic leakage. In induction heating applications, many practical work pieces possess cylindrical shapes and are heated by placement within coils featuring one or more turns. When the coil is supplied with alternating current, it induces a magnetic field, generating eddy currents within the workpiece, thereby producing the heating effect. Fig. 1 illustrates a basic system, consisting of inductive heating coils and current, to explain electromagnetic induction.

When the coil of the secondary is turned only once and short-circuited, there is a substantial heat loss due to the increased load current. In the concept of induction heating, the energy provided matches the total loss in both the primary and secondary systems. The primary coil has multiple turns while the secondary coil has only one turn and is short-circuited. They're separated by a small gap, and the skin effect at high frequencies. Induction heating aims to maximize heat in the secondary, so the coil's opening is kept small, and the secondary is made of a material with low resistance and high permeability. Nonferrous (non magnetic) metals are less efficient because they have high resistance and low permeability. The principle of electromagnetic induction, as formulated by Faraday's law of electromagnetic induction and Lenz's law, establishes the relationship between changing magnetic flux and induced electromotive force (emf) in a conductor. Mathematically, Faraday's law can be expressed as:

$$\mathcal{E} = -\frac{d\Phi}{dt} \quad (1)$$

Where \mathcal{E} is the induced emf and Φ is the magnetic flux.

III. Power Topology for Induction Heating

There are various power topologies of induction heating. Here Series Resonant Full-bridge converter topology is discussed. Fig. 2 displays a common setup for a series Resonant Full-bridge inverter used in induction heating. The power output stage includes a single-phase voltage-source inverter employing four IGBTs. The inverter's output connects to a series resonant circuit with a matching transformer. To maintain the inverter's reliability, the output current is restricted to manage power losses. This converter is a type of power electronics converter used for high frequency power conversion applications. It consists of a full-bridge configuration of power switches (usually MOSFETs or IGBTs) on the primary side, and a resonant tank circuit on the secondary side. The resonant tank typically comprises an inductor and a capacitor connected in series. Unlike conventional converters, which operate in either continuous or

discontinuous modes, this operates in a resonant mode. This means that the switching of the power devices is synchronized with the resonant frequency of the tank circuit.

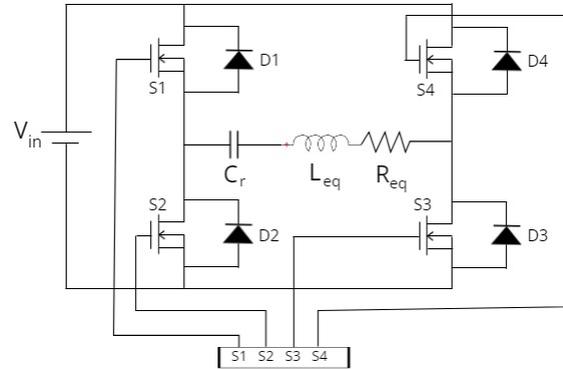


Figure 2: Series Resonant Full Bridge Inverter

IV. Operating phases of a Series Resonant Full-bridge converter

Fig. 3 shows the operation of Series Resonant Full-bridge inverter also paths for current flow can be seen for ever operation. The concept like switching of devices will be cleared. The waveform of the topology is shown in Fig. 4.

Operating phases of a Series Resonant Full bridge converter during a switching cycle:

- Phase I: MOSFETs S1 and S3 are triggered with high frequency square pulses. The current follows the direction as indicated in the as S1-C-LR-Vi-S3. During this operation Vdc will appear across the load. At the end of this phase S1 will be turned OFF.
- Phase II: Phase begins when switching transition from S1 to body diode (D2) of S2. The load current will not change instantaneously in the inductive load applications. The direction of load current from C-L-R-S3-D2. During this operation zero voltage appears across the load. This phase ends when current in the load comes to zero.
- Phase III: Phase starts similarly Phase I. In this phase S2 and S4 will triggered. The current follows the direction as changed and also voltage across load circuit became Vdc. The direction of load current from S2-R-L-C-Vi-S4. During this operation Vdc voltage appears across the load. This phase ends with turned OFF of S2.
- Phase IV: Phase begins when switching transition from S4 to body diode (D2) of S3. The load current will not change instantaneously in the inductive load applications. The direction of load current from D3-R-L-C-S2. During this operation zero voltage appears across

the load. This phase ends when current in the load comes to zero.

