International Journal for Innovative Engineering and Management Research
PEER REVIEWED OPEN ACCESS INTERNATIONAL JOURNAL
www.ijiemr.org

FPGA Controlled Induction Motor Drive Using Space Vector Pulse Width Modulation

P.Radhik Sanju[1], S..Mohammed Abdulla[2], G.Varshitha[3], V..Kalyani[4]
[1,2,3,4] B.Tech student, EEE Department, G.Pulla Reddy Engineering college (A), Kurnool-518007

Abstract— Field Programmable Gate Arrays (FPGAs) have emerged as a powerful hardware platform for implementing high-speed digital controllers in power electronic applications. Their inherent parallel processing capability, deterministic execution, and reconfigurable architecture make them well suited for induction motor drive systems requiring precise switching pulse generation and real-time control. This paper presents the design and implementation of an FPGA-controlled three-phase induction motor drive employing a Voltage Source Inverter (VSI) with Pulse Width Modulation (PWM) techniques. Three modulation strategies, namely Sinusoidal Pulse Width Modulation (SPWM), Third Harmonic Injection Pulse Width Modulation (THIPWM), and Space Vector Pulse Width Modulation (SVPWM), are investigated and compared. MATLAB/Simulink is used to evaluate the dynamic performance of the drive, while Xilinx System Generator is utilized to implement the PWM controller on FPGA hardware. Simulation and experimental results demonstrate that SVPWM provides improved DC bus utilization, lower Total Harmonic Distortion (THD), smoother torque characteristics, and superior overall performance compared with SPWM and THIPWM. The proposed FPGA-based implementation offers an efficient and reliable solution for industrial variable-speed induction motor applications.

Keywords— FPGA, Induction Motor Drive, Voltage Source Inverter, SPWM, THIPWM, SVPWM, Xilinx System Generator, Pulse Width Modulation.

I. Introduction

Three-phase induction motors are extensively employed in industrial automation because of their rugged construction, high efficiency, low maintenance requirements, and economical operation. Modern industrial processes demand accurate speed regulation and fast dynamic response, making advanced digital controllers essential for high-performance motor drive systems. Recent developments in Field Programmable Gate Arrays (FPGAs) have significantly improved the implementation of real-time control algorithms for power electronic converters. Unlike Digital Signal Processors (DSPs), FPGA devices execute multiple operations simultaneously through parallel hardware architecture, resulting in lower execution delay and improved computational efficiency. These characteristics enable the implementation of sophisticated PWM algorithms with precise timing and high switching frequencies. Pulse Width Modulation (PWM) is one of the most effective techniques for controlling Voltage Source Inverters used in induction motor drives. Among various PWM methods, SPWM, THIPWM, and SVPWM are widely adopted because of their capability to improve voltage quality and reduce harmonic distortion. Space Vector PWM further enhances inverter performance by maximizing DC-link voltage utilization while minimizing harmonic components in the output voltage. In this work, an FPGA-based controller is developed using Xilinx System Generator to generate PWM gating signals for a three-phase Voltage Source Inverter. The proposed controller is evaluated through MATLAB/Simulink simulations and FPGA implementation. The comparative analysis of SPWM, THIPWM, and SVPWM demonstrates that the SVPWM technique achieves the best harmonic performance and overall drive characteristics, making it highly suitable for modern industrial motor control applications.

II. System Description

The proposed FPGA-controlled induction motor drive consists of four major subsystems: a DC power source, a three-phase Voltage Source Inverter (VSI), a squirrel-cage induction motor, and an FPGA-based digital controller. The FPGA generates high-speed Pulse Width Modulation (PWM) gating signals that control the switching operation of the inverter, thereby regulating the voltage and frequency supplied to the induction motor. The overall system is designed to provide reliable variable-speed operation with improved efficiency and reduced harmonic distortion.

A. Three-Phase Induction Motor

The induction motor is one of the most widely used electrical machines in industrial applications due to its simple construction, ruggedness, high efficiency, and low maintenance requirements. Unlike synchronous machines, the rotor of an induction motor does not require an external DC excitation. Instead, the rotor current is induced by the rotating magnetic field produced by the three-phase stator windings. When a balanced three-phase AC supply is applied to the stator, a rotating magnetic field (RMF) is produced at synchronous speed. This rotating field cuts the rotor conductors, inducing an electromotive force (EMF) according to Faraday's law of electromagnetic induction. Since the rotor conductors are short-circuited, induced currents flow through them, producing another magnetic field. The interaction between the stator and rotor magnetic fields generates electromagnetic torque, causing the rotor to rotate in the direction of the rotating field. The speed of the induction motor is determined by the synchronous speed of the rotating magnetic field and the slip between the stator field and rotor speed. The synchronous speed is expressed as

$$N_s = \frac{120f}{p} \text{ rpm (or) } \omega_m = \frac{4\pi f}{p} \text{ rad/sec}$$

Where Ns = synchronous speed (rpm), f is the supply frequency (Hz), and P is the number of poles. The rotor always rotates at a speed slightly lower than the synchronous speed, and the difference between these speeds is defined as slip:

$$S = \frac{\omega_s - \omega_m}{\omega_s} \text{ ; Where, } \omega_s \text{ and } \omega_m \text{ are synchronous speeds, respectively}$$

The electromagnetic torque developed by the induction motor depends upon the applied voltage, rotor resistance, leakage reactance, and slip. Therefore, proper regulation of the inverter output voltage and frequency is essential for achieving smooth speed control and efficient operation.

International Journal for Innovative Engineering and Management Research
PEER REVIEWED OPEN ACCESS INTERNATIONAL JOURNAL
www.ijiemr.org

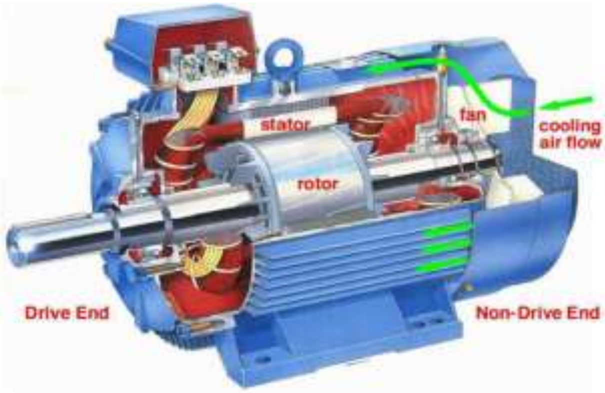

Fig. 1. Physical view of the three-phase induction motor.

