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Design and Simulation of a Three-Phase Induction Motor for Speed Control using Constant V/f Technique with Sinusoidal PWM-Based Inverter

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***Abstract**: Induction motor (IM) drives are extensively employed in a wide range of industrial and process control applications due to their robustness, cost-effectiveness, and maintenance-free operation. In high-performance drive systems, precise control of the motor speed is essential to meet stringent dynamic and steady-state requirements. These systems must ensure that the motor speed accurately tracks a predefined reference trajectory, even in the presence of external load disturbances and variations in system parameters. This paper presents an analysis of the speed control system of an induction motor driven by a voltage source inverter (VSI), incorporating a Proportional-Integral (PI) controller into the feedback loop. The control methodology adopts a constant volts-per-hertz (V/f) ratio to ensure efficient motor performance. A comparative evaluation between open-loop and closed-loop configurations of a squirrel-cage rotor type induction motor is done using the Sinusoidal Pulse Width Modulation (SPWM) technique based on MATLAB/Simulink under the Discrete mode of operation. Simulation results confirm that the closed-loop SPWM method outperforms the open-loop SPWM method under load disturbances, rendering it a highly effective strategy for dynamic industrial applications.*

***Keywords:** VSI, PWM, SPWM, SVPWM, Induction Motor, IGBT, Closed-Loop Control, Constant V/F, PI Controller.*

Abbreviations:
DOL: Direct-On-Line
DC: Direct Current
AC: Alternating Current
SPWM: Sinusoidal Pulse Width Modulation
SVM: Space Vector Modulation
PI: Proportional-Integral
VSI: Voltage Source Inverter
IM: Induction Motor
ANFIS: Adaptive Neuro-Fuzzy Inference System
ASD: Adjustable Speed Drive
PWM: Pulse Width Modulation
PID: Proportional–Integral–Derivative
DSPs: Digital Signal Processors

I. INTRODUCTION

In terms of industries, DC motors have historically been widely used in industrial drives due to their excellent speed control and high starting torque. However, due to frequent maintenance of commutators and brushes, which limited their reliability and lifespan in demanding environments, Induction Motors became a more reliable alternative. With the advent of power electronics and variable frequency drives, the VFDs enabled precise speed control of AC induction motors, which was once considered a significant drawback of DC machines. This technological breakthrough allowed industries to transition from conventional DC motors to robust, brushless, low-maintenance induction motors without sacrificing performance. Power inverters are crucial in modern electrical systems for converting direct current (DC) to alternating current (AC). Their ability to modulate output voltage and frequency makes them essential in motor drive applications. However, the conversion of AC to DC and DC to AC again introduces harmonics in addition to the fundamental components in the output of the inverter. Thus, the pure sinusoidal wave is not obtained, reducing system efficiency.

Therefore, the quality of the inverter can be improved by employing various modulation techniques, as well as by designing filters to eliminate harmonic distortion at higher frequencies in the system [1]. The speed characteristics of the induction motor change when the mechanical loads are changed. Many control methods for the induction motor are available to obtain constant speed characteristics. The Scalar control and Vector control methods are widely used for speed regulation of an AC Induction motor. MATLAB/Simulink-based sensorless scalar speed control of squirrel-cage three-phase induction motors using slip-frequency compensation with SPWM is also suitable for low-dynamics industrial applications [2]. A PI-controlled-based speed regulation scheme for a three-phase induction motor, which achieves stable dynamic performance and minimal steady-state error, is also widely studied using MATLAB/Simulink modelling within an SPWM inverter framework [3]. The system maintains a constant voltage-to-frequency ratio, ensuring speed control stability in a three-phase induction motor when using the scalar control method with a PID controller, regardless of any load changes. A proposed system demonstrates stable motor operation with effective voltage-frequency regulation and satisfactory dynamic response under varying load conditions [4]. A MATLAB/Simulink model demonstrating decoupled torque flux loops and PI feedback in a field-oriented control architecture is studied [5]. Simulation results also show that a SPWM-based PI controller reaches a target of 1500 rpm with only a nearly 0.32% overshoot, outperforming the standard PI (approximately

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0.55%) under parameter variation [6]. A hybrid ANN–PID controller with predictive current regulation optimized via PSO demonstrates higher dynamic performance and robustness in V/f drives [7]. A Five-Phase SVPWM and Wavelet-Fuzzy Speed Control employs a space-vector PWM in a five-phase IM drive, with a wavelet-decomposed fuzzy logic controller improving performance under parameter variations [8].

Three PWM strategies, including Sinusoidal PWM (SPWM), Third-Harmonic PWM (THPWM), and Space Vector PWM (SVPWM), within a V/f scalar control scheme for three-phase induction motors, have been studied in depth using MATLAB/Simulink for modelling and simulation [9]. Their work evaluated each approach based on harmonic distortion (THD), DC-link voltage utilization, output voltage quality, and motor speed behaviour, particularly under full-load conditions. Neural sensor-based and flux control of the induction motor have also been developed in recent trends. A few studies aim to enhance the resilience and dynamic performance of MRAS by integrating an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller into sensorless vector-controlled IM drives in [10].

