

Variable Frequency Drive of Induction Motor Using Various SPWM Technique

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ABSTRACT

This paper presents the implementation of the Sinusoidal Pulse Width Modulation (SPWM) technique for controlling an induction motor in a variable frequency drive (VFD) system. The SPWM technique generates sinusoidal three-phase alternating current (AC) by comparing the amplitudes of carrier and modulation waves, which is then applied to an induction motor (IM), specifically an asynchronous three-phase motor. Simulations are conducted to compare the performance of conventional Pulse Width Modulation (PWM) and SPWM techniques in terms of current, electromagnetic torque, and rotor speed. The results indicate that the SPWM control technique provides greater stability for the induction motor system, especially during low-speed operation, where it reduces starting current and minimizes mechanical stress. The current waveform shows that the SPWM-controlled motor draws a significantly lower inrush current of 25A compared to the 37A drawn by the PWM-controlled motor. Similarly, the SPWM-controlled motor produces a starting torque of 16 Nm, compared to 32 Nm generated by the PWM-controlled motor. These findings suggest that SPWM offers superior performance at low speeds, mitigating the high inrush current associated with PWM, which can harm the motor over time. The SPWM technique demonstrates better control and stability for induction motors at low speeds, making it a more effective and reliable choice than PWM in applications where minimizing mechanical stress and enhancing motor longevity are critical.

1. Introduction

Variable frequency drives (VFDs) are employed across a wide range of applications, from small appliances to large compressors. Stricter pollution regulations and the increasing demand for greater reliability and availability have led to a growing interest in electric drive systems among end customers, as noted by Aazmi *et al.*, [1]. I. M. Alsofyani and Idris [2] highlighted that VFD-based systems can be more efficient than those relying on throttling control of fluid flow, such as in systems with pumps and fan dampers. Moreover, VFDs are gaining prominence in industrial and commercial environments due to their ability to control motor speed and improve energy efficiency. According

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to Hassan *et al.*, [3], among the three main VFD designs for pulse-width modulation (PWM), current source inverter, and voltage source inverter which PWM is the most commonly used, as it effectively adjusts pulse width to control output frequency and voltage.

However, the growing use of VFDs raises concerns about issues such as total harmonic distortion and power quality. Research conducted by Hassan *et al.*, [4] suggests that VFD-fed electric motors (EMs) may experience challenges related to power quality and reliability, particularly due to voltage harmonics, which can affect the performance of systems like heating, ventilation, and air conditioning (HVAC) chillers. Additionally, Xu *et al.*, [5] noted that the high switching speed and frequency of wide-bandgap motor drives can introduce motor bearing current issues, potentially causing bearing degradation over time. With the increased integration of renewable energy sources into power grids, enhancing system flexibility and optimizing the placement of components has become essential. Yang *et al.*, [6] developed models to co-optimize the locations of variable series reactors and phase-shifting transformers to accommodate high levels of wind power penetration, thus ensuring the stability and efficiency of power systems with substantial renewable energy generation.

The integration of variable renewables, such as wind and solar power, into electricity markets has also prompted concerns about market value and effective policy actions. Chatterjee and Das [7] argued that strategies to prevent the decline in market value for variable renewables require policy interventions to address the challenges of high penetration, thereby supporting their continued integration and contribution to the energy mix.

Markovic *et al.*, [8] explained that the PWM technique is widely adopted for controlling induction motors, offering a more effective solution compared to traditional methods such as voltage supply management, rotor resistance control, and pole changing. In industrial settings, electricity powers motors, and Xu and Liu [9] noted that if traditional methods are continued, the power dissipation of induction motors will result in high energy consumption, potentially leading to increased electricity costs. Another issue with inverter drives is the non-sinusoidal nature of the supply voltage, which increases motor losses and introduces undesirable torque pulsations, leading to speed oscillations. Low-frequency torque pulsations and speed ripples, though sometimes imperceptible, can cause abnormal gear tooth wear or torsional shaft failure, as noted by Bae *et al.*, [10] and Aazmi *et al.*, [11]. Thus, regulating induction motor speed is critical in many applications. Shindo and Jin'no [12] explained that when a voltage source inverter is used, PWM techniques are typically employed to modify the quasi-square waveform, reducing or eliminating low-order harmonic voltage components, which in turn minimizes torque pulsations and enhances efficiency.

Control methods such as sinusoidal pulse width modulation (SPWM) are essential in improving the performance of VFDs with induction motors, as demonstrated by Sharma *et al.*, [13] and Shim *et al.*, [14]. Irimie *et al.*, [15] recognized SPWM for its effectiveness in reducing common-mode voltage in asynchronous motor drives, which is crucial for improving overall system reliability and stability. Comparing traditional PWM with SPWM based on parameters such as current, electromagnetic torque, and rotor speed provides insights into the advantages of advanced modulation techniques like SPWM in VFDs. These studies contribute significantly to ongoing efforts to enhance the efficiency and control of induction motor systems, ultimately leading to improved performance and reliability in both industrial and commercial applications.

2. Methodology

The methodology for analyzing the dynamic response of an Induction Motor (IM) in a Variable Frequency Drive (VFD) system employing various Sinusoidal Pulse Width Modulation (SPWM) techniques involves several key steps. Firstly, the motor model is developed considering its dynamic characteristics, such as inertia, resistance, and leakage inductance. The SPWM modulation technique parameters are configured based on the desired motor performance specifications.

Next, transient simulations are conducted using tools like MATLAB/Simulink to observe the motor's dynamic response to changes in speed or load torque. These simulations evaluate key performance metrics, including settling time, overshoot, and transient stability, under different operating conditions.

Analysis of the dynamic response data helps optimize the SPWM modulation technique parameters to enhance the motor's transient performance while ensuring stability and reliability. Iterative refinement of the control algorithm and modulation technique may be performed based on the observed dynamic response characteristics, ultimately leading to an efficient and responsive VFD system for induction motor control

2.1 Sinusoidal Pulse Width Modulation Technique

In the SPWM approach, the sinusoidal AC voltage reference is compared to the high frequency triangle carrier in real time to identify the switching states for each pole in the inverter. The peak-to-peak value of the triangle carrier wave is represented by the DC-link voltage, V_{dc} . For linear modulation in this PWM approach, the voltage reference V_{ref} must have an amplitude less than the peak of the triangle carrier V_c , i.e., $V_{ref} < V_{dc}/2$. A carrier-based PWM approach is one that uses a high frequency carrier wave for voltage modulation. This carrier-based approach is known as SPWM because the reference is shaped like a sine wave. This is also known as the triangle comparison PWM technique since it employs a triangular wave's carrier. Figure 1 illustrates the sinusoidal pulse width modulation (SPWM) technique for single phase, as described by L. T. Phuc and D. C. Tri[16].

