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Simulation of Adjustable Speed Drives under non-sinusoidal waveform and Analysis of Harmonic Mitigation Techniques

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ABSTRACT:
In power electronic systems, specifically inverters used for variable frequency drives (VFDs), controlling the harmonic content of the output waveform is crucial for enhancing system performance and reducing electromagnetic interference (EMI). Two widely used modulation techniques for controlling the harmonic content in inverter output are Selective Harmonic Elimination (SHE) and Multiple Pulse Width Modulation (Multiple PWM). To achieve some intriguing research objectives such as trade-offs between cost and circuit complexity; single Pulse width modulation, sinusoidal pulse width modulation and space vector pulse width modulation may be adopted in drive systems. In this paper, comparative studies have been carried out on Pulse Width Modulation (PWM) designed with a single pulse, multiple pulses, sinusoidal reference pulses and space vector PWM to underscore optimizing power delivery systems, preventing equipment failures, and reducing energy waste. Harmonic mitigation was also explored using selective harmonic Elimination (SHE) which offers simple mitigation technique as it effectively eliminates specific harmonics but may leave behind higher-frequency harmonics, making it less versatile in applications with more complex harmonic requirements. Multiple PWM provides a more uniform reduction in harmonic distortion across a wide frequency spectrum but may not eliminate specific low-order harmonics as precisely as SHE. Using MATLAB, this work models control systems for an Induction Motor (IM), with the potential for application to other motor types, including Permanent Magnet Synchronous Motors (PMSM) and DC motors. The results reveal the impact of power electronics on Electromagnetic Interference (EMI) and ensures compliance with IEC 61000-4-7 standards through careful design considerations, such as effective shielding and layout strategies.

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INTRODUCTION

Variable Speed Drives (VSD) are essential systems for controlling the speed of electric motors by adjusting the frequency and voltage supplied. They are widely used in industrial, commercial, and domestic applications where dynamic motor speed adjustments are required for optimal performance, efficiency, and specific operational needs.

Non-sinusoidal waveforms, which are typically characterized by harmonic distortion, voltage sags, or transient conditions, can have significant impacts on the performance of Variable Speed Drives (VSDs). Since VSDs are used to control the speed of electric motors by adjusting the frequency and amplitude of the power supplied, the quality of the input waveform plays a crucial role in determining their efficiency, operation, and longevity. Variable Speed Drives (VSDs) are used in a wide range of applications across various industries due to their ability to precisely control motor speed, improve energy efficiency, and optimize system performance.

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In Industrial Automation for Conveyor Systems VSDs are used to control the speed of conveyor belts in manufacturing plants, improving efficiency, and reducing energy consumption by adjusting the motor speed based on load demands. (Bostan, Stroia & Haţiegan,, 2021 [1]; Sureshkumar *et al.,* 2021 [2]; Palacios 2021 [3]; Rahman et al.,2024 [4]) while VSD in robotics allow for precise control of robotic arms and other automated equipment in industrial robots, improving performance and accuracy (Wang et al., 2023 [5];. Qiu & Xue, 2021 [6]).

For HVAC Systems such as Air Handling Units, pumps and compressor and Chilled Water Pumps VSDs are used to control the speed of fans and blowers, pumps and compressor and chilled water pump for optimal operations and efficiency (Sugarman, 2024 [7]; Sayed & Abu, 2021 [8]).

Other areas of application of VSD are tabulated in Table 1.

Table 1: Areas of Applications of Induction Motor Variable Speed Drives

Plant	**Application**	**Induction Motor Types**	**Power Range**
Water and Wastewater Treatment	Pumping Stations: VSDs control pump	Standard Induction Motors	50 kW - 300 kW
Water and Wastewater Treatment	Aeration Systems: VSDs adjust the speed of aeration blowers	Squirrel Cage Induction Motors	30 kW - 200 kW
Electric Vehicles (EVs)	Traction Motors: VSDs control the speed of traction motors in electric vehicle	Permanent Split Capacitor (PSC) Motors	1 kW - 200 kW
Centrifugal and Positive Displacement Pumps	Oil and Gas Industry: VSDs regulate pump speeds in oil and gas operations.	Squirrel Cage Induction Motors	50 kW - 500 kW
Centrifugal and Positive Displacement Pumps	Chemical Processing: VSDs control pump speed in chemical plants	Wound Rotor Induction Motors	50 kW - 300 kW
Mining and Materials Handling	Mining Equipment: VSDs control motors in mining machinery like crushers and conveyors.	Squirrel Cage Induction Motors	100 kW - 1 MW
Mining and Materials Handling	Material Handling: VSDs regulate motor speed in large-scale handling systems like cranes.	Wound Rotor Induction Motors	100 kW - 1 MW
Textile and Paper Industries	Spinning and Weaving: VSDs control motor speed for textile machinery to improve quality.	Squirrel Cage Induction Motors	30 kW - 200 kW
Textile and Paper Industries	Paper Mills: VSDs control motors in paper-making machinery for optimized throughput.	Squirrel Cage Induction Motors	50 kW - 500 kW
Food and Beverage Industry	Processing Equipment: VSDs control speed in food processing machinery to ensure consistency.	Squirrel Cage Induction Motors	30 kW - 150 kW
Food and Beverage Industry	Packaging Systems: VSDs control motors in packaging machines for better synchronization.	Squirrel Cage Induction Motors	20 kW - 200 kW
Renewable Energy Systems	Wind Turbines: VSDs optimize turbine blade speed in response to wind conditions.	Squirrel Cage Induction Motors	100 kW - 3 MW

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Plant	Application	Induction Motor Types	Power Range
Renewable Energy Systems	Solar Energy Systems: VSDs control solar water pumps or battery charging systems.	Permanent Split Capacitor (PSC) Motors	5 kW - 100 kW
Transportation Systems	Elevators and Escalators: VSDs manage motor speed to reduce energy consumption and ensure smooth operation.	Wound Rotor Induction Motors	30 kW - 500 kW
Transportation Systems	Trains and Subways: VSDs control motor speed for smoother acceleration and deceleration.	Squirrel Cage Induction Motors	100 kW - 2 MW
Power Generation	Generators: VSDs regulate auxiliary equipment speeds, improving performance.	Squirrel Cage Induction Motors	50 kW - 1 MW
Power Generation	Hydropower Plants: VSDs control water flow through turbines, optimizing generation.	Squirrel Cage Induction Motors	200 kW - 10 MW
Marine and Ship Applications	Ship Propulsion: VSDs optimize motor speed in ship propulsion systems for better fuel efficiency.	Wound Rotor Induction Motors	200 kW - 3 MW
Marine and Ship Applications	Cargo Handling: VSDs control crane and winch motors, improving efficiency.	Squirrel Cage Induction Motors	50 kW - 500 kW
Printing Industry	Printing Presses: VSDs manage motor speed for precise registration and consistent output.	Squirrel Cage Induction Motors	20 kW - 200 kW
Printing Industry	Cutting and Binding Machines: VSDs control motor speed for smooth, reliable operation.	Squirrel Cage Induction Motors	10 kW - 150 kW
Airports and Building Services	Airport Conveyor Systems: VSDs adapt motor speeds for varying loads in baggage handling systems.	Squirrel Cage Induction Motors	50 kW - 500 kW
Airports and Building Services	Building HVAC Systems: VSDs control motor speeds in HVAC systems, improving efficiency.	Wound Rotor Induction Motors	50 kW - 1 MW

The following benefits and many more potential applications continue to put VSDs in the lime-light of industrial developments:

1. Energy Efficiency: VSDs adjust motor speed to match load demands, reducing energy consumption by avoiding unnecessary high-speed operation.
2. Process Control: VSDs enable precise control over speed, torque, and other parameters, ensuring better performance and reliability of the system.
3. Reduced Mechanical Stress: By controlling motor speed, VSDs minimize mechanical wear and tear, leading to extended equipment lifespan and reduced maintenance.
4. Cost Savings: VSDs help reduce operational costs by improving energy efficiency and reducing the need for oversized motors and equipment.