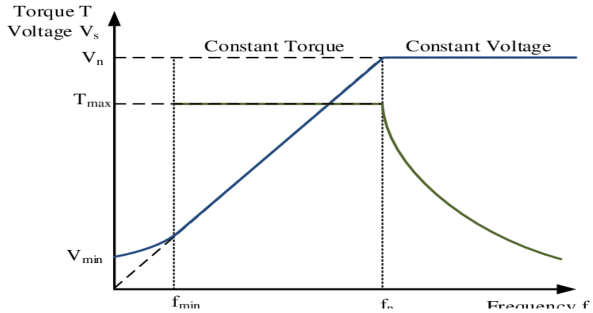
A novel carrier-based PWM strategy synchronizes a frequency-modulated triangular carrier to suppress motor vibrations and reduce torque ripple, validated on multilevel inverters [11]. Demonstration of effectiveness in regulating motor speed under varying load conditions is also implemented using MATLAB Simulation, for implementing scalar (V/f) control techniques [12].

This paper focuses on speed regulation of a three-phase induction motor. The experimental implementation is performed by simulating a sinusoidal-based voltage source inverter control using MATLAB/Simulink. Comparison and measurement of parameters in real-time for both open-loop and closed-loop techniques were implemented using a PI Controller for different load torque variations, initially increasing from 0 Nm to 8 Nm, for the configured three-phase induction motor, with consideration for the high rotor currents that can eventually disrupt motor performance. The objective is to identify and compare the efficiency of the SPWM strategy in terms of waveform quality and real-time control capability, while examining the speed-torque characteristics and harmonics for a Discrete mode of operation, set at 50 microseconds.

II. SCALAR V/F CONTROL

To control the speed of an induction motor effectively, a constant volts-per-hertz (V/f) ratio is maintained. This approach helps maintain a stable air-gap flux, ensuring a continuous torque and preventing unwanted variations. Here, both the stator voltage and frequency can be increased together until they reach their rated or base speed values. However, when the frequency exceeds the rated level, the stator voltage must be maintained at its rated maximum to protect the motor's insulation and prevent electrical damage.

The relationship between voltage and frequency in this control strategy, known as the constant V/F characteristic, is shown in Fig. 1



[Fig.1: Constant V/f Characteristics of Induction Motor]

Besides its simplicity and easy implementation, V/f scalar control has the following advantages concerning the starting current and torque:

1. **Reduced Starting Current:** V/f control enables a gradual increase in voltage and frequency, significantly reducing the inrush current compared to direct-on-line (DOL) starting. This safeguards both the motor and the power supply system.
2. **Improved Starting Torque**: By maintaining a constant V/f ratio, the motor can generate adequate starting torque without drawing excessive current, making it suitable for many industrial applications.
3. **Avoids Mechanical Stress**: Smooth torque buildup during startup reduces mechanical shocks to the motor and connected load, improving overall system longevity.
4. **Customizable Acceleration**: Users can configure acceleration ramps to optimize torque vs. current demands during startup, adapting to various load conditions.
5. **Prevention of Voltage Dips**: Lower starting current means less voltage drop in the power system, reducing the risk of affecting other equipment on the same supply.
6. **No Need for Star-Delta or Soft Starters**: V/f control eliminates the need for traditional starting methods, simplifying motor control panels and reducing cost.

III. INVERTER TOPOLOGY

In modern adjustable speed drive (ASD) systems, the voltage source inverter (VSI) is the most commonly used topology for controlling the speed and torque of AC motors. As shown in Fig. 2, a conventional VSI-based ASD typically comprises three main components: a diode bridge rectifier that converts the AC input to DC, a DC-link capacitor that smoothens the DC voltage, and an inverter bridge that generates the desired three-phase AC output.

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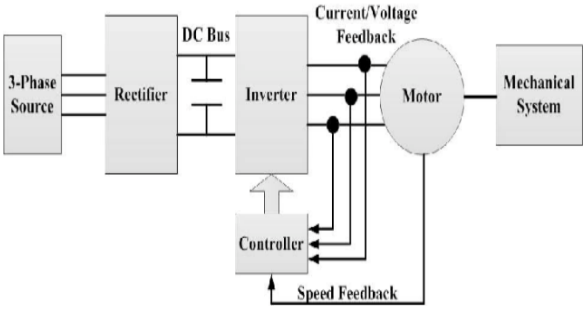
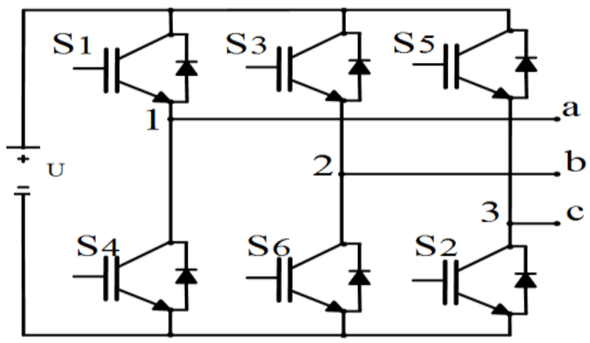


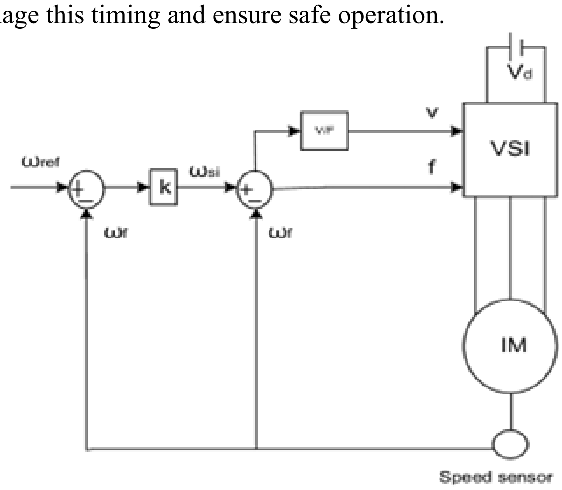
[Fig.2: Conventional Variable Speed Drive System]

The inverter section, often realised in a three-phase configuration, is composed of six semiconductor switches arranged in three legs. Each leg consists of two switches connected in series between the positive and negative terminals of the DC bus. Fig. 3 illustrates a standard three-phase inverter structure. These switches are controlled in such a way that they synthesise a three-phase AC output waveform from the fixed DC input.