B. Open-Loop V/f Speed Control

Among various induction motor speed control techniques, the constant Voltage-to-Frequency (V/f) method is widely adopted because of its simplicity and ease of implementation. In this method, the supply voltage is varied proportionally with the supply frequency so that the air-gap flux remains approximately constant throughout the operating range. Maintaining a constant V/f ratio prevents magnetic saturation at low frequencies and avoids flux weakening at higher frequencies. Consequently, the motor is capable of producing nearly constant torque below the rated frequency while maintaining stable dynamic performance.

In the proposed system, the desired motor speed is first converted into the corresponding operating frequency. Based on this frequency, the reference voltage is calculated by maintaining the constant V/f ratio. The FPGA controller subsequently generates PWM pulses with an appropriate modulation index, enabling the three-phase inverter to synthesize the required AC output voltage. Although open-loop V/f control does not employ speed feedback, it offers satisfactory steady-state performance for pumps, fans, conveyors, compressors, and several industrial drive applications where high dynamic accuracy is not mandatory.

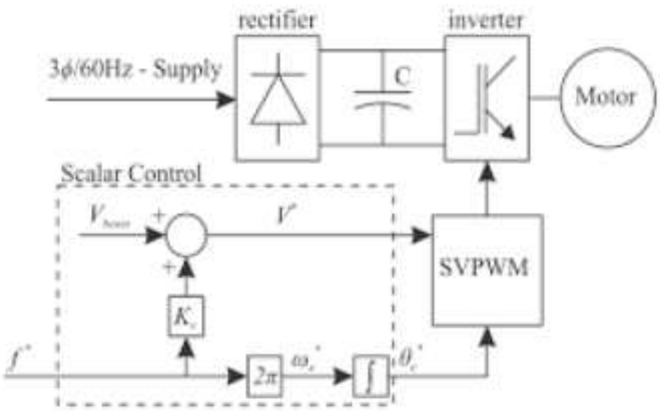

Fig. 2. Block diagram of the open-loop V/f control scheme.

C. Three-Phase Voltage Source Inverter

International Journal for Innovative Engineering and Management Research
PEER REVIEWED OPEN ACCESS INTERNATIONAL JOURNAL
www.ijiemr.org

The Voltage Source Inverter (VSI) serves as the interface between the DC supply and the three-phase induction motor. It converts the constant DC input voltage into a balanced three-phase AC output with controllable amplitude and frequency. The inverter consists of six power semiconductor switches arranged in a three-leg bridge configuration. Each leg contains two complementary switches that operate under PWM control. Proper switching sequences ensure the generation of three sinusoidal phase voltages displaced by 120°, thereby supplying balanced power to the motor. The switching pulses for the VSI are generated by comparing sinusoidal reference signals with a high-frequency carrier waveform. Different PWM strategies influence the harmonic content, switching losses, and voltage utilization of the inverter. Therefore, the selection of an appropriate modulation technique directly affects the overall performance of the induction motor drive.

In this work, three PWM techniques—SPWM, THIPWM, and SVPWM—are implemented and evaluated using MATLAB/Simulink and FPGA hardware. The comparative study demonstrates that the Space Vector PWM technique provides superior DC bus utilization and lower harmonic distortion, making it the preferred choice for high-performance induction motor drives.

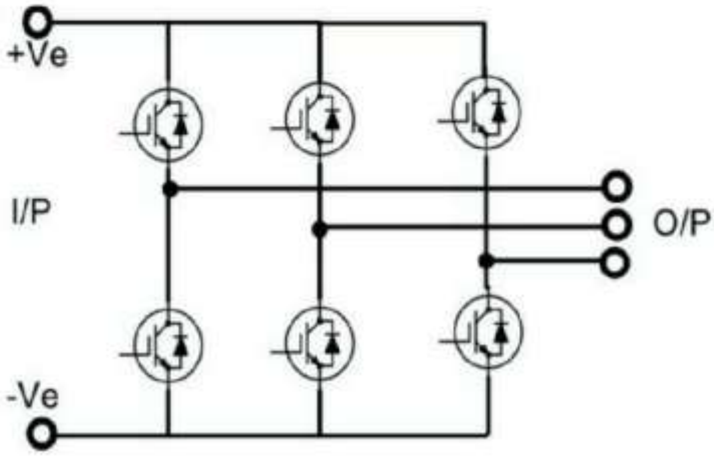

Fig. 3. Three-phase two-level Voltage Source Inverter.

D. Overall System Operation

The complete drive system operates by converting the available DC supply into a variable-frequency three-phase AC output using the FPGA-controlled inverter. Initially, the reference speed is converted into the desired frequency and modulation index through the V/f control algorithm. The FPGA then generates six synchronized PWM gate signals that drive the inverter switches. The inverter synthesizes a balanced three-phase voltage that energizes the induction motor. The motor accelerates until the developed electromagnetic torque balances the applied load torque. During operation, different PWM techniques are employed to investigate their influence on inverter output quality, motor current waveform, electromagnetic torque ripple, and Total Harmonic Distortion (THD). The proposed architecture combines the computational capability of FPGA technology with advanced PWM algorithms to achieve precise switching control, fast dynamic response, and improved power quality suitable for modern industrial motor drive applications.

III. PWM Techniques

The performance of a Voltage Source Inverter (VSI) is primarily determined by its switching strategy. Pulse Width Modulation (PWM) is the most widely adopted switching technique in modern power electronic converters because it enables precise control of the inverter output voltage while simultaneously reducing harmonic distortion. In induction motor drive applications, PWM techniques improve motor efficiency, minimize torque pulsations, and enhance the dynamic response of the drive system. The basic principle of PWM is to control the conduction intervals of the inverter switches such that the fundamental component of the output voltage closely resembles a sinusoidal waveform. By varying the pulse widths according to a predefined modulation strategy, the inverter can synthesize an AC voltage of variable magnitude and frequency from a constant DC source.

In this work, a three-phase two-level Voltage Source Inverter is employed, and three carrier-based modulation techniques are investigated: Sinusoidal Pulse Width Modulation (SPWM), Third Harmonic Injection Pulse Width Modulation (THIPWM), and Space Vector Pulse Width Modulation (SVPWM). Their performance is evaluated through simulation and FPGA implementation.

A. Three-Phase Voltage Source Inverter

A three-phase Voltage Source Inverter converts a fixed DC voltage into a balanced three-phase AC supply suitable for driving induction motors. The inverter consists of six controlled semiconductor switches arranged in three bridge legs, with each leg supplying one motor phase.

During operation, complementary switching is maintained between the upper and lower switches of each leg to prevent short-circuiting of the DC link. The switching sequence is generated by the FPGA controller according to the selected PWM algorithm. The inverter output frequency is determined by the reference signal, whereas the output voltage magnitude depends upon the modulation index.

