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INDIVIDUAL PROJECT

Investigation of Control Techniques for Performance Improvement of Multilevel Inverters

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Abstract

This report presents a comprehensive investigation into the application of a specific control technique for multilevel inverter-driven permanent magnet synchronous motors, with a focus on electric vehicle applications. The objective of this research is to identify and validate the advantages of multilevel inverters over typical three-phase voltage source inverters utilizing thorough simulation analyses using MATLAB/Simulink. The emphasis is on the feasibility of executing the control approach across various inverter topologies, evaluating control complexity, component count, and operating speed.

The evaluation of system stability, specifically the rate of establishing steady-state conditions and the level of overshoot in system response, is central to this research. The performance of the control methodology in issue will be compared to conventional methods, with a focus on its effectiveness when applied to multilevel inverters for permanent magnet synchronous motors. To aid in this research, the project will create simulation models for both multilevel and three-phase voltage source inverters, using the same control method to compare performance.

The study also investigates the effect of various parameters on controller design complexity, such as changes in inverter levels, motor pole pair counts, and DC link voltages. The simulations are designed to capture important performance data, which will then be analysed to show the advantages of the selected control strategy for both inverter types. This research will not only advance academic understanding but also provide practical insights into the progress of electric car drivetrain technologies.

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Chapter 1

Introduction

With the global shift towards sustainable energy, electric vehicles are gaining popularity since they are essential for reducing carbon emissions and improving energy efficiency. The primary obstacle preventing electric vehicles (from achieving widespread adoption is their limited range. The powertrains of most electric vehicles operate between 350 to 400V, which falls short for extended driving distances. Additionally, the infrastructure for electric vehicle charging is not yet fully developed, with charging stations being few and far between, coupled with the inconvenience of lengthy charging times. A potential remedy could be to adopt powertrains with higher voltages; however, this can lead to reduced inverter durability. An inverter, crucial for converting direct current (DC) to alternating current (AC) to power the vehicle's motor, can produce either sinusoidal or non-sinusoidal waveforms tailored to the specific needs of the vehicle. Inverters are the linchpin in the electrical system of electric vehicles, and there's a variety of designs and control methods employed to generate the necessary AC power. The two-level three-phase voltage source inverter has been the standard in electric vehicles for years, despite its various limitations.

In a two-level configuration, increasing the voltage can cause increased electromagnetic interference which causes considerable damage to the electric motor. It also causes more stress on the switches of the inverter. Additionally, this configuration tends to generate greater harmonic distortion. When considering loss factors, the two-level inverter typically exhibits increased switching losses that surpass any reduction in conduction losses, leading to a net decrease in inverter efficiency. Consequently, multilevel inverters have attracted considerable attention for their potential to overcome these issues. (Bubert et al., 2018). Using multilevel inverters instead of two-level voltage source inverters might be the solution to the problem, however, designing a motor controller that is driven by multilevel inverters comes with its complexities. Optimizing electric motor function across diverse applications hinges on advanced motor control methodologies. These techniques are pivotal in achieving energy efficiency, modulating speed and torque, and ensuring precise positioning—attributes essential in industrial settings. They play a significant role in preventing motor overheating and unwarranted current surges, while also facilitating quick response times, particularly in electric vehicle technologies. The effectiveness of motor control is intrinsically linked to the type of inverter deployed. The chosen control strategy must be tailored to align with the inverter's specific attributes and capabilities, ensuring that motor performance, energy efficiency, and operational safety are optimized for the intended application. Integral to the success of a motor control system is the seamless integration of the control technique with the inverter's design.

1.1 Project Overview

This research conducted a thorough assessment of control techniques for multilevel inverter-driven permanent magnet synchronous motors, with a special emphasis on assessing the efficacy and adaptability of these strategies across various inverter configurations. The goal is to gain a better knowledge of how different inverter levels influence the control and performance of permanent magnet synchronous motors, such as two-level voltage source inverters, three-level, and five-level cascaded H-bridge inverters. This investigation is critical in the field of improving power electronics and motor control technologies, where efficiency and precision are critical.

An extensive simulation study utilizing MATLAB/Simulink is the core of this research. At the beginning, a simulation of a permanent magnet synchronous motor powered by a two-level voltage source inverter and controlled by a field-oriented control technique which is well-known for its precision in motor control. This first phase serves as a baseline for the assessments that follow. Then the research was expanded to include more complex inverter configurations, notably three-level and five-level cascaded H-bridge inverters, while using the same control technique and motor. This constant approach enabled us to compare different inverter levels in a fair and accurate manner.

This study had two goals: first, to investigate the control complexities that arose with higher-level inverter designs, and second, to evaluate the influence of these configurations on motor performance measures such as speed and torque. A critical component of this research was assessing the system's stability, namely how quickly and effectively it establishes a steady state with various inverter types and the level of overshooting during this process. The investigation of how variations between inverter levels and motor poles affect controller gains and system responses was also a key component of this research. This will provide insights into the field-orientated control's flexibility across multiple configurations as well as any future tuning or optimization requirements. It is expected that by the completion of this research, a full comparison of several inverter configurations in terms of control complexity, system stability, and motor performance will be presented.

1.2 Objective of The Project

The main objectives of my project include a thorough investigation into the control techniques of multilevel inverter-driven permanent magnet synchronous motors, with a focus on understanding and validating the performance dynamics across different inverter configurations. The project's initial goal is to investigate and analyze the control dynamics of permanent magnet synchronous motors when driven by several inverter types, such as two-level voltage source inverters, three-level, and five-level cascaded H-bridge inverters. This comparison is critical in understanding how inverter levels affect motor control and performance. Validating the usefulness of a field-oriented control technique across these many inverter topologies, as well as testing its adaptability and performance consistency, is a critical goal. Furthermore, the research project intends to investigate the control complexities of managing multilevel inverters rather than standard two-level inverters. This contains a comparison analysis that focuses on component counts, operational difficulties, and operational speed. Another critical goal is to measure the system's stability, specifically the response time and the time required to achieve steady-state equilibrium and the rate of overshooting under various inverter configurations. This analysis is critical in determining the control strategy's practical viability in a variety of operational settings. The project will also look into how differences in inverter levels and motor poles affect controller gains and system outputs like speed and torque. This investigation is crucial to comprehending the efficiency and effectiveness of multilevel inverters versus standard two-level inverters. The study also includes an examination of the system's responsiveness, including speed and torque characteristics, under changing inverter level and motor pole conditions.

1.3 Research Plan

The aim of the project is to perform a thorough analysis of a specific control technique for usage in both three-phase voltage source inverters and multilevel inverters within permanent magnet synchronous motors, with an emphasis on electric vehicles. The study began with an in-depth examination of various control strategies, followed by a thorough review of the existing literature to identify knowledge gaps and best practices in the sector. This step was critical for determining the best control technique. MATLAB/Simulink was used to create simulation models for the three-level and five-level cascaded H-bridge multilevel inverter and the three-phase voltage source inverter. The research then compared the identical control technique applied to different inverter types, emphasizing the complexities inherent in controller design. Detailed simulations were then run to collect performance data, which was then thoroughly analysed to determine the effectiveness of the selected control strategy in different inverter scenarios. The ultimate goal was to find the most effective control mechanism for permanent magnet synchronous motors powered by multilevel inverters, particularly in the context of electric vehicles.

1.4 Methodology

This section outlines the methodology adopted for the research project aimed at investigating an effective control strategy for multilevel inverter-driven permanent magnet synchronous motors. The research encompasses a comprehensive approach, beginning with a literature review, followed by software familiarization, and then the development and simulation of various inverter models.

A thorough literature review was conducted to understand the various control techniques for permanent magnet synchronous motors. This review encompassed a comparative analysis of different control strategies, focusing on their advantages and disadvantages. The emphasis was on identifying the most efficient control methods that could be integrated with multilevel inverters. Another aspect of the literature review focused on multilevel inverters, examining their types, advantages, and limitations. This comprehensive review helped to understand the operational principles of multilevel inverters and their compatibility with permanent magnet synchronous motors. The literature review also included an in-depth study of permanent magnet synchronous motors, covering their operational characteristics, efficiency, and suitability for various applications. This review provided a solid foundation for understanding the interaction between the motor and the inverter systems. To simulate and analyze the proposed models, proficiency in MATLAB/Simulink was essential. Training was undertaken through courses and tutorials offered by MathWorks, focusing specifically on Simulink's capabilities in simulating electrical and control systems.

The initial stage of the project focused on designing a two-level, three-phase inverter, seamlessly integrated with a field-oriented controller and paired with a permanent magnet synchronous motor, serving as the foundational model for the research. The simulation process entailed rigorously testing this inverter with a permanent magnet synchronous motor combination under diverse load and speed scenarios, properly documenting vital parameters like torque, speed, and current. Simultaneously, the field-oriented controller underwent precise calibration to ensure optimal motor performance, particularly in terms of accurate torque and speed control. The project's scope later expanded to include the development of three-level and five-level cascaded H-bridge inverters, necessitating adjustments in the field-oriented controller to align with these more intricate inverter designs. Particular focus was placed on recalibrating the field-oriented control's parameters to effectively handle the heightened complexity presented by the multilevel inverters. To evaluate the efficacy of each inverter configuration, simulations were conducted under conditions akin to those applied to the initial two-level inverter setup. This methodical approach in testing ensured uniformity in experimental conditions, allowing for a direct, comparative analysis of the different inverter types' performance metrics, thereby providing a comprehensive overview of their respective efficiencies and operational dynamics.

The study focused on how increasing inverter levels affect control complexity and system performance by thoroughly analysing the control parameters for various types of inverters. This investigation included comparing the number of components and operating speeds for each type of inverter as well as assessing the complexity of the control approach as inverter levels rose. Finding the ideal ratio between performance efficiency and complexity was the goal of this comparison. The study also looked at several motor pole configurations for various kinds of inverters, which helped to clarify how control techniques, inverter complexity, and motor pole arrangement interact. Assessing the performance and stability of the system was a crucial component of the study. This involved monitoring the amount of overshooting in various configurations and calculating the rate at which each system reached a steady-state equilibrium. Additionally, the study compared the multilayer inverter-driven permanent magnet synchronous motor's performance to that of conventional three-phase voltage source inverters. The purpose of this comparison analysis was to determine how well the applied control strategies preserved system stability while improving performance. Through this comprehensive analysis, the research sought to provide insights into optimizing inverter and motor configurations for improved operational efficiency and stability in electric motor-driven systems.

Through a combination of literature review, software proficiency development, and extensive simulation and analysis, the research aims to contribute significant insights into the effective control of multilevel inverter-driven PMSM motors. The outcomes of this study are expected to offer valuable contributions to the field of electrical motor control and power electronics.

1.5 Project Requirements

The project required the use of specialized simulation tools such as MATLAB/Simulink and associated toolsets. This configuration was required to conduct a simulation-based comparison analysis of the selected control strategy across several inverters in permanent magnet synchronous motors designed for electric vehicle applications.

Chapter 2

Literature Review

This chapter critically evaluates the literature on two-level voltage source inverters, multilevel inverters, motor control techniques, and permanent magnet synchronous motors. It contributes insights to the understanding of how multilevel inverters would impact the electric vehicle industry and how the use of multilevel inverters instead of conventional two- level inverters would affect the control complexity which will provide valuable information for researchers and industry practitioners. In the context of the research topic scoping into the control technique for multilevel inverters, this chapter shall explore existing research on the concepts of multilevel inverters, motor control techniques, and their adaptability in the electrical vehicle industry for the development of this study's conceptual framework. IEEE Explore and Science Direct for seminal works, and Google Scholar are some of the many sources that were used in the process of extensively comprehensive research on credible sources of literature. In the process of the research, no paper has been studied and considered for analysis other than journal and conference papers. This ensured the quality of analysis at all levels.

2.1 Electrical Vehicle

Electric vehicles are regarded as a superior choice than internal combustion engine vehicles, with several major advantages. K. Poornesh et al., (2020) highlights that electric vehicles emit significantly less greenhouse gas emissions than conventional petrol or diesel engines, helping to combat climate change. Furthermore, their reliance on electricity rather than petrol or diesel reduces their reliance on finite fossil fuel supply. This made electrical vehicles more desirable and the demand for these vehicles skyrocketed. As the demand for electric vehicles grows, it is essential to know the current technology used by these vehicles. (J. Reimers et al., 2019) provides an in-depth analysis of existing traction inverter technology in production vehicles, emphasizing their progress in response to the growing desire for more efficient and environmentally friendly electric vehicles. The article evaluates numerous inverter designs from multiple manufacturers, focusing on developments in wide bandgap devices, device packaging, active gate driver implementations, and improved manufacturing procedures, with a focus on essential components of electric vehicle powertrains. It emphasizes the critical importance of electric machines in electric vehicles, which require traction inverters to convert direct electricity from batteries into variable frequency alternating current for mobility and regenerative braking. The majority of electric vehicles in production today use three-phase voltage source inverters based on IGBTs. These inverters are popular due to their great efficiency, low cost, and ease of design and manufacture. This technology is critical for the transition to cleaner and more efficient vehicles, including hybrids, plug-in hybrids, battery-electric vehicles, and fuel-cell vehicles. According to the article, permanent magnet synchronous motors are the most prevalent electric machines utilized in today's electric vehicles. These machines are well-suited for automotive applications because of their efficiency and power density.

2.2 Inverter

Inverters are a crucial component in power electronic applications such as electric vehicles. E. L. Owen, (1996) dives into early developments of inverters, with a focus on David Prince's work, who is likely the first to use the name "inverter." It follows the concept's evolution beginning in 1925 when Prince wrote an article explaining fundamental aspects of modern inverters, such as grid management mixed with phase retard for AC power modulation. It explains how Prince coined the term "inverter" from the concept of "inverted rectification," which effectively reverses the function of a rectifier to convert direct current to alternating current. The study also explores the early sorts of rectifier devices that Prince had access to, such as mechanical rectifiers, electrolytic cells, and gas-discharge tubes. These early achievements paved the way for subsequent advances in inverter technology. Prince's 1925 definition of an inverter as an inverse rectifier is noted, as are his novel procedures for converting direct current to alternating current.

The inverters are categorized into two-level inverters and multilevel inverters. Current electric vehicles use two-level voltage source inverters. S. Kharjule, (2015) discusses numerous drawbacks of three-phase voltage source inverters. One critical issue is the attenuation of the fundamental component in the waveform, which can impair power conversion efficiency. Furthermore, these inverters work at higher switching frequencies, exerting additional strain on the switching devices and frequently necessitating their derating to meet the increased operational needs. The development of high-frequency harmonic components is another key disadvantage. These harmonics can cause power system difficulties like as noise and interference, putting on three-phase two-level voltage source inverter's efficiency and reliability at risk in a variety of industrial and power conversion situations. To overcome these issues many researches are going on for the use of multilevel inverters instead of two-level voltage sources inverters. B. Ch et al., (2018) compares five- phase three-level neutral point clamped with five-phase two-level inverters used in industrial electric drives. It compares the performance of these two inverters under similar loads and modulation indices. The results show that five-phase three-level neutral point clamped inverters perform better in terms of control mode voltage and total harmonic distortion reduction. While the five-phase two-level inverter provides easier dc-link voltage balancing, the five-phase three-level neutral point clamped achieves virtually zero percent control mode voltage using a modified space vector pulse width modulation method, exceeding the five-phase two-level inverter in terms of total harmonic distortion in line voltage and load current. Another research done by J. Rodriguez et al., (2007) gives a comprehensive overview of voltage-source-converter topologies for industrial medium-voltage drives, focusing on high-power voltage source inverters and multilevel inverters such as the neutral-point-clamped, flying capacitor, and cascaded H-bridge. It delves into the evolution of traditional two-level voltage source inverters, which are bound by semiconductor voltage restrictions, to modern multilevel inverters that overcome these constraints. The research investigates each topology's distinct structural properties and application applicability, highlighting neutral-point-clamped inverters for low switching frequency efficiency, flying capacitor inverters for high-bandwidth applications such as medium-voltage traction motors, and cascaded H-bridge inverters for their modularity, which is ideal for high-power applications. It emphasizes the technological advantages and disadvantages of each, demonstrating their distinct market responsibilities. To summarise, while two-level voltage source inverters are simple and inexpensive, their greater harmonic distortion and limited scaling make them unsuitable for high-voltage applications. Multilevel inverters, on the other hand, provide improved performance in high-power and high-voltage applications, with each suited to unique application needs based on power level, voltage, and output waveform quality. Lastly, another comparison is made by R. Mali et al., (2019) where two-level inverters using space vector pulse width modulation to five-level classical multilevel inverters using phase disposition multi-carrier modulation, focusing on parameters such as total harmonic distortion), electromagnetic interference, switching frequency, switching losses, and the number of switching devices. Although multilevel inverters require more switches, they are becoming more popular in industrial settings due to their advantages in decreasing electromagnetic interference, total harmonic distortion, and switching losses when compared to two-level inverters. However, one key difficulty with multilevel inverters is the increased cost at higher operating voltages. Therefore, it supports the first objective of this research of using multilevel inverters instead of two-level voltage source inverters. However, it was necessary to choose a specific inverter topology for this research. The following study by A. Prayag & S. Bodkhe, (2016) compares neutral-point-clamped, flying capacitor, and cascaded H-bridge topologies are compared in this study for high-power three-phase industrial applications. The cascaded H-bridge is the most advantageous of the three, with the least complex circuitry and fewest components while providing lower harmonic distortion in output voltage waveforms than either alternative multilevel or standard two-level inverters. When compared to multilevel inverters and two-level inverter approaches, the cascaded H-bridge multilevel inverter proves uniquely suited for electric vehicle motor drive systems due to its simultaneous simplicity and superior performance, particularly in terms of component utilization and waveform quality.

2.3 Motor

Vehicles can be categorized into three types based on their driving mechanisms. They are internal combustion engine vehicles, electric vehicles, and hybrid electric vehicles. Traditional internal combustion engine vehicles rely only on petrol, diesel, or other fossil fuel-burning engines to power the wheels. Electric vehicles, on the other hand, are propelled solely by one or more electric motors powered by battery-supplied electricity. Finally, hybrid electric vehicles combine both technologies, driving the vehicle using an internal combustion engine and electric motors. Hybrid electric vehicles take advantage of the benefits of having two independent power sources on board (M. Yildirim et al., 2014). This shows that the electric motor is one of the most integral parts of an electric vehicle's drive train. Selecting a suitable motor for an electric vehicle drive train is very important. M. Zeraoulia et al., (2006) compares four major electric motor technologies used in electric vehicles and hybrid electric vehicles direct current motors, induction motors, permanent magnet synchronous motors, and switching reluctance motors. It concludes that cage induction motors are very suited for both electric vehicles and hybrid electric vehicles electric motor because they meet key needs such as high-power density, strong torque at low speeds for starting and climbing, a wide speed range, fast torque response, and good efficiency over a wide range of speed and torque ranges. Cage induction motors are popular because of their dependability, robustness, low maintenance, low cost, and ability to run in hostile situations, making them ideal for industrial and traction drive applications. Permanent magnet synchronous motors have been used by various automakers for electric vehicles and hybrid electric vehicles, and have benefits such as high power density, as well as improved efficiency. However, because of the potential of permanent magnet demagnetization, their efficiency may suffer at very high speeds. Switching reluctance motors are gaining popularity for electric vehicles and hybrid electric vehicle applications due to their simple and durable construction, fault-tolerant operation, simple control, and outstanding torque-speed characteristics. However, their efficiency is not up to the mark with the other electric motors. Z. Yang et al., (2015) examines four motor topologies for electric and hybrid vehicle applications, with an emphasis on interior permanent magnet synchronous motors, induction motors, and switching reluctance motors. The interior permanent magnet synchronous motors are shown to be highly efficient, especially at low speeds, but lose some efficiency at very high speeds due to higher losses. The induction motors excel in high-speed applications, providing dependable performance, but their efficiency suffers at lower speeds due to greater copper loss. While the switching reluctance motors are economical in medium torque levels, their power output is limited, making them less adaptable than the other two. Overall, because of their balanced efficiency at all speeds and operational conditions, interior permanent magnet synchronous motors emerge as the most ideal for a wide range of electric vehicles and hybrid electric vehicle applications. In both studies, it is suggested that permanent magnet synchronous motors and induction motors are the most promising ones used in electric vehicles. For this research permanent magnet synchronous motor was chosen over an induction motor as this research by G. Pellegrino et al., (2012) makes a comparison of motor drives for electric vehicle applications, three types are evaluated based on output power and efficiency which are induction motors, surface-mounted permanent-magnet synchronous motors, and interior permanent-magnet synchronous motors. The induction motor is preferred for its low cost and inherent safety during inverter failures caused by natural de-excitation, although it is less efficient due to cage losses at different speeds. While surface-mounted permanent-magnet synchronous motors are easier to build and have shorter connections, they suffer from eddy-current losses at high speeds and have limited transient overload power. In contrast, the interior permanent-magnet synchronous motors outperform the competition with improved power overload curves and efficiency across all loads and speeds, especially when designed for high saliency. Despite its more complicated production process, the interior permanent-magnet synchronous motor's balanced characteristics make it the best choice for a wide range of electric vehicle applications. Hence it justifies the use of a permanent-magnet synchronous motor for this research.