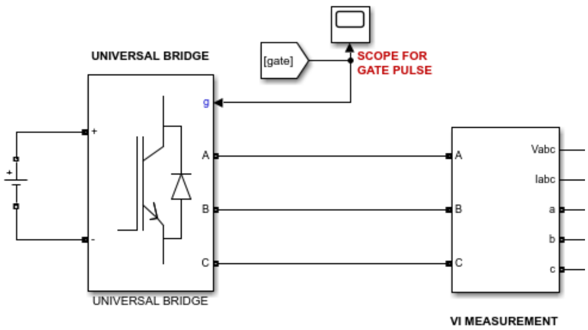
[Fig.3: Topology of a Basic IGBT-Based Three-Phase Inverter]

To prevent short circuits across the DC supply, it is essential to ensure that the upper and lower switches in each inverter leg are not activated simultaneously. Appropriate gating signals and dead-time insertion techniques are employed to manage this timing and ensure safe operation.



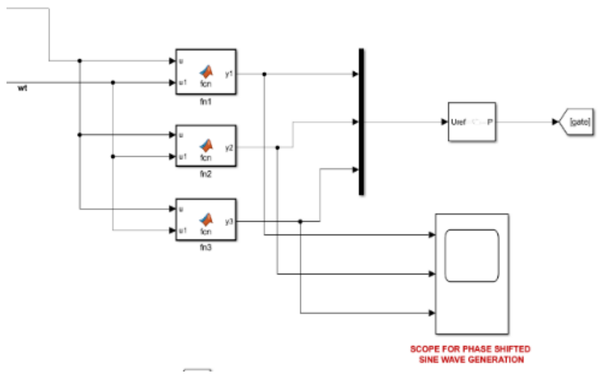
[Fig.4: Block Diagram Summarizing the Overall Control Strategy]

When any of the switches are turned off, the current flowing through the inductive load—such as motor windings—does not immediately drop to zero due to the stored magnetic energy. This characteristic of inductive components opposes sudden changes in current flow, which can potentially damage the switches. Fast recovery diodes, also known as freewheeling diodes, are connected across each switch to handle this issue. These diodes provide an alternate path for the current to circulate until the energy stored in the inductance is entirely dissipated, ensuring smooth transitions and protecting the inverter from overvoltage conditions.



[Fig.5: Universal Bridge Block of Three-Phase VSI]

In MATLAB SIMULINK, one can also use the Universal Bridge Block and set it accordingly to implement a three-phase IGBT/Diode or MOSFET/Diode-based inverter. The Universal Bridge Simulink block performs the same function as providing a three-phase output signal to the Induction Motor presented in the figure below. Additionally, the gate signal for switching the VSI can be generated using a two-level SPWM pulse generator Block in Simulink.



[Fig.6: Two-level SPWM Pulse Generator Block in Simulink]

Through the coordinated operation of these components, the VSI effectively controls the output voltage and frequency, enabling efficient and precise motor control in various industrial applications.

IV. PULSE WITH MODULATION

Pulse Width Modulation (PWM) plays a critical role in controlling the switching actions of inverter power devices in variable-speed drive systems. By adjusting the duty cycle of the PWM pulses, the inverter can effectively regulate the amplitude of the output voltage. In this process, the inverter generates a series of rectangular voltage pulses, which, although inherently rich in harmonic content, are essential to emulate a desired output waveform.

Due to the inductive properties of the stator windings in AC motors, these high-frequency switching pulses undergo natural filtering. The motor windings act as a low-pass filter, smoothing out the sharp transitions and effectively shaping the current waveform into a near-sinusoidal form.

This filtering effect significantly reduces harmonic distortion in the motor currents, improving the overall performance and efficiency of the drive system.

The primary objective of any PWM strategy is to produce an output voltage with a high-quality fundamental component while minimising the presence of lower-order and high-frequency harmonics. Among the various PWM techniques developed, Sinusoidal Pulse Width Modulation (SPWM) and Space Vector Modulation (SVM) are the most widely adopted due to their balance of simplicity, efficiency, and effectiveness.

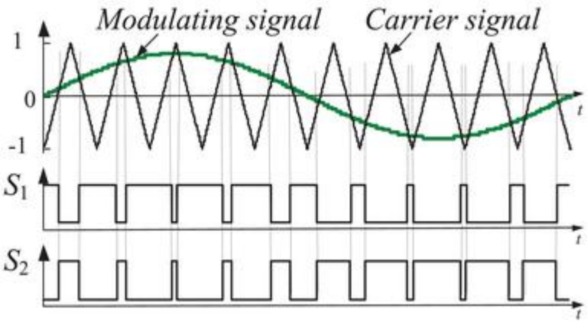
SPWM works by comparing a sinusoidal reference signal with a high-frequency triangular carrier wave to generate gate signals for the inverter switches. This method allows for smooth variation of output voltage and frequency, making it suitable for most standard industrial applications.