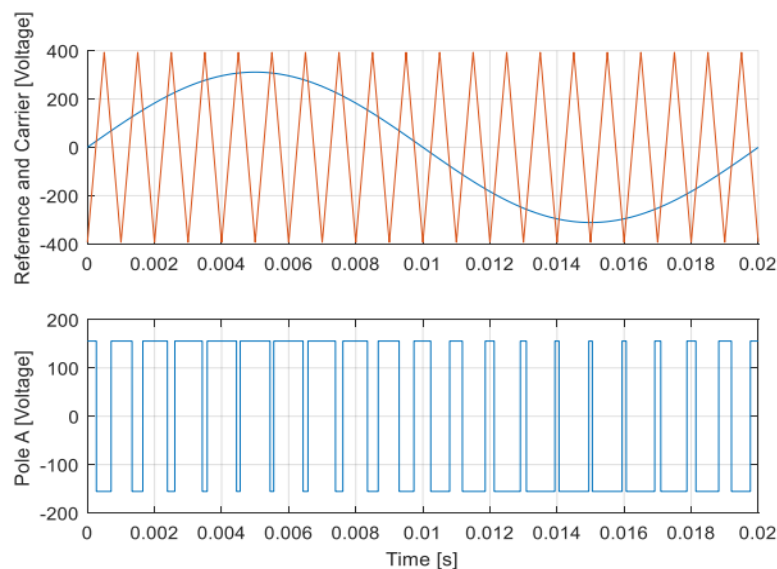


Fig. 1. Sinusoidal pulse width modulation (SPWM) for single phase

In carrier-based PWM approaches, the desired voltage reference waveform is known as a modulating wave. Furthermore, a wave modulated by the modulating wave is referred to as a carrier

wave or carrier. The carrier wave often has a significantly greater frequency than the modulation wave. The triangle waveform is the most often utilised carrier in the PWM method for modulating AC voltages was stated by Suresh *et al.*, [17]. In contrast, the PWM approach allows for the employment of several types of modulating waves. Sinusoidal modulation is the most used SPWM method.

The pole voltage is an inverter output that is calculated by comparing a voltage reference to the triangular carrier wave. Thus, the voltage reference compared to the triangular carrier wave is referred to as the pole voltage reference. The typical SPWM approach employs a phase voltage reference as the pole voltage reference. In contrast, PWM approaches allow for the use of different pole voltage references was mentioned by Lapcin *et al.*, [18]. In this PWM based on the triangle wave, if the ratio of carrier frequency to fundamental frequency is big enough (more than 21), the fundamental component of the output voltage fluctuates linearly with the reference voltage for a constant DC-link voltage as Eq. (1) and Eq. (2);

$$V_{o1} = V_{ref} \sin \omega t \quad (1)$$

Here, since

$$V_{ref} \leq \frac{V_{dc}}{2}, \text{ so } 0 \leq M \leq 1 \quad (2)$$

Where M is modulation index. The range of $0 \leq M \leq 1$ is called the linear modulation range. In this range, the inverter can generate an output voltage linearly proportional to the reference voltage. In this case, the PWM inverter is considered to be simply a voltage amplifier with a unit gain.

2.2 Simulation PWM with Induction Motor

Figure 2 presents a sophisticated MATLAB Simulink simulation model designed to emulate the operation of an induction motor driven by a pulse width modulation (PWM) inverter. The depicted model incorporates a DC voltage source, representing a battery, that supplies power to an inverter circuit implementing a PWM switching method. The target of this system is a 3-phase induction motor with specified characteristics of 5.5 horsepower, a rotational speed of 1500 rpm, consisting of four poles, operating at a frequency of 50 Hz, and a rated voltage of 400 V.

The pivotal element of this simulation is the PWM inverter, which manipulates the DC input voltage to generate a variable-frequency, variable-voltage AC output to control the speed and torque of the induction motor. The core principle of PWM involves generating electrical pulses of varying widths to synthesize an analog signal from a digital source. This modulation technique adjusts the power supplied to the motor by altering the width of these pulses, effectively changing the average voltage and frequency of the electrical supply.

In this simulation, the PWM inverter employs a carrier-based PWM method. This specific strategy involves the generation of PWM signals by comparing a high-frequency triangular carrier waveform with a low-frequency sinusoidal reference signal. The comparison yields a set of pulses with widths that vary in proportion to the amplitude of the sinusoidal reference, which is pivotal for accurately controlling the inverter output.

This generated set of pulses is then used to control the conduction state of the IGBTs (Insulated Gate Bipolar Transistors) in the inverter bridge. IGBTs, with their high efficiency and fast switching capabilities, are semiconductor devices that serve as the switching elements within the inverter. Each

IGBT is paired with a diode to ensure that current can flow in the appropriate direction during each part of the electrical cycle.

The model is designed with pulse generators labelled PG1 through PG6, which are responsible for dictating the precise timing of the IGBT gate signals. These gate signals determine the sequence of switching events that ultimately shape the AC output that drives the motor be placed at the center.