2.4 Control System

Motor control in electric vehicles is critical for achieving optimal performance and efficiency. An electric vehicle's motor is controlled by an inverter, which manipulates the current supply to the motor to produce the appropriate speed and torque. The inverter serves as the driving mechanism, allowing precise regulation of the motor's operation to meet real-time performance requirements. Thus, the motor control technique of an electric vehicle is centered on effectively utilizing the inverter to actively direct the motor's output in terms of rotational velocity and twisting force produced. Rather than passively supplying the motor, the inverter drive dynamically influences its characteristics. Vijaya Sambhavi & Ramachandran, 2023) dives into several electric car motor control systems, focusing on scalar and vector controllers for motor drive inverters. Scalar control, which includes both open-loop and closed-loop systems, is simple and cost-effective, but it lacks dynamic reaction, making it unsuitable for rapid fluctuation scenarios. Vector control, which includes field-oriented control and direct torque control, enables precise torque and speed regulation, with field-oriented control being especially resilient during transients. Direct torque control distinguishes itself by providing direct control of torque and stator flux, as well as quick reaction and simplicity. Predictive control is gaining popularity because of its capacity to improve performance by forecasting future states and minimizing cost functions. Finally, sensorless control approaches are developed, providing improved noise immunity and endurance at a greater installation cost.

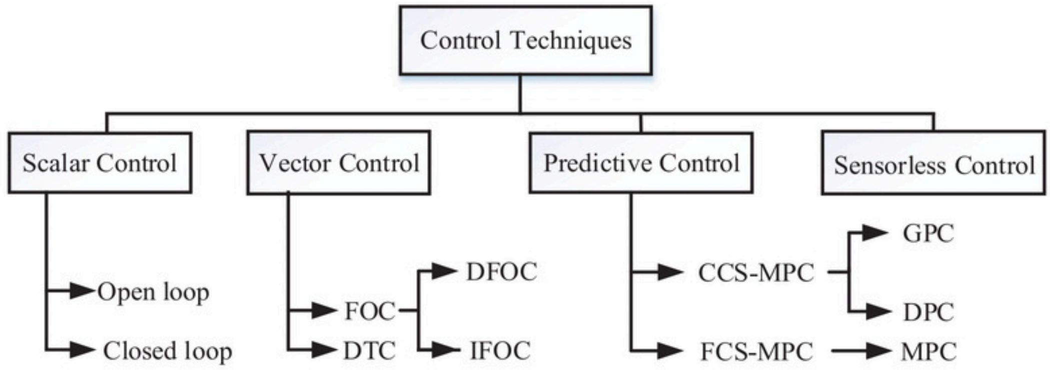

Figure 1: Classifications of motor control techniques for EV (Vijaya Sambhavi & Ramachandran,2023a)

The objective of this research is to develop a control technique suitable for multilevel inverters. A. Poorfakhraei et al., (2021) compares three different control techniques for multilevel inverter-driven electric vehicles. Scalar control in electric vehicles involves the simple control of parameters such as voltage and frequency, with two variants which are open-loop control, which is known for its cost-effectiveness and simplicity but lacks dynamic response due to the lack of feedback, and closed-loop control, which provides better regulation of speed, torque, and flux. Field-oriented control, a vector control approach, allows for separate control of a motor's flux and torque through the use of a two-dimensional coordinate system. It can be direct, utilizing sensors to monitor air gap flux, or indirect, computing flux position without direct measurement, and is known for its resilient performance during transients. It could be deduced that vector control is more suitable for a better output. V. M. Bida et al., (2018) discusses various motor control strategies used in electric vehicles to regulate torque and speed by regulating electrical flow to the motor via an inverter drive, each having their own advantages and limitations. Field-oriented control provides precise and adaptive control but necessitates more complicated computing. Direct torque control features very sensitive dynamics but larger ripple effects. Voltage vector control is simple and sturdy, although it causes higher torque overshoot than alternatives. Passivity-based control performs similarly to field-oriented control but suffers from torque peaks and accuracy losses due to higher ripples. Finally, nonlinear torque control produces extremely efficient output with minimum ripple and outstanding stability, making it well-suited for high-precision motor regulation at the expense of increased system complexity. For the simplicity of control complexity field-oriented control and direct torque control are the most suitable ones. However, for this research field-oriented control as the study by F. Korkmaz et al., (2013) indicates significant advantages and trade-offs for each in the comparison of field-oriented control and direct torque control for permanent magnet synchronous motors). Field-oriented control provides faster speed dynamic response and smaller torque ripple at the expense of increased inverter switching frequency and control complexity. Direct torque control, on the other hand, has faster dynamic performance and a simpler control scheme due to fewer motor parameter needs, but it has a higher torque ripple. The decision between these two control systems is determined by the unique application requirements: direct torque control is better suited for scenarios that prioritize fast response and simplicity, whilst field-oriented control is better suited for applications that require good torque quality which makes it the most suitable for this research.

Pulse width modulation is also an integral part of the control system as it is used to control the speed and torque of the motor in an electric vehicle. Pulse width modulation is used to generate control inverter outputs which are used to control the speed and torque of the motor. The study by Vijaya Sambhavi & Ramachandran, (2023b) provided numerous methods for modulating inverters for multilevel inverters, each adapted to unique application needs. Space vector modulation, which is ideal for low-frequency switching, adjusts the number of vectors with the multilevel inverter levels and extends to 2D and 3D forms for handling unbalanced loads and harmonics. It is a complex inverter modulation technology that is noted for its low total harmonic distortion excellent efficiency, and flexibility in adjusting the output voltage and current. Space vector modulation, becomes computationally intensive as the number of levels increases, necessitating simplification attempts for efficient implementation in multilevel inverter systems (A. Mohamed A. S. et al., 2009). Despite its difficulties in open- loop systems and higher-level multilevel inverters, selective harmonic elimination uses Fourier equations to minimize odd harmonics and is frequently implemented with evolutionary algorithms. It is noted for its low switching frequency and excellent efficiency, making it suited for high-speed operations in high-power traction drives, yet because of its low switching frequency, it encounters issues with capacitor voltage balancing in multilevel inverter systems (S. S. Lee et al., 2016). Sinusoidal pulse width modulation also known as multicarrier pulse width modulation, a high-frequency technique, generates pulses by comparing carrier signals to a sinusoidal reference, with modifications such as carrier disposition and phase-shifted pulse width modulation. To balance efficiency and performance in high-power cells, hybrid modulation techniques mix low and high-frequency pulse width modulation. Finally, nearest level control seeks the closest voltage level feasible by the multilevel inverters, allowing for greater flexibility and ease of digital implementation while potentially increasing total harmonic distortion, particularly at lower modulation indices. Power level, harmonic performance, and control complexity are all considered while selecting a technique. Discontinuous pulse width modulation is a technique designed to reduce switching losses in inverters by eliminating switching at the peak of sinusoidal currents, but it has issues with voltage balancing and higher total harmonic distortion, particularly in multilevel inverters. Windowed pulse width modulation, on the other hand, is a novel strategy that combines the reduced switching loss of nearest-level control with the high-quality output waveform of standard pulse width modulation approaches. Pulse width modulation is used in windowed pulse width modulation at particular intervals that are dynamically selected based on the traction drive's operating circumstances, thereby balancing the benefits of both nearest-level control and pulse width modulation (A. Poorfakhraei et al., 2021a)

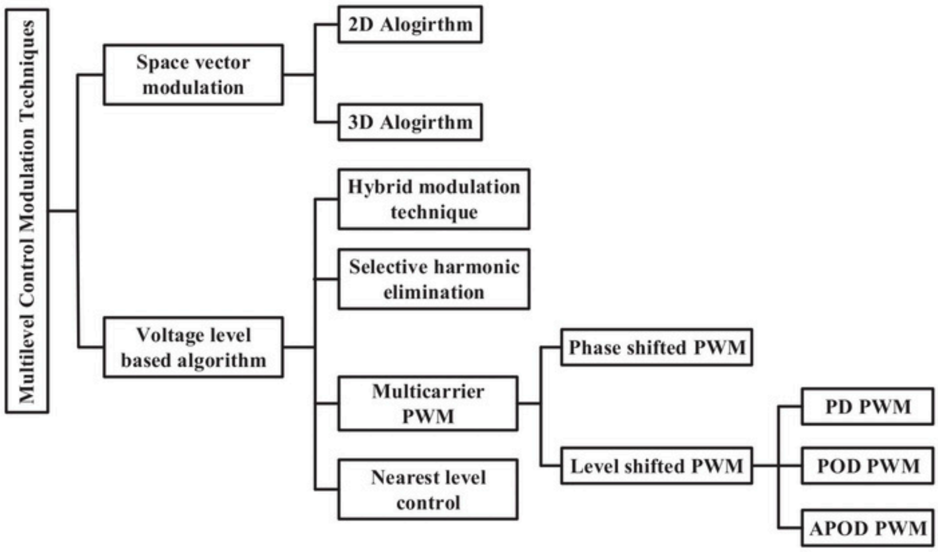

Figure 2: Classification of multilevel inverter modulation techniques (K. K. Gupta & S.Jain, 2014)

From the earlier research, it is concluded that sinusoidal pulse width and space vector modulation are the two preferred modulation techniques suitable for this research purpose. J. Sabarad & G. H. Kulkarni, (2015) compares space-vector pulse width modulation and Sinusoidal pulse width modulation approaches for three-phase multilevel inverters, concentrating on total harmonic distortion and effectiveness in high power applications. Space-vector pulse width modulation gives greater fundamental output phase and line voltages than sinusoidal pulse width modulation due to superior DC bus utilization, according to the study. Furthermore, when compared to sinusoidal pulse width modulation, space-vector pulse width modulation has a greater fundamental output peak load current and a lower total harmonic distortion. However, due to the simple design of sinusoidal pulse width modulation and a very small margin degradation of the output quality over space-vector pulse width modulation, it was the adopted pulse width modulation technique for this research.

2.5 Relevant Work

In the past few decades, much research has been carried out related to the control design of electric vehicle motors driven by multilevel inverters. The work focuses on the modelling, analysis, and design of a multilevel inverter-fed permanent magnet synchronous motor drive using sinusoidal pulse width modulation. In a permanent magnet synchronous motor, vector control is used to provide linear dynamics similar to a DC motor, and sinusoidal pulse width modulation is used to generate regulated switching pulses to the multilayer inverter. The system consists of a five-level cascaded inverter-fed permanent magnet synchronous motor drive. A comparison of three and five-level cascaded inverter-fed permanent magnet synchronous motor drivers is included in the study. The result emphasizes that the sinusoidal pulse width modulation current control technique employed in the five-level inverter-fed drive provides a faster reaction and better quality of voltage and current waveforms while preserving their five levels. Another research was done by B. Lingamchetty et al., (2023) design and simulation of a battery-connected multilevel inverter-fed permanent magnet synchronous motor for electric vehicle applications are presented in this research. It emphasizes the benefits of permanent magnet synchronous motors, such as their high efficiency, low torque ripple, and maintenance-free operation, which make them superior to induction and DC motors in a variety of industrial and automobile applications. The research focuses on improving performance by employing a five-level cascaded H-bridge type multi- level inverter controlled by field-oriented control and sinusoidal pulse width modulation approaches. The finding shows that non-linear controllers such as fuzzy logic or sliding mode controllers, as well as better pulse width modulation techniques, could be used to improve motor responsiveness even more. More detailed research is done by V. Patel et al., (2018) which focuses on the increasing power demands of electric vehicles, which necessitate the usage of improved power electronic converters. It emphasizes the limitations of current two- level inverter technology, such as the fast rate of change of voltage and common mode voltage, which leads to performance loss. In contrast, multilevel inverters, particularly those with a cascaded H-bridge topology, efficiently handle these difficulties, providing smoother output waveforms and lower total harmonic distortion, but at a higher complexity and cost. The research looks at the appropriate number of levels for multilevel inverters in electric vehicle powertrains, taking into account issues like complexity, cost, and DC source availability, with an emphasis on five-level, seven-level, and nine-level architectures. The conclusion indicates that a five-level inverter is best suited for electric vehicle applications, balancing the benefits of multilevel inverters, such as lower initial cost and increased performance, against the complexity of higher-level systems. Lastly, the following research done by M. F. Elmorshedy et al., (2022) covers a similar hypothesis to my research. The research focuses on the application of a seven-level cascaded H-bridge multilevel Inverter in electric vehicle drive systems. The study emphasizes the importance of efficient inverters in electric vehicles for improved performance and efficiency, as well as addressing issues such as greenhouse gas emissions and fossil fuel dependence. The cascaded H-bridge multilevel Inverter is proposed with a permanent magnet synchronous motor for its improved efficiency, better waveform quality, and high-power density. Field-oriented control is used to govern the speed of the permanent magnet synchronous motor by decoupling flux and torque-producing currents, with two controllers for outer speed control and inner current management. The system's performance demonstrates that the cascaded H-bridge multilevel Inverter can dramatically reduce total harmonic distortion when compared to traditional inverters. Various experiments are performed to illustrate the drive system's performance under various speed and load fluctuations, demonstrating the advantages of the cascaded H-bridge multilevel Inverter pin managing the permanent magnet synchronous motor, making it a preferable choice for electric vehicle applications over typical two-level inverters.

Chapter 3

3.1 Comprehensive System Analysis

The main objective is to perfectly drive a permanent magnet synchronous motor using a multilevel cascaded H-bridge inverter architecture and field-oriented control algorithm. The cascaded H-bridge inverter takes a DC source as an input and transforms it to a three-phase AC output using referenced voltage signals. It feeds the permanent magnet synchronous motor with an n-level stepped waveform generated by numerous H-bridge cells per phase. The permanent magnet synchronous motor converts electrical energy to mechanical torque and speed in an efficient manner. It monitors stator currents, speed, and rotor position for feedback. The field-oriented control technique, which is similar to DC motor control, uses mathematical coordinate transformations to regulate permanent magnet synchronous motor torque and flux vectors individually. It analyses reference and measured speed and torque data to determine suitable voltage and frequency levels as inverter control inputs. This enables the inverter to generate the multilevel waveforms required to achieve the specified permanent magnet synchronous motor state per load. The measured motor parametric signals are constantly supplied back to the field-oriented controller, which dynamically recalculates the inverter voltage input to accurately run the permanent magnet synchronous motor at the desired reference speed and torque. The field-oriented control algorithm delicately balances the coordinate transformations and adjusts the voltage and frequency levels generated by the CHB inverter to maintain a constant steady-state speed and torque or to alter it in response to external loads. As a result, synchronized field-oriented control signals assist the inverter in producing an appropriate, low-distortion multilevel supply to the permanent magnet synchronous motor to ensure correct speed and torque response.

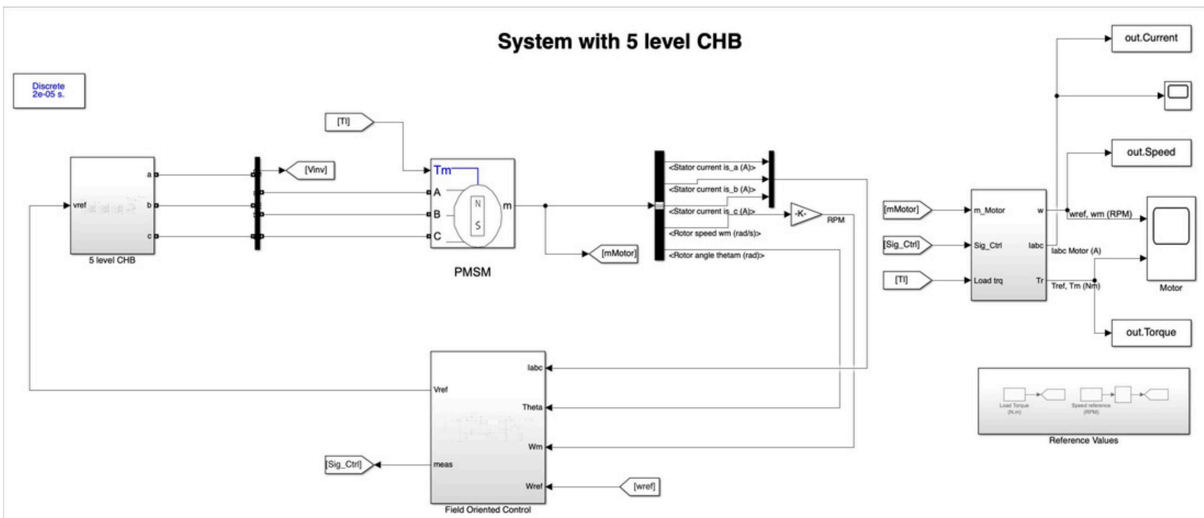

Figure 3: System with five level CHB

3.2 Three-phase Voltage Source Inverters

A three-phase voltage source inverter is a complicated power electronics device that converts direct current (DC) to alternating current (AC) across three phases. Six switches, commonly transistors, MOSFETS, or IGBTs, are organized into three legs, each representing one of the three AC output phases. Each leg has two switches that connect to either the positive or negative terminal of the DC source. The inverter generates three-phase alternating current power by selectively engaging these switches. Each leg's top switch links the phase to the positive DC rail, while the bottom switch connects it to the negative rail. The inverter generates three-phase alternating current output via a synchronized sequence of these switch activations, with each phase voltage being 120 degrees out of phase with the others. This three-phase output is critical in a wide range of industrial and power distribution applications. Pulse width modulation is widely used to modulate output voltage and frequency. Pulse width modulation involves rapidly switching on and off the inverter's switches at high frequencies, altering the duration of the 'on' state which is known as the duty cycle to change the average voltage delivered to the load. This method provides fine control over the amplitude and frequency of the alternating current power.

The inverter's "two-level" name implies its capacity to generate output at two unique voltage levels for each phase - matching the positive and negative DC supply values. By rapidly alternating between these voltage levels, binary switching generates a quasi-sinusoidal waveform. However, the output waveform's quality is an important factor to consider. Because of the inverter's intrinsic switching nature, the output is a stepped approximation rather than a perfect sine wave. The harmonic content and overall quality of the waveform are affected by the switching frequency and the exact pulse width modulation approach used, affecting the inverter's usefulness in a variety of applications such as motor drives, renewable energy systems, and power supply units. The careful balance between efficient three-phase AC power generation and harmonics and waveform quality management highlights the complexity and versatility of the two-level three-phase voltage source inverter in modern electrical systems (Bin Wu & Mehdi Narimani, 2017).