On the other hand, SPM is a more advanced technique that utilises the concept of space vectors to synthesise the desired output voltages. It offers better DC bus utilisation, lower harmonic distortion, and improved efficiency compared to SPWM, especially in high-performance drive applications.

Pulse Width Modulation Techniques

A. Sinusoidal PWM (SPWM)

This method generates PWM pulses by comparing a sinusoidal reference signal with a triangular carrier wave. For three-phase systems, three reference signals displaced by 120° are used, corresponding to each phase, to generate the gating pulses for that phase. Comparing the carrier signal with three sin reference waves, the result is a 2-level PWM pulse for each phase, controlling the corresponding inverter switch as shown in Fig. 7.



[Fig.7: 2-Level PWM Pulses for Three-Phase Inverter]

B. Space Vector PWM (SVPWM)

SVPWM treats the three-phase inverter output as a rotating voltage vector in the α-β reference frame. It synthesizes this reference vector using combinations of eight switching states (six active and two zero vectors), forming a hexagonal space vector diagram. This technique offers improved DC bus utilisation and lower harmonic distortion compared to SPWM. The switching sequence depends on the sector where the reference vector lies.

V. PID CONTROLLER

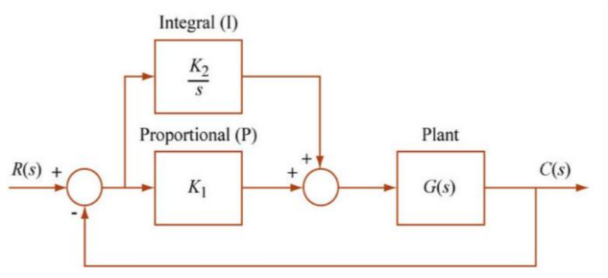
The Proportional–Integral–Derivative (PID) controller plays a vital role in regulating the speed of induction motors within closed-loop control systems. It is designed to generate precise control signals for the Pulse Width Modulation (PWM) generator, ensuring that the motor operates at the desired speed under varying load conditions.

In this configuration, the actual speed of the motor is continuously monitored and fed back to the controller. This feedback signal is compared with a predefined reference or set-point speed. The resulting difference, or error signal, is supplied to the PID controller, which processes it to produce a corrective control signal. This signal then modulates the PWM pattern applied to the inverter switches, thus adjusting the motor voltage and frequency accordingly.

PID is composed of three distinct parameters:

- **Proportional (P)**: Reacts to the current error value, providing a control signal proportional to the magnitude of the error.
- **Integral (I)**: Accounts for the cumulative sum of past errors, eliminating steady-state offsets and improving accuracy over time.
- **Derivative (D)**: Predicts future error trends by observing the rate of change, enhancing system stability and dynamic response.

In this project, the derivative component is omitted, as it causes noise sensitivity and instability in systems. A schematic of a closed-loop speed control system using a PI controller is shown in Fig. 8. This setup ensures precise tracking of the reference speed, minimizes steady-state error, and enhances dynamic performance under load disturbances.



[Fig.10: Closed Loop System Applying PI Controller]

VI. SIMULATION RESULTS AND DISCUSSION

For the Simulink model design, the Induction motor ratings used are listed in TABLE I below.

Table I. Induction Motor Ratings for Squirrel Cage Rotor

Rated Power	5.4 HP (4 KW)
Speed	1430 RPM
Voltage	400V
Frequency	50 Hz
Number of Poles	2

To analyse the open-loop and closed-loop speed control of an induction motor by a three-phase VSI (IGBT-based universal bridge) using a constant V/F ratio and compare the performance of SPWM-based inverters, MATLAB/Simulink has been used. The simulation model has been illustrated in Fig. 8.

A. Control Strategies for Speed Regulation

i. Open-Loop Control

Open-loop systems operate without feedback, offering

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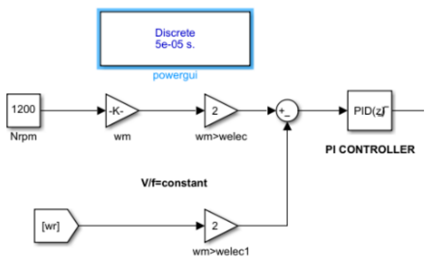
simplicity but limited adaptability. Here, the inverter delivers SPWM-controlled voltage to the induction motor without any speed feedback. Although the system responds to the input conditions, its dynamic performance is limited.

ii. Closed-Loop Control

In closed-loop control, a feedback signal constantly improves the speed response, reduces the error, and a better dynamic behaviour is obtained. Hence, a PI controller was used in place of a PID controller, as it is commonly employed in scalar control techniques. The Proportional-Integral (PI) controller adjusts the inverter's output based on the real-time speed of the motor, measured in RPM.

The system dynamically adjusts the modulation frequency, thereby fine-tuning the induction motor speed without requiring a system restart.

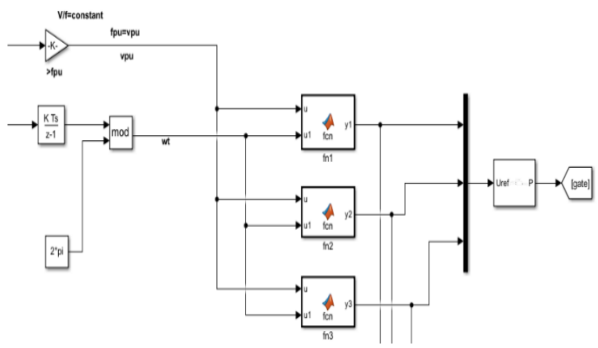
A PI controller with constants Kp = 1 and Ki = 30 was used. Simulations were carried out to obtain the results through manual tuning of the Proportional-Integral Controller. The PI gains were selected and tuned to this by a trial-and-error method based on minimizing the THD values and overshoots. The reference speed is set to a specific RPM in a closed-loop system. With the discrete sampling time being $50\mu sec$. The induction motor used has two poles.