The principal advantages of the VSI include

- Simple circuit configuration
- High conversion efficiency
- Wide output frequency range
- Easy implementation of digital control algorithms
- Compatibility with advanced PWM techniques

B. Pulse Width Modulation

Pulse Width Modulation is a digital switching technique used to generate variable AC voltage from a fixed DC source. Instead of varying the amplitude of the output voltage directly, PWM controls the average output voltage by varying the duration of switching pulses. A high-frequency triangular carrier signal is continuously compared with a low-frequency reference waveform. Whenever the reference signal exceeds the carrier waveform, the corresponding inverter switch is turned ON; otherwise, it remains OFF. This comparison produces a sequence of pulses whose widths vary according to the instantaneous value of the reference waveform.

The modulation index is defined as

International Journal for Innovative Engineering and Management Research
PEER REVIEWED OPEN ACCESS INTERNATIONAL JOURNAL
www.ijiemr.org

The modulation index is defined as

$$m_a = \frac{V_r}{V_c}$$

where

- V_r = amplitude of the reference signal
- V_c = amplitude of the carrier signal

Similarly, the frequency modulation ratio is expressed as

$$m_f = \frac{f_c}{f_r}$$

where

- f_c = carrier frequency
- f_r = reference frequency

Proper selection of these parameters significantly influences inverter output quality, switching losses, and harmonic performance.

The major benefits of PWM include

1. Improved voltage regulation
2. Reduced lower-order harmonics
3. Better power quality
4. Reduced filter requirements
5. Higher system efficiency
6. Easy digital implementation using FPGA hardware
7. C. Sinusoidal Pulse Width Modulation (SPWM)

Sinusoidal Pulse Width Modulation is the most widely used carrier-based PWM technique because of its simple implementation and predictable switching behavior. In SPWM, three sinusoidal reference signals displaced by 120° are compared with a common high-frequency triangular carrier waveform. Whenever the instantaneous value of the sinusoidal reference exceeds the carrier waveform, the corresponding inverter switch is turned ON. Otherwise, the switch remains OFF. The resulting switching pulses produce a three-phase AC output whose fundamental component closely approximates a sinusoidal waveform. Although SPWM offers good voltage control and straightforward implementation, it suffers from relatively poor DC bus utilization and comparatively higher harmonic distortion. These limitations become more noticeable in high-power industrial drive applications where improved power quality is required.

International Journal for Innovative Engineering and Management Research
PEER REVIEWED OPEN ACCESS INTERNATIONAL JOURNAL
www.ijiemr.org

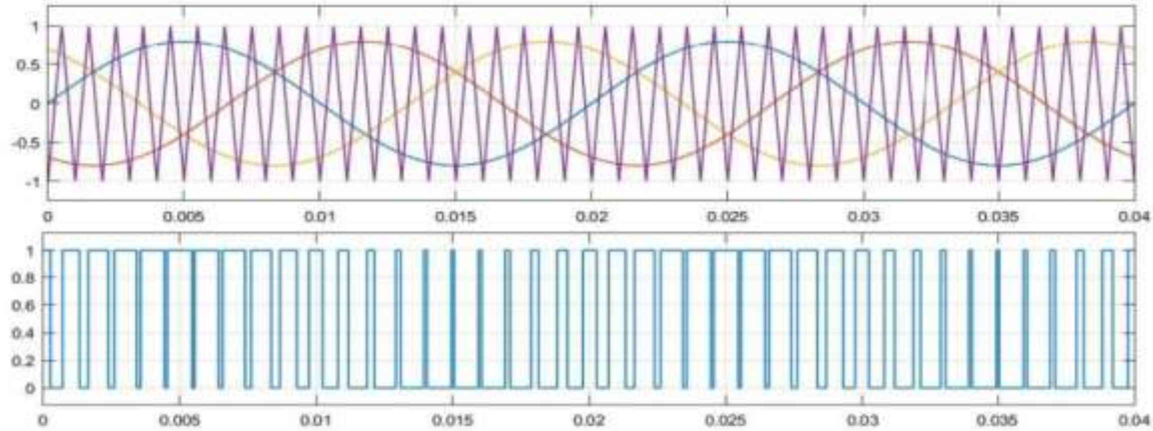

Fig. 5. Generation of SPWM switching pulses.

The main advantages of SPWM are

- Simple implementation
- Stable switching pattern
- Easy FPGA realization
- Suitable for medium-performance motor drives

However, its limitations include

- Lower DC-link voltage utilization
- Higher Total Harmonic Distortion (THD)
- Increased switching losses compared with advanced modulation techniques
- Third Harmonic Injection PWM (THIPWM)

Third Harmonic Injection Pulse Width Modulation enhances the performance of conventional SPWM by adding a third harmonic component to the fundamental reference waveform before comparison with the carrier signal. The injected third harmonic does not appear in the line-to-line output voltage because it is a zero-sequence component. Instead, it increases the achievable modulation range and improves DC-link voltage utilization without affecting the fundamental output frequency. Compared with SPWM, THIPWM provides

- Better voltage utilization
- Lower harmonic distortion
- Reduced inverter switching stress
- Improved fundamental output voltage

These improvements make THIPWM attractive for medium- and high-power induction motor drives requiring enhanced performance without significant computational complexity.

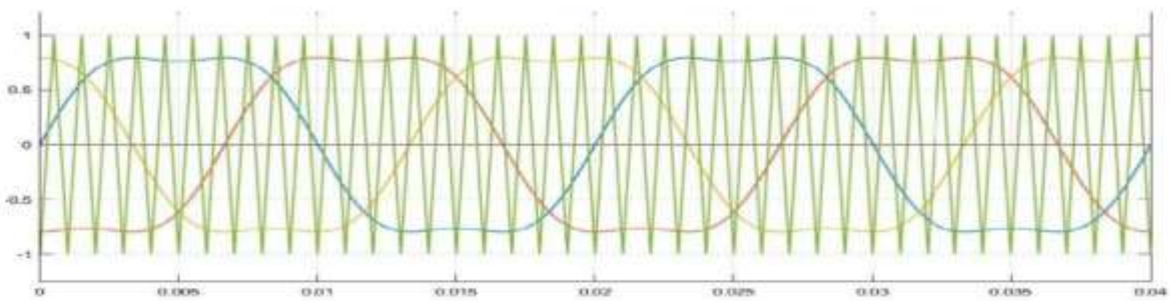

Fig. 6. Third Harmonic Injection PWM reference waveform.

International Journal for Innovative Engineering and Management Research
PEER REVIEWED OPEN ACCESS INTERNATIONAL JOURNAL
www.ijiemr.org

E. Space Vector Pulse Width Modulation (SVPWM)

Space Vector Pulse Width Modulation is one of the most advanced digital modulation techniques employed in modern motor drive systems. Unlike carrier-based methods, SVPWM represents the inverter switching states as vectors in a two-dimensional stationary reference frame. A three-phase inverter has eight possible switching states consisting of six active voltage vectors and two zero vectors. During every sampling interval, the desired reference voltage vector is synthesized by appropriately combining the adjacent active vectors and zero vectors. This vector-based approach minimizes switching transitions while maximizing the utilization of the available DC-link voltage.