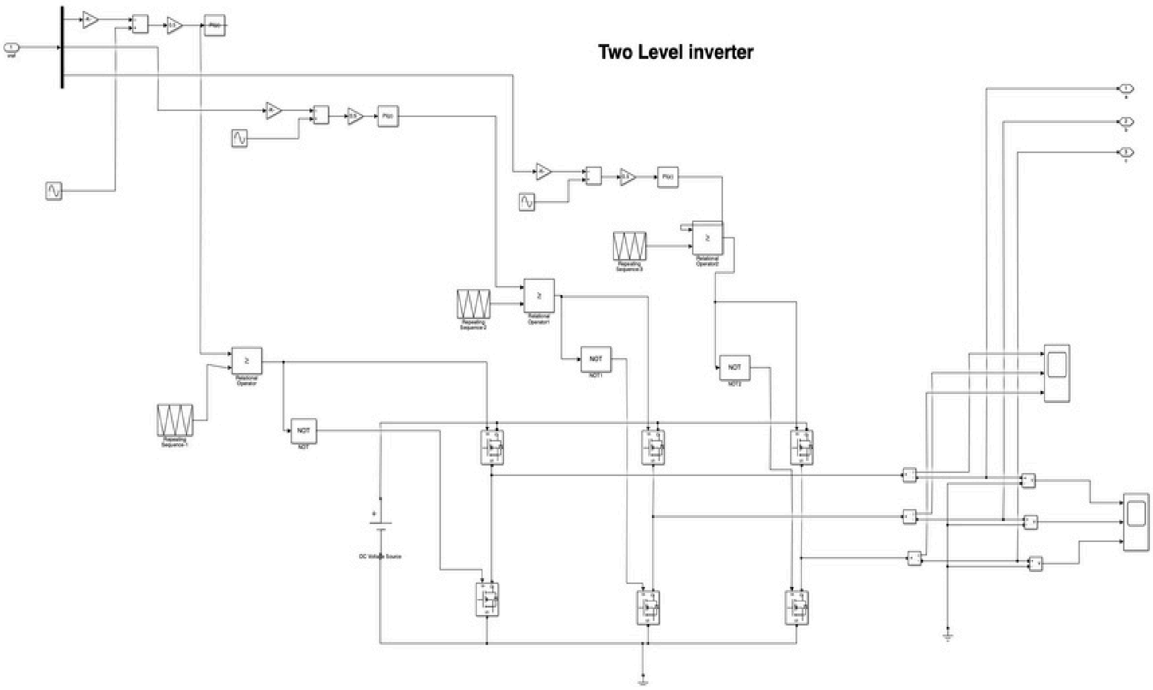

Figure 4: Two-level voltage source inverter

3.3 Cascaded H-bridge Inverters

The three-phase cascaded H-bridge inverter is a high-tech power electronic device that converts direct current (DC) to three-phase alternating current (AC). It is especially popular in high-power applications where the quality and efficiency of the alternating current output are critical. This inverter is made up of many single-phase H-bridge units that are coupled in such a way that they form three phases. Each phase of the inverter is made up of many H- bridge cells, and each cell is made up of four switches which are typically IGBTs or MOSFETs, that may turn on and off individually. The load is linked across the diagonal of these switches, which are placed in a square form. The alternating current supply is linked across the opposite diagonal. Each H-bridge cell may provide three distinct output voltages by manipulating the on and off states of these switches: positive DC bus voltage (+Vdc), zero voltage (0 V), and negative DC bus voltage (-Vdc). In the cascaded setup, the single-phase H-bridge inverter cells are linked in series for each phase. This means that the AC side of each cell is linked to the AC side of the next, thereby summing their voltages.

Each H-bridge is powered by its own separate DC source, which might be a battery, supercapacitor, or DC link capacitor charged to a certain voltage. There are three sets of these cascaded H-bridge cells in a three-phase inverter, each set matching one phase of the AC output. Because most high-power systems run on three-phase AC, the three-phase output is required for industrial and electrical vehicle applications. Each phase's output voltage is generated by the cumulative switching action of the H-bridges in that phase. Each H-bridge provides a stepped voltage level through careful control, which when put in series with the other H-bridges in the same phase results in a stepped waveform that approximates a sine wave. A microprocessor, digital signal processor, or equivalent processor that can handle the complicated algorithms necessary for precision switching controls the inverter. Typically, pulse width modulation is utilized to adjust the output voltage and frequency. The pulse width modulation is designed in such a way that the switches in the H-bridges function in sync to generate the required multilevel waveform. Feedback loops are typically included in the control system to regulate the output voltage and current, ensuring that the inverter responds accurately to changes in load or input voltage. Advanced control systems like as space vector modulation or sinusoidal pulse width modulation can be used to improve inverter performance by reducing harmonics and increasing efficiency (J. Rodriguez et al., 2002).

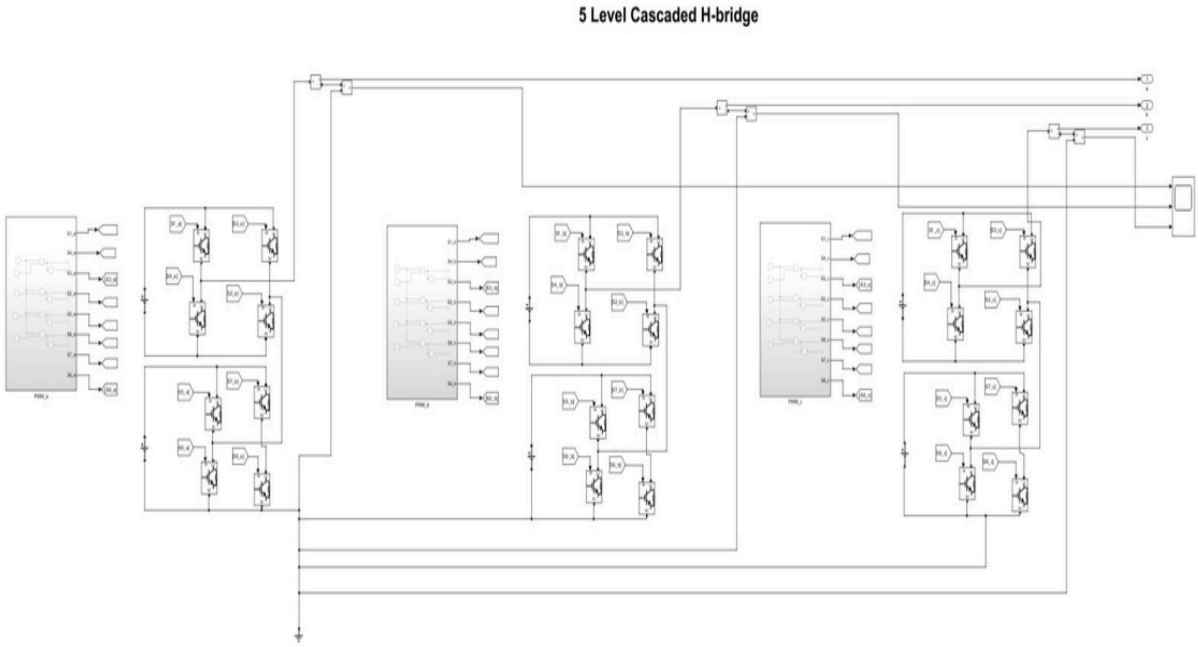

Figure 5: Five-level cascaded H-Bridge inverter

3.4 Sinusoidal Pulse Width Modulation

The primary goal of three-phase sinusoidal pulse width modulation is to operate the power electronic switches in a three-phase voltage source inverter and cascaded H-bridge inverter topology using a set of high frequency switching signals. This enables the inverter's output terminals to generate the requisite pseudo-sinusoidal three-phase AC voltage waveforms from a connected DC power supply. It aims to modulate the DC input voltage in a controlled variable way using precise timing of the switch gate signals in order to reshape and transcribe it into the required AC waveform supply for feeding three-phase AC loads. The gating signals are created by comparing three unique reference sinusoidal waves, one for each phase, and a rapid triangular carrier wave. The reference waves represent the required frequency, amplitude, and phase angles of the resultant alternating current voltage in each phase. The triangle wave has a much higher frequency than the reference sinusoid and a peak-to-peak amplitude that is termed the modulation index. The modulation index determines the breadth of amplitude modulation for sinusoidal pulse width modulation by defining the boundaries of sine waveform reconstruction in proportion to the available DC bus voltage. The size of the sinusoid is quantitatively examined against the contemporaneous value of the repeated triangle wave for each phase independently at each time. When the sine wave surpasses the triangle, the active high-side switch in that inverter leg is instructed to turn on, while the lower switch is instructed to turn off.

When the triangular wave exceeds the supplied sine reference, the reasoning reverses. As the sinusoidal set cycles through its waveform, the intersections with the quickly cycling triangle carrier produce narrow pulses whose widths vary proportionately to the instantaneous amplitudes of sine waveforms. The output is a phase-shifted train of changing-width sinusoidal pulse width modulation pulses that discretely transfer selected input DC voltage levels to assemble approximate sinusoidal waveforms with the same essential properties as the reference signals on the AC side of the inverter. Controlling the quality and characteristics of the synthesized AC output is possible by varying the modulation index and switching frequencies. This comparative method includes the fundamental working concept of sinusoidal pulse width modulation for three-phase voltage source inverters (Chaturvedi, 2018).

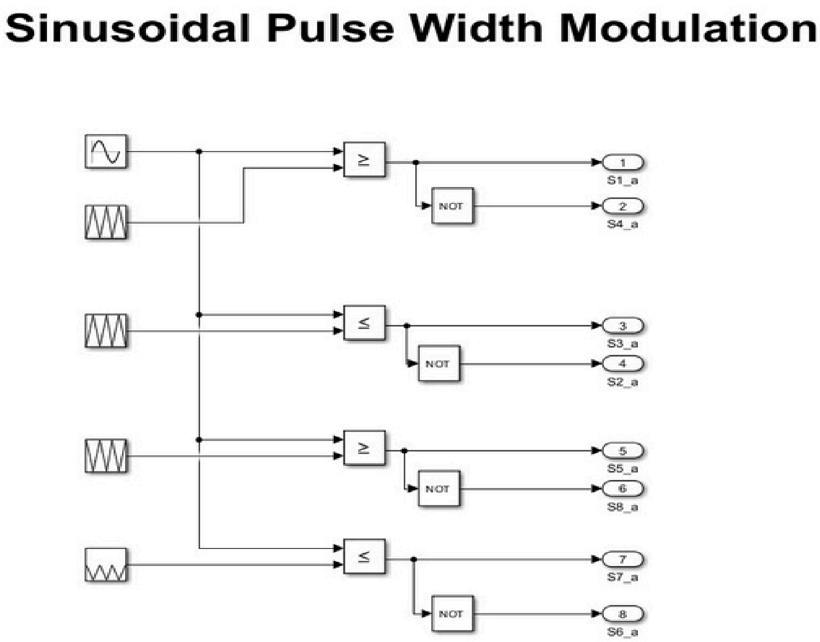

Figure 6: Sinusoidal pulse width modulation

3.5 Field-Oriented Control

Field-oriented control is a complex approach for controlling the speed and torque of permanent magnet synchronous motors that uses an advanced algorithm to achieve excellent performance and efficiency. The approach is based on decomposing the motor's stator currents into two orthogonal components that may be controlled independently, similar to manipulating the armature and field currents in a separately excited DC motor. This breakdown allows for exact control of the magnetic field dynamics of the motor, and thus its mechanical output. The procedure begins with the transformation of the motor's three-phase current into two direct components using the Clarke and Park transformations. The transformed currents, known as direct (Id) and quadrature (Iq) currents, are aligned with the rotor's magnetic field. The Id component is in phase with the rotor field and is in charge of motor magnetization, whereas the Iq component is 90 degrees out of phase with the rotor field and is in charge of torque production. For speed control, a reference speed is compared to the motor speed, which is detected by a sensor. The difference, or mistake, is processed by a proportional-integral controller, which adjusts the Iq current to increase or reduce torque and therefore bring the motor speed to the required level. The speed control loop is often slower than the current control loop because it monitors the mechanical dynamics of the motor, which are slower than the electrical dynamo.

In the current control element of field-oriented control, each component is regulated by a distinct proportional-integral controller. The Id current is normally tuned to a value that delivers the appropriate flux level within the motor, optimising efficiency and minimizing losses. The Iq current is adjusted directly to manage the output torque. The controllers' outputs are voltages that must be applied to the motor windings. The voltage commands from the proportional-integral controllers are then transformed back into three-phase voltage signals by doing inverse Park and inverse Clarke, which are then used to operate the motor. This is accomplished by the use of an inverter, which commonly uses pulse width modulation to generate variable voltage and frequency AC signals from a DC source. The inverter switches at a high frequency to approach the specified voltages by varying the width of the voltage pulses, and so controls the amount of power given to the motor. The field- oriented control algorithm rapidly adjusts the Id and Iq currents in response to changes in motor load and speed orders, resulting in a dynamic response that can manage sudden changes in load or speed requirements. The exact regulation of these currents enables smooth acceleration and deceleration, as well as the capacity to maintain a steady speed under varied load situations. This control system frequently utilizes rotor position sensors, such as encoders or resolvers, to give real-time feedback to maintain correct control. This feedback guarantees that transformations to and from the d-q coordinate system are precisely aligned with the magnetic field of the rotor. Some modern field-oriented control systems use sensorless algorithms to predict rotor position from motor currents and voltages, however, these systems are less dependable at low speeds and under dynamic circumstances (Amin et al., 2019).

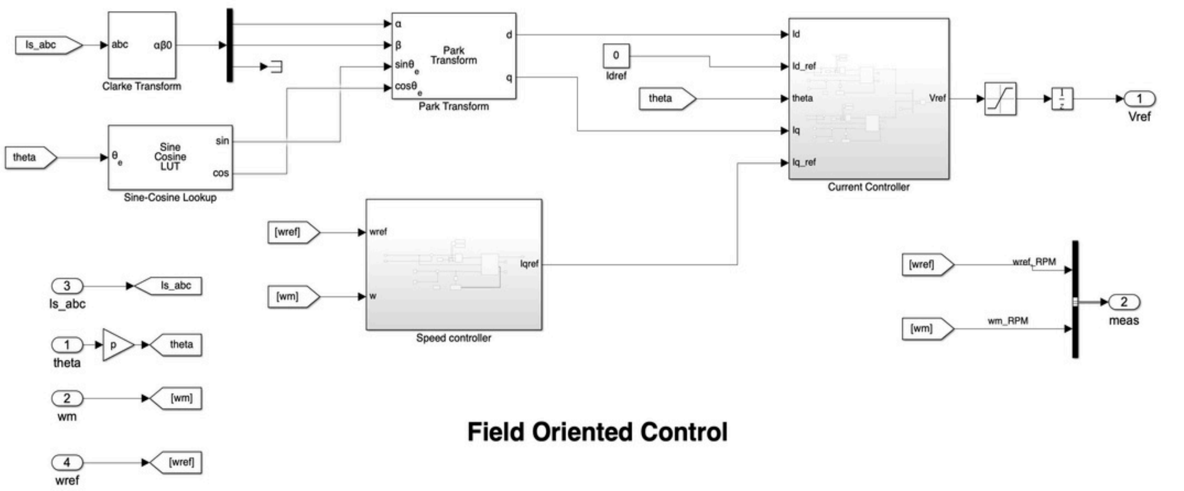

Figure 7: Field-oriented control

3.6 Permanent Magnet Synchronous Motor

A permanent magnet synchronous motor differentiates itself from conventional motors by the use of permanent magnets installed on or incorporated in its rotor to provide a steady magnetic field without the requirement for field excitation current. The stator is made up of coiled-coil windings that, when powered by a three-phase alternating current, form a revolving magnetic field within the motor owing to phase-shifted currents progressively magnetizing the individual stator poles. This spinning stator field magnetically locks with the rotor's permanent magnet field, leading the rotor to spin exactly synchronized to the rotational frequency of the stator's field, which is referred to as synchronous operation. The electromagnetic interaction of the two magnetic fields generates a torque that rotates the rotor at the chosen frequency indefinitely. Because speed is directly related to supply frequency, smooth permanent magnet synchronous motor speed control is possible with a variable frequency drive or inverter that can regulate the frequency delivered to the stator. The torque is produced by magnetic field interactions between the permanent magnet rotor and the stator's electromagnets. The angle between the rotor poles' position and the stator poles reversing magnetic axis has a sinusoidal connection with the intensity of torque, with the highest torque produced at a certain torque angle when the rotor lags behind the stator field by an optimal phase difference. This torque angle is normally regulated such that the permanent magnet synchronous motor always produces the maximum torque output. As a result, the working principle of a permanent magnet synchronous motor is based on the interaction between the permanent magnets on the rotor and the rotating magnetic fields created within the stator by the three-phase power supply, which governs both its speed based on the supplied frequency as well as torque output based on optimized magnetic phase coupling between the rotor and stator (A. Loganayaki & R. B. Kumar, 2019).

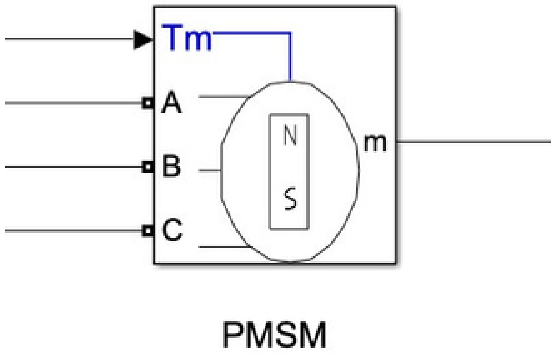

Figure 8: Permanent magnet synchronous motor

Chapter 4

Critical Evaluation of Simulation Results

This critical analysis thoroughly examined the subtle dynamics of electric motor control systems by running extensive simulations that highlighted the vital role of inverters. The objective was to demonstrate how adopting multilevel inverter topologies, instead of conventional two-level inverters, enhances system outputs, thereby addressing a critical aspect of power electronics and drive technologies. Additionally, the study thoroughly explored the effects of adjusting controller gains and motor pole numbers on response behaviour under different inverter configurations. The simulations gave factual insights into the subtle dependency between inverter architectural choices and motor design characteristics for optimizing current electric powertrains. The investigation aims to demonstrate the possible operational efficiency benefits and precise control that multilevel inverters may offer by thoroughly exploring these complicated interactions, including the effects of modifying motor settings, by closely investigating these deep relationships. Ultimately, the purpose was to provide an optimized set of requirements for optimizing electric motor control system performance for the application in electrical vehicles.

4.1 Model parameters

The table below details the parameters that drive the simulation model, laying the groundwork for comparing the performance of multilevel and two-level inverters, as well as the implications of different controller gains and motor poles on system behaviour.

Inverter	Motor
Sample time: 2 x10-5 s	Rated voltage: 560 V
Modulation technique: Sinusoidal PWM	Rated speed:3000 RPM
DC link voltage: 400 V	Rated torque: 126 Nm
Switching frequency: 1000 Hz	Simulationtime: 1.2 s
Carrierratio: 20	
Modulation index: $\frac{Am}{(m-1)Ac}$	

Table 1: Model parameters

4.2 Voltage output

The voltage output waveforms of a two-level voltage source inverter, a three-level cascaded H-bridge inverter, and a five-level cascaded H-bridge inverter are illustrated in this section. The voltage output waveform of the inverter has a significant impact on the performance and efficiency of a permanent magnet synchronous motor. When the waveform is a clean sinusoid, a steady torque is generated. Similarly, when the waveform matches the electrical parameters of the motor, its operating efficiency improves. Furthermore, waveform reliability is crucial for the efficient use of control approaches such as field-oriented control, which allows for more precise regulation of motor activities.