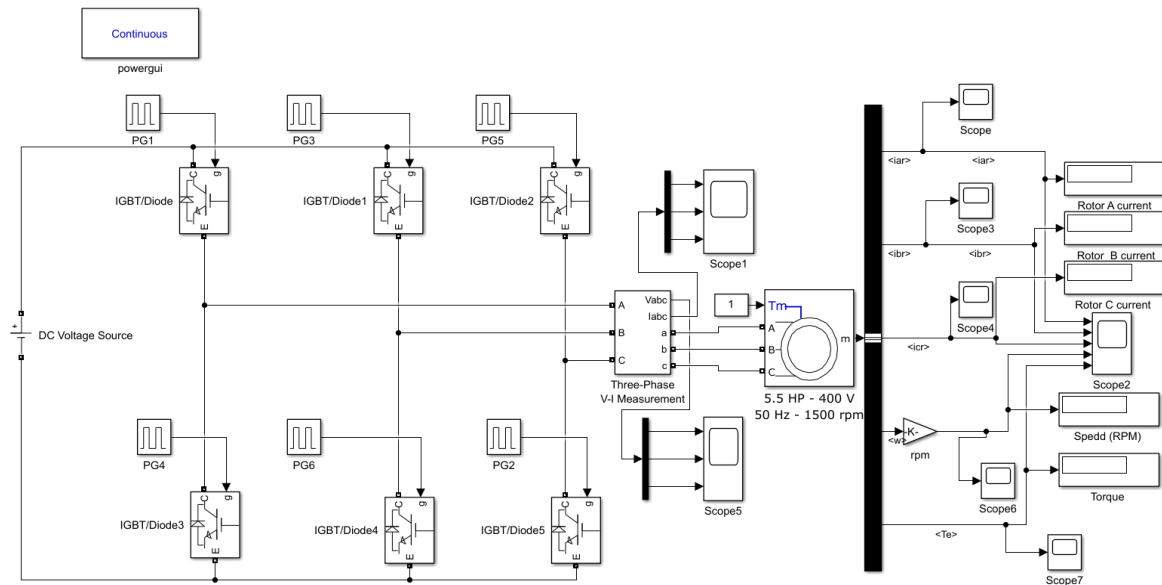


Fig. 2. Simulation model of PWM with induction motor

The intention of the simulation is to yield outputs that represent key performance characteristics of the motor, specifically the current waveform, the electromagnetic torque, and the rotor speed. The current waveform is a crucial output of the simulation, representing the instantaneous flow of electric current through the motor windings. The PWM inverter's primary function is to manipulate the supplied DC voltage into an AC waveform that resembles the sinusoidal input power of conventional AC motors. The quality of the current waveform is significant because it directly impacts the motor's efficiency, power factor, and harmonic distortion.

The electromagnetic torque is another critical output of the simulation. It is the torque produced by the electromagnetic interaction between the stator and rotor magnetic fields. This torque is what eventually causes the rotor to turn and is a direct indicator of the mechanical power output of the motor. In the context of this simulation, electromagnetic torque is a pivotal metric to assess how effectively the PWM inverter drives the motor under various load conditions. It is an essential aspect for understanding the dynamic performance and tuning the control strategy to achieve the desired speed-torque characteristics.

The rotor speed of the induction motor, which is the speed at which the motor's rotor rotates, is a critical output that can be monitored. It is measured in revolutions per minute (rpm). The simulation aims to determine how changes in the input voltage and frequency, as controlled by the PWM inverter, affect the rotor speed. This aspect of the simulation is vital for applications where precise speed control is necessary, such as in variable-speed drives used in industrial applications. The interplay between the current waveform, electromagnetic torque, and rotor speed is at the heart of the simulation model's purpose. By adjusting the PWM signals, engineers can explore the motor's response to different control strategies and operational scenarios. The simulation allows for the adjustment and fine-tuning of the PWM control method to optimize the motor's performance for efficiency, reduced electrical noise, and improved speed control.

2.3 Simulation SPWM with Induction Motor

The SPWM is generated by comparing the amplitude values of two waves with different frequency, the carrier and the reference wave. Normally, the carrier wave takes the form of a triangle, represented by f_c . The reference wave is represented as f_m . The relation between the carrier and the reference wave is in Eq. (3) state by H. Huiming *et al.*, [19].

$$M = \frac{f_c}{f_m} \quad (3)$$

The carrier frequency will be significantly larger than the modulation frequency. This value is determined by the motor's and the power transistor's operating modes. If the carrier frequency is set too high, power transistors might overheat. On the contrary, the carrier frequency is set too low, resulting in an unstable output voltage was also mentioned by Sreenivasa *et al.*, [20] and Oraon *et al.*, [21].

Figure 3 is a graphical representation of a MATLAB Simulink model demonstrating the implementation of sine pulse width modulation (SPWM) as the inverter switching technique for an induction motor system. In this simulation model, the core component is the SPWM generator block that intricately modulates the gating signals for the inverter's switches, typically Insulated Gate Bipolar Transistors (IGBTs) paired with diodes for current rectification. These switches are represented by the IGBT/Diode blocks, which receive the SPWM signals and accordingly convert the steady DC voltage supplied by the DC voltage source into a three-phase AC output.

In this SPWM generator model, three sine wave blocks generate reference sine wave signals, each likely representing a phase of the three-phase system. These signals are each compared against a common triangular waveform, typically produced by the sawtooth generator block. The triangular waveform, or carrier signal, serves as a comparison threshold for the modulation process. The comparison effectively modulates the width of the pulses based on the amplitude of the sine wave. The outputs of the comparator blocks are then passed through logical operator blocks to produce the complementary gating signals. In an actual inverter, these signals would drive the high-side and low-side switches of each inverter leg, creating an AC output from a DC input.

The SPWM technique allows for the creation of a stepped voltage waveform that approximates a sine wave with less harmonic distortion than simple square wave PWM, providing finer control over the motor speed and torque by varying the frequency and amplitude of these pulses.

The IGBTs (Insulated-Gate Bipolar Transistors) function as switches in the inverter to convert the DC from the voltage source into AC. Each IGBT is paired with a diode. When the SPWM signals trigger the IGBTs, they switch on and off at high frequency, creating a pseudo-AC waveform. The phase and frequency of the voltage applied to the motor determine the speed and direction of the rotor. The DC voltage source provides the direct current input to the inverter, which is then switched by the IGBTs to produce a variable frequency, variable voltage output to drive the motor. The output from the inverter is fed to the motor. The variable-frequency AC creates a rotating magnetic field within the motor stator, which induces current in the rotor. This induced current in the rotor interacts with the magnetic field, producing electromagnetic torque that causes the rotor to turn.

The electromagnetic torque and speed of the rotor are controlled by adjusting the frequency and amplitude of the SPWM signals, which, in turn, control the output voltage and frequency of the inverter. The torque produced is proportional to the product of the stator current and the strength of the magnetic field. The rotor speed can be adjusted by changing the frequency of the inverter's output. For an induction motor, the rotor speed is slightly less than the synchronous speed, which is determined by the frequency of the stator's magnetic field.