The principal advantages of SVPWM include

- Maximum DC bus voltage utilization
- Lower harmonic distortion
- Reduced torque ripple
- Better dynamic response
- Higher inverter efficiency
- Lower switching losses

Because of these characteristics, SVPWM has become the preferred modulation strategy for high-performance induction motor drives and digital control platforms such as FPGA and DSP.

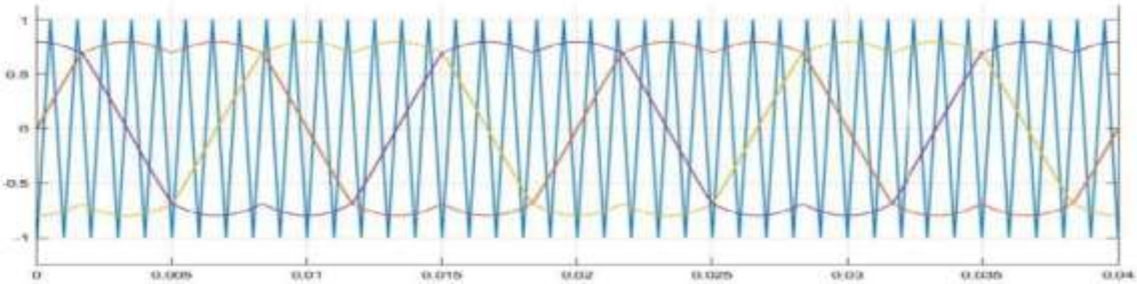

Fig. 7. Space Vector PWM switching concept.

F. Comparative Analysis of PWM Techniques

The three modulation techniques were evaluated using MATLAB/Simulink and subsequently implemented on FPGA hardware. Their performance was compared in terms of harmonic distortion, output waveform quality, torque ripple, and inverter voltage utilization. SPWM provides the simplest implementation but exhibits relatively higher harmonic distortion. THIPWM improves voltage utilization by introducing a third harmonic component, resulting in lower THD than SPWM. SVPWM achieves the best overall performance owing to its optimal switching sequence and efficient utilization of the DC-link voltage. Simulation results indicate that SVPWM produces smoother stator currents, reduced electromagnetic torque ripple, and the lowest Total Harmonic Distortion among the investigated modulation techniques. Consequently, SVPWM is selected as the preferred control strategy for FPGA-based induction motor drive applications.

IV. FPGA-Based Controller Design and Implementation

The implementation of digital control algorithms using Field Programmable Gate Arrays (FPGAs) has become increasingly popular in modern motor drive applications due to their high processing speed, deterministic timing, parallel execution capability, and hardware

International Journal for Innovative Engineering and Management Research
PEER REVIEWED OPEN ACCESS INTERNATIONAL JOURNAL
www.ijiemr.org

reconfigurability. Unlike conventional Digital Signal Processors (DSPs), which execute instructions sequentially, FPGA devices perform multiple operations simultaneously. This parallel architecture significantly reduces computation time and enables the implementation of high-frequency switching algorithms with precise timing accuracy. In the proposed induction motor drive, an FPGA is employed to generate the gating pulses required for controlling a three-phase Voltage Source Inverter (VSI). The PWM controller is developed using Xilinx System Generator integrated with MATLAB/Simulink, allowing both graphical modelling and automatic HDL code generation. The generated HDL design is synthesized in Xilinx Vivado, and the resulting bitstream is downloaded to the FPGA development board for real-time operation.

A. FPGA Architecture

A typical FPGA consists of three fundamental hardware resources:

- Configurable Logic Blocks (CLBs)
- Programmable Interconnection Network
- Input/Output (I/O) Blocks

The Configurable Logic Blocks contain Look-Up Tables (LUTs), flip-flops, multiplexers, and arithmetic logic required to implement digital control functions. The programmable routing network interconnects these logic elements, enabling customized digital circuit realization. The Input/Output blocks provide communication between the FPGA and external hardware such as inverter gate drivers, sensors, and peripheral devices. The modular structure of the FPGA permits rapid implementation of complex control algorithms while maintaining deterministic execution independent of algorithm complexity. This capability makes FPGA technology highly suitable for real-time power electronic applications involving high switching frequencies.

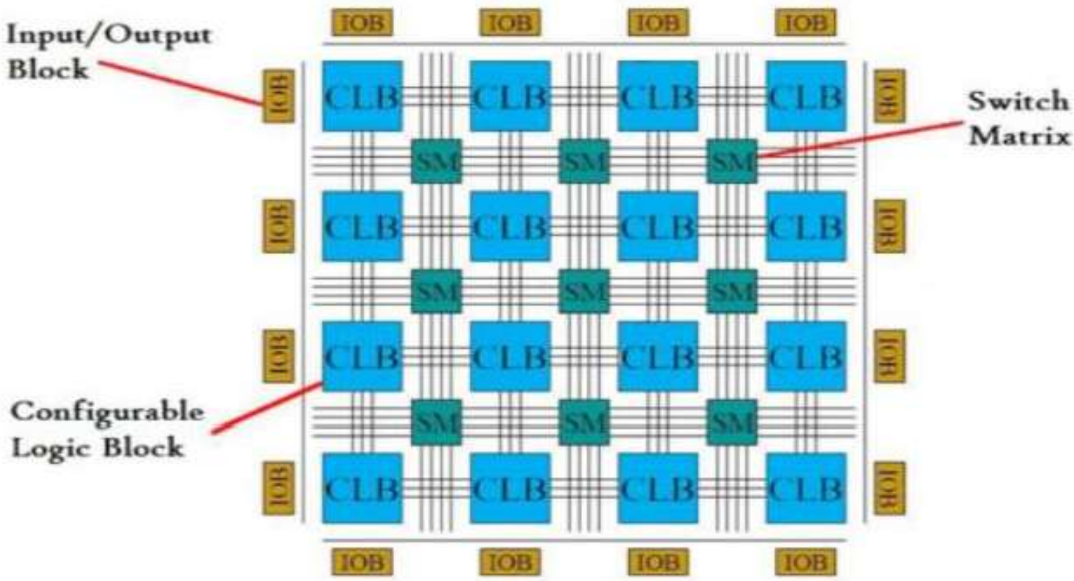

Fig. 8. General architecture of the FPGA device.

