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Design and Analysis of a Three-Phase Inverter-Driven Induction Motor with PWM Control in MATLAB

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Abstract

This study focuses on the development and simulation of a three-phase induction motor drive system powered by a Pulse Width Modulated (PWM) inverter, using MATLAB as the modeling platform. Induction motors are commonly employed across various industrial sectors due to their durability, cost-effectiveness, and low maintenance. However, efficient control of motor speed and torque is vital for optimizing performance and energy usage. To address this, a voltage source inverter (VSI) is modeled and controlled through sinusoidal PWM techniques, enabling flexible and precise motor control by varying supply voltage and frequency. The switching signals for the inverter are generated by comparing a reference sine wave with a high-frequency triangular waveform, ensuring smooth voltage transitions and reduced harmonics. The induction motor is simulated using the d-q axis transformation method, allowing for detailed analysis of dynamic characteristics. Simulation results confirm that PWM control significantly improves the system's efficiency, stability, and responsiveness under different operational conditions. The proposed model demonstrates how inverter-based control can enhance the overall performance of induction motor drives in practical applications.

Keywords: Induction Motor, Three-Phase Inverter, PWM Control, MATLAB, Electric Drives, Voltage Source Inverter

1. Literature Review

The advancement of inverter-fed induction motor drives has been a focal point of research in modern electric drives due to their flexibility, high performance, and wide applicability in industrial systems. Traditional control techniques, such as the scalar (V/f) control method, are simple to implement but fail to provide precise dynamic performance in terms of speed and torque control. These methods are limited in their ability to handle transient states and rapid changes in load conditions, often leading to inefficient operation and performance degradation [1].

In contrast, the introduction of vector control (also known as field-oriented control, FOC) and Pulse Width Modulation (PWM) has led to significant improvements in induction motor drive systems. Vector control decouples the motor’s magnetic flux and torque, enabling more accurate control over motor speed and torque. This approach allows for high-performance drive systems with improved efficiency and dynamic response. Similarly, PWM techniques have been found to effectively control the inverter's output voltage and frequency, thereby minimizing harmonic distortion and improving the quality of the motor's input signals. The use of PWM also enhances the efficiency of the system by controlling the power delivered to the motor based on load requirements, reducing power losses during operation [2].

Another significant development in this field is the use of simulation platforms like MATLAB/Simulink, which provide an efficient and accurate environment for modeling electric motor drives. MATLAB/Simulink allows for the rapid design and testing of complex systems, including the simulation of motor dynamics, control strategies, and the performance of various inverter types. Researchers have demonstrated the advantages of MATLAB/Simulink in developing models of induction motors controlled by PWM inverters, highlighting the flexibility and effectiveness of these tools in the design and analysis of power electronic systems [3].

2. System Description

The overall system consists of three major components: a **three-phase voltage source inverter (VSI)**, a **squirrel cage induction motor**, and a **PWM-based control mechanism**. These components work together to form an efficient and reliable motor drive system capable of variable-speed operation.

2.1 Induction Motor

The induction motor used in this study is a **three-phase squirrel cage type**, widely adopted in industrial applications due to its simple construction, robustness, and low cost. It operates on the principle of electromagnetic induction, where a rotating magnetic field in the stator induces current in the rotor, producing torque.

In the MATLAB/Simulink environment, the motor is modeled using the standard **'Asynchronous Machine'** block. The key parameters defined for the motor include:

- Rated Voltage: 400 V (Line-to-Line)
- Rated Power: 3.7 kW
- Rated Frequency: 50 Hz
- Number of Poles: 4
- Stator Resistance and Inductance
- Rotor Resistance and Inductance

These parameters influence the dynamic behavior of the motor during operation.

2.2 Three-Phase Voltage Source Inverter (VSI)

The inverter is responsible for converting the constant DC supply into a variable-frequency, variable-amplitude AC output that drives the induction motor. It consists of six **Insulated Gate Bipolar Transistors (IGBTs)** arranged in a typical three-phase bridge configuration.

The inverter operates by sequentially switching the IGBTs to produce a three-phase output voltage waveform. The magnitude and frequency of the output voltage are controlled using PWM techniques, which determine the motor's speed and torque.

2.3 PWM Control Strategy

A **Sinusoidal Pulse Width Modulation (SPWM)** technique is employed in this model. SPWM is a widely used control strategy in industrial drives due to its simplicity and ability to generate smooth output voltages.

The PWM signal is generated by comparing a sinusoidal reference signal (representing the desired output voltage) with a high-frequency triangular carrier wave. The points of intersection determine the gating signals for the inverter switches. The frequency of the sinusoidal reference determines the output frequency, and the amplitude controls the output voltage.