This system works as a closed-loop control system, where the SPWM generator adjusts the IGBT gating to regulate the output power of the inverter, which in turn controls the speed and torque of the motor. The actual speed and torque are continuously monitored and compared to the desired values, and the SPWM signals are adjusted accordingly to achieve precise control of the motor operation.

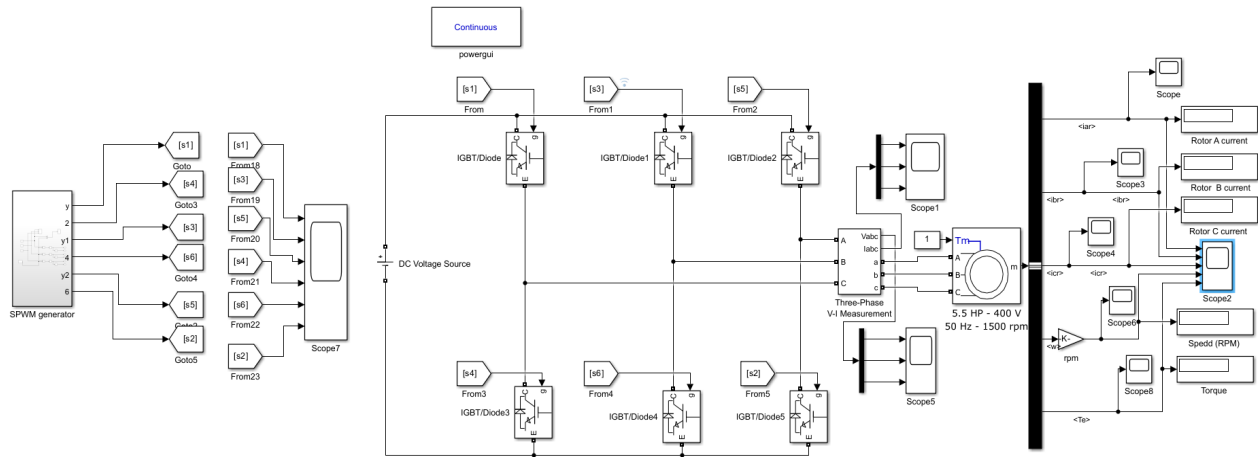


Fig. 3. Simulation model of SPWM with induction motor

3. Results

The development of three-phase inverters for powering induction motors represents a cornerstone in modern power electronics and motor control strategies. Specifically, the design of such inverters to energize a three-phase induction motor with characteristics like 5.5 horsepower, a rated voltage of 400 V, a frequency of 50 Hz, and a speed of 1500 rpm is a scenario closely aligned with industrial applications where precision and efficiency are paramount.

Recent simulation studies shed light on the efficiency gains achieved when Sinusoidal Pulse Width Modulation (SPWM) control is employed in three-phase inverters as opposed to traditional Pulse Width Modulation (PWM) techniques. SPWM stands out in its ability to mimic a pure sinusoidal voltage waveform more closely than PWM, which is inherently blocky and less sinusoidal. This improved waveform fidelity directly correlates with enhanced motor performance.

One of the key findings from these simulations is the reduction in starting current required by the motor when powered by an SPWM-controlled inverter. The high inrush current commonly associated with the initiation phase of motor operation is significantly mitigated, which is essential to reduce electrical stresses and potential damage to the motor windings and related electrical components.

In terms of torque, SPWM provides a more stable and consistent torque output, which eliminates the torque pulsations that can occur with traditional PWM. This smooth torque delivery is crucial for applications requiring precision and for the longevity of mechanical components connected to the motor shaft.

Finally, rotor speed regulation under SPWM control shows improved consistency. The ability to finely control the frequency of the voltage waveform ensures that the motor operates at the desired speed with minimal deviation, which is particularly important for processes that are sensitive to speed variations. The adoption of SPWM control in three-phase inverters demonstrates clear advantages over traditional PWM for operating a three-phase induction motor. The simulation results convincingly advocate for SPWM's role in improving starting current profiles, torque

smoothness, voltage quality, and rotor speed stability, thus enhancing overall motor efficiency and reliability in industrial settings

3.1 Induction Motor Current Waveform

Figure 4 and Figure 5 visually compare the current waveforms of an induction motor when operated using Pulse Width Modulation (PWM) and Sinusoidal Pulse Width Modulation (SPWM) techniques. These graphical representations provide a clear insight into how each control method affects the motor's initial and steady-state performance characteristics, offering a basis for evaluating the efficiency, operational smoothness, and longevity of the motor under each method.

In Figure 4, which represents the PWM technique, a significant inrush current of approximately 37 amperes is observed at start-up. This high initial current is due to the sudden application of voltage to the motor windings, which, in their initial state, offer minimal resistance and therefore draw a large amount of current. This surge can result in increased mechanical and thermal stress, potentially shortening the motor's operational lifespan. While the PWM method efficiently regulates the motor's speed, the large inrush current and subsequent torque pulsations caused by the stepped nature of PWM can introduce mechanical strain. Nevertheless, the PWM-controlled motor reaches a steady state relatively quickly around 0.25 seconds where the current stabilizes and the motor operates more efficiently. This rapid transition is ideal for applications that require a quick response time, but it comes with the trade-off of potential wear and tear on the motor due to the abrupt starting current.

In contrast, Figure 5 demonstrates the SPWM technique, where the starting current is significantly lower, approximately 25 amperes. This gentler start is a result of SPWM's gradual voltage increments, which effectively reduce the inrush current and thus impose less strain on the motor's components during start-up. The SPWM technique introduces smoother voltage transitions, which not only reduce the initial mechanical stress but also decrease the likelihood of thermal overload. While the SPWM-controlled motor takes longer approximately 0.4 seconds to reach a steady state, the benefits of this smoother waveform are evident. SPWM produces a more sinusoidal current with fewer ripples, resulting in reduced harmonic distortion and less electrical noise. This smoother operation is particularly advantageous for applications where efficiency, noise reduction, and motor longevity are paramount.