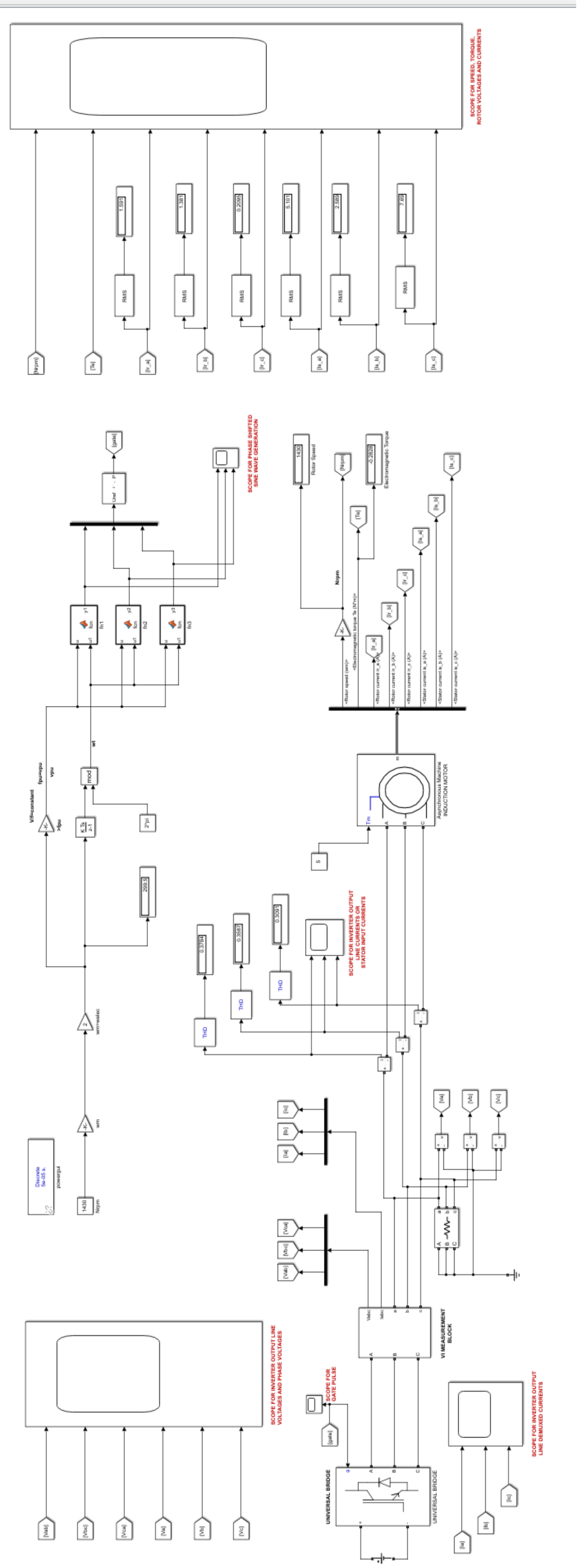
[Fig.11: Closed-Loop PI Controller Design for Discrete Mode]

Here, the actual speed of the induction motor is compared to the reference speed, and the difference between the two generates an error signal for the PI controller, which is processed by it. Then the controller output sets the frequency of the VSI, and a faster, steady-state response is achieved using a PI controller instead of a PID Controller.

For evaluating the performance of the SPWM-based inverter and for generating sinusoidal control signals required for the PWM generator, the following SPWM structure has been illustrated using MATLAB Function Blocks, as shown in Fig. 10.



[Fig.12: SPWM Structure for Closed-Loop VSI]



[Fig.8: Simulink Model for Open-Loop Speed Control of Three-Phase Induction Motor using Three-Phase Inverter and Sinusoidal Pulse Width Modulation]