B. Development Using Xilinx System Generator

Xilinx System Generator provides a model-based design environment for implementing FPGA-based digital controllers directly from MATLAB/Simulink. It enables designers to construct complete hardware architectures using graphical blocks

International Journal for Innovative Engineering and Management Research
PEER REVIEWED OPEN ACCESS INTERNATIONAL JOURNAL
www.ijiemr.org

without manually writing HDL code. In this work, the PWM controller is developed using Xilinx block libraries, including counters, ROM memories, arithmetic blocks, comparators, gateway interfaces, and system generator blocks. After verification through Simulink simulation, the design is automatically converted into synthesizable Verilog HDL code. The generated HDL project is exported to Xilinx Vivado, where logic synthesis, implementation, timing analysis, and bitstream generation are performed. The bitstream is subsequently programmed into the FPGA development board to verify the controller under real operating conditions. The model-based development methodology considerably reduces development time while improving design reliability and portability.

Fig. 9. Xilinx System Generator model for PWM implementation.

C. PWM Pulse Generation Algorithm

The generation of PWM pulses constitutes the core function of the FPGA controller. The algorithm begins with the generation of three sinusoidal reference signals displaced by 120 electrical degrees. These reference waveforms correspond to the desired three-phase output voltages. A high-frequency triangular carrier waveform is generated using digital counters and lookup tables implemented within the FPGA. The carrier frequency determines the inverter switching frequency, whereas the sinusoidal reference frequency determines the output frequency supplied to the induction motor. The PWM pulses are produced by continuously comparing the instantaneous amplitude of each sinusoidal reference waveform with the carrier signal. Whenever the reference waveform exceeds the carrier signal, the corresponding inverter switch is turned ON; otherwise, it is turned OFF. This process is simultaneously executed for all three phases, producing six complementary gate pulses required for the three-phase inverter. The modulation index is adjusted according to the required operating voltage while maintaining the desired V/f ratio. The FPGA performs these operations concurrently, thereby ensuring accurate pulse generation with minimal timing error.

The overall PWM generation procedure can be summarized as follows:

- Generate three sinusoidal reference waveforms.
- Generate a common triangular carrier waveform.
- Compare each reference waveform with the carrier signal.
- Generate complementary PWM gate pulses.
- Apply dead-time protection between complementary switches.
- Deliver synchronized gate pulses to the VSI.

International Journal for Innovative Engineering and Management Research
PEER REVIEWED OPEN ACCESS INTERNATIONAL JOURNAL
www.ijiemr.org

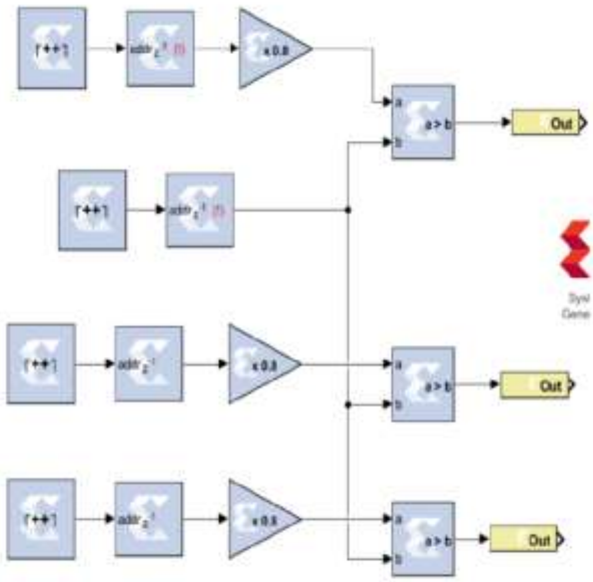

Fig. 10. Flow diagram for FPGA-based PWM pulse generation.

D. Hardware Implementation

The controller is synthesized using Xilinx Vivado and implemented on the FPGA development platform. The synthesized design is verified through RTL analysis, timing verification, and resource utilization reports before hardware programming. The FPGA outputs six synchronized PWM pulses through its programmable I/O pins. These pulses are isolated and applied to the gate-driver circuits that control the six switches of the three-phase Voltage Source Inverter. Experimental verification is carried out using an FPGA-controlled induction motor drive prototype. Oscilloscope measurements confirm correct pulse generation for all inverter legs with appropriate phase displacement and switching frequency. The hardware results closely match the simulation waveforms obtained from MATLAB/Simulink, validating the correctness of the proposed controller. The FPGA implementation demonstrates excellent switching accuracy and real-time performance while requiring only a modest percentage of the available FPGA logic resources.

International Journal for Innovative Engineering and Management Research
PEER REVIEWED OPEN ACCESS INTERNATIONAL JOURNAL
www.ijiemr.org

Fig. 11. Experimental setup of the FPGA-controlled induction motor drive.

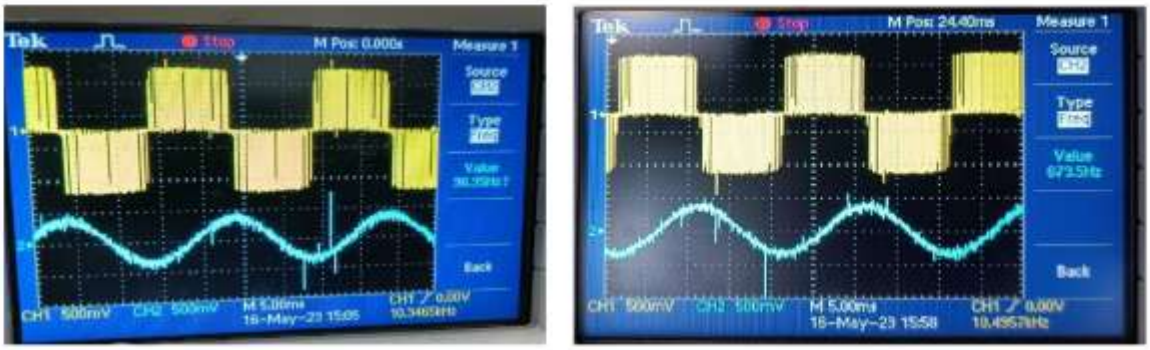

Fig. 12. FPGA-generated three-phase PWM gate pulses.

E. Advantages of FPGA-Based Motor Control

Compared with conventional DSP-based implementations, the proposed FPGA controller provides several practical advantages for industrial motor drive applications.

- High-speed parallel execution of digital control algorithms.
- Deterministic timing with negligible computational delay.
- Accurate high-frequency PWM pulse generation.
- Easy implementation of advanced modulation techniques such as SVPWM.
- Reduced processor overhead and improved system reliability.
- Reconfigurable hardware allowing future algorithm upgrades.
- Excellent scalability for multi-motor and multilevel inverter applications.

The use of FPGA technology also enables seamless integration of additional control functions such as fault detection, current regulation, speed estimation, communication interfaces, and protection logic without significantly affecting system performance. Overall, the FPGA-based controller provides a flexible and efficient platform for implementing advanced inverter control strategies while achieving superior dynamic performance and improved power quality.