Therefore, VSDs find applications across a broad spectrum of industries, contributing to enhanced performance, energy savings, and operational efficiency. Their versatility in controlling the speed and operation

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of motors makes them essential in many critical systems.

Selective Harmonic Elimination (SHE) aims to explicitly eliminate specific low-order harmonics by adjusting the switching angles of the inverter. By solving a set of nonlinear equations, SHE allows for precise control over the harmonic spectrum, ensuring that targeted harmonics, such as the 3rd, 5th, and 7th, are minimized or completely removed. This method is particularly useful in applications where minimizing specific harmonics is required.

On the other hand, Multiple PWM involves using multiple phase-shifted triangular carriers to modulate the inverter output. This technique reduces harmonic distortion by spreading the harmonics over a broader frequency range, leading to a smoother output waveform. The use of multiple carriers also helps in reducing the peak harmonic content and alleviating the need for complex harmonic elimination.

This study compares the time-domain and frequency-domain characteristics of both techniques through simulation. The results demonstrate that while SHE effectively eliminates specific harmonics, it may leave behind higher-frequency harmonics, making it less versatile in applications with more complex harmonic requirements. In contrast, Multiple PWM provides a more uniform reduction in harmonic distortion across a wide frequency spectrum but may not eliminate specific low-order harmonics as precisely as SHE.

The comparative results underscore the trade-offs between these two techniques: SHE offers targeted harmonic elimination, but requires careful optimization and may result in residual high-frequency harmonics, whereas Multiple PWM delivers a more generalized harmonic reduction, making it more suitable for applications where overall waveform smoothness is prioritized over exact harmonic elimination. In a simplified version, the space vector PWM has been simulated under non-sinusoidal waveform distortion to herald its novelty among to pulse switching techniques.

This paper serves as a valuable guide for selecting the appropriate modulation technique based on specific harmonic reduction requirements in power electronic systems. The justification propounded mainly to assess how non-sinusoidal electrical supplies affect the performance of Variable Speed Drives (VSDs) and to propose effective solutions to mitigate these issues. Non-sinusoidal supplies, often characterized by distorted waveforms due to harmonic distortions, can lead to operational challenges in VSDs, such as increased losses, overheating, and reduced efficiency. These problems can degrade the performance of both the drive systems and connected equipment, impacting overall system reliability and lifespan. Other key contributions to the body of knowledge are accentuated as follows:

Key Contributions:

1. Simulation-based comparison of SHE and Multiple PWM techniques.
2. Analysis of harmonic content using Fast Fourier Transform (FFT) for both methods.
3. Discussion on the advantages and limitations of SHE and Multiple PWM in real-world inverter applications.

REVIEW OF RELATED WORKS

Li et al. [9] introduced a new approach to assess motor efficiency at varying speeds. Their method incorporates a load-to-speed ratio, leveraging motor nameplate data, with standard analog outputs from the VSD facilitating the efficiency calculation. The focus of this study is on calculating the efficiency of a well-functioning motor under different speed or load conditions, without addressing how imbalances in the motor affect efficiency or power factor. This research will evaluate the effectiveness of the efficiency calculation methods in identifying reductions in motor efficiency resulting from faults.

Lee et al. [10] proposed innovative off-line methods for monitoring AC motors driven by VSDs, utilizing the VSD to generate necessary test signals while the motor is not running. The proposed strategies enable the monitoring of various drive system components such as DC link capacitors, insulation and cabling, as well as the condition of the stator windings, rotor, and stator core. This approach simplifies the process by eliminating the need for spectral analysis or referencing the motor's mathematical model. Since the method operates off-line, it is unaffected by the motor's operating frequency or load. The method applies a pulsating AC magnetic field to the motor through the DC link voltage in such a way

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that the rotor remains stationary. While the technique detects specific faults, it does not account for efficiency losses resulting from those faults. Implementing this system requires modifications to the VSD, which could pose challenges for continuous plant operations, as the motor must be halted to take measurements.

Salomon et al. [11] introduced a method for estimating motor efficiency using Air-Gap Torque (AGT) based on motor nameplate data, voltage, and current measurements. Using stator flux equations alongside particle swarm optimization, they estimated the stator resistance from the measured motor data. AGT is derived from the estimated stator resistance, which accounts for losses in the system. The AGT provides a reliable approximation of the motor's mechanical torque output. Although these methods were applied to a Direct-On-Line (DOL) motor system, their accuracy in VSD applications remains uncertain. Potential challenges include noise in voltage or current waveforms, which could affect the precision of the calculations. This paper will apply AGT techniques to motor faults to assess whether efficiency reductions can be identified.

Research has explored methods to enhance motor efficiency when driven by contemporary VSDs. Ashari et al. demonstrated that an adaptive flux simulator could enhance motor efficiency, with simulations in SIMULINK confirming the results [12]. While Ashari et al.'s research suggests that various VSD control strategies can improve motor efficiency, practical validation through tests was not conducted. Several efficiency monitoring techniques have been previously employed for assessing the efficiency of healthy motors in DOL applications.

Ndung'u, [13] examines the impact of current harmonic distortions on low voltage distribution networks, particularly focusing on residential areas. Traditionally, harmonic distortions were thought to have minimal effect on low voltage equipment. However, recent data shows that these distortions, caused by nonlinear residential loads such as electronic appliances with Switch Mode Power Supplies (SMPS), are damaging distribution transformers. These harmonics contribute to transformer insulation deterioration, premature failures, inaccurate energy meter readings, and overloaded neutral conductors. However, the study mainly focuses on a single mitigation technique (shunt active filter) and might not explore or compare other possible solutions for harmonic mitigation, such as single or multiple PWM, SHE, passive filters or hybrid systems, which could offer different advantages or drawbacks in various scenarios.

Ibrahim [14] offers valuable insights into improving grid stability by leveraging distributed energy resources (DERs) for inertial response, particularly in the context of renewable energy integration. The work explores innovative use of real-time simulations using the detailed grid model for its rigorous analytical approach. However, there might be practical challenges of large-scale implementation, as it only focuses on specific types of loads such as resistive heating loads and heat pumps. This recommends areas for further exploration and refinement considering VSDs supplied with non-sinusoidal waveform from DER

Thanabal [15] provides a comparison between conventional motor starters and variable speed drives (VSDs), which is useful for understanding the efficiency improvements that can be achieved with modern control technologies. This comparison offers valuable insights for industries looking to optimize their motor-driven processes but does not explore newer or more advanced control techniques such as sensorless control, direct torque control (DTC), or other sophisticated algorithms that could further improve motor performance and energy efficiency.

Lane [16] offers valuable contributions to the field of condition monitoring and efficiency optimization for VSD-controlled motor systems. It fills a gap in understanding how minor faults impact the efficiency of these systems, and it provides practical solutions for improving motor efficiency by adjusting VSD operating modes. However, the study's scope is limited by its focus on a narrow set of faults, a controlled experimental setup, and a lack of discussion on the broader applicability and implementation challenges of its findings. Further work that includes a wider range of faults, real-world validation, and a cost-benefit analysis would strengthen the research's practical impact and relevance.

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Tsalas et al. [17] provides a valuable overview of global practices for reducing energy consumption in WWTPs, a critical issue for both environmental sustainability and operational efficiency. Its garnered timely focus on energy efficiency, comprehensive literature review, and practical implications for industry stakeholders for variable-speed pumps by creating models for dynamic optimization and scheduling purposes. However, the work relied on existing studies without new experimental data, lack of detailed methodologies, and limited exploration of implementation barriers are notable limitations. To enhance the research, future studies could focus on more specific case studies, experimental validations, and a deeper analysis of the practical challenges operators face in applying these methods.

Faisal et al [18] highlights the technical aspects of energy optimization in pumping systems, motors, and control systems. It relied too heavily on theoretical discussion. More focus on practical implementations, including challenges encountered in the field and the real-world feasibility of suggested solutions, would have more significant contributions making it more actionable for industry professionals.