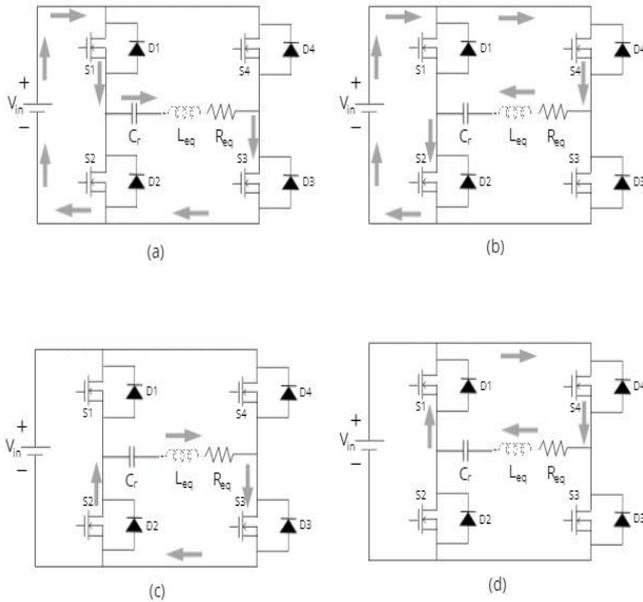


Figure 3: Operating States (modes) of Series Resonant Full Bridge Inverter

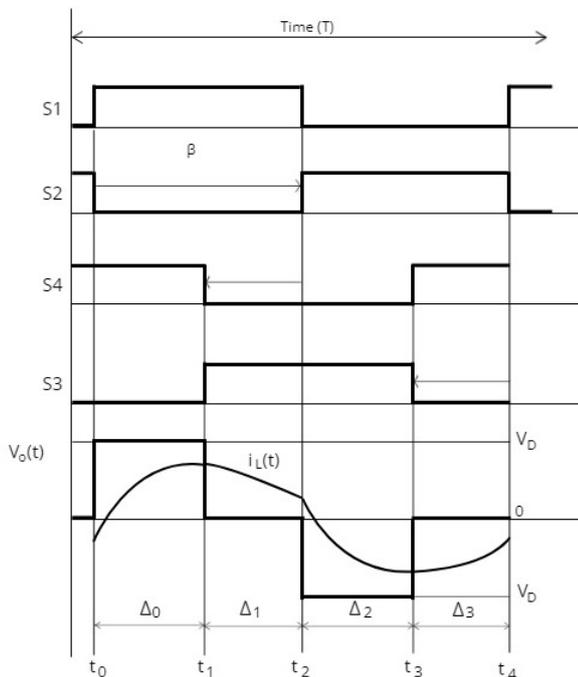


Figure 4: Waveform Operating States of Series Resonant Full Bridge Inverter

$$\delta = \sqrt{\frac{\rho}{\pi \cdot f_s \cdot \mu_o \cdot \mu_r}} \quad (2)$$

Where,

δ = Skin depth

ρ = resistivity of the material (ohm-m)

f_s = switching frequency of in Hz

$\mu_o = 4 \pi * e-7$ H/m

μ_r = relative permeability

For a current of I through a load resistance (R_l) the heat developed is $I^2 * R_l$. The frequency (f_0) of induced currents is determined by the inductance of the coil (L_r) and resonant capacitor (C_r). It is given by the equation.

$$f_0 = \frac{1}{2 * \pi * \sqrt{L_r * C_r}} \quad (3)$$

Operating losses in this topology:

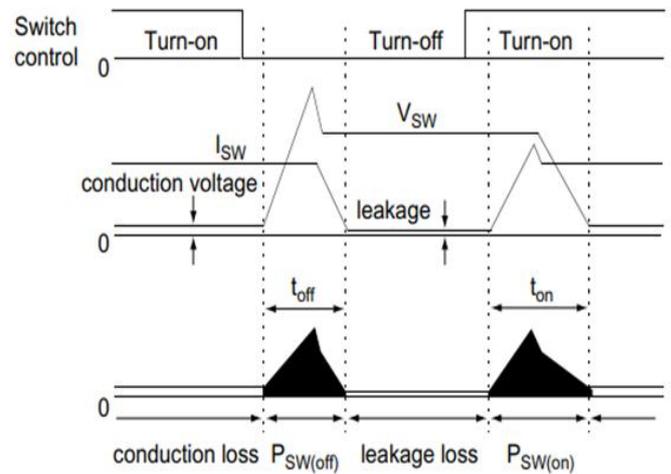


Figure 5: Power Losses in Series Resonant Full Bridge Inverter While Operating

V. Introduction to Switching Scheme of PDM

As shows in Fig. 2 the equivalent circuit of the voltage-fed series-resonant PDM inverter operates in different switching modes to generate a square-wave AC voltage. In conventional SRIs, modes I and II are used, while the PDM inverter adds modes III and IV to achieve a zero-voltage state at the output terminals.[1]