Two-level voltage source inverter:

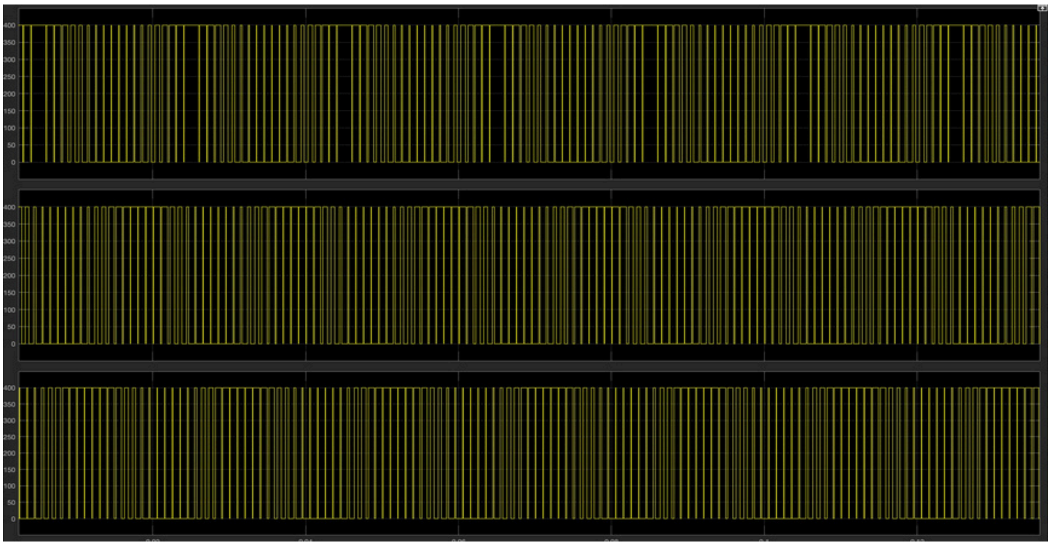

Figure 9: Voltage output of two-level inverter

The figure above shows the output voltage waveform of a two-level voltage source inverter. It has three output voltage graphs for three phases. The three phases are phase A which is the top graph, phase B which is at the middle, and phase C which is at the bottom. These voltage waveforms are electrically phase-shifted by 120 degrees. From the figure, it could also be seen that the voltage waveform for each phase is a square wave. This is due to the inverter's two switching states for each phase. When the switch is turned on, the maximum magnitude of the voltage for each square pulse will be equal to the DC link voltage and zero. The output voltage levels for a 400V DC connection voltage (Vdc) are seen to be +400V and 0V.

Three-level cascaded H-bridge inverter:

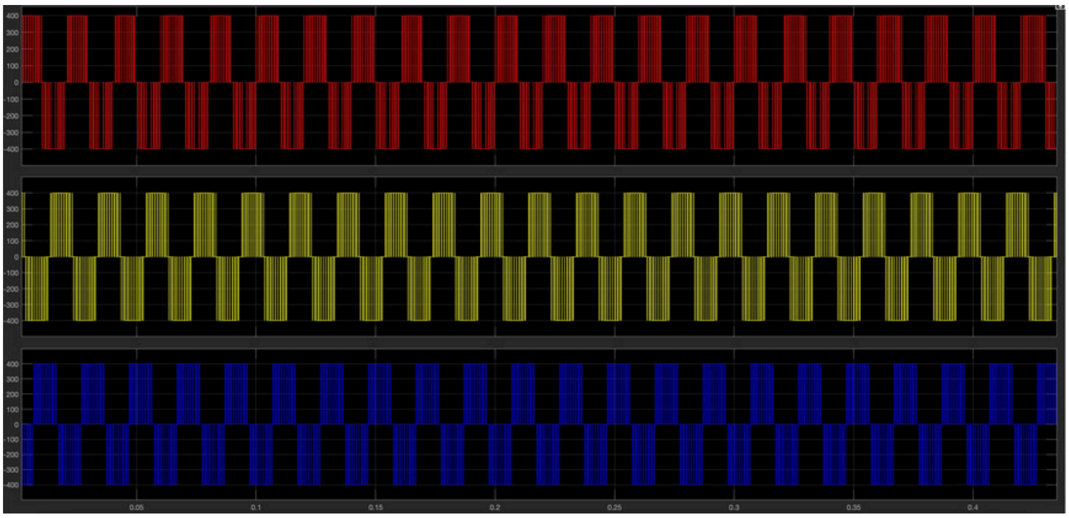

Figure 10: Voltage output of three-level cascaded H-bridge inverter

The figure above shows three graphs illustrating the voltage-time relationship for the outputs of a three-level cascaded H-bridge inverter over three separate phases. The voltage outputs for phases A, B, and C are represented by the red, yellow, and blue graphs, with each phase demonstrating a 120-degree electrical shift from the others. According to the graphical interpretation, the inverter generates a triad of voltage levels per phase, peaking at +400V, decreasing to 0V, and reaching a trough at -400V, producing a stepped structure. These voltage steps are caused by the inverter's power electronic switches within each H-bridge unit being strategically activated and deactivated. The persistence of each voltage level inside the waveform is determined by the modulation technique used.

Five-level cascaded H-bridge inverter:

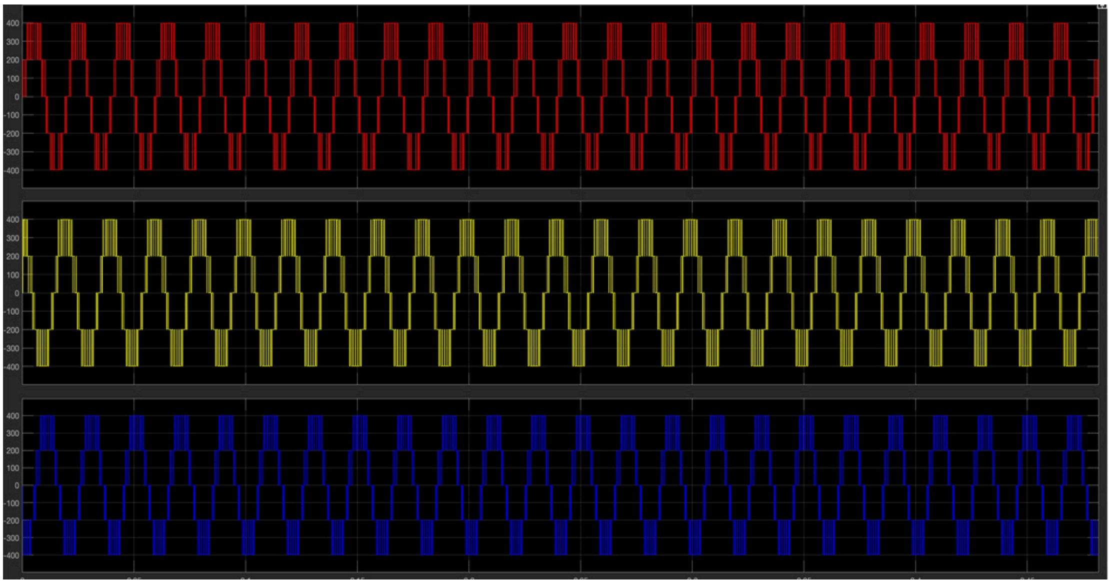

Figure 11: Voltage output of five-level cascaded H-bridge inverter

The graphs above demonstrate the voltage-time relationship for the outputs of a five-level cascaded H-bridge inverter for three distinct phases. The red, yellow, and blue graphs indicate the voltage outputs for phases A, B, and C, with each phase exhibiting a 120-degree electrical shift from the others. It is observed that each phase's waveforms have a stepped shape with five levels. This stepping is caused by the inverter transitioning between voltage levels. A five-level inverter's output voltage levels would generally comprise +400V, +200V, 0V, -200V, and -400V for a given DC link voltage (Vdc) of 400V. The precise values of the intermediary levels (+200V and -200V) are determined by how the DC link voltage is distributed among the cascaded H-bridges.

Analysis:

After comparing all three waveforms from three different figures it could be concluded that the output waveform of the five-level cascaded H-bridge inverter is the closest to actual sinusoidal wave as it has the most voltage steps. The two-level voltage source inverter produces a waveform of a square shape between two voltage levels and the three-level cascaded H-bridge inverter offers a stepped waveform with an intermediate zero voltage for smoother transitions.

4.3 Speed and Torque Responses for Constant Load Torque

In this section speed and torque responses have been analysed for a constant load of 100 Nm. The responses were compared for a two-level voltage source inverter, three-level, and five-level cascaded H-bridge.

Two-level voltage source inverter:

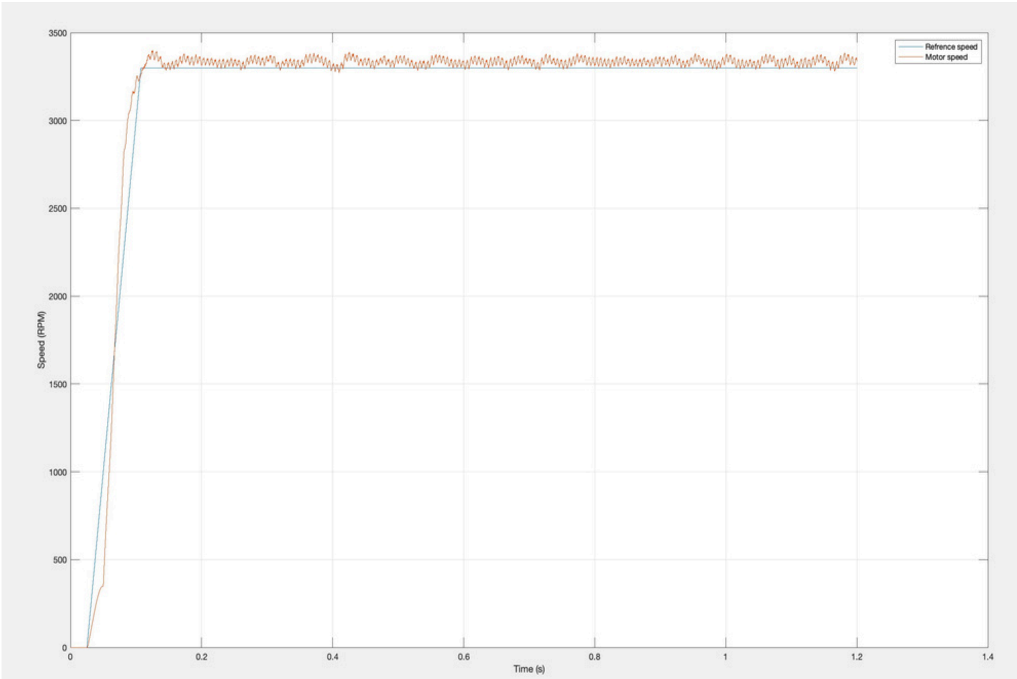

Figure 12: Speed response for two-level inverter

The above figure illustrates the speed-time graph of the permanent magnet synchronous motor that is driven by a two-level voltage source inverter. The x-axis represents the simulation time in seconds and the y-axis represents the motor speed in revolutions per minute (RPM). The blue graph represents the reference speed given to the motor while the red graph is the speed generated by the motor. From the figure, it could be observed that the motor is rotating at a speed very close to the reference speed. However, an overshoot of 4.14 RPM could be seen in the speed response and some ripples could also be observed even after the motor speed reaches the steady state.

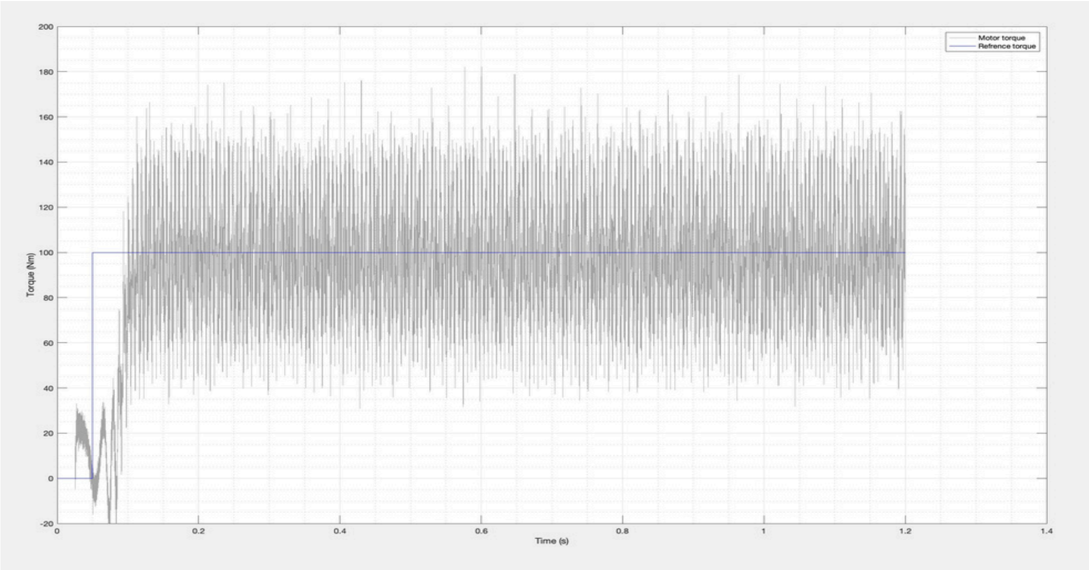

Figure 13: Torque response for two-level inverter

The graph above displays the torque vs time graph of a permanent magnet synchronous motor operated by a two-level voltage source inverter. The x-axis shows the simulation duration in seconds, while the y-axis represents the torque generated by the motor in Newton meters (Nm). The blue graph depicts the reference load torque applied to the motor, while the grey curve reflects the torque generated by the motor. The reference load torque given to the motor is 100 Nm. It is observed that the motor was able to track the reference load torque given to the motor, however, it generates continuous high ripples with an overshoot of 82.2 Nm and undershoot of 74 Nm.

Three-level cascaded H-bridge inverter:

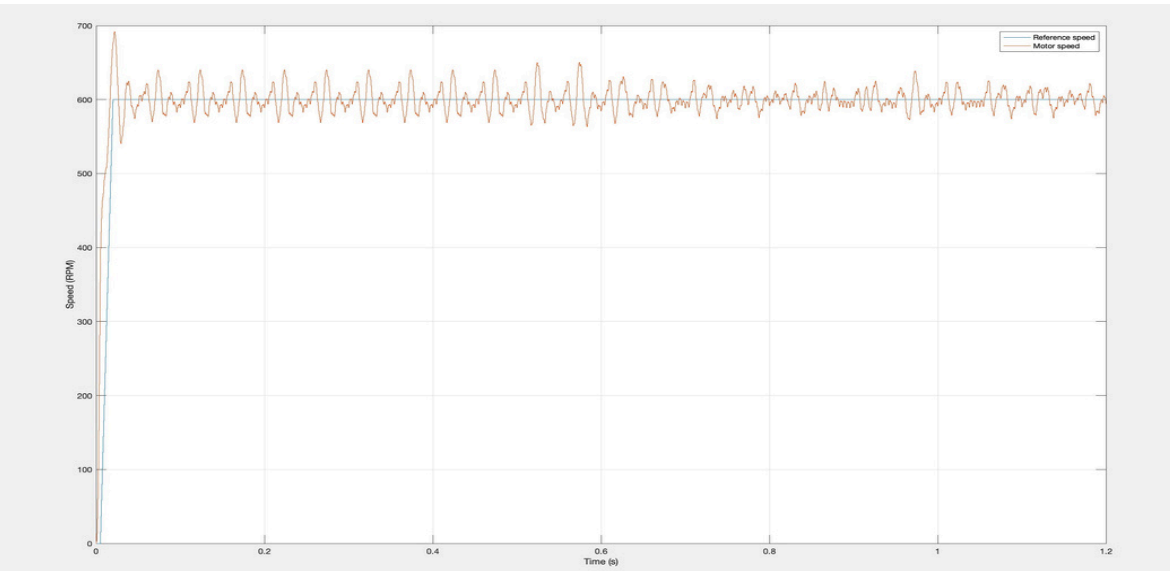

Figure 14: Speed response for three-level CHB inverter

The graph presented showcases the speed profile over time for a permanent magnet synchronous motor powered by a three-level cascaded H-bridge inverter. On the graph, the horizontal axis measures simulation time in seconds, and the vertical axis measures the motor's speed in revolutions per minute (RPM). The reference speed set for the motor is indicated by the blue line, while the red line illustrates the actual speed that the motor achieves during operation. From the figure, it could be observed that the motor is able to track the reference speed. There are ripples in the speed response just like the two-level voltage source inverter however, the ripples are less than the speed response of the two- level. Overshoot was also observed which has a value of 81.22 RPM.

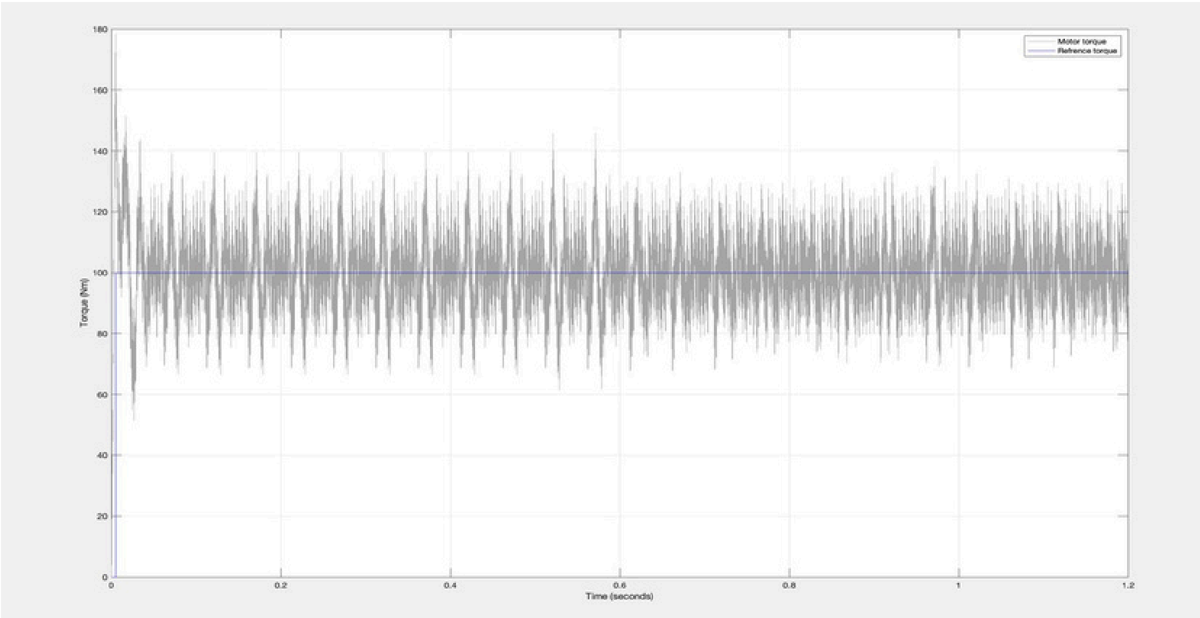

Figure 15: Torque response for three-level CHB inverter

The provided graph portrays a comparison of torque over time for a permanent magnet synchronous motor driven by a three-level cascaded H-bridge inverter. The horizontal axis represents time in seconds, while the vertical axis represents the motor's output torque in Newton meters (Nm). The blue line represents the motor's reference load torque, while the grey line represents the motor's actual torque output. The motor was able to monitor the reference load torque applied to it, however, it generated continuous torque ripples with an overshoot of 49.2 Nm and a undershoot of 42.8 Nm. But compared to two-level inverter the toque ripple is less.

Five-level cascaded H-bridge inverter:

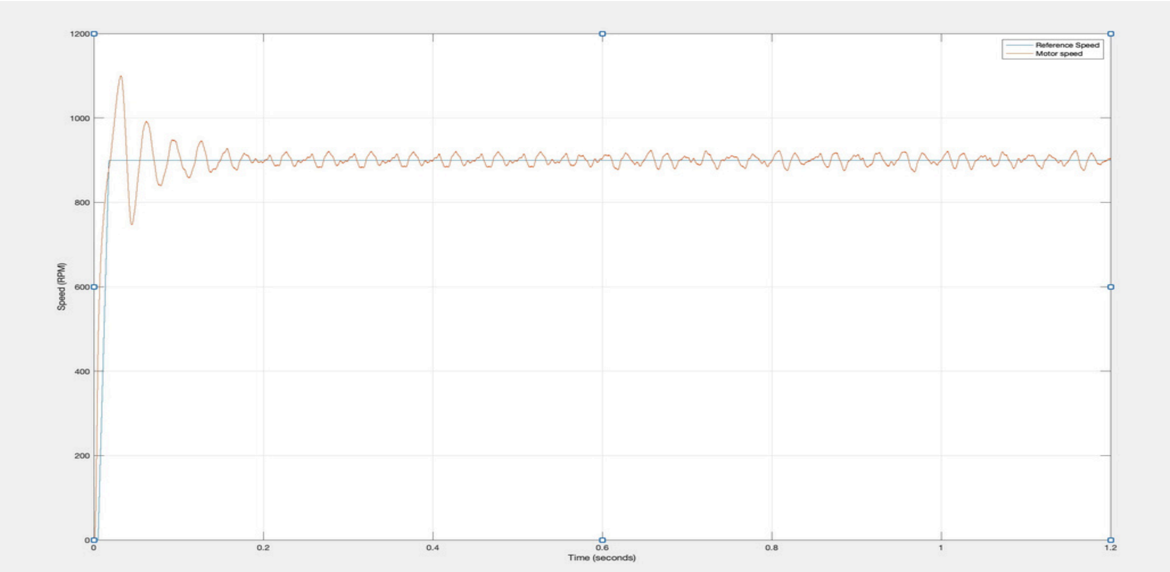

Figure 16: Speed response for five-level CHB inverter

The graph illustrates a permanent magnet synchronous motor's speed as it operates over a period, driven by a five-level cascaded H-bridge inverter. The horizontal axis measures the time of the simulation in seconds, while the motor's operational speed (RPM) is marked on the vertical axis. The blue line on the graph specifies the reference speed for the motor, and the red line demonstrates the real speed attained by the motor throughout the simulation. The motor was capable of tracking the reference speed, as shown in the figure. The speed response has ripples, just like the two-level voltage source inverter and three-level cascaded H-bridge inverter, although the ripples are less than in the other two types of inverters. Overshoot was also seen, with a value of 150 RPM.