This paper explores the MATLAB simulation of Adjustable Speed Drives (VSDs) operating under non-sinusoidal waveform supply, focusing on harmonic mitigation techniques to optimize power delivery, prevent equipment failures, and reduce energy waste.

THEORETICAL CONSIDERATIONS OF VARIABLE SPEED DRIVES

Variable Speed Drives (VSDs) are widely used in industrial and commercial applications to control the speed of electric motors. They work by adjusting the frequency and/or voltage supplied to the motor, which in turn controls its speed. Theoretical considerations for VSDs operating under non-sinusoidal waveform supplies are important because the presence of harmonics and distortions in the power supply can affect the performance, efficiency, and lifespan of both the drive and the motor.

Here are the main theoretical considerations for VSDs operating under non-sinusoidal waveform supplies:

1. Harmonics in Non-Sinusoidal Waveforms

a) Origin of Harmonics: In a typical VSD, power is converted from AC to DC through rectification, and then converted back from DC to AC using an inverter. Non-sinusoidal waveforms, often resulting from these conversion processes, contain harmonics—multiples of the fundamental frequency.

b) Harmonic Distortion: These harmonics lead to distortion in the supply voltage and current, which is a significant consideration for VSDs. Common sources of harmonic distortion in a VSD system include:

i. Rectifiers (DC side of the VSD)

ii. Inverters (AC side of the VSD)

iii. Pulse width modulation (PWM) techniques used to control the inverter switching

c) Effect of Harmonics on VSDs: Harmonic currents create additional losses (heat) in the drive and motor windings, potentially leading to overheating, increased electromagnetic interference (EMI), and mechanical vibration. These factors can reduce the efficiency of the system and shorten the lifespan of the components.

2. Effects on Motor Performance

a) Motor Heating: Harmonics can induce higher currents in the motor windings, particularly at harmonic frequencies, which result in additional heat generation. This can lead to thermal stress and reduced operational life.

b) Torque Ripple: Non-sinusoidal waveforms lead to torque ripple, which can cause mechanical vibration and noise in the motor. This ripple varies at different speeds and can result in mechanical wear over time, especially at low-speed operation.

c) Motor Efficiency: The non-sinusoidal nature of the supply voltage leads to distorted motor current waveforms. As a result, the motor may operate at a lower efficiency compared to a system with a pure sinusoidal waveform.

d) Voltage and Current Unbalance: In three-phase systems, non-sinusoidal waveforms can cause voltage and current imbalances. This can degrade the performance of the motor, increase losses, and lead to potential overheating.

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3. Power Factor and Current Distortion

a) Reduced Power Factor: Non-sinusoidal waveforms lead to a poor power factor, which means that the energy supplied to the motor is not fully utilized in producing useful work. A lower power factor can lead to increased energy consumption and higher operating costs.

b) Current Harmonics: VSDs introduce current harmonics that contribute to total harmonic distortion (THD). These harmonics can impact the quality of the power supply, leading to overheating of transformers, cables, and circuit breakers, and can also interfere with sensitive electronic equipment.

4. Filtering and Mitigation

a) Active and Passive Filters: To mitigate the effects of non-sinusoidal waveforms, harmonic filters (either active or passive) are used to reduce the harmonic content in the supply voltage and current. Passive filters are typically used to filter out specific harmonic frequencies, while active filters can adapt dynamically to various harmonic frequencies and reduce their impact more effectively.

b) PWM Techniques: The use of advanced PWM techniques can minimize harmonic distortion in the output voltage of the inverter. Methods like sinusoidal PWM, space vector PWM, and multi-level PWM can be employed to reduce the total harmonic distortion and improve the quality of the waveform supplied to the motor.

5. Efficiency Considerations

a) Reduced System Efficiency: Non-sinusoidal waveforms result in losses in both the VSD and the motor. The harmonic currents can cause additional copper losses in the motor and drive, reducing overall system efficiency.

b) Increased Losses in Power Electronics: The presence of harmonics in the supply also increases losses in power electronics such as diodes, transistors, and capacitors in the VSD. These losses must be accounted for when designing drives for systems with non-sinusoidal waveforms.

6. Control Systems for Non-Sinusoidal Waveforms

a) Modified Control Strategies: In response to non-sinusoidal waveforms, VSD control strategies, such as vector control (field-oriented control), may need to be modified to compensate for harmonic distortions. This may involve adjusting the motor's flux and torque control algorithms to account for the effects of harmonics.

b) Frequency Response Considerations: The VSD control system must be capable of handling frequency response distortions due to the harmonic content of the waveform. A properly designed control system should be able to recognize and mitigate the influence of these harmonics on the motor's operation.

7. Regulatory and Standards Compliance

a) Standards for Harmonic Distortion: In many regions, regulatory bodies such as IEEE, IEC, and IEC 61800-3 provide standards for permissible levels of harmonic distortion in industrial electrical systems. VSD systems must be designed to comply with these standards to minimize the impact on the wider electrical grid and other equipment.

b) Efficiency Standards: Some regions and applications have specific efficiency standards for VSDs to reduce energy consumption. VSDs operating under non-sinusoidal conditions must meet these standards while minimizing the losses associated with harmonics.

8. Motor Design and Selection

a) Motor Type: The choice of motor is important when dealing with non-sinusoidal waveforms. Induction motors, for example, can experience significant effects from harmonic distortion, while permanent magnet motors may be less sensitive to harmonics. Selection of a motor with a higher tolerance for harmonic currents can help mitigate some of the negative effects.

b) Motor Insulation: Higher harmonic currents can affect the motor's insulation system. Motor manufacturers must account for this when designing motors for use with VSDs operating under non-sinusoidal conditions.

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Theoretical considerations for VSDs under non-sinusoidal waveform supplies include the effects of harmonics on motor performance, the need for efficient filtering techniques, and the impact on system efficiency. To mitigate the negative effects, advanced PWM strategies, harmonic filtering, and careful selection of motor and drive technologies are essential. Understanding and addressing the implications of non-sinusoidal waveforms are crucial for ensuring reliable, efficient, and cost-effective operation of VSD-driven motor systems.

When dealing with Variable Speed Drives (VSDs) under non-sinusoidal waveform supplies, various model equations are used to describe the behavior of the system and its components, including the drive, motor, and the effects of harmonic distortions. Below are some of the relevant model equations related to VSDs under non-sinusoidal conditions:

9. Motor Voltage Equation under Non-Sinusoidal Supply

For a three-phase induction motor, the voltage equation can be expressed as in Eqn. (1):

$$V(t) = V_m sin(\omega_m t + \varphi) \qquad ...(1)$$

where:

- V(t)\ is the instantaneous motor voltage,
- V_m is the amplitude of the voltage,
- $\omega_m$is the motor's electrical angular frequency,
- φ is the phase angle of the voltage supply.

In the presence of harmonics, the voltage waveform becomes distorted and can be expressed as Eqn. (2):

$$V(t) = \sum_{n=1}^{N} V_n sin(n\omega t + \varphi_n) \qquad ...(2)$$

where:

- V_n is the magnitude of the nn-th harmonic,
- $n\omega$ represents the angular frequency of the nn-th harmonic,
- φ_ns the phase shift for the nn-th harmonic.

10. Motor Current Equation under Non-Sinusoidal Supply

The current supplied to the motor will also be non-sinusoidal due to the harmonic content. The motor current equation under non-sinusoidal supply can be expressed as in Eqn. (3):

$$I(t) = I_m sin(\omega_m t + \theta) \qquad ...(3)$$

where:

- I(t)\ is the instantaneous motor current,
- I_m is the amplitude of the current,
- $\omega_m$is the motor's electrical angular frequency,
- θ is the phase angle of the current supply.

In the presence of harmonics, the current waveform becomes distorted and can be expressed as Eqn. (4):
For distorted waveforms:

$$I(t) = \sum_{n=1}^{N} I_n sin(n\omega t + \theta_n) \qquad ...(4)$$

where:

- $I(t)$ is the instantaneous motor current,
- I_n is the magnitude of the nn-th harmonic current,
- θ_n is the phase shift for the nn-th harmonic of the current.