2.4 Speed Control Loop

To regulate the motor's speed, a closed-loop control system is implemented using a **Proportional-Integral (PI) controller**. The actual motor speed is continuously compared to a reference speed. The error signal is processed by the PI controller, which adjusts the modulation index of the PWM generator to achieve the desired speed.

3. Methodology

The proposed work is carried out through a structured simulation approach using MATLAB/Simulink. The goal is to replicate the behavior of a three-phase inverter-fed induction motor controlled via PWM. The methodology involves developing an accurate model of each system component, implementing a control strategy, and evaluating the performance under different conditions. The major steps are outlined as follows:

3.1 System Modeling

The simulation model consists of four main sections:

- **DC Power Supply:** This provides a fixed voltage source to the inverter. It represents the input from a rectified AC supply or a DC battery system.
- **PWM-Based Inverter:** A three-phase voltage source inverter is modeled using power electronic switches (IGBTs). The inverter converts the DC voltage into a controlled three-phase AC supply with variable frequency and amplitude.
- **Induction Motor Model:** A squirrel cage induction motor is simulated using predefined blocks available in Simulink's Simscape Electrical library. Motor parameters such as power rating, frequency, voltage, and resistance values are set according to standard industrial ratings.
- **Control Subsystem:** A PWM control scheme is implemented to generate gating pulses for the inverter switches. This control loop adjusts the output frequency and voltage, regulating the motor's speed and torque.

3.2 PWM Generation

The inverter switching is controlled using a **Sinusoidal Pulse Width Modulation (SPWM)** technique. The method involves:

- Generating a sinusoidal reference signal representing the desired AC output.
- Producing a high-frequency triangular carrier signal.
- Comparing the two waveforms to produce switching signals.

The intersections between the reference and carrier signals determine when each switch turns on and off, effectively shaping the AC output waveform.

3.3 Speed Control Strategy

To maintain a constant or variable speed operation, a **Proportional-Integral (PI) controller** is used. This controller monitors the actual motor speed and compares it with the desired speed setpoint. The difference (error) is processed to update the modulation index of the PWM generator. This feedback mechanism ensures that the motor operates efficiently and stably across different load conditions.

3.4 Simulation Setup

Key simulation configurations include:

- **Simulation Time:** Typically set between 1 and 5 seconds to observe both transient and steady-state behavior.
- **Time Step:** A small fixed time step is used to capture high-frequency switching details.
- **Output Monitoring:** Speed, torque, current, and voltage waveforms are recorded using scope and display blocks.

3.5 Performance Analysis

After the simulation runs, the output data is analyzed to evaluate the system’s performance. The response of the motor to changes in speed demand and load conditions is observed. Smooth current waveforms, consistent speed tracking, and stable torque response indicate effective control and reliable system behavior.

4. SIMULATION MODEL WITH DIFFERENT PULSES

Motive is to analyses the performance of inverter by giving above pulses to the 3-phase inverter. For this, it is required to develop three Simulink models for respective PWM techniques for the purpose of comparison of their output line voltages or current quality. Quality means what % of harmonic of its fundamental is present in line voltage or current which is provided to the stator to the motor. Hence % THD (total harmonics distortion) determines which output voltage is more close to sine wave.