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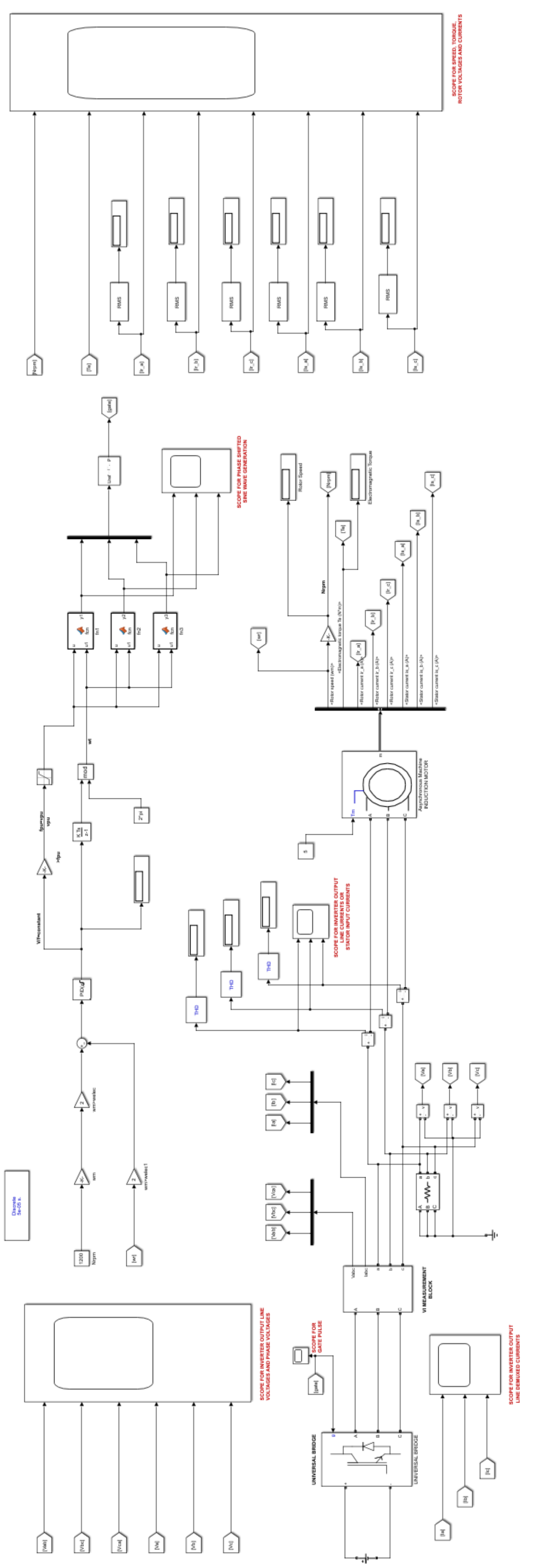
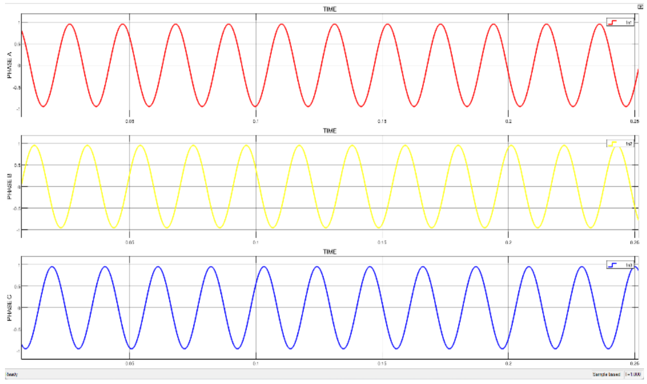


[Fig.9: Simulink Model for Closed-Loop Speed Control of Three-Phase Induction Motor using Three-Phase Inverter and Sinusoidal Pulse Width Modulation]

The generated sinewaves are shown in the figure below.

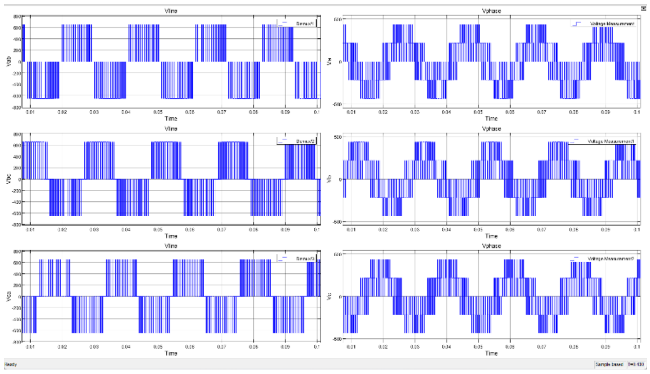


[Fig.13: Phase Shifted Sine Waveforms for 2-Level SPWM Injection]

B. Comparison And Evaluation of Open-Loop and Closed-Loop Simulations

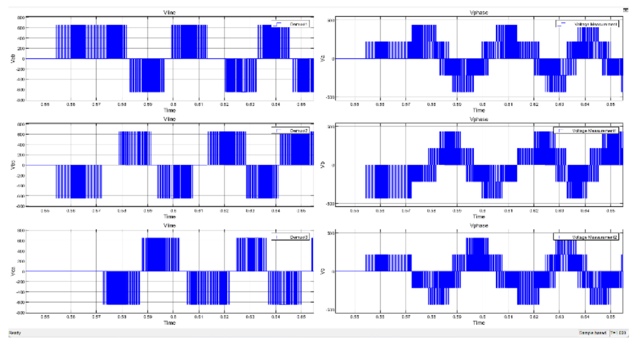
From the simulations, it is observed that speed fluctuations occur when loads are varied. The PI controller adjusts the speed accordingly when the load changes.

Additionally, dimensional variations in height and width are observed for the Voltage Source Inverter outputs, including the Line and Phase Voltages and Line Currents. These rectangular voltage pulses maintain a sinusoidal pattern.



[Fig.14: VSI Output Waveforms of Line Voltage, Phase Voltage of Open-Loop at 1Nm Torque]

Since no significant changes in speed and torque can be observed due to mechanical load variation in Open-Loop control, it can be inferred that an Open-Loop V/f control works well in applications with near-constant load torque and gradual changes in rotational speed.