The comparison between these two techniques highlights several key differences. PWM provides a quicker response and reaches a steady state faster, making it suitable for applications where speed of operation is a priority. However, the higher inrush current and resultant torque pulsations may introduce wear over time. On the other hand, SPWM, with its smoother and more sinusoidal waveform, offers a more refined approach. By minimizing harmonic distortion and inrush current, it not only contributes to quieter operation but also enhances the overall efficiency and lifespan of the motor. The trade-off, however, is a slightly delayed response in reaching steady state, which may be a limitation in applications requiring rapid motor control.

From an efficiency perspective, SPWM holds an advantage in maintaining motor performance over long periods, particularly in sensitive applications such as precision manufacturing or HVAC systems, where smoother operation and lower noise levels are essential. PWM, while robust and quick to respond, may be better suited for industrial applications where high-power output and rapid speed adjustments are required, and the slight increase in wear and tear is less of a concern.

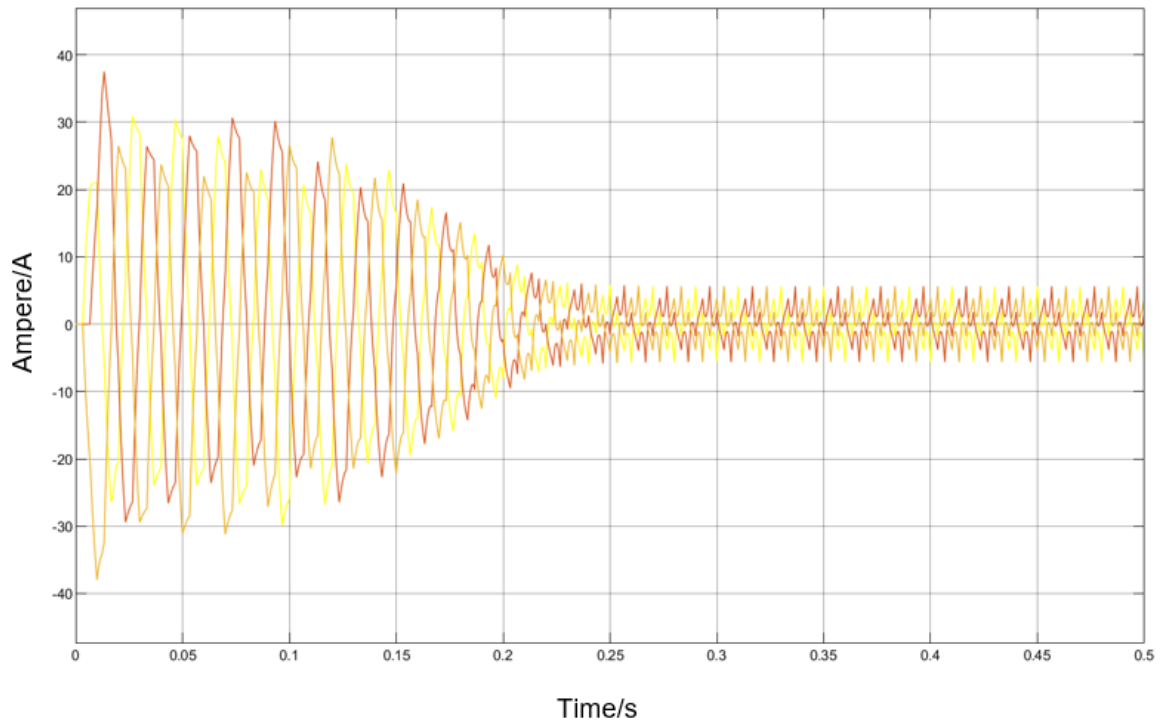


Fig. 4. Current waveform of PWM with induction motor

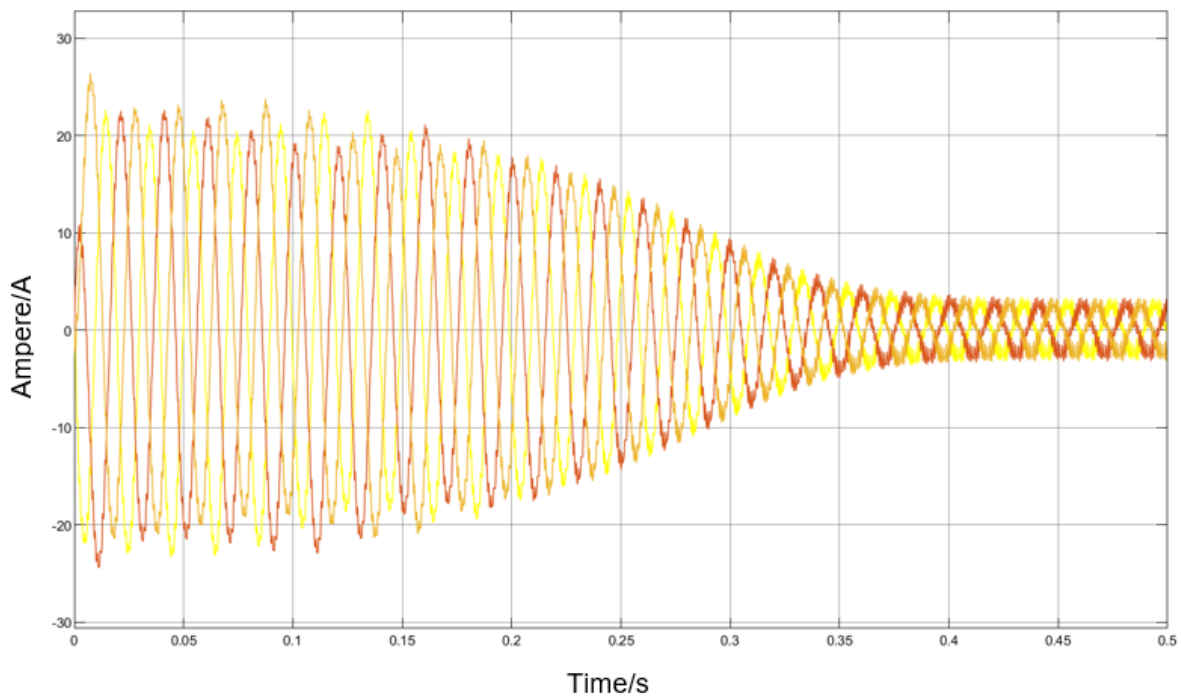


Fig. 5. Current waveform of SPWM with induction motor

3.2 Induction Motor Electromagnetic Torque

Figure 6 and Figure 7 provide a comparative analysis of the electromagnetic torque response of an induction motor controlled by Pulse Width Modulation (PWM) and Sinusoidal Pulse Width Modulation (SPWM) techniques, respectively. These figures allow for a detailed assessment of how

each switching method affects motor performance, particularly during the critical start-up phase and as the motor approaches steady-state operation.