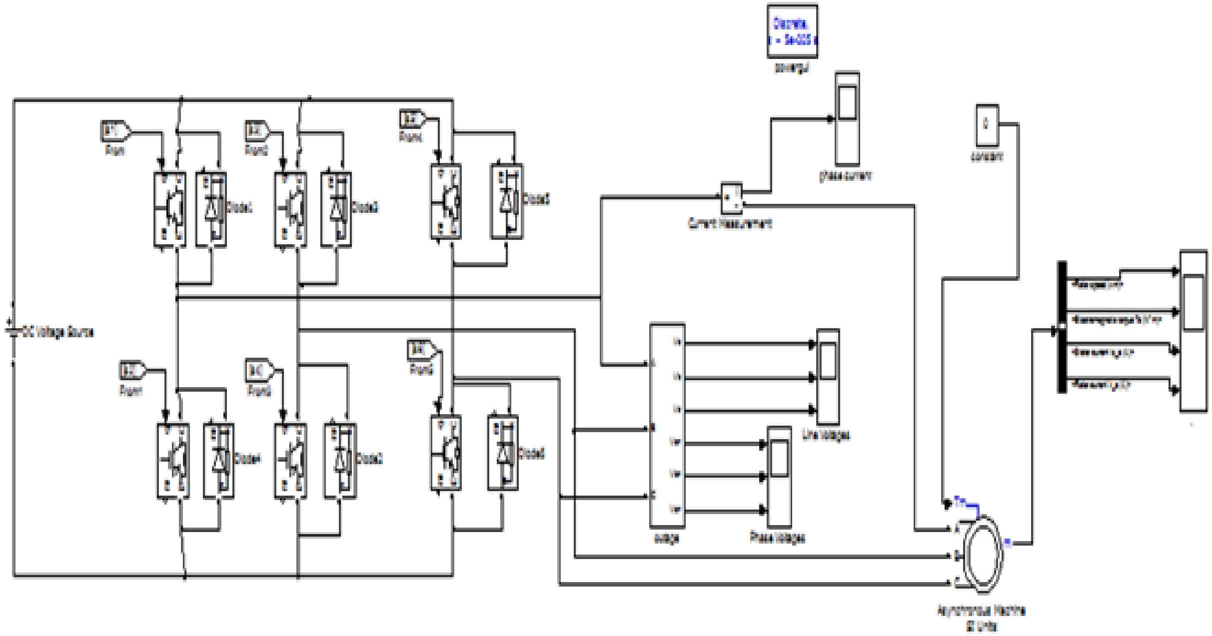


Figure : MATLAB Simulation model for three phase PWM VSI fed IM

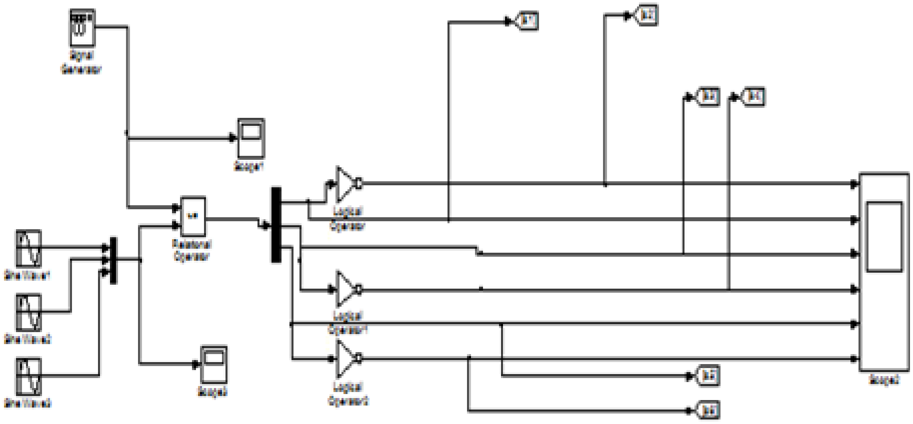


Figure: MATLAB Simulation model internal part for three phase PWM VSI fed IM

5. SIMULATION RESULT FOR SINUSOIDAL INPUT SIGNAL

Results are obtained by simulating the circuit. Here we analyze the inverter and motor performance for under modulation range i.e. for the value of $m_a < 1$. Amplitude Modulation index is defined as the ratio of control signal amplitude and carrier signal amplitude i.e. $m_a = A_r/A_c$. The number of pulses per half cycle depends upon the value of the frequency modulation index mf defined by the relation $m_f = f_c/(2f)$

Where

f_c= frequency of the carrier signal and

f= frequency of the modulating signal

First of all the inverter is operated in the under modulation range i.e. the value of m_a =0.7 is maintained

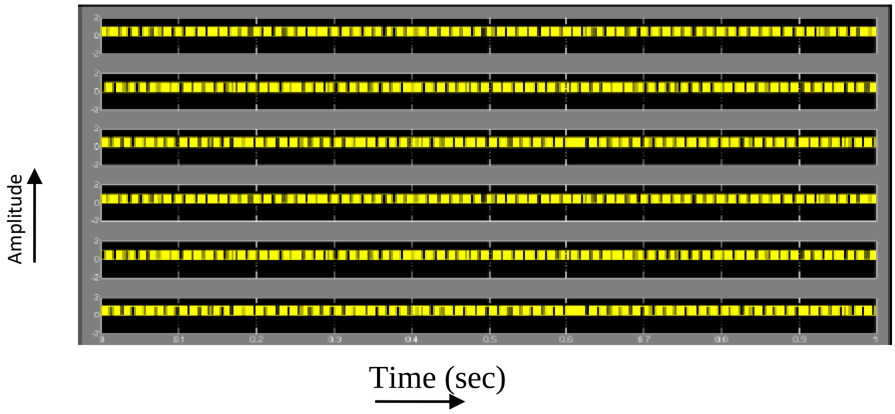


Figure: Generation of firing pulses supplied to the IGBT of the three phase Inverter for m_a=0.7

The figure 5.4 shows the six pulses generated as the output of the firing circuit. The generated pulses are applied to the gate circuit of the six IGBTs which in turn produce the balanced pulse width modulated three phase output voltages.