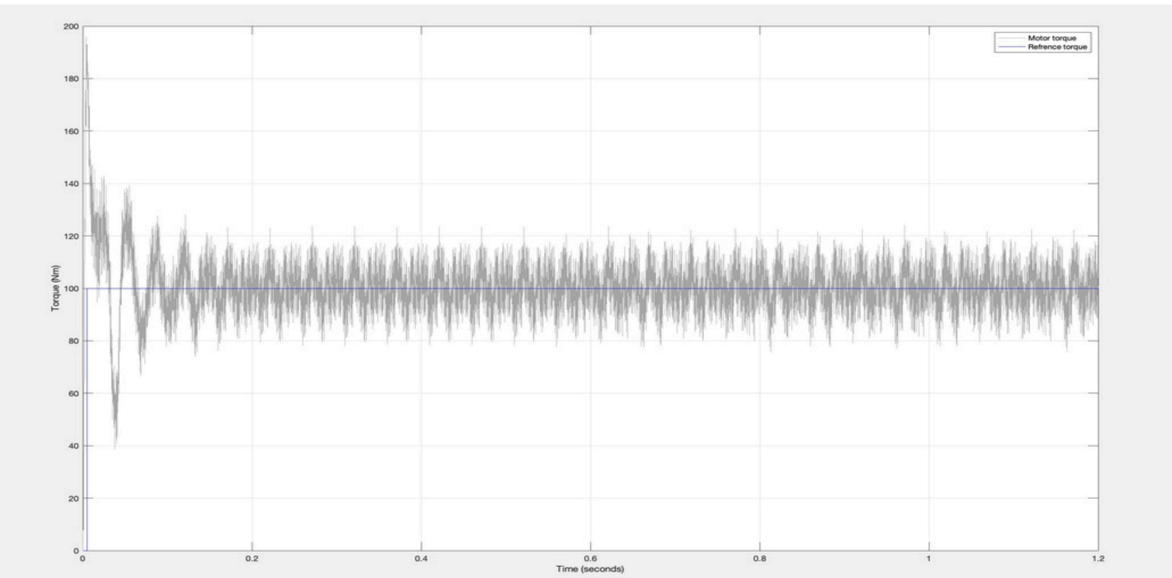

Figure 17: Torque response for five-level CHB inverter

The graph compares the torque output over time of a permanent magnet synchronous motor powered by a five-level cascaded H-bridge inverter. Time is charted along the horizontal axis in seconds, and the torque produced by the motor is shown on the vertical axis in Newton meters (Nm). The blue line represents the motor's expected load torque, and the grey line represents the motor's actual torque. The motor was able to monitor the applied reference load torque, however it produced continuous torque ripples with an overshoot of 38.9 Nm and an undershoot of 40 Nm. However, the toque ripple is reduced when compared to a two- level inverter and a three-level cascaded H-bridge inverter.

Analysis: Higher-level inverters, such as three-level and five-level cascaded H-bridge inverters, significantly improve the quality of voltage waveforms provided to motors, as seen by their closer approximation to pure sine waves. This increased waveform integrity is critical for eliminating torque and speed ripples, which are common concerns in motor operations driven by lower-level inverters such as two-level kinds. In a higher-level inverter, the output voltage passes through more intermediary levels, resulting in a smoother, more progressive voltage change. This quicker transition translates directly to more consistent and stable motor action, providing smoother motor operation with substantially reduced mechanical stress and vibration. Furthermore, increasing the number of voltage levels in the inverter adds directly to a significant reduction in total harmonic distortion in its output. Total harmonic distortion measures how far the waveform deviates from an ideal sinusoidal shape, and a lower total harmonic distortion indicates a waveform that is closer to a pure sine wave. This reduction in harmonic content substantially reduces the motor's current harmonics, which are responsible for undesired effects including torque ripple, extra heating, and electromagnetic noise. As a result, the motor has reduced torque and speed ripple, which improves its efficiency and longevity. Such waveform quality enhancements are especially advantageous in applications requiring high precision and smooth motor operation, such as robotic systems, precision manufacturing, and electric vehicle propulsion. Overall, higher-level inverters represent a substantial breakthrough in motor drive technology, providing improved performance while reducing wear and tear on motor components (Abou-ElSoud et al., 2023).

4.4 Speed Responses for Different Reference Speeds

This section of the research focuses on the speed and torque behaviour of a permanent magnet synchronous motor that is powered by a five-level cascaded H-bridge inverter. The purpose here is to change the reference speed and observe if the controller successfully enables the motor to follow this set reference speed.

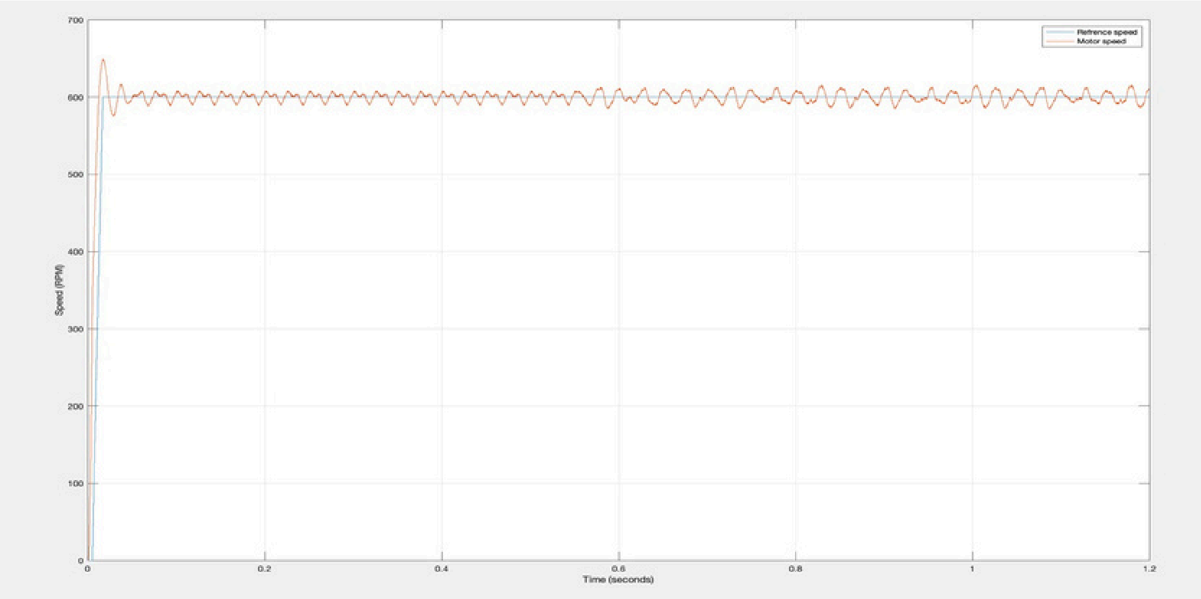

Figure 18: Speed responsewith of reference 600 rpm

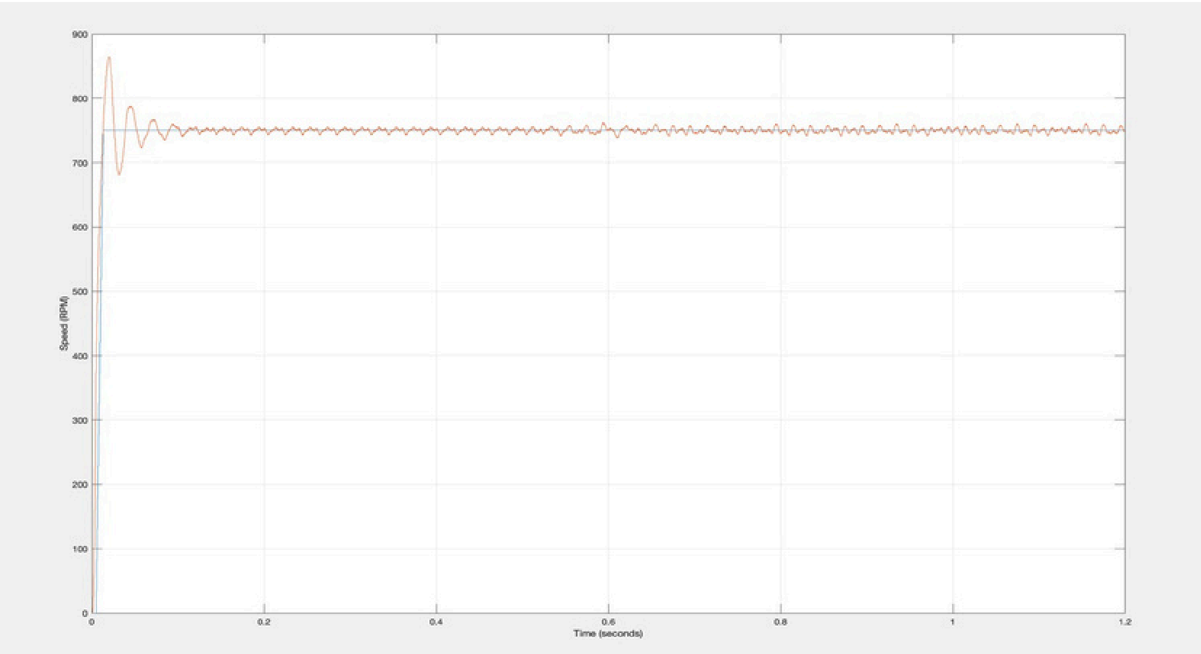

Figure 19: Speed responsewith of reference 750 rpm

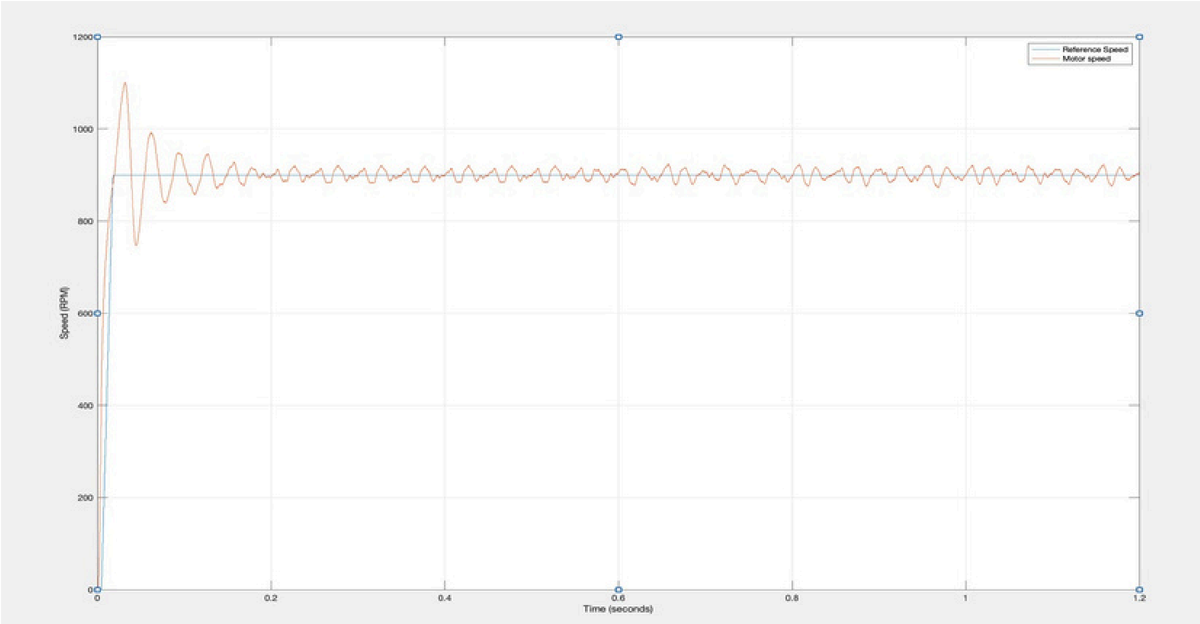

Figure 20: Speed response with of reference 950 rpm

Analysis:

The above figures 16, 17, and 18 show the speed responses of the permanent magnet synchronous motor for three different reference speeds. At first, the reference speed was taken to be 600 rpm and the motor was able to track that speed with some speed ripples. Subsequently, when the reference speeds were raised to 750 RPM and 950 RPM, the motor continued to align with these higher speeds, again exhibiting some degree of speed ripples.

4.5 Influence of Pole Pairs on Total Harmonic Distortion

This part of the report focuses on examining how varying the number of pole pairs impacts the output of the inverter. Initially, the motor operated with a single pole pair. This was subsequently increased to two and then to three pole pairs. For each of these configurations, the total harmonic distortion was analysed and compared across different inverter types: the two-level voltage source inverter and the three-level and five-level cascaded H-bridge inverters.

Pole pair	THD Level 2	THD Level 3	THD Level 5
1	49.04%	13.07%	12.04%
2	54.10%	19.86%	17.40%
3	59.38%	29.08%	25.09%

Table 2: Pole pair vs THD

The table shows the percentage total harmonic distortion of the two-level voltage source inverter, three-level and five-level cascaded H-bridge for three different pole pairs.

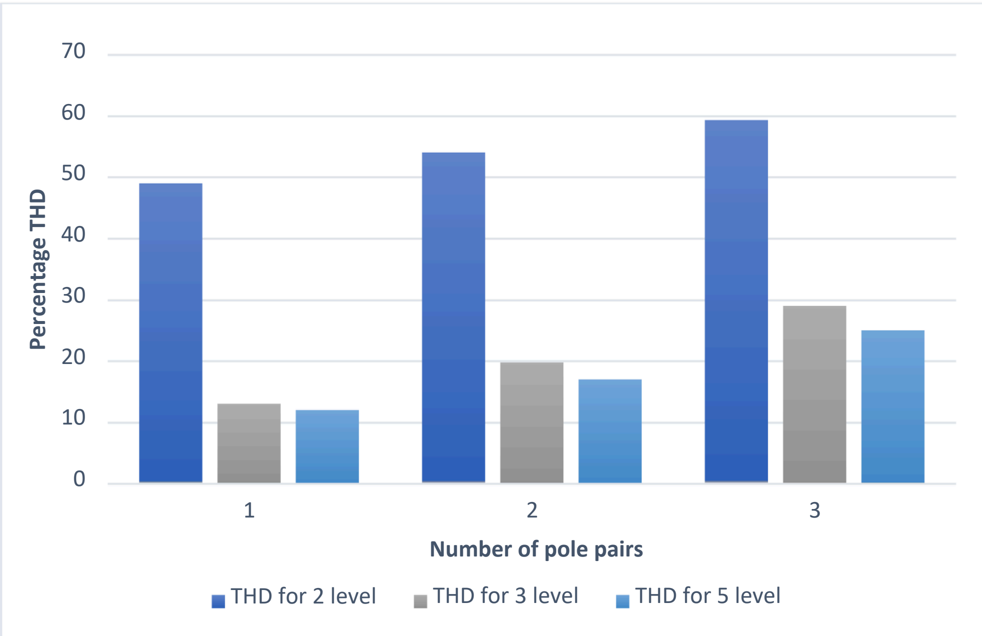

Figure 21: Pole pair vs THD

The figure shows a bar chart that presents a comparative analysis of total harmonic distortion across inverters with varying levels—two, three, and five—while also considering the impact of increasing the number of pole pairs within a motor. On the horizontal axis, the chart lists one, two, and three pole pairs, signifying the complexity of the motor's construction, and on the vertical axis, it measures the total harmonic distortion percentage, indicative of the quality of the electrical output. Each pole pair category is accompanied by a set of three coloured bars that correspond to the different inverter levels. The bar colours are designated to differentiate between the two-level, three-level, and five-level inverters. The chart demonstrates a clear trend: as the number of pole pairs in the motor increases, there is a consequent rise in total harmonic distortion for each type of inverter. This suggests that more complex motor designs with more pole pairs tend to induce higher levels of harmonic distortion. However, an inverse relationship is observed between the number of inverter levels and total harmonic distortion; as the inverter level ascends from two to five, there is a notable decrement in total harmonic distortion. This indicates that multilevel inverters are more capable of mitigating harmonic distortion. This data is critical for optimizing motor design and selecting appropriate inverter technology, maintaining motor efficiency and longevity by minimizing the negative impacts of electrical harmonics on motor operation and the overall system.

Analysis:

An inverter with a greater number of levels generates an output voltage waveform that is more akin to a pure sine wave. This similarity is beneficial in reducing total harmonic distortion. The presence of higher levels in the inverter means that the harmonic content is less pronounced. This is because smoother transitions between voltage levels reduce the occurrence of high-frequency harmonics. Additionally, the smaller steps in voltage associated with multilevel inverters contribute to more gradual changes in the voltage waveform. This results in fewer sudden voltage shifts, which further contributes to a lower total harmonic distortion. The overall effect of these smoother transitions is an improved quality of the output waveform, making it more desirable for applications that require a clean and stable power supply (R. Mali et al., 2019). Increasing the number of pole pairs in a motor results in a higher electrical frequency, requiring the inverter to switch more quickly. The harmonic content in the motor's output is amplified by the frequent switching. Essentially, when the pole pairs of the motor expand, the inverter must run at a faster rate to keep up with the motor's increased frequency, increasing the harmonics present in the electrical output. This increase in harmonic content can affect the motor's quality and efficiency, demonstrating the direct impact of pole pair count on the performance parameters of motor-driven systems.

4.6 Relationship Between Pole Pair and Speed Response Rise Time

This section of the report investigates the effect of different pole pair counts on rise time of the speed response rise time. Starting with a baseline of one pole pair, the motor's configuration was incrementally enhanced to include two and then three pole pairs. The rise time that is the time it takes for the motor to reach its goal speed, was investigated and compared with different inverter configurations, including two-level voltage source inverters, three-level, and five-level cascaded H-bridge inverters.

Pole pair	Rise time Level 2	Rise time Level 3	Rise time Level 5
1	0.0414	0.0113	0.0071
2	0.0379	0.0084	0.0065
3	0.0330	0.0079	0.0051

Table 3: Pole pair vs rise time

The table displays the rise time, for the speed response across two-level voltage source inverters and three- and five-level cascaded H-bridge inverters, comparing three distinct pole pair configurations.