F. Discussion

The proposed FPGA implementation successfully combines model-based design with hardware realization to achieve precise real-time control of a three-phase induction motor drive. The integration of MATLAB/Simulink, Xilinx System Generator, and Vivado simplifies the development process while maintaining high computational efficiency. By generating synchronized PWM gate signals with accurate timing, the FPGA ensures reliable inverter operation over a wide range of operating conditions. The hardware implementation confirms that FPGA technology is a practical and cost-effective solution for modern industrial motor drives requiring high switching performance and low harmonic distortion.

V. Results and Discussion

To validate the effectiveness of the proposed FPGA-controlled induction motor drive, both simulation and hardware implementation were carried out. The simulation model was developed in MATLAB/Simulink R2018a, while the PWM controller was implemented using Xilinx System Generator and deployed on an FPGA development board. The performance of three PWM techniques—Sinusoidal Pulse Width Modulation (SPWM), Third Harmonic Injection Pulse Width Modulation (THIPWM), and Space Vector Pulse Width Modulation (SVPWM)—was investigated and compared in terms of motor dynamic response, inverter output waveform quality, and Total Harmonic Distortion (THD). The induction motor used in the simulation is a 4-kW, 400-V, three-phase squirrel-cage induction motor supplied through a two-level Voltage Source Inverter. The inverter is powered from a 540-V DC source, and the PWM switching frequency is varied between 1 kHz and 10 kHz to evaluate the influence of switching frequency on harmonic performance. The modulation index is maintained at 0.8, while the motor is operated under constant V/f control.

A. Simulation Model

The complete induction motor drive system was modeled in MATLAB/Simulink by integrating the DC voltage source, three-phase Voltage Source Inverter, PWM controller, and asynchronous induction motor. Separate simulation models were developed for SPWM, THIPWM, and SVPWM to ensure a fair performance comparison. The simulation generated the following performance characteristics for each PWM technique:

1. Rotor speed response
2. Electromagnetic torque
3. Three-phase stator current
4. Line voltage waveform
5. FFT spectrum of inverter output voltage

These waveforms were analyzed to evaluate the transient response, steady-state performance, and harmonic characteristics of the proposed controller.

International Journal for Innovative Engineering and Management Research
PEER REVIEWED OPEN ACCESS INTERNATIONAL JOURNAL
www.ijiemr.org

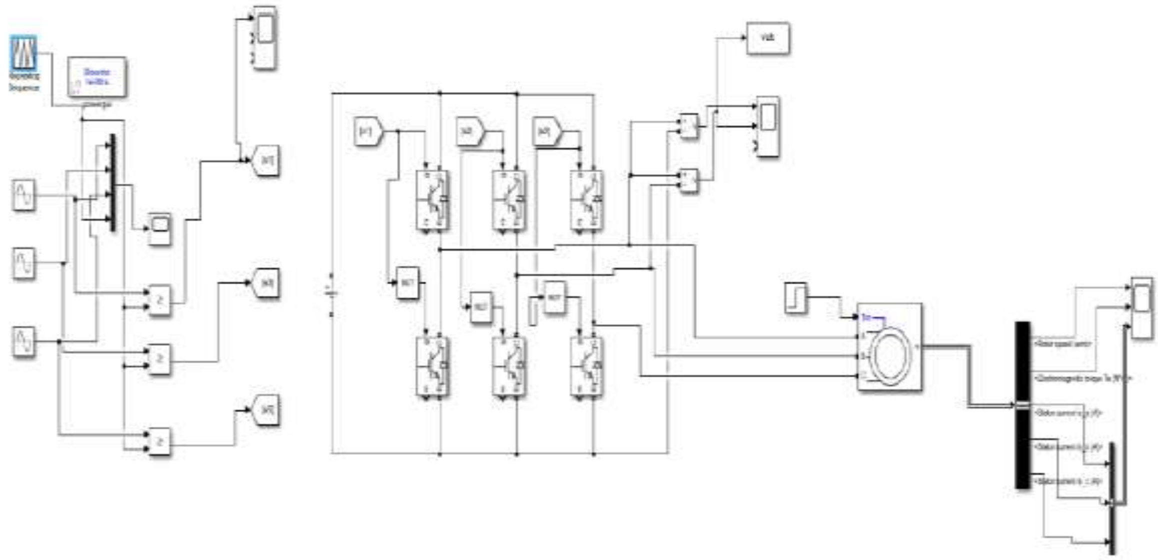

Fig. 13. MATLAB/Simulink model of the FPGA-controlled induction motor drive.

B. Dynamic Performance of the Induction Motor

The transient characteristics of the induction motor were evaluated using rotor speed, electromagnetic torque, and stator current waveforms.

1) Rotor Speed

At startup, the induction motor accelerates rapidly from standstill to its rated operating speed with minimal overshoot. The rotor speed reaches steady state within a short duration, demonstrating the effectiveness of the FPGA-generated PWM pulses in regulating the inverter output frequency. Among the investigated modulation techniques, SVPWM exhibits the fastest settling time and the smallest steady-state speed variation due to its improved voltage utilization and smoother output waveform.

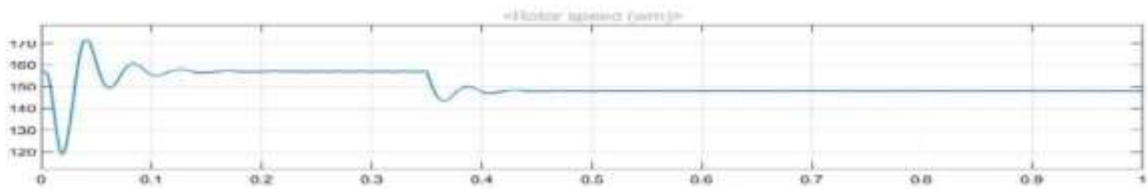

Fig. 14. Rotor speed response of the induction motor.

2) Electromagnetic Torque

The electromagnetic torque initially exhibits a transient peak during motor acceleration before stabilizing near the rated operating value. Torque ripple is mainly influenced by the harmonic content of the inverter output voltage. SPWM produces comparatively larger torque pulsations because of its higher harmonic distortion. THIPWM reduces the torque ripple through improved modulation, whereas SVPWM provides the smoothest torque profile owing to its optimized switching sequence and superior harmonic performance. The reduction in torque ripple contributes to improved mechanical stability, lower acoustic noise, and enhanced drive efficiency.