[Fig.15: VSI Output Waveforms of Line Voltage, Phase Voltage of Closed-Loop at 1Nm Torque]

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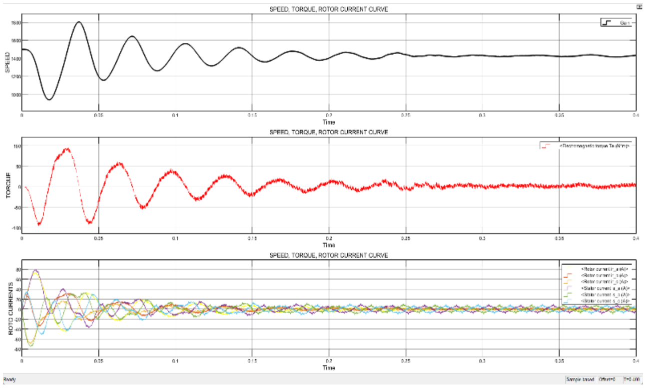
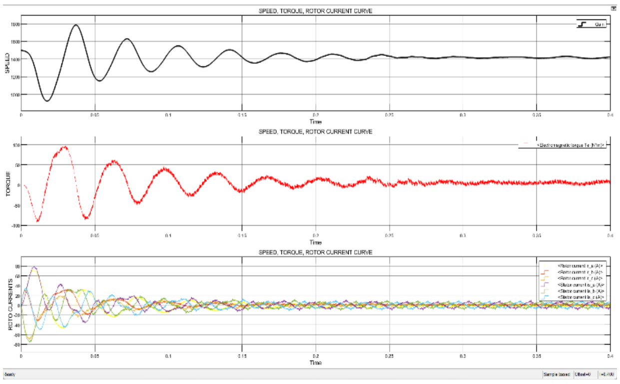


[Fig.16: Waveforms of Speed, Torque and Rotor Currents of Open-Loop 1Nm Load]



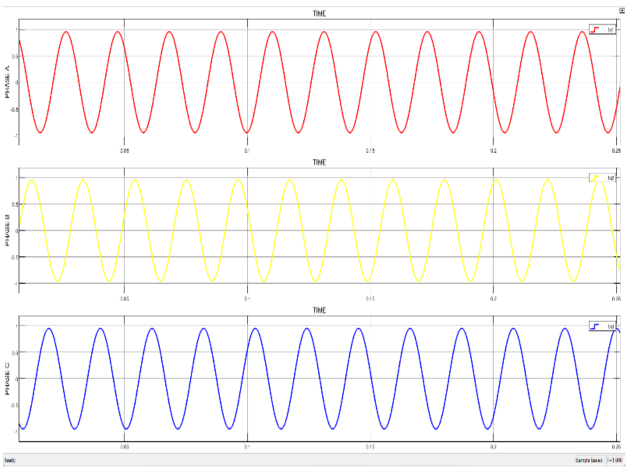
[Fig.17: Waveforms of Speed, Torque and Rotor Currents for Open-Loop at 5Nm Load]

The controllers implementing this method are referred to as general-purpose AC drives. Whereas in the later part of this section, variations in the above parameters are visible for Closed-Loop.

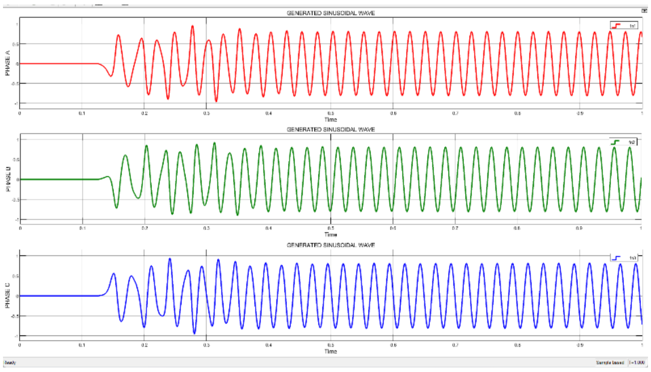
The variation in generated sine waveforms between open-loop and closed-loop configurations at a constant load of 5 Nm is shown in the figures below. No significant overshoot is visible in either of the figures.

The PI Controller with SPWM technique significantly reduces harmonics after manual tuning, delivering an almost sinusoidal waveform in the Stator input line currents**.**

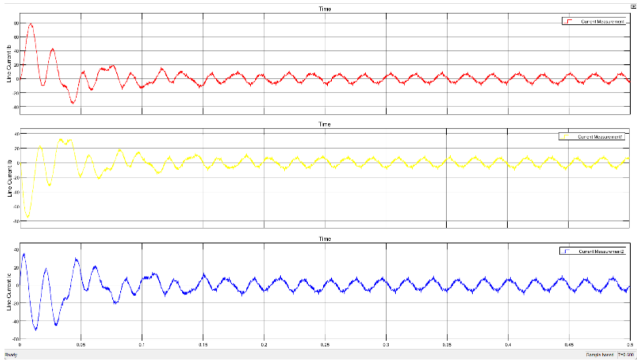
The following simulation results illustrate the changes in speed, torque, and rotor currents as the mechanical loads increase.



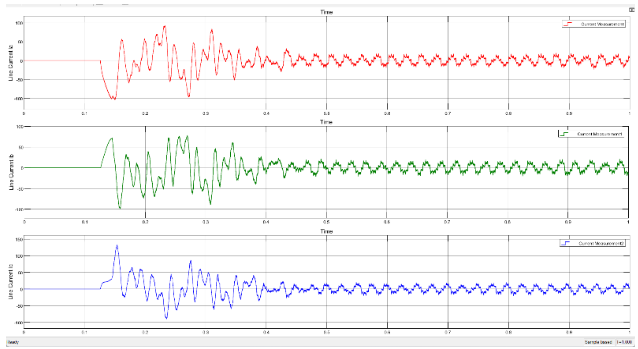
[Fig.18: 120-degree Phase-Shifted Sinusoidal Waveforms Generated for Open Loop at 5Nm Load Run for 1 Sec]