In modes I and II shown in Fig. 3 (a) and (b), the SRI produces a square-wave AC voltage by switching between these modes. However, the PDM inverter introduces modes III and IV shown in Fig.3. (c) and (d), where a gate turn-on signal is provided to either the lower or upper leg IGBTs. This result in one IGBT and the diode connected in antiparallel to the opposite IGBT remaining turned on. The PDM based power control principle is illustrated in Fig.6. It shows the output voltage (V_o), output current (I_o), and gate signals for transistors S1 and S3. The complementary signals for S2 and S4 are not shown. The PDM inverter adjusts its RMS output voltage by repeating a "run and stop" control sequence.

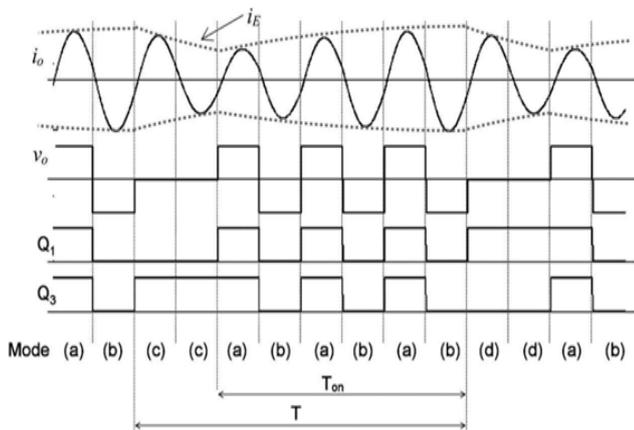


Figure 6: Switching pattern in PDM

By simplifying the information provided, we can summarize the key points as follows:

- The voltage-fed series-resonant PDM inverter has different switching modes: I, II, III, and IV.
- Modes I and II produce a square-wave AC voltage, while modes III and IV achieve a zero voltage state.
- In modes III and IV, a gate turn-on signal is provided to specific IGBTs, keeping them turned on.
- The PDM-based power control adjusts the RMS output voltage through a "run and stop" control sequence.

Shown in Fig. 5 how losses occurs in system, considering that the inverter power losses depends on the frequency, and the proportional relationship between the equivalent switching frequency of the PDM inverter and the pulse density, it becomes crucial to analyze the efficiency of the PDM inverter across various pulse density values. Given our primary focus on reliability as a design parameter, we conduct tests while maintaining consistent IGBT module power losses for each measurement.

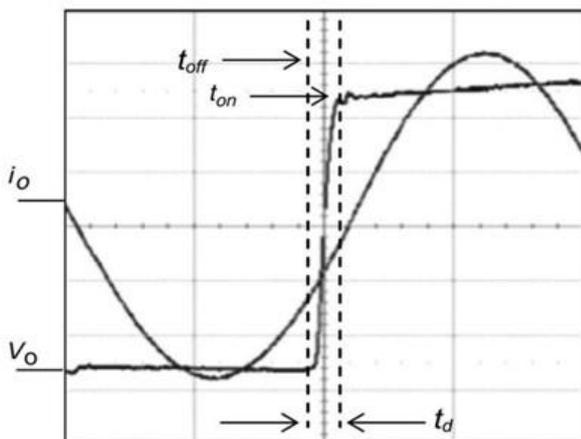


Figure 7: Waveforms of the inverter in the switching process

ZVS

Provides a detailed depiction of the voltage and current profiles at the output of the inverter during mode I or II operation. The vertical dashed lines denote the moments when the IGBTs are turned off (toff) and turned on (ton), while t_d represents the blanking time during which all transistors are switched off.

Under these test conditions, wherein the transformer ratio of the matching transformer T1 is adjusted and the pulse density is varied, we observe varying operational scenarios to achieve maximum output power.

VI. Conclusion

This study introduces a voltage-source series resonant PDM inverter designed specifically for industrial applications in induction heating. The power control strategy employed enables the inverter to operate in close proximity to the resonance frequency across all levels of output power. This approach facilitates Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) conditions, effectively minimizing switching losses. Consequently, IGBT transistors can be utilized for the power stage design, optimizing overall performance.

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Citation of this Article:

Shubham Tapase, Prof. A. P. Kinge, Prof. Dr. S. G. Kanade, "Study of PDM for Enhancing Performance of IGBT Series-Resonant Inverter", Published in *International Research Journal of Innovations in Engineering and Technology - IRJIET*, Volume 8, Issue 3, pp 362-366, March 2024. Article DOI <https://doi.org/10.47001/IRJIET/2024.803056>