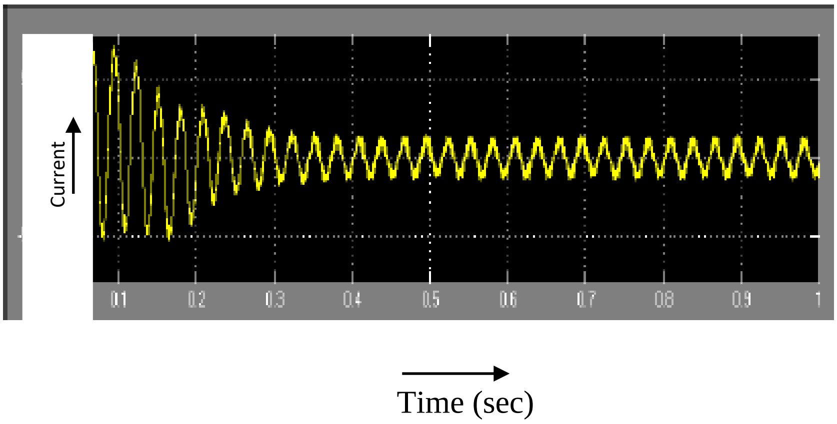


Figure: Phase Current waveform for m_a=0.7

Figure 5.5 shows the waveform for the phase current. Form the waveform it is clear that the part of the wave form present before the time 0.33 sec is the transient part and after that it acquires it steady state value of x amperes.

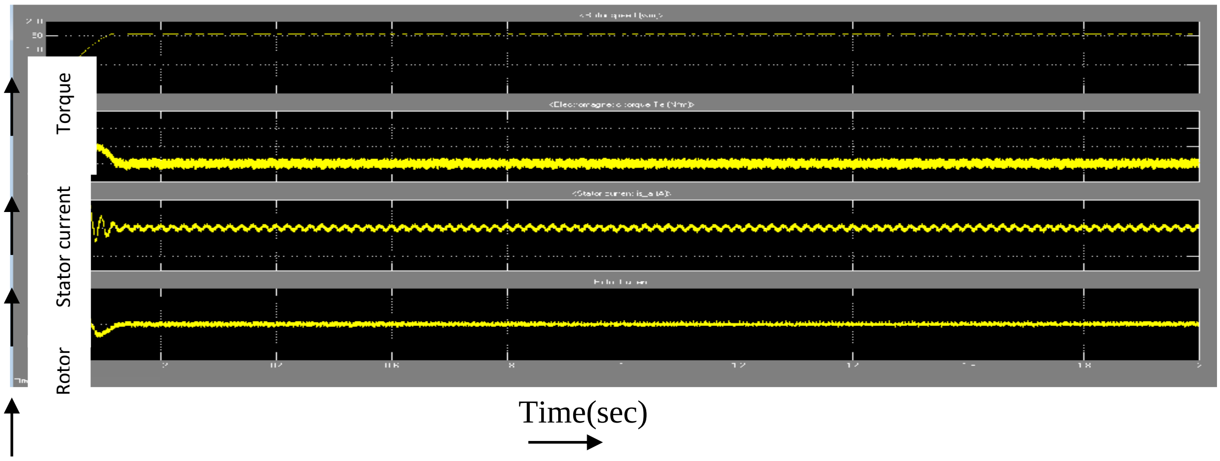
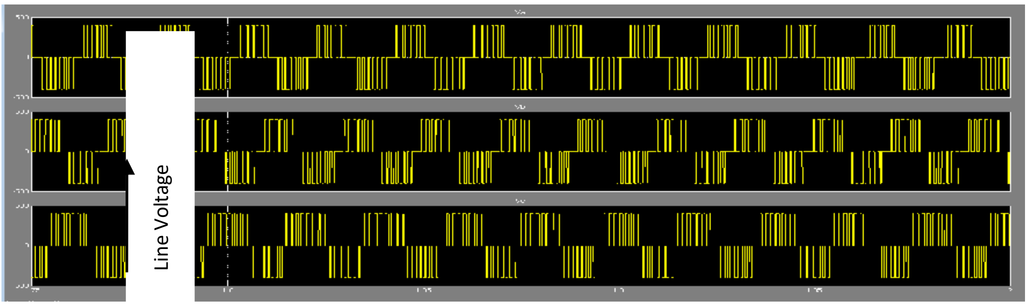