[Fig.19: 120degree Phase-Shifted Sinusoidal Waveforms Generated for Closed loop at 5Nm Load Run for 1sec]

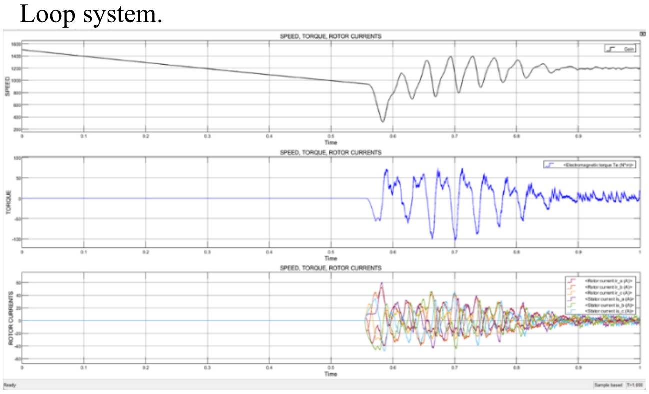


[Fig.20: Waveform of Line Currents Open-loop at 5Nm Load]



[Fig.21: Waveform of Line Currents Closed-Loop at 5Nm Load]

Gradually from 1 Nm to 5 Nm and so on for the Closed-Loop system.



[Fig.22: Waveforms of Speed and Torque of Closed-Loop Speed Control of Three-Phase Induction Motor using Three-Phase Inverter at 1Nm Load]

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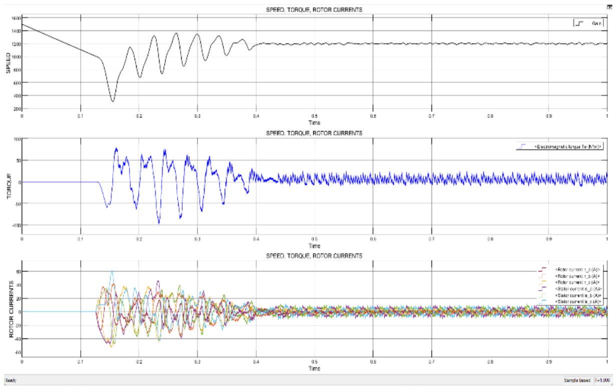
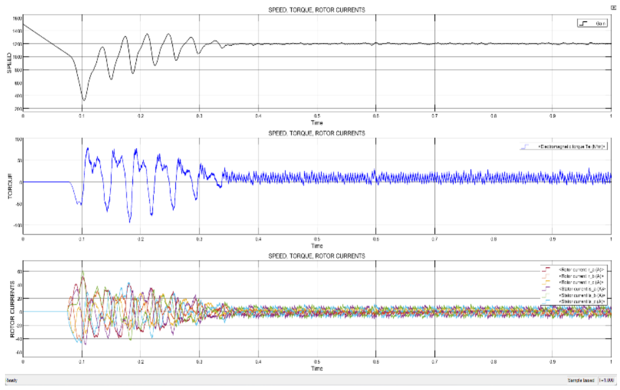


[Fig.23: Waveforms of Speed and Torque of Closed-Loop Speed Control of Three-Phase Induction Motor using Three-Phase Inverter at 5Nm Load]



[Fig.24: Waveforms of Speed and Torque of Closed-Loop Speed Control of Three-Phase Induction Motor using Three-Phase Inverter at 8 Nm Load]

Initially, the rotor is at standstill for a 1 Nm load, and a fast speed response is observed at higher loads due to the presence of the PI controller in the feedback loop. Thus, it achieves a better performance by settling around the reference speed faster in a closed loop.

VII. CONCLUSIONS

The scalar control V/f method was implemented successfully for both open-loop and closed-loop schemes. Appropriate speed responses to changes in load and speed, as well as torque responses, were observed, and the controller's response to load applications was found satisfactory. Several MATLAB/Simulink simulations involving the IGBT-based universal Bridge VSI with SPWM control were performed by varying the PI Controller gains to analyse the induction motor and controller behaviour. SPWM control technique lowered the THD with a sine wave output in the stator and rotor currents of the induction motor.

From the simulations and results, it can be concluded that the scalar V/f control in the Closed-Loop provides a better and faster response compared to the Open-Loop V/f control of the three-phase induction motor, especially when using SPWM. Thus, SPWM sets the stage for a deeper investigation into inverter-based speed control strategies for induction motors, emphasising the practical relevance, technical complexity, and importance of high-fidelity control techniques.

Additionally, the MATLAB simulation environment enables safe and flexible testing, making it a powerful tool for verifying designs and comparing performance before implementing them in real-world scenarios.

FUTURE SCOPE

The future scope of V/f control can be significantly enhanced through integration with intelligent control algorithms, such as incorporating artificial intelligence (AI), fuzzy logic, or neural network-based tuning mechanisms. Incorporating these mechanisms into scalar V/f control could enable adaptive and self-optimising performance, reducing sensitivity to load disturbances and parameter variations. Hybrid Control Strategies, such as combining V/f control with aspects of vector control or model predictive control (MPC), can create hybrid systems that offer improved dynamic response while retaining the simplicity of scalar methods in steady-state conditions.

The increasing availability of powerful yet inexpensive microcontrollers and digital signal processors (DSPs) enables more advanced V/f implementations with real-time monitoring, diagnostics, and remote control capabilities through Internet of Things (IoT) platforms. Advanced PWM techniques, when integrated with V/f control, can also improve voltage utilization, reduce harmonics, and enhance motor efficiency, especially in low-speed operations.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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