In Figure 6, the torque response produced by the PWM method shows a sharp initial peak of approximately 34 Nm. This high starting torque is directly related to the significant inrush current associated with the PWM technique, where the rapid on-off switching of the voltage supply creates an immediate and forceful reaction from the motor. While this high starting torque can be beneficial in applications requiring quick acceleration, it also introduces mechanical stress, which can lead to increased wear and tear on the motor's components. However, despite this initial surge, the motor achieves a steady-state condition relatively quickly, stabilizing at around 0.3 seconds. This rapid transition is an advantage in applications where prompt and efficient motor operation is essential.

Conversely, in Figure 7, the SPWM technique exhibits a much lower starting torque of approximately 16 Nm. This reduced torque is due to SPWM's ability to emulate a smoother, more sinusoidal waveform, thereby reducing the initial inrush current and minimizing mechanical stress on the motor. The gentler torque increase not only helps to extend the life of the motor by reducing wear but is also advantageous in applications that require smooth start-up performance, such as precision machinery or systems where gradual acceleration is preferable. However, this advantage comes with a trade-off for SPWM method takes longer to reach a steady state, achieving stable torque output around 0.45 seconds, which is notably slower than the PWM method.

One noteworthy aspect of the comparison is the presence of increased torque ripple in the SPWM-controlled motor. Torque ripple refers to the small fluctuations in torque output that occur with each rotation of the motor shaft, potentially leading to vibrations and noise. While SPWM is generally associated with smoother operation due to its closer approximation to a sine wave, the increased torque ripple observed in this instance may be attributed to specific implementation factors or the modulation parameters chosen for the comparison. Torque ripple can impact applications where precision in motion control is critical, as it may lead to instability or inaccuracies in positioning. On the other hand, PWM, despite its higher starting torque and quicker stabilization, may exhibit less torque ripple in certain scenarios, which could be a deciding factor for applications where precise torque control is essential.

When comparing the two techniques, several key factors emerge. PWM is more suitable for applications where high starting torque and rapid acceleration are required, making it ideal for motors in industrial settings where speed and efficiency are prioritized. However, this comes at the cost of potential mechanical stress and reduced motor longevity due to the higher inrush current and abrupt torque changes. On the other hand, SPWM provides a smoother and more controlled start-up, which is beneficial for applications where minimizing mechanical stress, noise, and torque fluctuations is important, such as in HVAC systems, elevators, or precision manufacturing.