International Journal for Innovative Engineering and Management Research
PEER REVIEWED OPEN ACCESS INTERNATIONAL JOURNAL
www.ijiemr.org

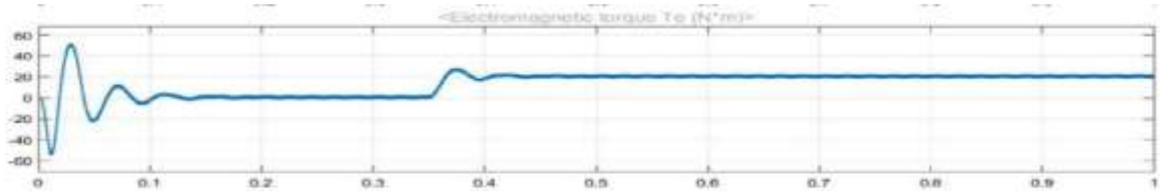

Fig. 15. Electromagnetic torque characteristics.

3) Three-Phase Stator Current

The three-phase stator currents generated using SVPWM are nearly sinusoidal and balanced under steady-state operation. Compared with SPWM, the stator current waveforms obtained using THIPWM and SVPWM contain fewer harmonic components, indicating improved inverter output quality. Balanced stator currents reduce copper losses and improve the overall efficiency of the induction motor.

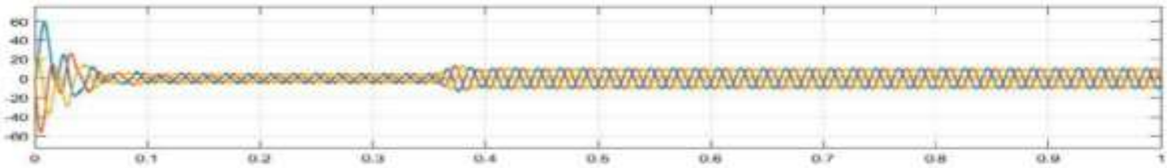

Fig. 16. Three-phase stator current waveforms.

C. Harmonic Analysis

The harmonic content of the inverter output voltage was evaluated using Fast Fourier Transform (FFT) analysis. Total Harmonic Distortion (THD) was selected as the primary performance index because it directly reflects the quality of the inverter output waveform. The FFT analysis confirms that SVPWM produces the lowest harmonic distortion among the investigated PWM techniques. The optimized switching sequence employed in SVPWM distributes switching events more effectively, thereby minimizing lower-order harmonics and improving waveform quality. The measured THD values at a switching frequency of 2 kHz are summarized in Table I.

Table I: Comparison of THD

PWM Technique	THD (%)	Performance
SPWM	91.58	Highest harmonic distortion
THIPWM	77.35	Improved waveform quality
SVPWM	77.01	Lowest harmonic distortion

The results clearly indicate that SVPWM provides the best harmonic performance, while SPWM exhibits the highest THD due to limited DC-link voltage utilization.

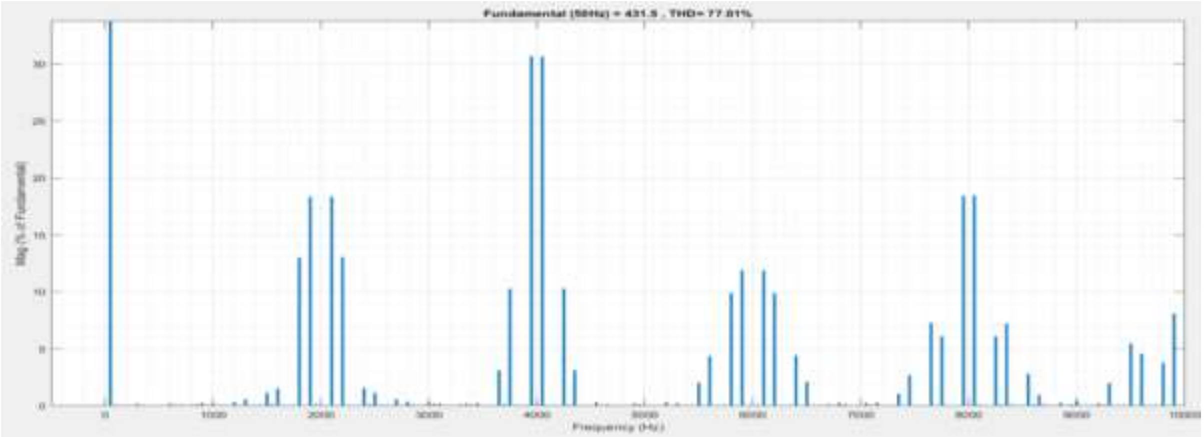
Fig. 17. FFT spectrum of inverter output voltage.

D. Effect of Switching Frequency

To investigate the influence of switching frequency on inverter performance, simulations were carried out for switching frequencies ranging from 1 kHz to 10 kHz. The obtained results indicate that the harmonic distortion remains relatively stable over the investigated switching frequency range. Although minor variations are observed, the overall trend demonstrates that SVPWM consistently produces the lowest THD compared with SPWM and THIPWM. The average THD values observed throughout the analysis are approximately: SPWM: 91–92%, THIPWM: 77–78%, SVPWM: 76.8–77.5%. These observations confirm the superior voltage synthesis capability of the SVPWM algorithm.

Table II. Comparison of THD at different switching frequencies.

S.No	Switching Frequency	SPWM	THIPWM	SVPWM
1.	1kHz	91.47	77.30	76.92
2.	2kHz	91.58	77.35	77.01
3.	3kHz	91.57	77.32	76.92
4.	4kHz	91.47	77.26	76.81
5.	5kHz	91.78	77.45	77.21
6.	6kHz	91.64	77.39	76.96
7.	7kHz	91.49	77.27	76.97
8.	8kHz	91.47	77.37	76.91
9.	9kHz	91.51	77.38	77
10.	10kHz	92.02	77.49	77.52

E. Experimental Validation

The proposed PWM controller was implemented on an FPGA development board using Xilinx Vivado. The generated gate pulses were applied to the gate-driver circuits of the three-phase Voltage Source Inverter, and the output waveforms were observed using a Digital Storage Oscilloscope (DSO). The experimentally obtained PWM waveforms closely matched the simulation results, confirming the correctness of the FPGA implementation. The hardware prototype demonstrated reliable pulse generation with accurate phase displacement and switching frequency, validating the feasibility of the proposed controller for practical industrial applications. The FPGA implementation also confirmed the advantages of

International Journal for Innovative Engineering and Management Research
PEER REVIEWED OPEN ACCESS INTERNATIONAL JOURNAL
www.ijiemr.org

hardware-based PWM generation, including deterministic execution, negligible computational delay, and high switching precision.