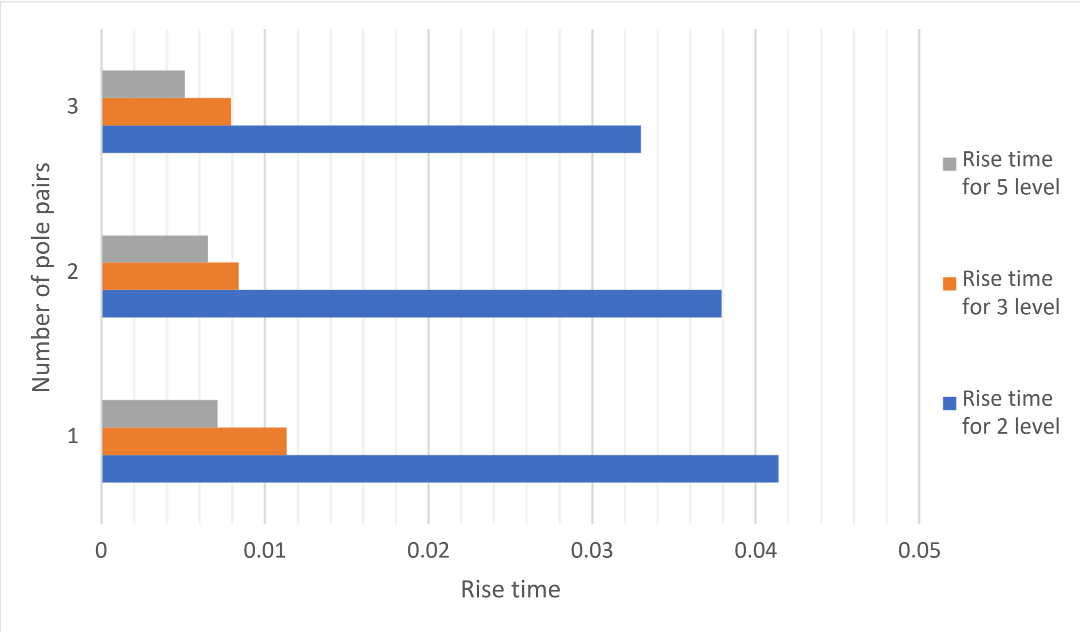

Figure 22: Pole pair vs rise time

The graph is a horizontal bar chart that analyses the increasetime for the speed response of different levels of inverters versus the number of pole pairs.The x-axis represents the rise time in seconds, and the y-axis represents the number of polepairs, which are classified as 1, 2, and 3. Each pole pair grouping contains three bars, one for each of the rise times associated with two-level voltage source inverter, three-level, and five-level cascaded H-bridge inverters. From the graph, it could be inferred that as the number of pole pairs increases, the rise time for the speed response of a given level of inverter decreases. Additionally, for any given number of pole pairs, the rise time is shorter for inverters with a higher number of levels. For example, the five-level inverter shows a faster rise time compared to the three-level and two-level inverters for the same number of pole pairs.

Analysis:

A shorter rise time indicates a system's quick response and acute sensitivity to changes in input, which are especially important in situations where dynamics and precision are critical. According to (A. G. Yepes et al., 2014), such agility in system response can substantially improve performance in scenarios that demand high-speed operations and exactitude, such as in robotics, aerospace, and high-speed manufacturing processes. When an inverter's level increases, it results in a more sophisticated output waveform with additional voltage steps. This improved waveform accuracy enables more accurate control of the motor's speed and torque, resulting in a more responsive system overall. As a result, higher-level inverters can achieve faster rise times, indicating that they are more suited for applications that require quick responses to changing conditions or input commands. Similarly, increasing the number of pole pairs in a motor also leads to a more responsive system. More pole pairs mean that the motor can generate the same electrical frequency with fewer revolutions, allowing for quicker achievement of the commanded speed. This can result in a reduced rise time as the motor's speed can be ramped up more rapidly, enhancing the system's overall responsiveness. Increased inverter levels and higher pole pair counts both indicate a shift towards improved system efficiency and control. Such advancements are essential in the design and operation of modern electromechanical systems, which demand not just speed and precision but also the capacity to manage complicated, frequently changing operational profiles with minimal delay.

4.7 Relationship Between Number of Pole Pairs and Overshoot

This segment of the report investigated how different pole pair counts affect the overshoot of the speed response. The investigation began with a motor configured with a single pole pair and progressed through enhancements to configurations of two and three pole pairs. The extent of overshoot was then measured and analysed across various inverter setups, ranging from two-level voltage source inverters to more complex three-level and five-level cascaded H-bridge inverters.

Pole pair	Overshoot for 2 level	Overshoot for 3 level	Overshoot for 5 level
1	4.514	41.463	21.7337
2	3.7346	27.23	15.21
3	1.7921	14.264	6.19

Table 4: Pole pair vs overshoot

The table compares the results of systems with one, two, and three pole pairs to show the overshoot in speed response for inverters with two, three, and five levels.

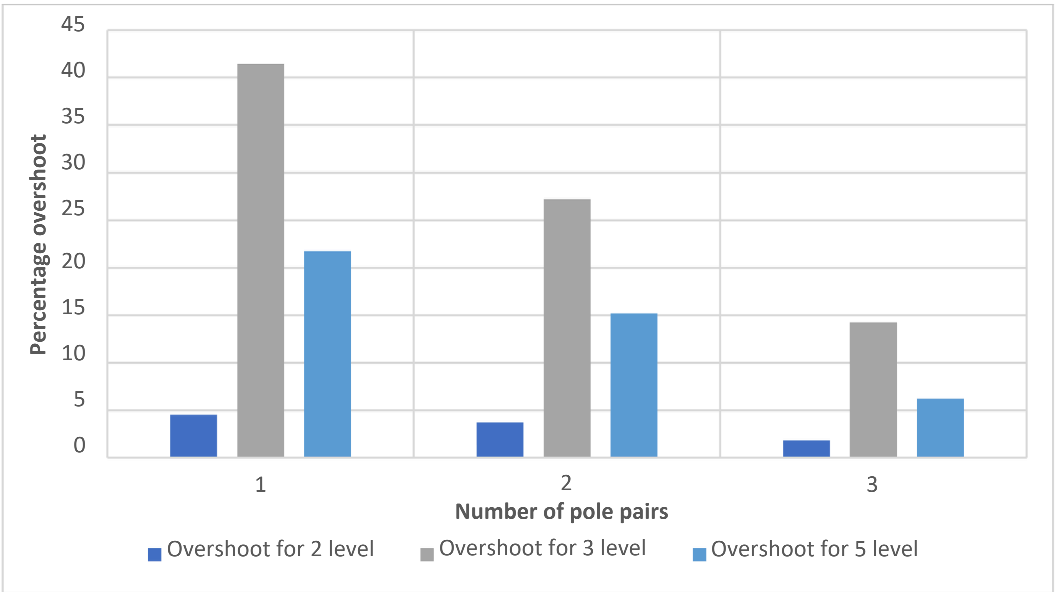

Figure 23: Pole pair vs overshoot

The figure is a bar chart that illustrates the relationship between the number of pole pairs in a motor and the corresponding overshoot in the speed response for various inverter levels. The chart shows that with an increase in the number of pole pairs, there is a trend of decreasing overshoot. For inverters with two levels, the overshoot is minimal across all pole pair counts. In comparison, inverters with three and five levels exhibit higher overshoot values. Notably, the overshoot for the five-level inverter is consistently less than that for the three-level inverter across all pole pair numbers.

Analysis:

An increase in overshoot is indicative of a system's response being too aggressive, which can raise concerns about stability and often necessitates a re-evaluation and adjustment of the controller settings. As noted by (A. G. Yepes et al., 2014), excessive overshoot can compromise the system's precision, safety, and efficiency, as the system may respond too strongly to changes and exceed desired performance parameters. This is particularly relevant in situations where exactitude and the avoidance of dynamic overshoots are critical for system operation and reliability. Despite its tendency to generate more significant harmonics due to its simpler voltage structure, the two-level inverter frequently results in less overshoot due to its less sophisticated control strategy. Its simplicity allows for more predictable and readily adjustable responses, which can be beneficial in maintaining system stability. The three-level inverter, on the other hand, poses a more complex control issue due to its additional voltage levels. The complexities of maintaining numerous voltage levels can initially result in less precise control, manifested as a higher overshoot as the system struggles to correctly match the required response. The five-level inverter, on the other hand, produces a smoother and more sinusoidal voltage waveform with less harmonic content. This smoother waveform enables finer and more subtle control over the motor's speed, potentially reducing overshoot. As waveform quality increases, the system's response may be fine-tuned more precisely, resulting in increased performance and a reduction in overshoot, and therefore improving overall system stability and control accuracy.

4.8 Correlation Between Number of Pole Pairs and Settling Time

This section of the paper investigates at how changing the number of pole pairs affects the settling time for the motor's speed response. The study began with a single pole pair motor and then studied the impact of increasing the number of pole pairs to two and three. Following that, the settling times for several inverter designs were studied and compared, ranging from simple two-level voltage source inverters to more complex three-level and five-level cascaded H-bridge inverters.

Pole pair	Settling time level 2	Settling time level 3	Settling time level 5
1	0.1927	0.1911	0.17
2	0.1958	0.1952	0.1718
3	0.1979	0.1966	0.1805

Table 5: Pole pairvs settling time

The table presents a comparison of settling times in the speed response among systems with one, two, and three pole pairs, across inverters with two, three, and five level configurations.

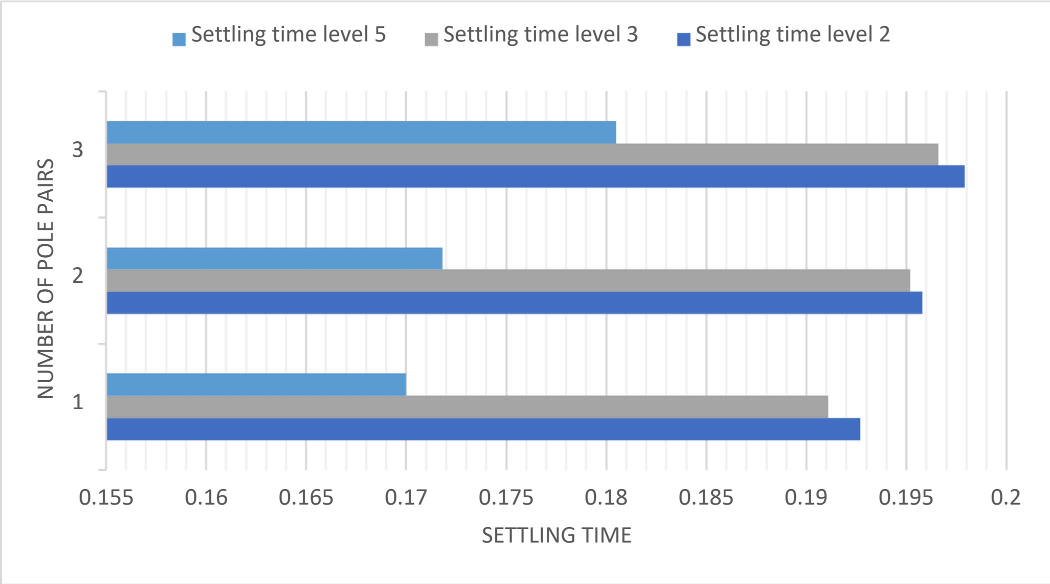

Figure 24: Pole pair vs settling time

The bar chart illustrates the relationship between the number of pole pairs in a motor and the settling time for different levels of inverters. The horizontal axis indicates the settling time in seconds, while the vertical axis represents the number of pole pairs, which range from one to three. The bars are color-coded to differentiate between the inverters with two, three, and five levels. From the chart, it's apparent that with an increase in inverter levels, the settling time tends to decrease. This suggests that higher-level inverters are more effective at quickly stabilizing the motor's speed after a change in operating conditions. Additionally, for a given level of inverter, the settling time becomes longer as the number of pole pairs increases.

Analysis:

Within control systems, settling time refers to the amount of time it takes for the system's response to a change or disturbance to stabilise and consistently remain within a set, acceptable range of the desired value. A longer settling time suggests that the system requires more time to stabilise at the desired performance level after suffering some type of disruption. According to A. G. Yepes et al., (2014), a longer settling time indicates a delayed return to the target value, which may be less desirable in situations requiring swift adaptation and precision. Contrary to the notion that higher inverter levels would lead to longer stabilization times, it is typically observed that more advanced inverters, with more levels, actually contribute to reduced settling times. This is due to the fact that multilevel inverters can generate voltage waveforms that are more similar to a pure sine wave, allowing for more refined and rapid control operations. However, increasing the number of motor poles can result in a system that exhibits longer settling times. This impact occurs when a motor with more poles operates at a higher electrical frequency for the same mechanical speed, introducing more complex dynamics into the control process. The system must adjust to the increased frequency, which can increase the time required to settle within a narrow error margin.

4.9 Relationship Between Pole Pair Count and PI Controller Gains

This section of the paper investigates how changing the number of pole pairs affects the controller's proportional-integral gains with time for the motor's speed response. The study began with a single pole pair motor and then studied the impact of increasing the number of pole pairs to two and three. Following that, the proportional-integral gains for several inverter designs were studied and compared, ranging from simple two-level voltage source inverters to more complex three-level and five-level cascaded H-bridge inverters.

Pole Pair	Proportional-Integral gains for 2-level		Proportional-Integral gains for 3-level		Proportional-Integral gains for 5-Level	
	Ki	Kp	Ki	Kp	Ki	Kp
1	3.339	0.01513	16.395	0.08655	8.570	0.02183
2	4.538	0.02236	23.549	0.08920	13.585	0.04040
3	4.700	0.02503	25.412	0.09308	19.970	0.05348

Table 6: Pole pair vs PI gains

The table compares the proportional-integral gains in speed control systems, highlighting the differences between one, two, and three pole pair setups and outlining these differences over inverter systems with two, three, and five levels.

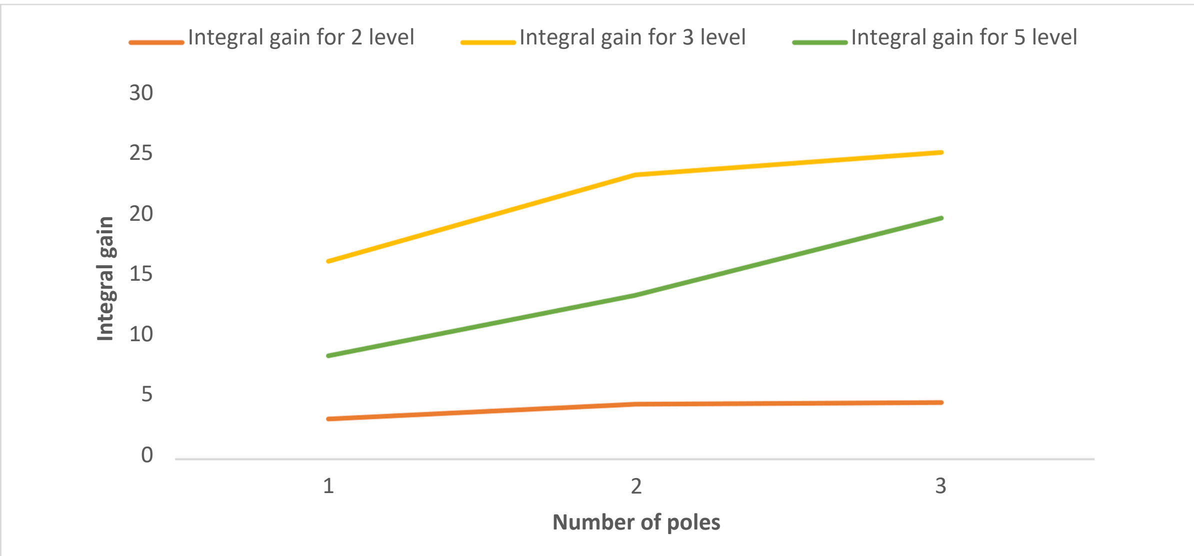

Figure 25: Pole pair vs integral gains

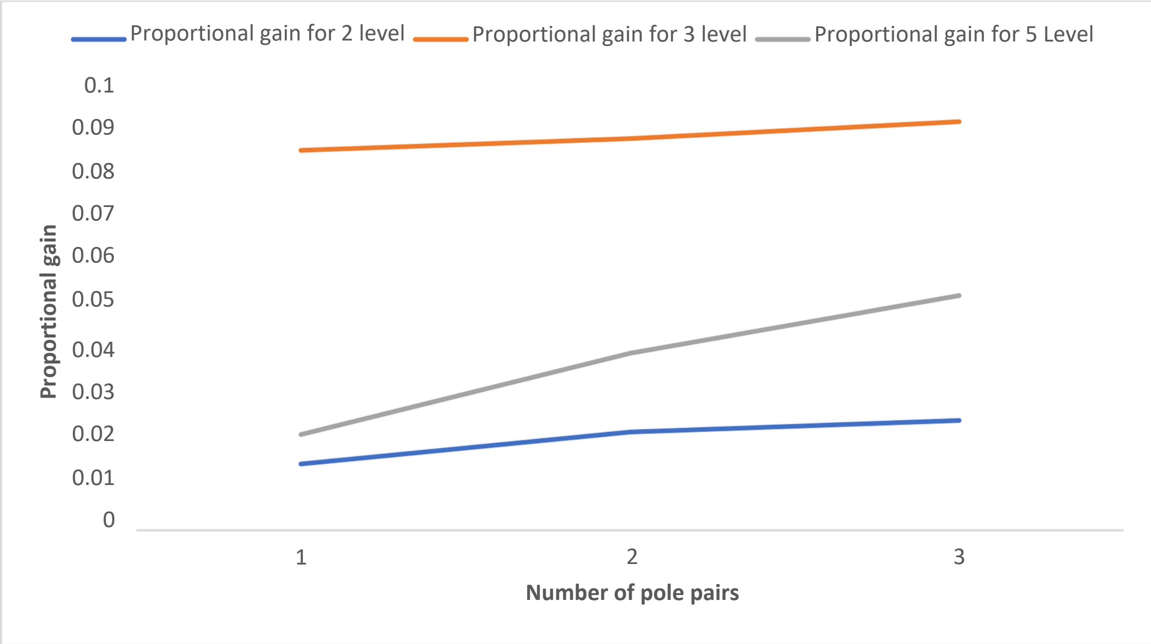

Figure 26: Pole pairvs proportional gains

The first graph demonstrates the correlationbetween the number of poles in a motor and the integral gain required for controllers intwo-level, three-level, and five-level inverter systems. The horizontal axis represents the number of poles, and the vertical axis represents the integral gain. The integral gain increases for each inverter level as the number of poles increases from one to three, although the rate of increase varies. The two-level inverter has the lowest integral gain requirement, while the five-level inverter has the greatest. The second graph demonstrates a similar relationship, but this time the proportional increase is highlighted. The number of pole pairs is plotted horizontally, while the proportional gain is plotted vertically. The trend indicates that as the number of pole pairs increases, so does the proportionate gain across all inverter levels. The two-level inverter requires less gain than the three-level and five-level inverters, with the five-level inverter having the largest proportional gain across all pole pair counts. When the two graphs are analysed, it is evident that as the complexity of the inverter system develops from two to five levels, so does the demand for higher proportional and integral controller gains.

Analysis:

Increasing the proportional and integral gains in a control system improves its ability to quickly correct steady-state faults, lowering the time required to reach the goal setpoint. This rapid correction is the result of the system's increased sensitivity to differences between the present output and the planned outcome, which prompts faster modifications. However, this increase in profit has significant downsides. Higher gains can cause the system to overshoot its aim while expediting mistake repair. This means that the output may first exceed the appropriate amount before adjusting down, resulting in a period of instability before settling down. Furthermore, as shown in S. K. Panda et al., (1997) research, an amplified integral and proportional gain can cause persistent oscillations around the setpoint. These oscillations are a sign of a system straining to exactly stabilize at the appropriate output, and they can also be a sign of a control system that is overly aggressive in its correction attempts. The faster response to mistake correction in the context of a three-level control system suggests that the system is more reactive. However, the trade-off is a proclivity for higher overshoots and more frequent oscillations, which might jeopardize the system's overall stability. As a result, while quick responsiveness is frequently a desirable attribute in control systems, it must be carefully balanced with the need for stability to avoid excessive overshoot and oscillations that can damage system performance and dependability.

Chapter 5

Project Management

The simulation and analysis of multilevel inverter-driven permanent magnet synchronous motors applying field-oriented control is the subject of this research. This project is divided into three parts, each increasing in complexity from a two-level voltage inverter to a three-level and five-level cascaded H-bridge inverter. The aim is to compare control complexity, speed, and torque outputs, hence advancing the field of power electronics in electric vehicle technologies.