11 Power Equation in the Presence of Harmonics

The total instantaneous power delivered to a motor with harmonics can be expressed as in Eqn. (5):

$$p(t) = (v(t)).(i(t)) \qquad ...(5)$$

For non-sinusoidal waveforms, this becomes (6):

$$p(t) = \sum_{n=1}^{N} V_n I_n cos(n\omega t + \varphi_n - \theta_n) \qquad ...(6)$$

The average power is then obtained by integrating over a full cycle is Eqn. (7):

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$$P_{avg} = \frac{1}{T}\int_0^T p(t)dt = \sum_{n=1}^{N} V_n I_n cos(\varphi_n - \theta_n) \quad ...(6)$$

where T is the period of the signal.

12 Torque Ripple due to Harmonics

The torque produced by an induction motor with harmonic currents is influenced by the harmonic content of the supply voltage. The torque equation for a motor under non-sinusoidal supply is given by (8):

$$T(t) = \frac{3}{2}\frac{P_{electrical}}{\omega_m} \quad ...(8)$$

Where $P_{electrical}$ is the electrical power given by Eqn. (9):

$$P = \sum_{n=1}^{N} V_n I_n cos(n\omega t + \varphi_n - \theta_n) \quad ...(9)$$

This results in torque ripple at the motor shaft, especially at lower speeds. The magnitude of the ripple will depend on the harmonic content in the supply current.

13 Total Harmonic Distortion (THD)

Total Harmonic Distortion (THD) is a key measure of the distortion in the waveform. For voltage and current, THD can be expressed as in Eqns. (10) and (11) respectively:

$$THD_v = \frac{\sqrt{\sum_{n=2}^{N} {V_n}^2}}{V_1} \quad ...(10)$$

$$THD_I = \frac{\sqrt{\sum_{n=2}^{N} {I_n}^2}}{I_1} \quad ...(11)$$

Where:

- V_n and I_1 are the amplitudes of the n-th harmonic voltage and current, respectively,
- V_1 and I_1 are the amplitudes of the fundamental voltage and current, respectively.

14 Efficiency Equation under Non-Sinusoidal Conditions

The efficiency of the motor under non-sinusoidal conditions is affected by the losses due to harmonics in both the motor and the VSD. The efficiency can be calculated as in Eqn. (12):

$$\eta = \frac{P_{output}}{P_{input}} \quad ...(12)$$

Where:

- P_{output} is the useful mechanical output power of the motor,
- P_{input} is the total electrical input power to the system.

The input power can be calculated by accounting for the harmonic losses:

$$P_{input} = P_{fundamental} - P_{harmonic\ losses} \quad ...(13)$$

Where:

- $P_{fundamental}$ is the power associated with the fundamental frequency,
- $P_{harmonic\ losses}$ represents additional losses due to harmonic distortions in both the VSD and the motor.

15 VSD Efficiency under Non-Sinusoidal Conditions

The efficiency of the Variable Speed Drive itself can be calculated by considering the losses in the rectifier, DC link, and inverter as in Eqn. (14):

$$\eta_{VSD} = \frac{P_{out}}{P_{in}} \quad ...(14)$$

Where:

- P_{out} is the power delivered to the motor,
- P_{in} is the power supplied to the VSD.

The VSD losses primarily include switching losses, conduction losses in power electronics, and losses due to harmonic currents.

16. Thermal Model for Motor under Harmonic Currents

Motor heating due to harmonic currents can be modeled by the following equation in Eqn. (15):

$$\frac{dT}{dt} = \frac{P_{losses}}{C_{thermal}} \quad ...(15)$$

Where:

- T is the temperature of the motor,
- P_{losses} is the total power loss due to harmonic currents and other factors,

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- $C_{thermal}$ is the thermal capacitance of the motor (which depends on the motor's size, materials, and cooling).

These model equations from Eqns (1) to (15) represent the core theoretical considerations for VSDs under non-sinusoidal waveform supplies. Harmonics affect the motor's performance, efficiency, and reliability by causing additional losses, torque ripple, heating, and reduced power quality. Using these equations, engineers can better design systems to mitigate the impact of non-sinusoidal waveforms, optimize motor control strategies, and ensure long-term efficiency and performance.

17. Speed Control Techniques for Induction Motors

Induction motors (IM) are widely used in industrial applications, but their performance can be significantly impacted when fed with non-sinusoidal waveform supplies. Non-sinusoidal voltage and current waveforms introduce harmonics, which can result in higher losses, reduced efficiency, and mechanical problems like torque ripple. Below is an overview of the basic equations, speed control techniques, and harmonic mitigation strategies like Pulse Width Modulation (PWM) and Selective Harmonic Elimination (SHE).

a. Volts per Hertz (V/f) Control

- This is the simplest method of speed control where the voltage supplied to the motor is adjusted in proportion to the frequency as in Eqn. (16). This technique maintains a constant flux in the motor to ensure the motor operates efficiently.

$$V \propto f \quad \dots.(16)$$

When the supply voltage is non-sinusoidal, harmonic content increases, and the performance of this technique can degrade.

b. Vector Control (Field-Oriented Control, FOC)

- FOC is a more sophisticated technique that decouples the torque and flux control of the motor. The motor is controlled by controlling the stator flux and torque-producing current in a rotating reference frame.
  Direct Axis Current: $I_d = I_{flux} \quad \dots.(17)$
  Quadrature Axis Current: $I_d = I_{Torque} \quad \dots.(18)$

- In the presence of harmonics, the decoupling of flux and torque may be less effective, and additional measures need to be taken for harmonic mitigation.

c. Direct Torque Control (DTC)

- DTC controls the torque and flux directly by selecting the optimal voltage vector to control both parameters in real time. It provides higher performance than V-/f control but may be more sensitive to non-sinusoidal supplies.

18. Harmonic Mitigation Techniques

a. Pulse Width Modulation (PWM)

PWM is used in VSDs to convert the DC voltage from the rectifier to an AC voltage for the induction motor. It can mitigate harmonics and improve power quality.

i. Single-Carrier PWM

- In single-carrier PWM, the carrier signal (a high-frequency triangular waveform) is compared with the reference signal (a sinusoidal waveform). The modulation generates a series of pulses to approximate a sinusoidal output waveform, reducing the harmonic content.

Equation for single-carrier PWM:

The single-carrier PWM modelling equation is given by Eqn. (19):

$$\begin{cases} V_m \; if \; carrier \leq reference \\ 0 \; if \; carrier > reference \end{cases} \quad (19)$$

Figure 1(a)-(c) shows the waveforms for the carrier signal and reference signal, gating signals and output signal respectively.