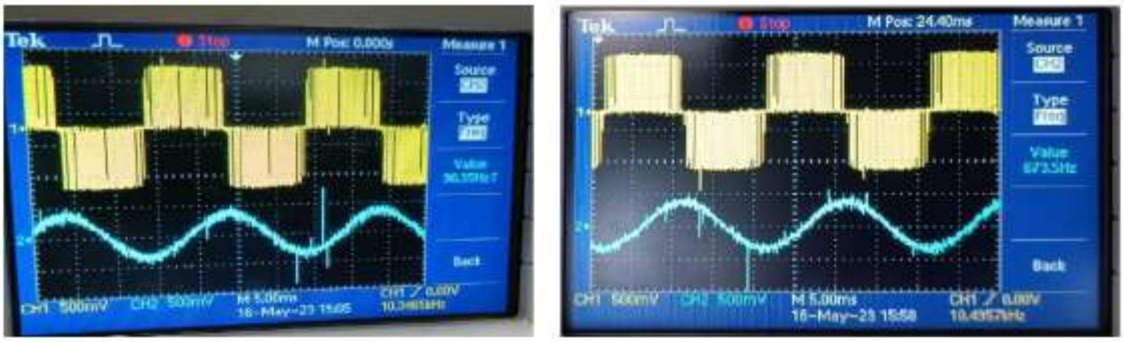

Fig. 19. Experimental FPGA-generated PWM pulses.

F. Performance Comparison

The comparative investigation of the three PWM techniques demonstrates distinct differences in inverter performance. SPWM offers the simplest implementation but suffers from poor DC bus utilization and relatively high harmonic distortion. THIPWM improves voltage utilization through third-harmonic injection, thereby reducing THD and torque ripple. SVPWM achieves the highest DC-link utilization, lowest harmonic distortion, smoother stator current, and reduced electromagnetic torque ripple. These characteristics make SVPWM the most suitable modulation technique for FPGA-controlled induction motor drives, particularly in applications requiring high efficiency, superior waveform quality, and accurate speed regulation.

Overall, the simulation and experimental results verify that the proposed FPGA-based controller effectively generates high-quality PWM signals for inverter-fed induction motor drives and significantly enhances system performance when combined with the SVPWM algorithm.

VI. Conclusion

This paper presented the design and implementation of an FPGA-controlled three-phase induction motor drive using a Voltage Source Inverter (VSI) and three PWM techniques: SPWM, THIPWM, and SVPWM. The controller was developed using MATLAB/Simulink and Xilinx System Generator, and its performance was validated through simulation and FPGA-based hardware implementation. A comparative analysis showed that SVPWM provides superior performance in terms of DC-link voltage utilization, waveform quality, and Total Harmonic Distortion (THD) compared with SPWM and THIPWM. The FPGA implementation successfully generated accurate real-time PWM gating signals with deterministic timing and high switching precision, resulting in smooth motor operation and improved dynamic performance. The results demonstrate that the proposed FPGA-based control strategy is an effective and reliable solution for high-performance induction motor drives. Owing to its flexibility, fast processing capability, and low harmonic distortion, the proposed system is well suited for industrial applications such as variable-speed drives, electric vehicles, renewable energy systems, and factory automation.

Future research can further enhance the proposed system by incorporating advanced control techniques such as Field-Oriented Control (FOC) or Direct Torque Control (DTC) to achieve improved dynamic performance and precise torque regulation. The implementation of intelligent controllers based on Artificial Intelligence (AI), Fuzzy Logic, or Machine Learning may further improve system adaptability under varying load conditions. In addition, extending the proposed controller to multilevel inverter topologies, wide-bandgap semiconductor devices (SiC/GaN), and Internet of Things (IoT)-enabled predictive monitoring could significantly improve efficiency, reliability, and fault diagnosis capabilities for next-generation industrial motor drive systems.

References

References

[1] Milan Curkovic, karel Jezernik and Robert Horvat, "*FPGA-Based Predictive Sliding Mode Controller of a Three-Phase Inverter*", IEEE Transactions on Industrial Electronics, Vol.60, No.2, pp.637-644.

[2] Aleksander Malinowski and Hao Yu, "*Comparison of Embedded System Design for Industrial Applications*", IEEE Transactions on Industrial Informatics, Vol.7, No.2, pp.244-254.

[3] Concettina Buccella, Carlo Cecati and Hamed Latafat, "*Digital Control of Power Converters-A Survey*", IEEE Transactions on Industrial Informatics, Vol.8, No.3, pp.437-447.

[4] Frede Blaabjerg and John K. Pedersen, "*Optimized Design of a Complete Three-phase PWM-VS Inverter*", IEEE Transactions on Power Electronics, Vol.12, No.3, pp.567-577.

[5] Osman Kukrer, Sertac Bayhan and Hasan Komurcugil, "*Model-Based Current Control Strategy with Virtual Time Constant for Improved Dynamic Response of Three-Phase Grid-Connected VSI*" IEEE Transactions on Industrial Electronics

[6] Prakash K. Ray, Soumya Ranjan Das and Asit Mohanty, *"Fuzzy Controller Designed PV based Custom Power Device for Power Quality Enhancement"*, IEEE Transaction on Energy Conversion.

[7] Bernardo Cougo, Thierry Meynard and Guillaume Gateau, "*Parallel Three-Phase Inverters: Optimal PWM Method for Flux Reduction in Intercell Transformers*", IEEE Transactions on Power Electronics, Vol.26, No.8, pp. 2184-2191.

[8] Vikram Roy Chowdhury and Jonathan Kimball, "*Control of a Three-Phase Grid-Connected Inverter Under Non-Ideal Grid Conditions with Online Parameter Update*", IEEE Transactions on Energy Conversion.

[9] Ning-Yi Dai, Man-Chung Wong, Fan Ng and Ying-Duo Han, "*A FPGA-Based Generalized Pulse Width Modulator for Three-Leg Center-Split and Four-Leg Voltage Source Inverters*", IEEE Transactions on Power Electronics, Vol.23, No.3, pp.1472-1484.

[10] William Shepherd and Li Zhang, "*Power Converter Circuits*", by Marcel Dekker, Inc in 2004.

[11] APPLY VOLT company, "*FPGA Manual*".

[12] P. Rama Mohan, T. Bramhananda Reddy, and M. Vijaya Kumar, "*Simple and Efficient High-Performance PWM Algorithm for Induction Motor Drives*", Journal of Electrical Engineering, Vol 11, Issue 4.

[13] Ahmet M. Hava, Russel J. Kerkman and Thomas A. Lipo, "*Simple Analytical and Graphical Methods for carrier-Based PWM-VSI Drives*", IEEE Transactions on Power Electronics, Vol.14, No.1,pp.49-61.

[14] Dae-Woong Chung, Joohn-Sheok Kim and Seung-Ki Sul, "*Unified Voltage Modulation Techniques for Real-Time Three-Phase Power Conversion*", IEEE Transactions on Industry Applications, Vol.34, No.2,pp.374-380.