5.1 Project Schedule

Weeks 0-2: Initial research and literature review on multilevel inverters, field-oriented control, and permanent magnet synchronous motors. **Weeks 2-4:** Development of the field-oriented control for a two-level voltage source inverter model and integration with the permanent magnet synchronous motor in MATLAB/Simulink. **Weeks 3-4:** Testing and simulation of the two-level system, initial data collection. **Weeks 4-6:** Development of the three-level cascaded H-bridge inverter, integration of the field-oriented control, and simulation. **Weeks 6-8:** Implementation of the five-level cascaded H-bridge inverter along with the integration of the field-oriented control and subsequent simulations. **Weeks 8-10:** Data analysis, comparing control complexities, and performance metrics across different levels. **Weeks 10-13:** Preparation and presentation of findings, and drafting the final report.

5.2 Risk Management

In the management of this project, a comprehensive risk strategy has been developed, encompassing the identification, analysis, and mitigation of key risks. Primary risks identified include software limitations, challenges in integrating different model components, and potential discrepancies between the simulated outcomes and real-world performance. Through a detailed risk analysis, the project focuses on evaluating the likelihood and potential impact of these risks, particularly in terms of technical feasibility and adherence to the project timeline. To manage these risks, the project takes a preventive approach that involves developing contingency plans such as investigating alternate modelling methodologies and executing regular progress assessments to guarantee quick detection and resolution of any difficulties that arise. This multimodal risk management technique is critical to maintaining the project's integrity and effectively fulfilling its objectives.

5.3 Quality Management

In order to achieve excellence and dependability in this project, a strict quality management method has been implemented, emphasizing three essential components: standard compliance, progress tracking, and peer review. To begin, the project rigorously conforms to IEEE standards for power electronics and motor control, guaranteeing that the models and simulations generated satisfy the highest industry criteria. This conformity not only attests to the work's technical accuracy but also to its credibility within the professional community. Secondly, the project incorporates a dynamic progress monitoring system. This system includes regular assessments against established milestones, allowing for real-time modifications and interventions in response to any obstacles or deviations observed during the project lifecycle. This iterative process ensures that the project stays on schedule and on track with its aims. Finally, the project makes use of the thoughts and skills of field specialists through a structured peer review process. By enabling experts and peers to review the approach and preliminary findings, the project gains external perspectives, resulting in improved quality assurance. This complete quality management method not only raises the project's standards but also fortifies its outcomes against potential hazards, ensuring a robust and dependable research process.

5.4 Social, Legal, Ethical, and Professional Considerations

The project is diligently supervised, with a heavy emphasis on professional integrity, legal compliance, ethical considerations, and social impact, to ensure a comprehensive and responsible research strategy. Professional integrity is maintained by transparent and ethical research procedures, as well as accurate data portrayal, which fosters trust and credibility in the research findings. Legal compliance is strictly enforced, particularly in the areas of data protection and privacy, with the project aligned with appropriate laws and regulations to protect sensitive information. Ethical issues are prioritized, with research performed in a way that acknowledges its consequences for sustainable mobility and environmental impact, reaffirming the commitment to responsible and conscientious scientific investigation. Furthermore, the project's social impact is constantly assessed, with a focus on how the outcomes contribute to the advancement of electric vehicle technology and the reduction of carbon emissions. This complete strategy not only improves the research's quality and trustworthiness but also assures that the project has a positive impact on the larger societal and environmental context, aligning with worldwide initiatives towards sustainable development.

Chapter 6

Conclusion

This research dives into an in-depth exploration of control strategies for multilevel inverter-driven permanent magnet synchronous motors. The primary purpose was to examine and appreciate the many characteristics and potential benefits of using multilayer inverters rather than traditional two-level voltage source inverters. This investigation was carried out through the use of sophisticated MATLAB/Simulink simulations, which served as a critical tool in achieving these objectives. The objective of this research was to comprehend the complexities inherent in the functioning and control of multilevel inverters. When compared to their two-level voltage source inverters, these advanced inverter systems present a new set of difficulties and opportunities due to their capacity to generate output voltages with multiple levels. This study used comprehensive simulations to shed light on the complex performance features of these systems, with a particular emphasis on how they influence the overall behaviour as well as the effectiveness of the permanent magnet synchronous motor drives.

6.1 Achievements

Improved Output Quality: The research showed a considerable improvement in the output quality of multilevel inverters. Multilevel inverters, as opposed to standard two-level inverters, can provide voltages that more nearly mimic a pure sine wave. This property is especially essential in the context of permanent magnet synchronous motors because the quality of the input voltage has a direct impact on the motor's performance.

One of the most noticeable advantages of this improved output quality is the significant reduction in harmonic distortions. Distortions in electrical systems can cause a range of detrimental impacts, including increased heat generation, noise, and vibration. Multilevel inverters successfully decrease these distortions by giving a smoother voltage output, resulting in more efficient and stable motor running. Furthermore, the reduction in distortion directly translates into reduced speed and torque ripple in the motor. Torque ripple, or variations in motor torque during rotation, can create unwanted vibration and noise, as well as mechanical degradation over time. Multilevel inverters contribute to more consistent and reliable motor running by smoothing out these irregularities. This is particularly useful in applications requiring great precision and smooth operation, such as electric vehicles.

Response and Error Improvements: The simulations in the research highlighted another important advantage of multilevel inverters: their capacity to deliver a faster control response and reduced steady-state error than two-level inverters. This finding is critical for applications that require a quick and accurate reaction to control inputs. A faster control response means that the inverter can quickly alter its output to match the desired performance, whether in terms of speed, torque, or position control. This responsiveness is critical in dynamic applications with rapidly changing conditions, such as electric automobiles or industrial automation systems. Apart from responsiveness, a lower steady-state error implies that the inverter can keep its output closer to the target value over time. The steady-state error measures the system's accuracy in sustaining a certain output, and lowering it leads to more precise control. This precision is especially crucial in situations where tiny variations from the planned output might cause major problems, such as precision machining or process control systems.

Control Stability Challenges: Despite these benefits, the study also discovered a significant disadvantage of multilevel inverters: a loss in control stability as the number of inverter levels increases. This phenomenon is characterized by a higher overshoot in the system's reaction, indicating that the system tends to surpass its goal output before stabilizing. The result implies that, while multilevel inverters provide various advantages, their greater complexity can provide new control issues. The complexity of maintaining and synchronizing these levels increases as the number of levels in the inverter increases. This can make sustaining stable operations challenging, especially under dynamic settings or with fast changes in load. The observation of higher overshoot in the investigation alludes to possible difficulties in the system's transient response, where the control algorithm may struggle to swiftly and accurately react to changes. To properly manage the complexities of multilevel inverter systems, more refined control strategies, maybe combining advanced techniques such as adaptive control are required.

6.2 Limitations

Model Precision and Realism: The authenticity of the permanent magnet synchronous motor, inverter, and control algorithm models is inextricably linked to the accuracy of the simulation results. When contrasted to real-world behaviour, the idealized assumptions, particularly regarding switching devices, may result in differences.

Controller tuning: The accuracy of the simulated FOC algorithm is heavily dependent on its correct implementation and controller gain setting. However, due to an insufficient amount of time, the controller was not adequately tweaked to produce more precise output.

6.3 Contributions to the Field

This investigation addresses a critical knowledge gap in multilevel inverter-driven motor systems. The research provides new insights into the realm of power electronics and motor control by rigorously comparing two-level and multilevel inverters and studying the effects of varying control parameters. These findings are critical for future improvements in high- precision motor applications, with the potential to influence design and control techniques in industries ranging from industrial automation to electric vehicles.

6.4 Future Work

Use of More Realistic Simulation Tools: Future work should emphasise the use of advanced simulation programmes such as Simscape and LTSpice, which provide more realistic modelling capabilities. These technologies can more realistically replicate the physical behaviours of components, including heat effects, real- world tolerances, and non-ideal component properties. Using these techniques can help to bridge the gap between theoretical simulations and real-world behaviours, resulting in more accurate forecasts and designs that are more suitable for practical applications.

Hardware Implementation of Simulations: The transition from theoretical simulations to real-world hardware implementations is a critical next step. Researchers can acquire crucial insights into how theoretical models transfer into practical applications by running generated MATLAB/Simulink simulations on actual hardware platforms. This approach entails not only replicating simulation circumstances but also adjusting and optimizing them for real-world constraints including physical component limitations and ambient considerations. The hardware implementation will serve as a strong validation method, giving a concrete baseline against which the theoretical conclusions' dependability and applicability may be tested. It also allows for the discovery of previously unknown obstacles and behaviours that can only be observed in a physical setting.

Exploration of this controller for more complex multilevel inverter designs: The research paves the way for further research into more advanced multilevel inverter designs, particularly those with more levels. Such research could help us understand how growing complexity affects overall system performance and efficiency. The potential benefits in terms of output quality and efficiency rise as the number of levels in an inverter increase. This, however, increases the complexity of control and stability, bringing new issues. The investigation of these more complicated systems may give insights into optimizing the balance between inverter complexity and operational efficiency, potentially leading to the creation of new inverter topologies or control strategies that maximize performance while retaining manageable complexity.

Fine-tuning of controller parameters: Finally, future studies should prioritize the fine-tuning of controller parameters. The effectiveness of the field-oriented control strategy used in this research is heavily dependent on the precision of its tuning. Adequate time and resources should be dedicated to carefully adjusting and optimizing these parameters, ensuring that the control system performs optimally under a variety of conditions. This fine-tuning is crucial for the simulated results to accurately represent expected real-world performance, and for the control system to be reliable and efficient in practical applications.

Chapter 7

Student Reflection

Reflecting on my dissertation journey, I've undergone a transformational period filled with learning, challenges, and personal growth. My work explored into simulating a permanent magnet synchronous motor using field-oriented control and different levels of voltage source inverters, leading me through an honest assessment of my capabilities and the lessons that come from facing and overcoming obstacles. Over three dedicated months, this academic project evolved into a profound learning experience, marked by deep exploration and discovery.

When I first embarked on this project, I was motivated by the potential to contribute to the field of motor control and power electronics. However, the complexity of simulating different levels of inverters and integrating them with a permanent magnet synchronous motor in the MATLAB/Simulink environment was daunting. Understanding the nuances of the simulation tools, the dynamics of the motor, and the subtleties of the control algorithms required considerable research on the basics of MATLAB/Simulink and exploring the software. The usage of MATLAB/Simulink software has helped me clear out the concept of its functionalities. This newly developed skill including the year-long academic instructions helped me in tackling certain technical issues and complexities. While ongoing my research, I had to dive into the depth of topics throughout which I have learned valuable skills and gained insights. Also, researching not only helped to expand my understanding but also sharpen my thinking skills. I could gather and analyze information, critically evaluate sources, and draw meaningful outcomes.

The project also emphasized the importance of collaboration. Transitioning from a two-level voltage source inverter to a three-level cascaded H-bridge inverter to a five-level cascaded H-bridge inverter, brought unforeseen challenges, necessitating discussions and idea-sharing with peers and experts. Discussions and sharing ideas with colleagues have helped to overcome obstacles, improve the brainstorming ideas, and lead to proper guidance also provided me with valuable insights and perspectives that helped me amend my project.

Furthermore, time management was a crucial factor throughout the months of the dissertation. Setting deadlines and breaking down the project into manageable tasks kept me more focused. Prioritizing tasks, setting realistic goals, and keeping track to meet deadlines, these skills will be helpful in further future. Another crucial lesson was organization. Creating a schedule, using digital tools, and detailed notes, and breaking the dissertation into chapters and small sections helped me tackle the project in a more manageable way. I could develop strategies to keep everything in order. The project also required flexibility and adaptation. Understanding system reactions and fine-tuning controller gains became more and more important as the phases of control became more complicated. Paying close attention to details was crucial, as even small errors in the parameters could result in large disparities. I became aware of the significance of thorough testing and iteration to guarantee simulation correctness.

My journey has been a continuous learning curve, expanding my knowledge in inverter technology, motor control, and simulation techniques. I realized that there were areas for improvement, such as more structured communication with mentors and exploring advanced modulation techniques. These insights will be invaluable for my future career in engineering. This journey was not only about technical proficiency in simulating motors and controls but also about personal and professional growth. It taught me the value of perseverance, and the need for continuous learning and adaptation, and enhanced my collaborative and critical thinking skills. These experiences have prepared me for future challenges in my academic and professional endeavors, equipping me with a robust set of skills and knowledge to navigate the dynamic world of engineering.

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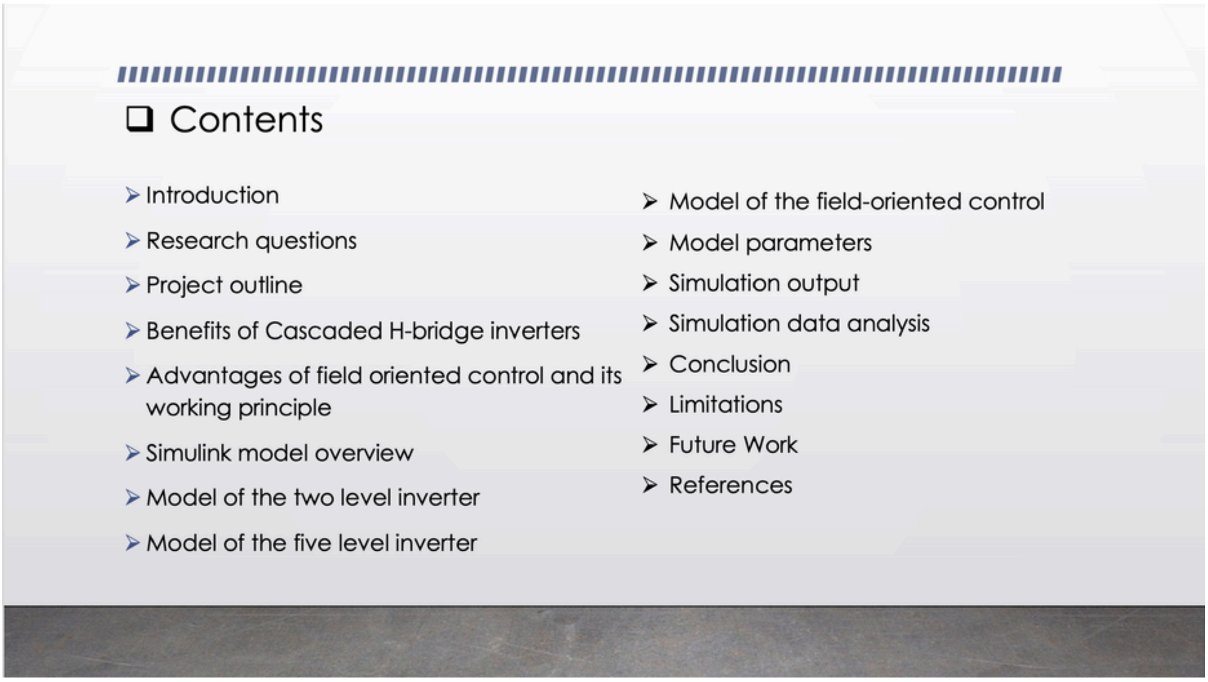
Appendix A

Project presentation



❑ Introduction

- The world progressing towards zero carbon emissions.
- Demand for EVs is rapidly increasing.
- Modern EVs use two-level voltage source inverters.
- Multilevel inverters are a major area of research as a replacement.
- The focus of this research is to find out the control complexities

❑ Research questions

- How the system output differs from using multilevel inverters compared to the two-level inverters
- How the controller gains are affected when the inverter level and the motor poles are varied.
- How the system responses are affected when the inverter level and motor poles are varied.

❑ Project outline

- A two-level, three-phase inverter was designed, incorporating a field-oriented controller, and was integrated with a permanent magnet synchronous motor.
- Three-level and five-level Cascaded H-bridge inverters were developed, with adjustments made to the FOC controller for integration.
- System parameters were compared across different inverter levels and motor pole configurations.

❑ Benefits of Cascaded H-Bridge

- Better power quality than other multilevel inverters.
- Better switching stress than the other multilevel inverters.
- Improved efficiency compared to the other multilevel inverters.
- Lower harmonic distortion compared to other multilevel inverters (Jamwal et al., 2018).

Advantages of field-oriented control and its working principle

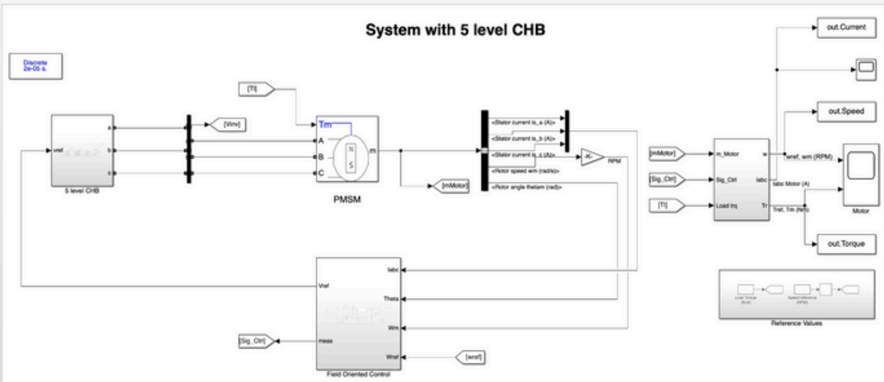
Advantages

- Faster response than other control techniques.
- Less torque ripple than other control techniques.
- Well suited for EV application (Bida et al., 2018).

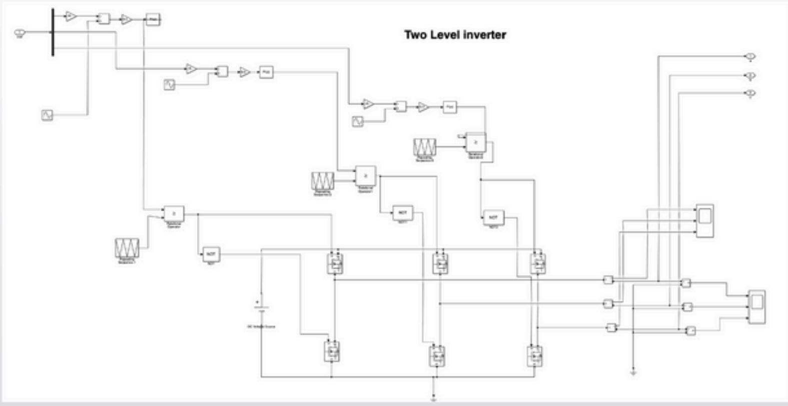
Working principle

- Measures the current passing through the system.
- Compares the actual current against the target current, producing an error signal.
- Enhances the error signal and creates a corrective voltage.
- The corrective voltage is subsequently supplied to the inverter (Le-Huy, 1999).