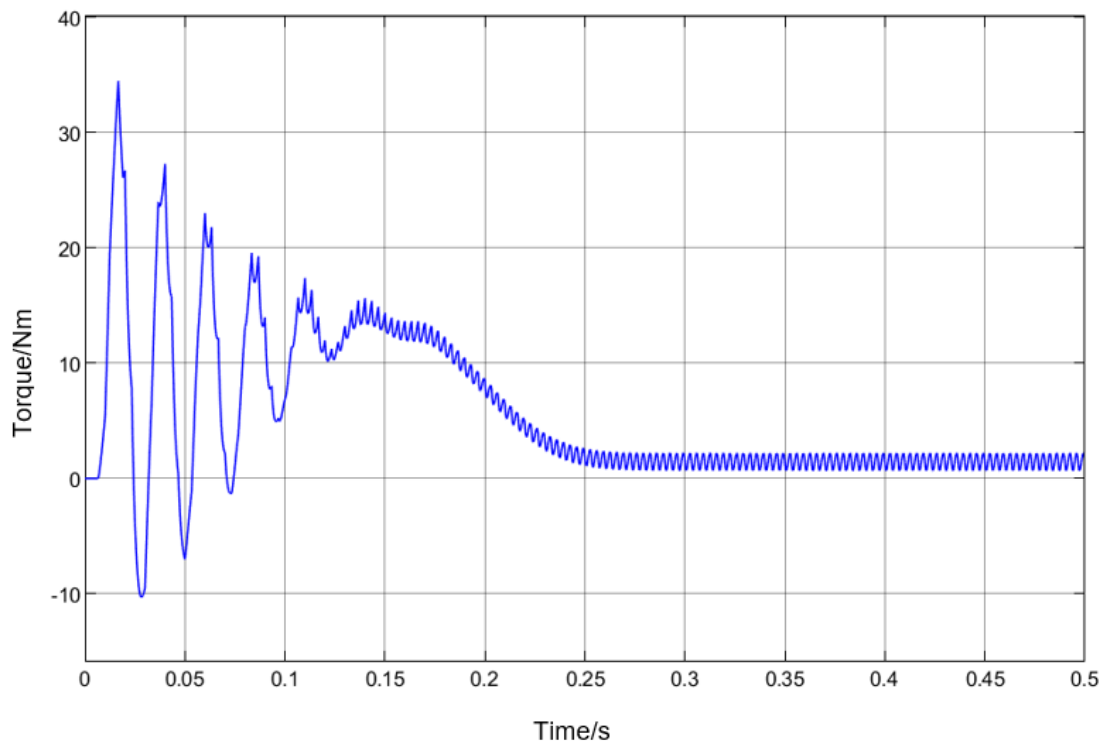


Fig. 6. Electromagnetic torque of PWM with induction motor

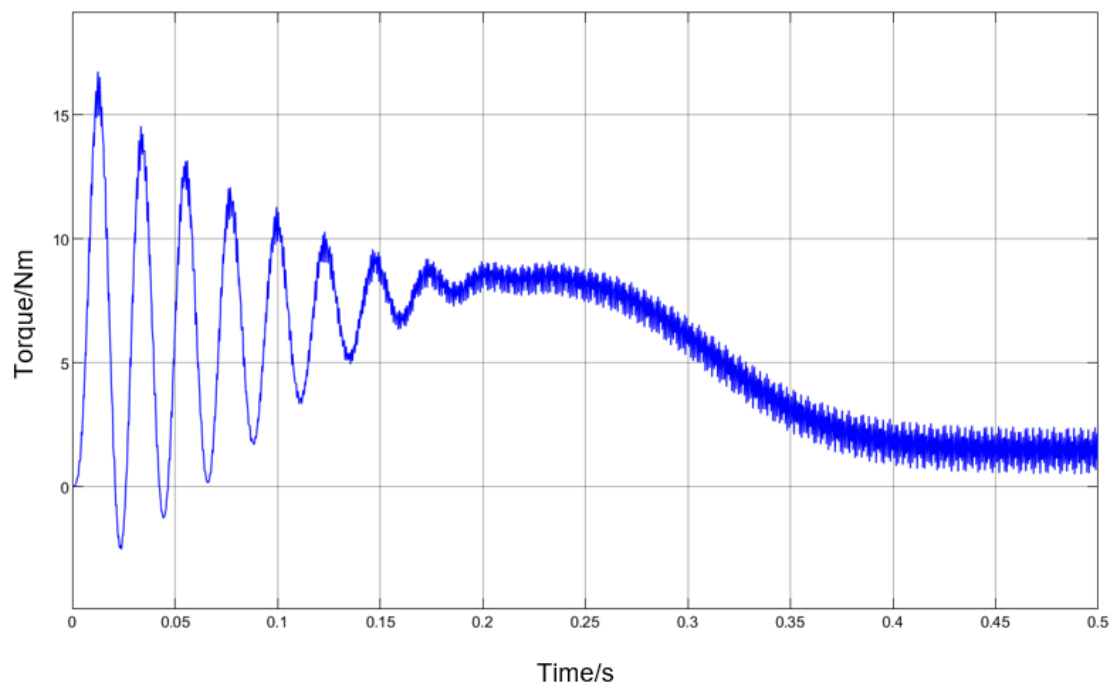


Fig. 7. Electromagnetic torque of SPWM with induction motor

3.3 Induction Motor Rotor Speed

The rotor speed of the induction motor controlled by both PWM and SPWM techniques is illustrated in Figures 8 and 9, respectively. In Figure 8, the motor undergoes a non-linear acceleration

during start-up, characterized by an initial rapid increase in speed, which suggests a quick response to the applied voltage. Early in the acceleration phase, the motor exhibits fluctuations, or 'ripples,' as shown by the small oscillations in the curve. These ripples in a PWM-controlled motor are likely due to the stepping nature of the PWM voltage output, which causes torque variations. After the initial phase, the motor's speed begins to stabilize, indicating that the PWM control system is adjusting the duty cycle to smooth the acceleration. As the curve starts to plateau, it suggests the motor is nearing its steady-state speed. The control system appears to slow the voltage increase to avoid overshooting the target speed. Around 0.15 seconds, the motor reaches a constant speed, maintaining it for the rest of the observation period, demonstrating effective regulation by the control system under a consistent load.

In contrast, Figure 9 shows a more gradual and controlled ramp-up in speed for the SPWM-controlled motor, which helps manage inrush current and reduce electrical stresses. Unlike the PWM graph, the SPWM-controlled motor experiences smoother acceleration with minimal ripple effects, a hallmark of SPWM's closer approximation to a sine wave, resulting in more uniform torque delivery. The consistent slope of the curve without significant fluctuations suggests the SPWM technique is highly effective at maintaining steady speed increases without instability. The motor reaches its rated speed before 0.2 seconds, transitioning smoothly from acceleration to steady state without noticeable overshoot or undershoot. The steady-state speed is maintained consistently, indicating that the SPWM control has successfully matched the motor's load conditions.

The lack of noticeable ripples or oscillations in the SPWM-controlled motor suggests the system delivers a high-quality waveform, contributing to efficient operation and smoother performance. SPWM appears to offer superior control during the start-up phase by minimizing torque pulsations and electromagnetic noise, which is particularly advantageous in applications requiring precise control and smooth motion. This smoother operation provided by SPWM can also reduce mechanical wear and improve the longevity of both the motor and any connected machinery.

While SPWM offers qualitative improvements over PWM, particularly in terms of smoother acceleration and reduced electromagnetic interference, PWM remains a robust method for reaching the desired speed efficiently. However, it may induce slightly more mechanical stress during the initial ramp-up. Ultimately, the choice between PWM and SPWM depends on the specific requirements of the application, including considerations of complexity, cost, and the need for precision.

In applications such as electric vehicles, acceleration is a crucial performance attribute. As noted by K. Poornesh *et al.*, [22] and G. Amar *et al.*, [23], increasing the voltage supplied to the motor can boost acceleration by raising the amperage in both the stator and rotor, which strengthens the magnetic interaction and results in a faster rotor response. However, this must be done cautiously, as increasing the amperage too much can lead to motor overheating. It is also important to remember that changing voltage or amperage does not alter the motor's power, which is determined by the motor's volume. Turbocharging the motor, or operating it in overload conditions, is only necessary in select circumstances where a quick response is critical. In simple terms, while boosting voltage can enhance acceleration, it must be balanced against the risk of overheating and efficiency loss.