Figure: Rotor rpm, torque, stator current and rotor current

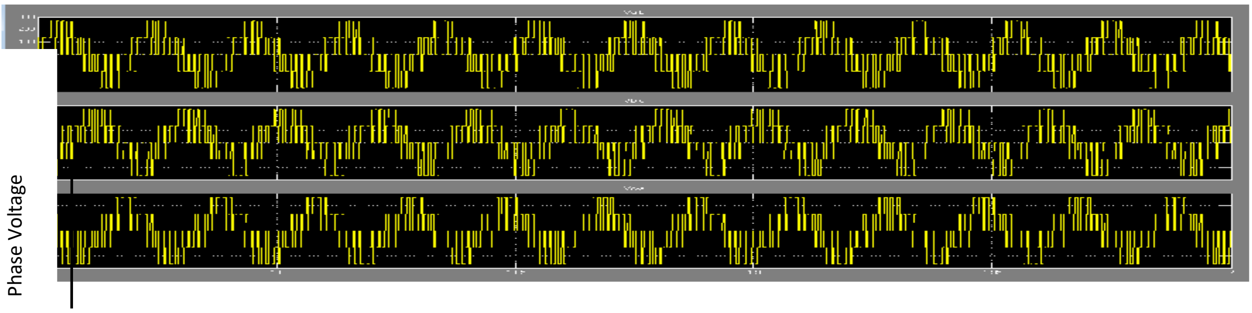
The variation of rotor and stator current i.e. I_r and I_s of phase of motor with respect to time is shown in fig 5.6 the rotor current has transient time of 0.3 Sec and stator current has 0.35 Sec.



Time (sec)

Figure: Line Voltage

Figure 5.7 shows the waveform of line voltage V_{ab}. Similar waveforms can be obtained for the other line voltages V_{bc} and V_{ca}. Form the waveform it is clear that the output waveform is pulse width modulated wave and the frequency of the output voltage wave is 50 Hz and its amplitude is 220V for the value of the dc input voltage of 400V.



Time (sec)

Figure: Phase Voltage

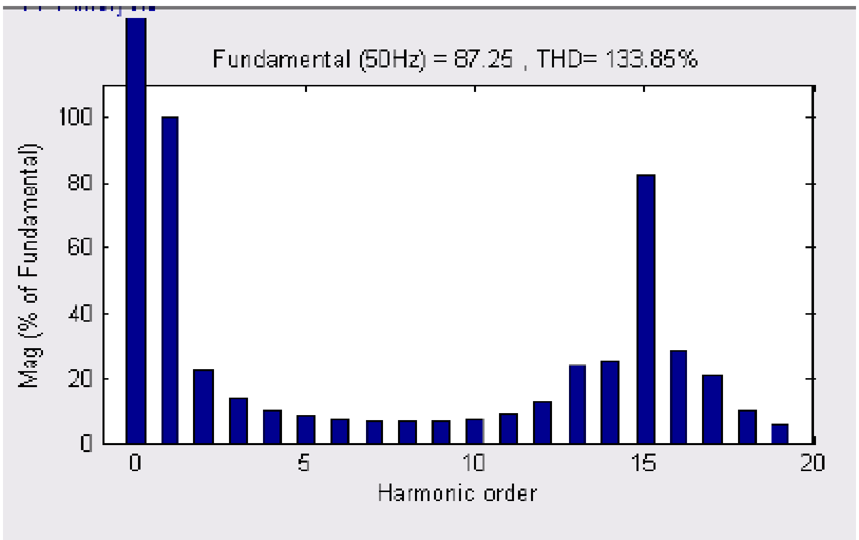


Figure: THD in phase voltage for m_a=0.7

6. Conclusion

This research successfully demonstrates the modeling and simulation of a three-phase induction motor controlled by a PWM-based inverter using MATLAB/Simulink. By integrating a sinusoidal PWM control strategy with a voltage source inverter, the system effectively regulates the speed and torque of the motor under various operating conditions. The simulation results confirm that the PWM-controlled inverter produces smooth and reliable output waveforms, allowing the motor to operate efficiently and respond quickly to changes in load and reference speed.

The study also highlights the benefits of using MATLAB as a simulation tool for electric drive systems, offering an intuitive environment for testing control strategies before physical implementation. The developed model can serve as a foundation for further enhancements, such as implementing advanced PWM techniques like space vector PWM or exploring sensorless control methods.

Overall, this work validates the effectiveness of PWM control in induction motor drives and provides a valuable reference for students, researchers, and engineers working in the field of electric machine control and industrial automation.

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