Simulink model overview



❑ Model of the two-level inverter



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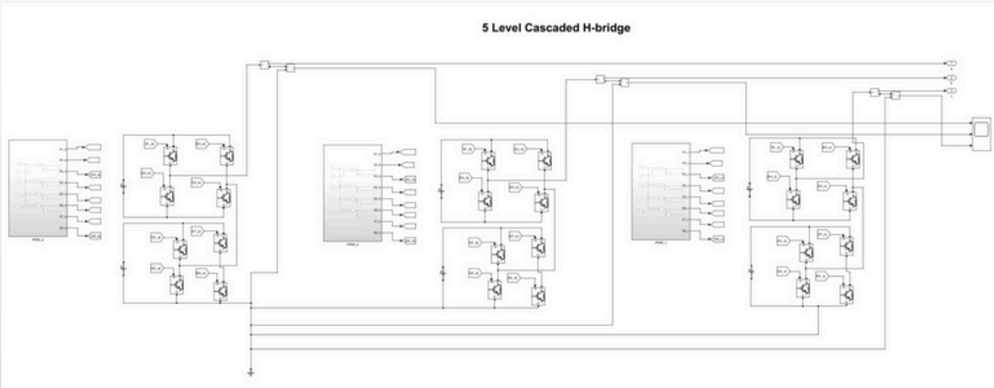
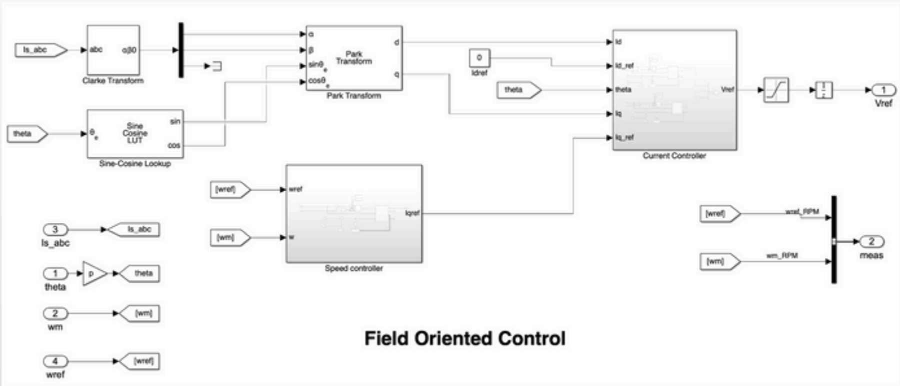
❑ Model of five-level inverter



❑ Model of the field-oriented control

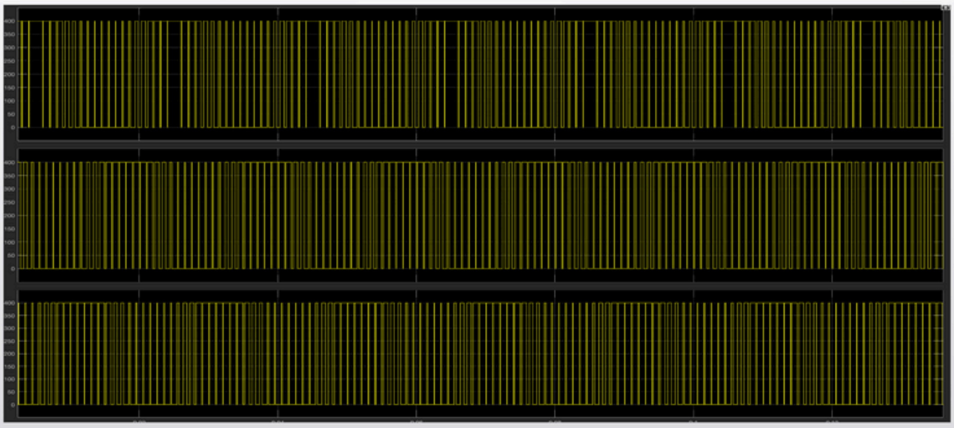


❑ Model parameters

Inverter	Motor
Sample time: 2 x10^{-5} s	Rated voltage: 560 V
Modulation technique: Sinusoidal PWM	Rated speed: 3000 RPM
DC link voltage: 400 V	Rated torque: 126 Nm
Switching frequency: 1000 Hz	Simulation time: 1.2 s
Carrier ratio: 20	
Modulation index: $\frac{Am}{(m-1)Ac}$	

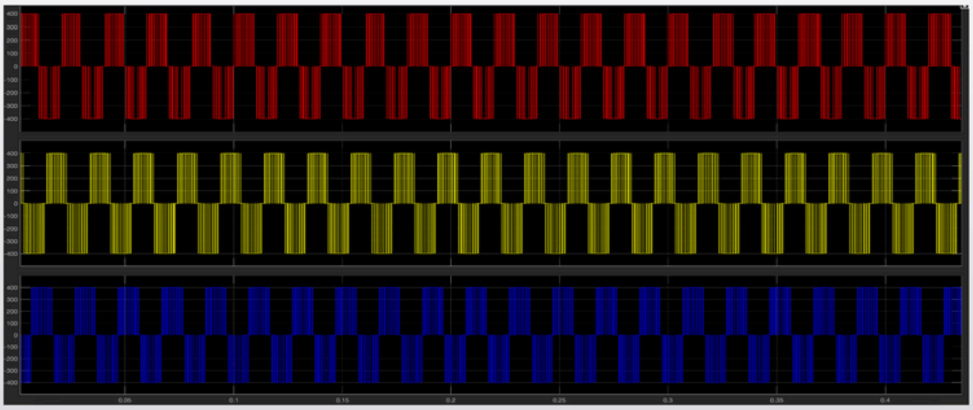
Simulation output

Two level voltage



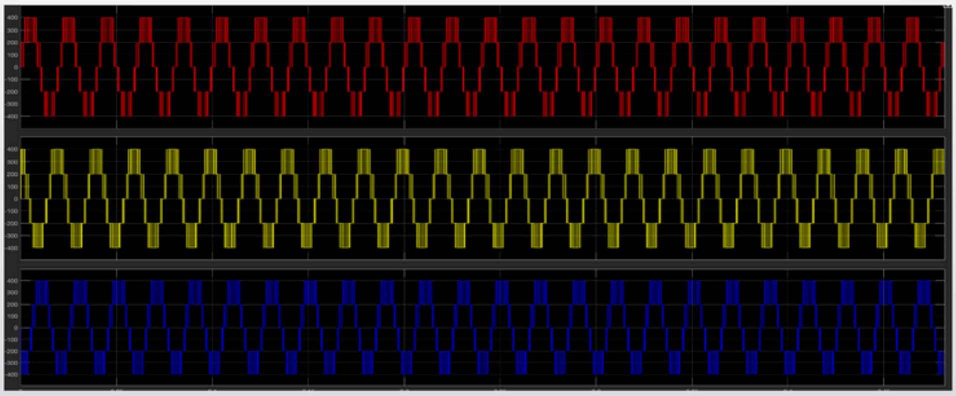
Simulation output

Three level voltage



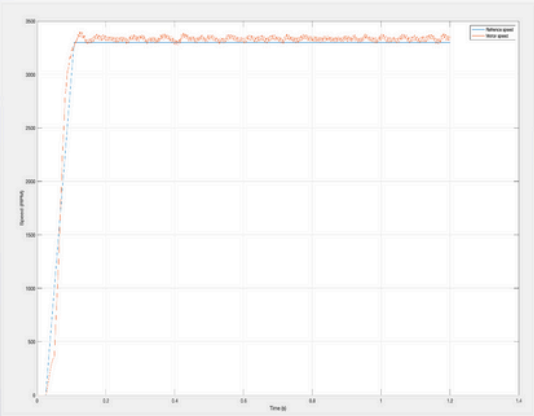
❑ Simulation output

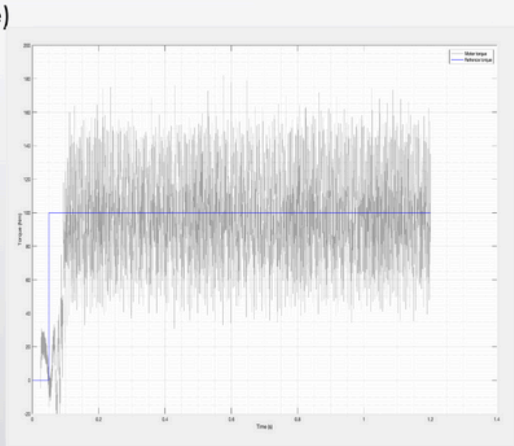
Five level voltage



❑ Simulation output

Two level inverter (constant load torque)



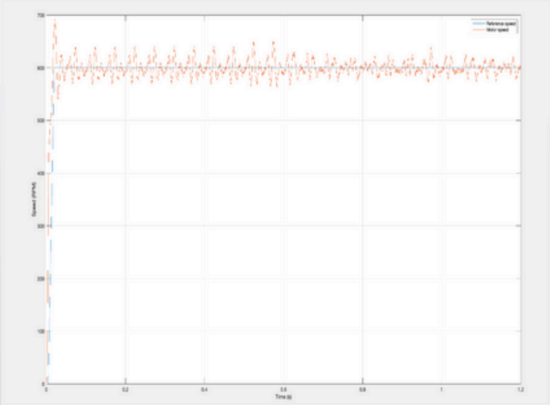


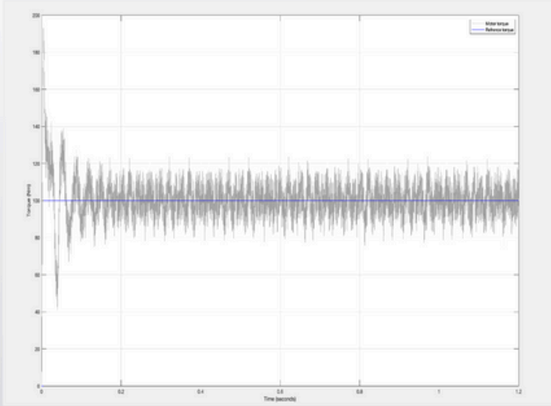
Speed response

Torque response

❑ Simulation output

Three level inverter (constant load torque)

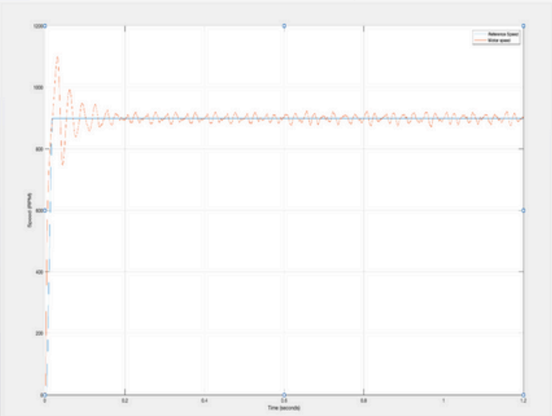


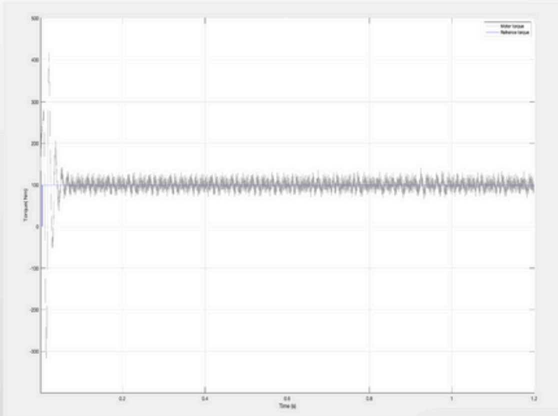


Speed response | Torque response

❑ Simulation output

Five level inverter (constant load torque)





Speed response | Torque response

❑ Simulation output

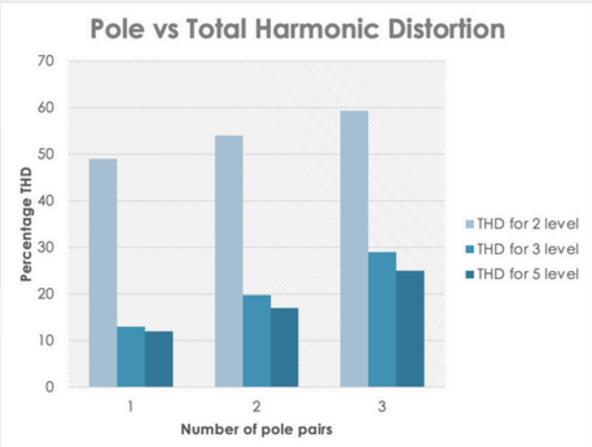
Observations:

- For all the levels, ripples could be seen for both speed and torque response.
- As the inverter level increases the speed and torque speed ripple decreases.

Discussion:

- Higher-level inverters generate voltage waveforms that are more closely aligned with a sine wave, resulting in much less torque and speed ripple for smoother motor running which justifies the findings of Abou-ElSoud et al., 2023.
- The increase in inverter levels leads to lower Total Harmonic Distortion in the output, thereby minimizing the current harmonics and contributing to less ripple in motor performance.

❑ Simulated data analysis



Observations:

- With an increase in the number of levels, there is a corresponding decrease in the Total Harmonic Distortion percentage which justifies the findings of Mali et al., 2019.
- When the number of pole pairs increases, the Total Harmonic Distortion percentage for a given level also increases.

❑ Simulated data analysis

Discussion:

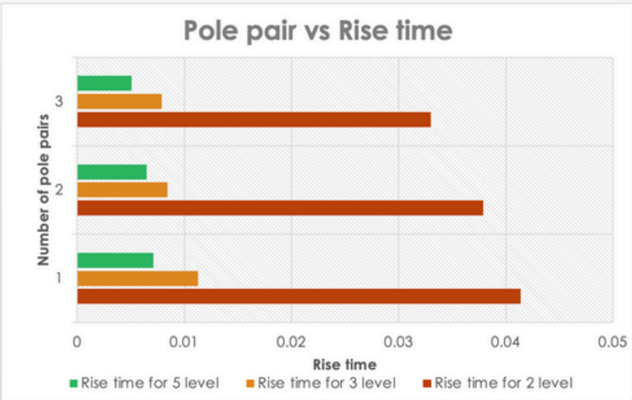
- A multilevel inverter with more levels produces an output voltage waveform that more closely resembles a pure sine wave, leading to a decrease in THD.
- Higher levels result in reduced harmonic content, as smoother voltage transitions between levels minimize high-frequency harmonics.
- Smaller voltage steps in multilevel inverters facilitate smoother transitions, further diminishing abrupt voltage changes and lowering THD.
- Adding pole pairs to a motor increases its electrical frequency, requiring more frequent inverter switching and thereby increasing the harmonic content in the output which suffices the findings of Merdžan, 2021.

❑ Simulated data analysis

Pole pair vs speed responses

Observations:

- The rise time of the speed response decreases for a specific level with an increase in the number of pole pairs.
- The rise time for a specific pole pair is lower for higher level inverter.



❑Simulated data analysis

Pole pair vs speed responses

Discussion:

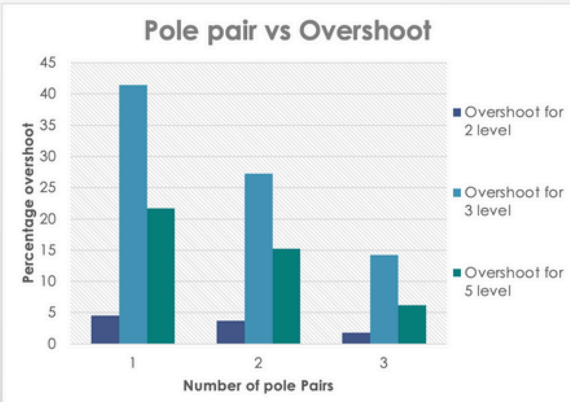
- A reduced rise time signifies a system's rapid response and high sensitivity to input changes, often essential in dynamic and precision-demanding applications (Yepes et al., 2013).
- As the level increases, the system becomes more responsive and highly sensitive.
- As the number of pole pairs increases, the system becomes more responsive and highly sensitive.

❑ Simulated data analysis

Pole pair vs speed responses (cont.)

Observation:

- It could be seen that as the number of pole pair increases the overshoot decreases.
- The overshoot value is the lowest for 2 levels but is comparatively more for 3 level and 5 level.
- However, the overshoot value of the 5 level is less than the 3 level.



❑ Simulated data analysis

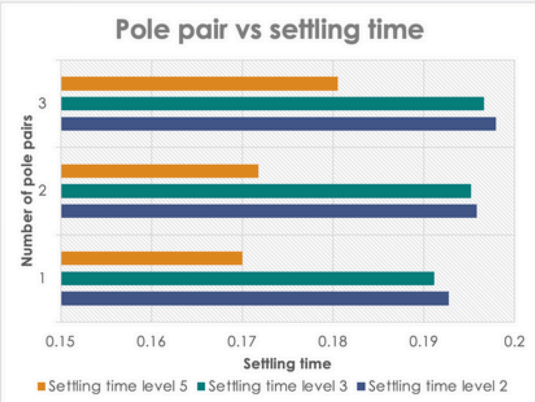
Pole pair vs speed responses (cont.)

Discussion:

- Increased overshoot implies an overly aggressive response, potential stability concerns, and the need for controller re-tuning, which frequently compromises precision, safety, and efficiency (Yepes et al., 2013).
- The two-level inverter typically produces more significant harmonics compared to multilevel inverters. However, it can be more straightforward in control due to its simpler structure, potentially leading to less overshoot.
- The three-level inverter introduces a more complex control scenario due to its additional voltage levels. This might temporarily increase the difficulty in achieving precise control, resulting in higher overshoot.
- In the five-level inverter, the voltage waveform becomes smoother with fewer harmonics, closer to a sine wave. This can facilitate more precise and smoother control of the motor speed, hence reducing overshoot again.

❑ Simulated data analysis

Pole pair vs speed responses (cont.)



Observation:

- It could be seen that as the number of level increases, the settling time decreases.
- For an individual level, when the pole pair increases, the settling time increases

❑ Simulated data analysis

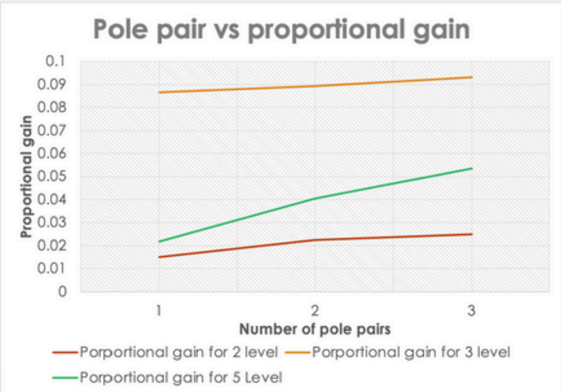
Pole pair vs speed responses (cont.)

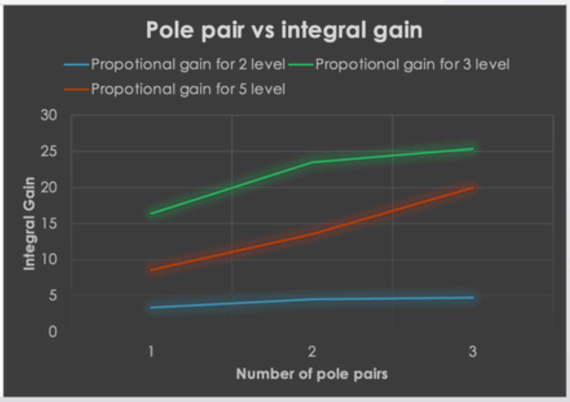
Discussion:

- The settling time in control systems is the time it takes from the start of a system's response to a change until it regularly stays within an acceptable error range of the desired value.
- Increased settling time It denotes that the system takes longer to stabilize at the intended value following disruptions (Yepes et al., 2013).
- This means as the inverter level increases, the system takes longer to stabilize.
- As the motor poles increases, the system takes longer reach within a small margin of error.

❑ Simulated data analysis

Pole pair vs speed responses (cont.)





❑ Simulated data analysis

Pole pair vs speed responses (cont.)

Observation:

- For a given level the proportional and integral gain increases with an increase in the number of pole pairs.
- For a given pole pair the proportional integral gain increases as the level increases.

❑ Simulated data analysis

Pole pair vs speed responses (cont.)

Discussion:

- Increase in proportional and integral gain causes the system to respond faster to correcting steady state errors, lowering the time required to achieve the desired setpoint.
- A higher Integral and proportional gain can lead to overshooting the target, where the system output temporarily exceeds the desired level before stabilizing.
- Higher integral proportional gain may cause oscillations near the setpoint, affecting system stability (Panda et al., 2002.).
- This means that the control system using the three-level reacts faster to error correction but produces large overshooting and more oscillations making the system less stable compartively.

Summary

- Multilevel inverters are better compared to two level inverters as they produce output close to sine wave which produces less distortions.
- Less distortion accounts for less speed and torque ripple.
- Multilevel inverters produce faster control response and less steady state error compare to two level inverter.
- However, the control stability decreases for multilevel inverters as the overshoot is greater .

Limitations

- The simulation's accuracy hinges on the precision of the PMSM, inverter, and control algorithm models, with simplifications potentially leading to variations between simulated and real-world behaviors.
- The switching devices are considered to be ideal which ignores the switching losses.
- Accurate setting and validation of key parameters like motor inductance and resistance are crucial, and inaccuracies here can result in inaccurate simulation outcomes.
- The effectiveness of the simulated FOC algorithm greatly depends on its accurate implementation and tuning of the controller gains. However due to lack of time the controller was not tuned properly to get more accurate output.

❑ Future Work

- Design the whole project in simscape and LTSpice that gives a closer result to actual hardware behavior.
- Implementation of the whole simulation on hardware.

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Thank You!!