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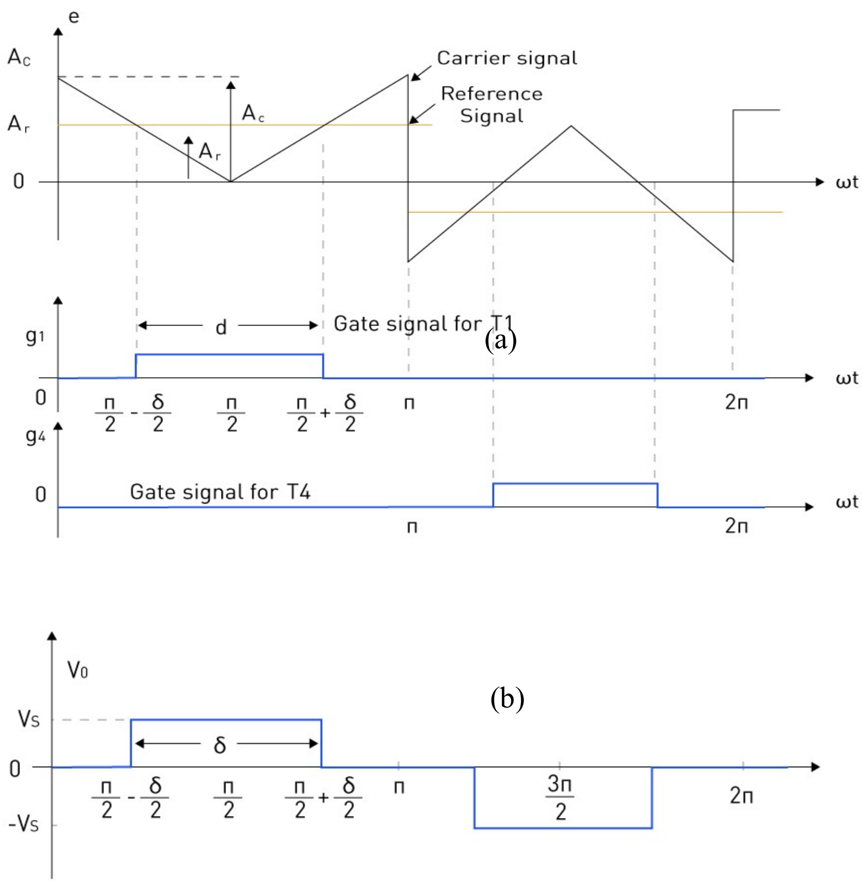
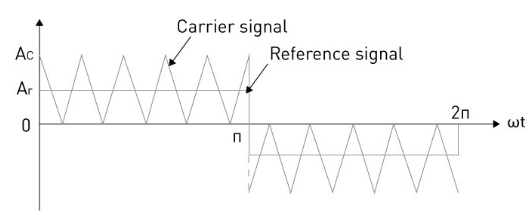


Figure 1: Single carrier pulse PWM Technique

(c)

ii. Multiple-Carrier PWM (Multicarrier PWM)

In multiple-carrier PWM, several triangular carrier waves with different frequencies are used to reduce harmonic distortion. This approach improves the harmonic spectrum, particularly for lower-order harmonics. Figure 2 (a)-(b) shows carrier signal and inverter output respectively.



(a)

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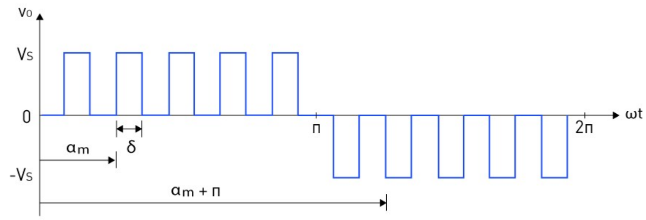
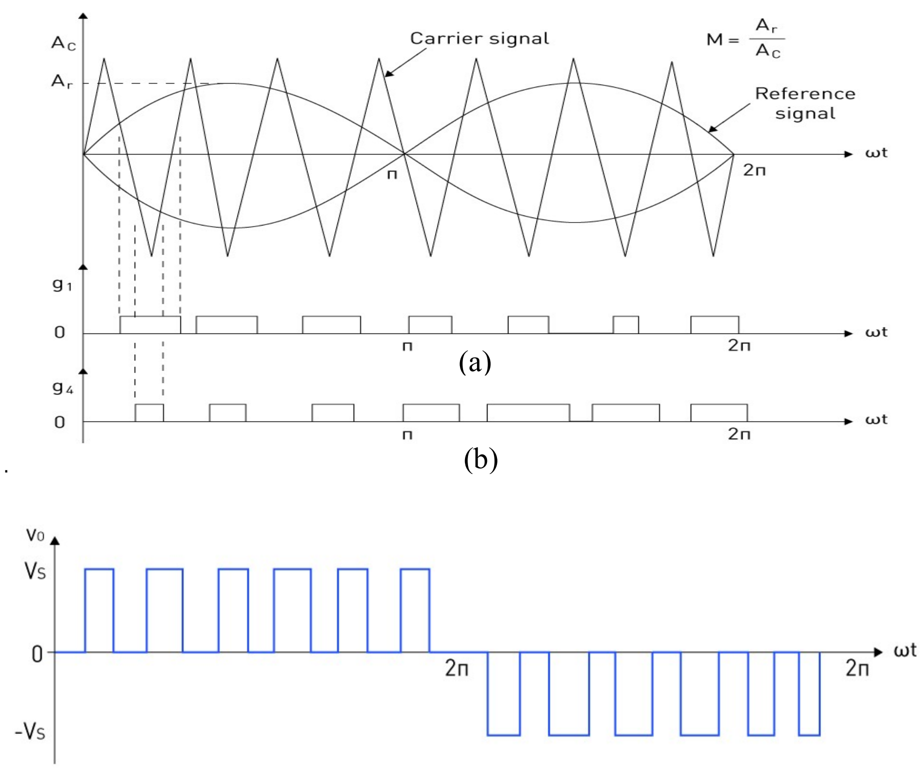


Figure 2: Multiple PWM Technique

iii. Sinusoidal PWM (SPWM)

SPWM generates a pulse train for each gating signal g1 and g4 by comparing a sinusoidal reference signal with a triangular carrier signal. Each pulse's width fluctuates in proportion to the amplitude of a reference sine wave at its centre. The reference signal frequency determines the output signal frequency in SPWM. Furthermore, the peak amplitude of the reference signal influences the modulation index M, which controls the output RMS voltage. The number of pulses in each output signal cycle is determined by the carrier frequency shown in Figure 3 (a) to (c).



(c)

Figure 3: SPWM Technique

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b. Selective Harmonic Elimination (SHE)

Selective Harmonic Elimination is a technique where certain harmonics are deliberately eliminated from the output waveform by choosing appropriate switching angles as shown in Figure 4.

SHE Methodology

The switching angles are selected such that the resulting waveform eliminates specific low-order harmonics (typically the 5th, 7th, 11th, etc.). This is done by solving the following equation in Eqn. (21):

$$V(t) = \sum_{n=1}^{N} V_n sin(n\omega t + \varphi_n) \qquad ...(21)$$

Where specific harmonic orders are set to zero by adjusting the phase angles φ_n.

To eliminate specific harmonics, the equation for the voltages can be solved using a numerical method such as Newton-Raphson, leading to the appropriate switching angles φ_n.

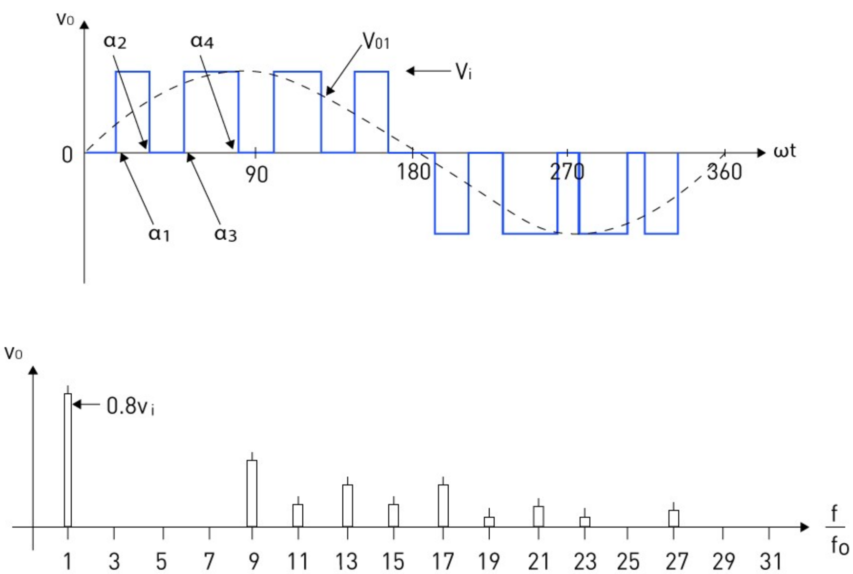

Figure 4: Selective Harmonic Elimination

c. Space Vector PWM

SVPWM improves the harmonic performance by choosing the optimal switching states for the inverter, resulting in better utilization of the DC bus voltage and reducing low-order harmonics. This is based d-q Park transformation technique as shown in Figure 4.