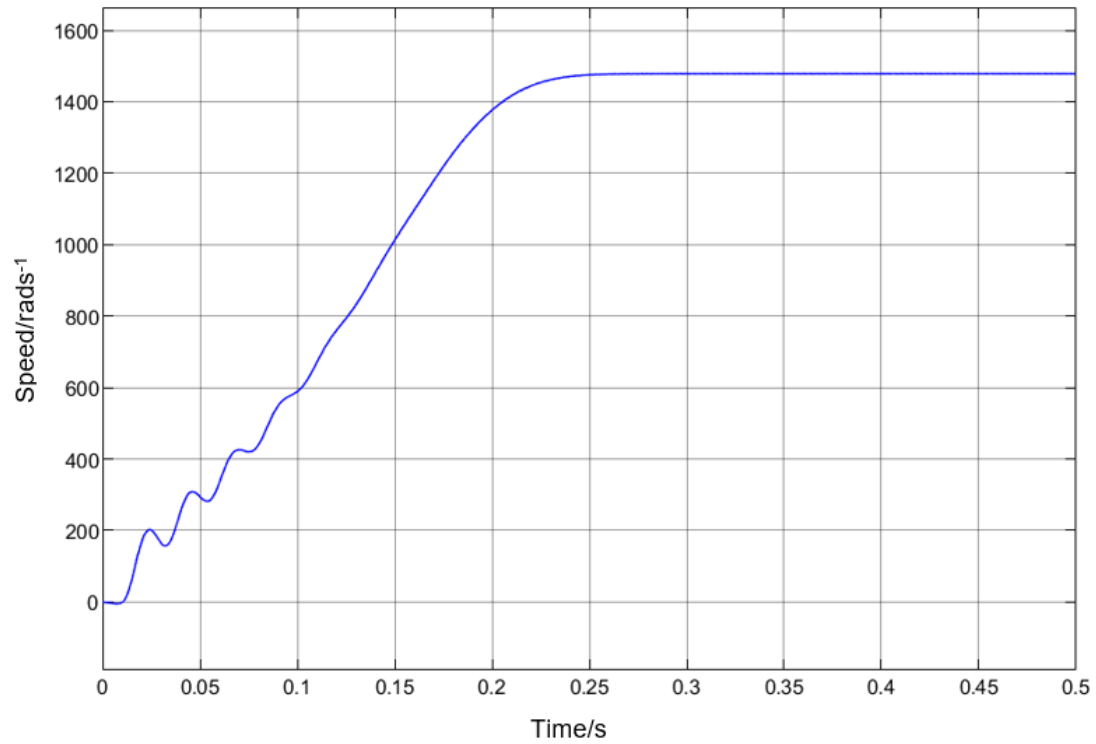


Fig. 8. Rotor speed of PWM with induction motor

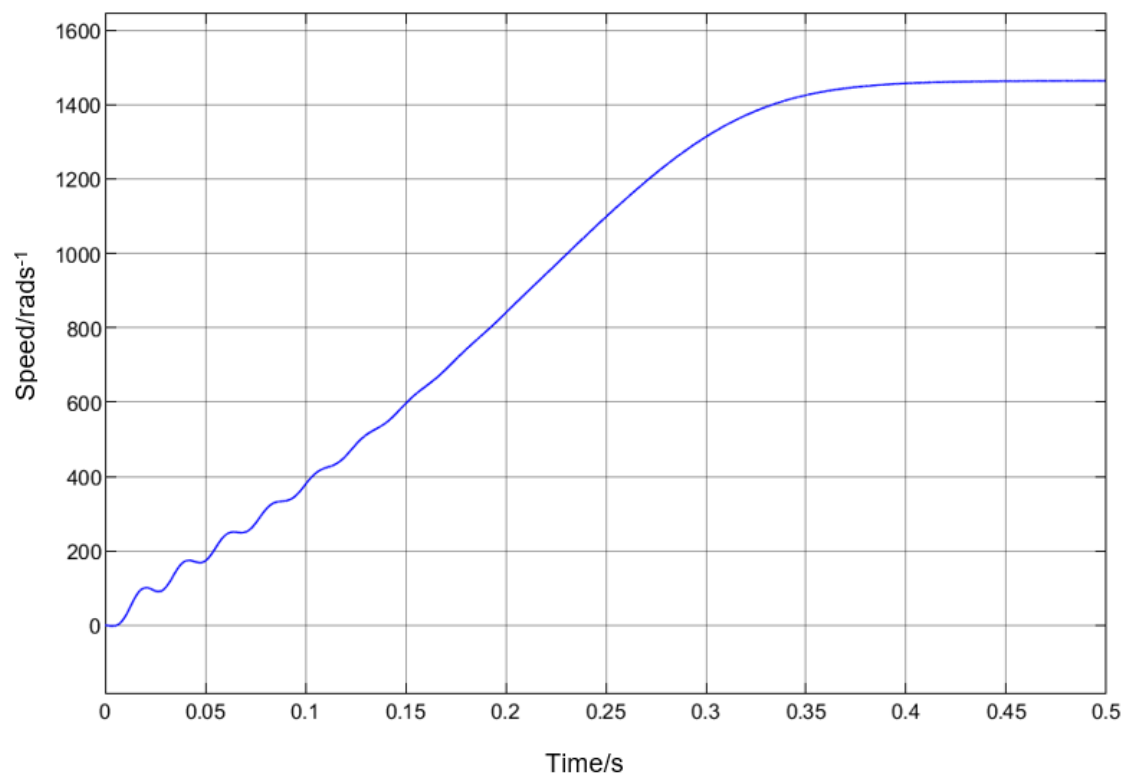


Fig. 9. Rotor speed of SPWM with induction motor

4. Conclusions

Multilevel inverters play a crucial role in modern power systems by producing output voltages at multiple levels, which significantly improves power quality and reduces electromagnetic interference. Among the various control strategies for these inverters, Sinusoidal Pulse Width Modulation (SPWM) is particularly effective in industrial settings due to its efficient harmonic management and ease of implementation. SPWM's ability to closely approximate a pure sine wave by modulating pulse duration based on a sinusoidal reference signal is central to controlling the inverter's output voltage and frequency, both of which directly impact the performance of AC motors and the stability of power grids.

Historically, SPWM implementation relied on analog controllers, but advancements in digital technology have led to the widespread adoption of Digital Signal Processors (DSPs) and microcontrollers. These digital controllers offer higher computational speed, precise timing, and adaptability, making them ideal for the complex demands of modern industrial environments. The focus of SPWM development continues to be on improving output quality, particularly by minimizing Total Harmonic Distortion (THD), which is essential for maximizing efficiency and protecting electrical components from potential damage.

Current efforts to enhance SPWM techniques involve refining the modulation process, developing more advanced digital control algorithms, and leveraging real-time feedback to dynamically adjust switching sequences. As energy efficiency, sustainability, and reliability become increasingly critical in industrial applications, ongoing research is centered on collecting comprehensive harmonic distortion data and employing adaptive algorithms capable of responding to real-time electrical load and source conditions. These innovations aim to ensure optimal power quality and performance, addressing the growing demands of various industrial sectors.

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