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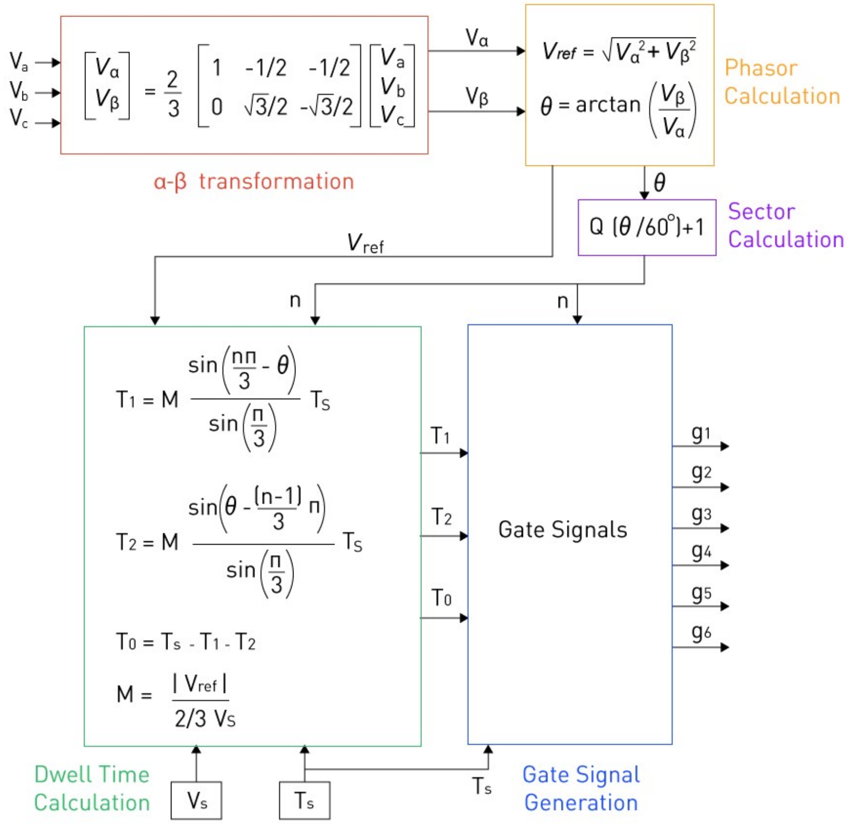

Figure 5: Space Vector PWM

19. Additional Considerations and Mitigation

a. Harmonic Filters

Passive or active filters can be used to filter out the high-frequency harmonics generated by VSDs and improve the quality of the supply voltage to the motor.

b. Motor and Drive Design

Motors designed for operation under non-sinusoidal waveforms may be used to better handle harmonic currents and reduce losses. High-quality VSDs with advanced PWM algorithms and harmonic reduction capabilities will also improve performance.

c. Improved Cooling

Higher harmonics can lead to increased heating in the motor. Improved cooling systems or the use of specialized motor windings designed for harmonic resilience can reduce the impact of harmonics.

RESULTS AND DISCUSSION

The induction motor power ratings ranged from 50 kW to 300 kW which fall within the different types presented in Table 1. The results obtained as presented in sequel.

i. **Full load Torque under non-sinusoidal waveform distortion**

The full load torque under non-sinusoidal waveform distortion for 5^{th} order harmonic was simulated with MATLAB script and different setting of slip are recorded as plotted as in Figure 6. The results compared the distortion attributed to 5^{th} harmonic order and after the mitigation of the harmonic order. When 5^{th} order was present, the torque showed high value changing at irregular pattern but after mitigation, the regular periodic waveform, smoother

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variation obtained. The full load current recoded against slip, at locked rotor to full loaded point, the current ramped down following the same pattern as the mitigated stator current-slip characteristics. The 5th harmonic showed as rapid variation as compared to the mitigated trend.

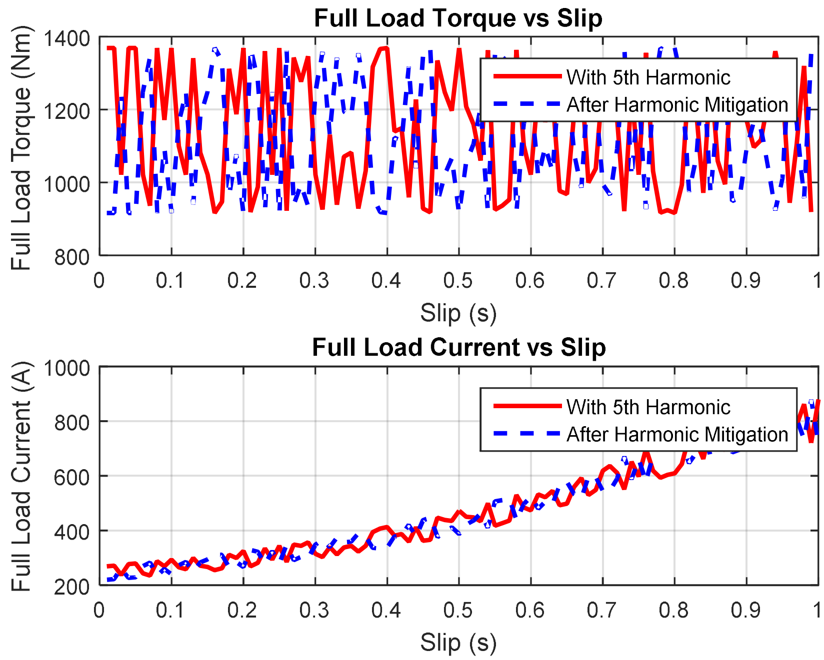

Figure 6: Full load Toque-current-slip characteristics before and after 5th harmonic order removal

b) Multiple harmonic orders

Figure 7 showed the distortion attributed to multiple harmonic orders (e.g. 5th , 7th, , 11th etc).

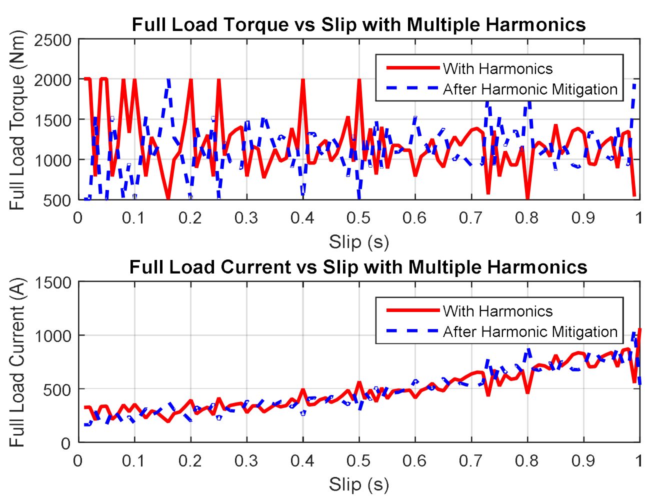

Figure 7: Full load Toque-current-slip characteristics before and after lower harmonic orders removal

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It was observed that, for slip values between 0.2 and 0.3 as well as between 0.4 and 0.5, the torque values with multiple harmonics were higher than the torque values after harmonic mitigation. This difference could be attributed to the inertia required for acceleration after overcoming the stalling condition. In contrast, after mitigating the harmonic multiple orders, the torque was observed to increase significantly for slip values between 0.7 and unity. However, before mitigation, the motor's overall torque was generally reduced, likely due to the counteracting torque generated by the harmonic orders. For instance, the 5th harmonic order generates a negative-sequence current, which tends to reduce the motor's thrust While the 7th, 11th, and 13th harmonic currents also affect motor performance, though in ways similar to the 5th harmonic. Here's a breakdown of their impacts:

1. 7th Harmonic Current:

a) Negative Sequence Component: The 7th harmonic typically contributes to a negative sequence current, which can create a reverse rotating field. This can result in increased motor heating, vibration, and mechanical stress. It also can cause the motor to run inefficiently, potentially reducing its overall torque output and leading to uneven motor performance.

b) Thrust Impact: Like the 5th harmonic, it can slow down the motor's thrust and affect its ability to maintain consistent speed.

2. 11th Harmonic Current:

a) Negative Sequence Component: The 11th harmonic current behaves similarly to the 5th and 7th harmonics by producing a negative sequence component that may cause undesirable effects like motor vibration, increased losses, and overheating.

b) **Thrust Impact: The** 11th **harmonic current can degrade the motor's efficiency and** torque, resulting in a reduced mechanical output and an increase in wear and tear.

3. 13th Harmonic Current:

a) Negative Sequence Component: The 13th harmonic, being an odd harmonic, similarly contributes to negative-sequence currents and can lead to vibration and additional heat generation in the motor windings. The impact is somewhat similar to the other harmonic currents (5th, 7th, and 11th).

b) Thrust Impact: The 13th harmonic can reduce the thrust capacity of the motor, especially at high-load or high-speed conditions, where the effects of harmonic distortion are more pronounced.

Overall Effects of Harmonics on Motor Performance:

a) Motor Efficiency: The presence of harmonics, particularly odd-order harmonics like the 5th, 7th, 11th, and 13th, results in higher losses due to additional heating and increased current distortions.

b) Reduced Torque and Thrust: These harmonics lead to distorted torque production. Since harmonics create rotating magnetic fields that oppose the fundamental field, they reduce the effective torque and can make it harder for the motor to maintain a steady speed.

c) Increased Vibration and Noise: Negative sequence harmonics create unbalanced magnetic fields, which can lead to vibration and mechanical stresses. This results in reduced lifespan and increased maintenance needs for the motor.

d) Increased Heating: Harmonics increase the total RMS current, which leads to excess heat generation, especially in the stator winding, degrading insulation over time.

Therefore, the cumulative impacts of the 7th, 11th, and 13th harmonic currents negatively affect motor performance by introducing negative-sequence currents, reducing torque, generating excess heat, increasing vibration, and leading to mechanical stress. It's important to mitigate these harmonic effects through appropriate filtering or design considerations to ensure optimal motor operation. As shown in Figure 6 after mitigation, the torque value increased. The full load current recoded against slip, at locked rotor to full loaded point, the current ramped down following the same pattern as the mitigated stator current-slip characteristics. The 5th harmonic showed as

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rapid variation as compared to the mitigated trends.

ii. Single-Multiple PWM Techniques

The single-multiple carriers PWM techniques were compared in the relation to the waveform distortions as evidence in the multiple plots: Figure 8.

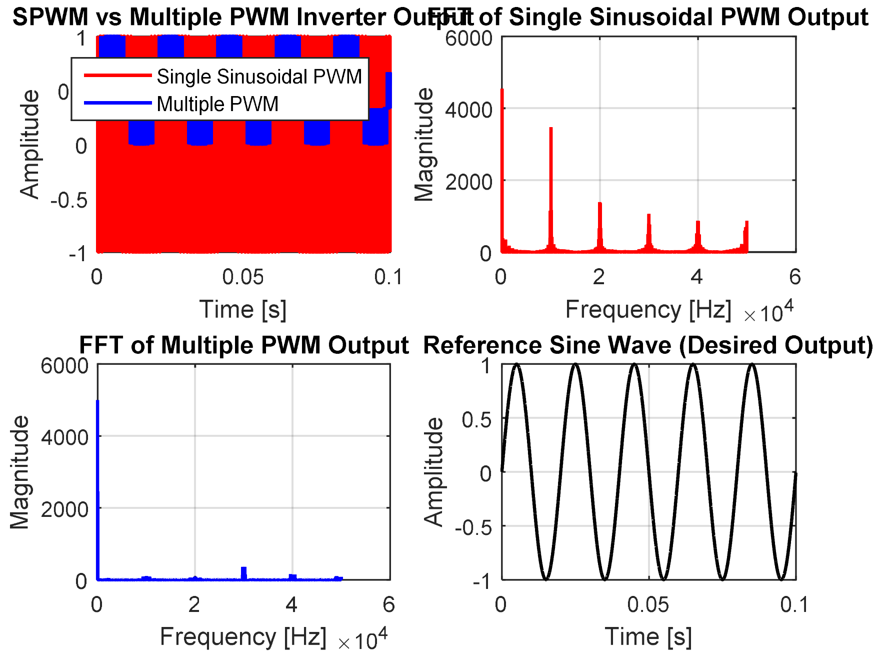

Figure 8: Single-Multiple PWM Techniques

1. Speed and Torque Performance: The comparison of motor speed and torque between the Single PWM and Multiple PWM give insights into how well each control strategy performs in terms of motor dynamics. Multiple PWM provided smoother operation with reduced torque ripple due to better harmonic cancellation.
2. Harmonic Content: The FFT plots shows that Multiple PWM has a lower harmonic distortion compared to Single PWM, which results in a cleaner voltage waveform with fewer high-frequency components. This leads to better performance and efficiency in the motor.

KEY FINDINGS:

a) Single PWM: Simpler to implement, but the motor might be experiencing higher torque ripple and harmonic distortion in the output.

b) Multiple PWM: Offers better harmonic performance (lower Total Harmonic Distortion or THD), resulting in smoother motor operation, reduced torque ripple, and higher efficiency, but at the cost of increased complexity and switching losses.

Therefore, the simulation shown in Figure 8 has provided a comparison of Single PWM and Multiple PWM in the context of variable speed control for induction motors.

iii. Selective Harmonic Elimination Versus Multiple PWM

Selective harmonic elimination was compared with multiple PWM technique being adjudged to offer better harmonic performance for induction motor operation than the single carrier PWM. This is shown in Figure 9, comparatively depicting SHE and Multiple PWM under time domain and frequency domain characteristics for each mitigation technique,

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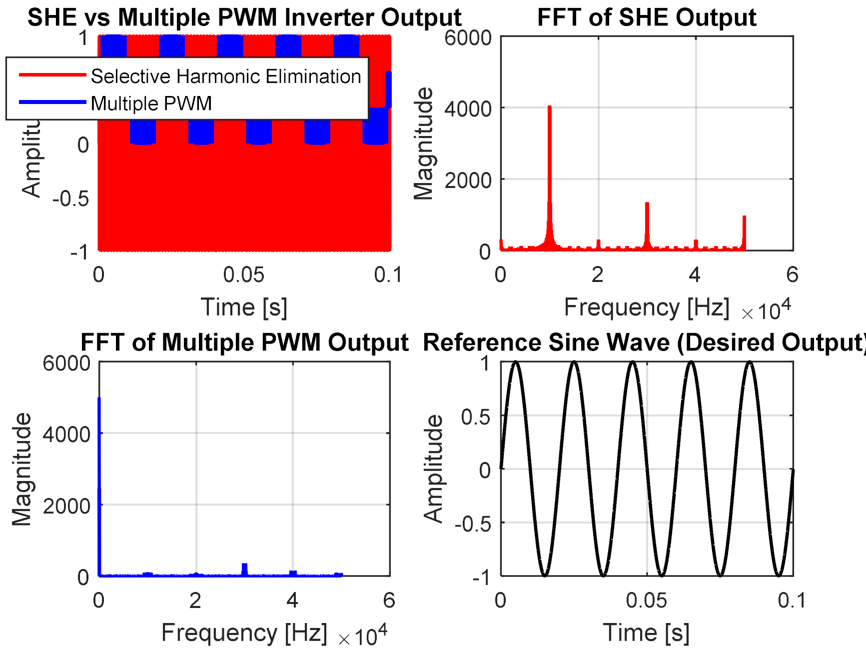

Figure 9: Selective Harmonic Elimination Versus Multiple PWM

KEY INSIGHTS:

Time-Domain Waveforms:

i. The SHE output shows sharp transitions based on the switching angles, with reduced harmonics at the selected frequencies (e.g., 3rd, 5th, and 7th).

ii. The Multiple PWM output was smoother than SHE and exhibit less ripple due to the averaging effect of multiple carriers.

Frequency domain Analysis:

iii. SHE gives low harmonic content at specific harmonics (the ones that were eliminated) but still have some harmonic distortion at higher frequencies.

iv. Multiple PWM reduced harmonic distortion and spread harmonics over a broader frequency range, leading to better overall waveform quality.

Selective Harmonic Elimination (SHE) is effective at eliminating specific low-order harmonics, which can be useful for applications requiring precise control of harmonic content. However, it may not eliminate all harmonics and can be more complex to implement.

Multiple PWM provides a smoother output with reduced harmonic distortion across a wider range of frequencies. It is simpler to implement than SHE and works well for reducing overall harmonic distortion without eliminating specific harmonics.

This comparison illustrates the trade-offs between SHE and Multiple PWM in terms of harmonic performance and simplicity of implementation which can be explored by designer in their choice for specialized or generic applications.

iv. Space Vector PWM Technique

Space Vector PWM maximizes the DC bus utilization and results in a better output waveform compared to traditional SPWM. Figure 10 shows the time-domain SVPWM for a 3-phase supply.

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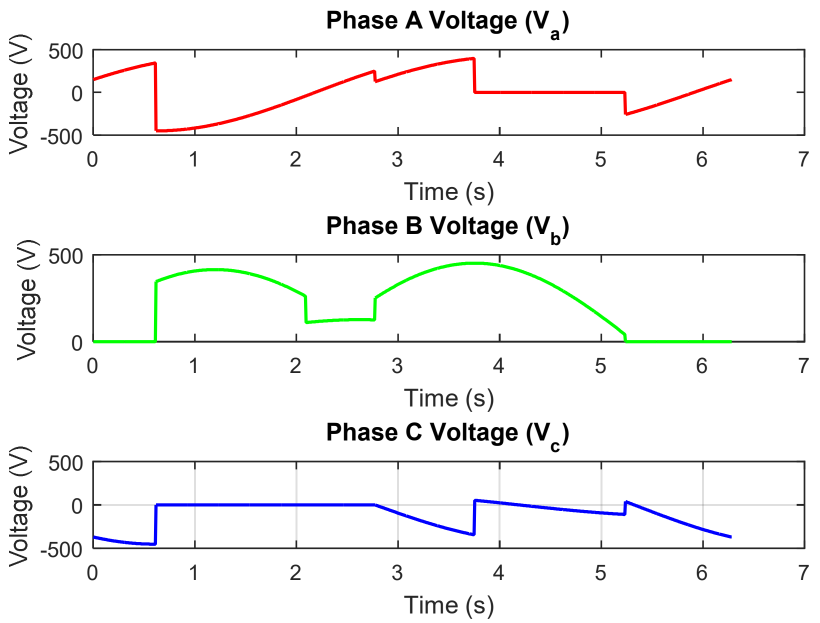

Figure 10: Time-domain waveform for a Space Vector PWM Technique

v. Space Vector PWM versus sinusoidal PWM Techniques

Space Vector PWM and sinusoidal PWM techniques were compared in Figure 11, while the SVPWM equally compared with squared PWM as shown in Figure 12.

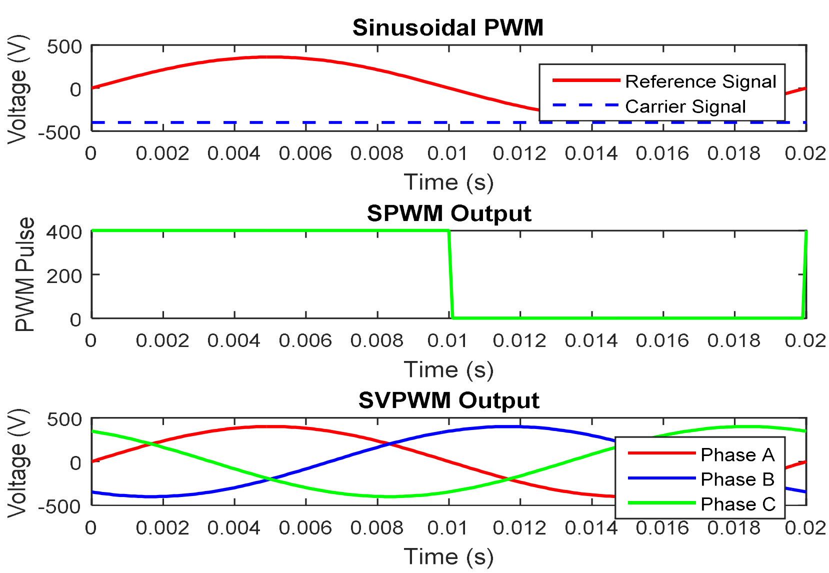

Figure 11: Space Vector PWM and sinusoidal PWM Technique

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- Space Vector PWM (SVPWM) has the following advantages:
  - Better DC Bus Utilization: SVPWM makes better use of the DC link voltage, giving higher output voltage for the same DC input voltage.
  - Reduced Harmonics: The harmonic content in the output voltage is typically lower in SVPWM compared to SPWM, resulting in a cleaner waveform.
  - Efficiency: It is more efficient in terms of power conversion, as the voltage utilization is maximized.

- Sinusoidal PWM (SPWM):
  - Simplicity: SPWM is simpler to implement and understand.
  - Moderate Efficiency: SPWM results in lower DC bus utilization, meaning it might need a higher DC input to achieve the same output voltage compared to SVPWM.
  - More Harmonics: SPWM generally produces more harmonic distortion compared to SVPWM.

SVPWM is superior in terms of efficiency and output quality because it utilizes the DC bus voltage better and produces less harmonic distortion. However, it is more complex to implement compared to SPWM, which is simpler and still useful for many applications where maximum voltage utilization and harmonic performance are not critical.

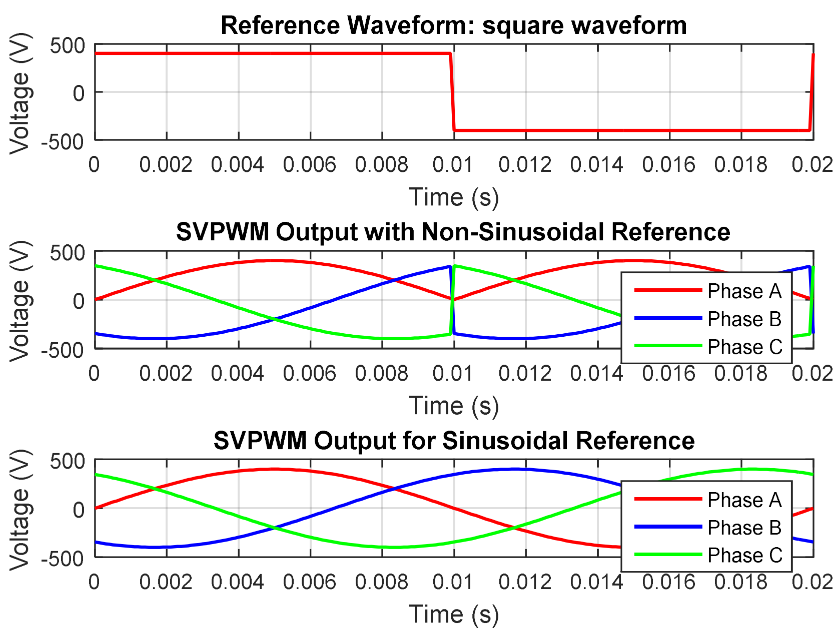

Figure 12: Space Vector PWM and squared PWM Technique

CONCLUSION

Induction motors, when driven by non-sinusoidal waveform supplies, experience a range of issues like harmonic distortion, torque ripple, and efficiency losses. To address these, speed control techniques like V/f control, vector control, and direct torque control can be applied, but these methods must be adapted to handle the effects of harmonic distortion. Additionally, harmonic mitigation strategies like single and multiple PWM schemes, as well as selective harmonic elimination (SHE), can significantly reduce the impact of harmonics, improving both motor and drive performance.

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