

Vector Controlled Dual Stator Induction Motor for Fast Dynamic Propulsion Control

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I, Ankita Singh, Roll No. 2K24/PES/10 student of MTech (Power Electronics & Systems), hereby declare that the project Dissertation titled “ **VECTOR CONTROLLED DUAL STATE INDUCTION MOTOR FOR FAST DYNAMIC PROPULSION CONTROL** ” which is submitted by me to the Department of Electrical Engineering, Delhi Technological university, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship, or other similar title or recognition.

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CERTIFICATE

I hereby certify that the project Dissertation titled “ **Vector controlled Dual Stator Induction Motor for fast dynamic propulsion control** ” which is Submitted by **Ankita Singh**, Roll No. **2K24/PES/10**, Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge, this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ABSTRACT

This discusses the control architecture for acceleration and deceleration process of a Dual Sator Induction motor (DSIM) that are used in EV applications. Dual Stator Induction Motor have two three-phase stator windings on a common rotor that provides high torque capability and increase the power density compared to the single stator induction motor. So, the DSIM motor is the best choice to use in electric vehicles because of its high starting torque, fast response and better performance.

A control scheme which is designed for DSIM have the modelling using the d-q axis representation of the DSIM motor. The three phase motor variables in d-q axis is controlled separately that is the rotor flux and electromagnetic torque can be controlled separately. This approach helps an induction motor to have the same dynamic characteristics as separately excited DC machines but with independent rotor flux and torque control that can be controlled separately.

To implement acceleration and deceleration of EV drives, the proposed control method is designed in such a way that it can control the acceleration and deacceleration of the motor. This control system offers fast torque production in acceleration stage to obtain the required speed and smooth reduction in speed during deceleration. In this paper, the machine configuration is discussed, mathematical model, control objectives, and drive implementation is also discussed. The advantages of the dual stator configuration are great torque capabilities, improved reliability, and better driving characteristics. Overall, the DSIM with field-oriented control satisfies the demanding specifications set for EV applications.

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LIST OF SYMBOLS, ABBREVIATIONS AND NOMENCLATURE

ω_r	Motor speed in rad/s
ω_e	Rated speed in rad/s
T_l	Load Torque
ω	Slip speed in rad/s
T_{em}	Electrical developed torque
$i_{ds1}, i_{qs1}, i_{ds2}, i_{qs2}$	d-q axis stator 1 & stator 2 currents
i_{dr}, i_{qr}	d-q axis rotor current
$v_{ds1}, v_{qs1}, v_{ds2}, v_{qs2}$	d-q axis stator 1 & stator 2 voltages
v_{dr}, v_{qr}	d-q axis rotor voltages
R_{s1}, R_{s2}	Stator 1 & stator 2 Resistances
R_r	Rotor referred resistance
L_{s1}, L_{s2}	Stator 1 & stator 2 inductances
L_m	Magnetizing Inductance
l_{sm}	Common mutual leakage inductance between the two sets of stator windings

CHAPTER 1 INTRODUCTION

Nikola Tesla's invention of the induction motor in the late nineteenth century was a big step in the electrical machines. The advances in machine construction, electromagnetic design and power electronic converters led to big improvements in the performance and controllability of induction motor drives. Today, the induction motors are commonly used in industrial and transportation systems due to their rugged construction, low maintenance, economical operation, and reliable operation under different operating conditions.

Three-phase induction motors are the highly used choice for industrial applications, because of the common availability of three-phase power systems. Recent developments in power electronics have renewed the interest in multiphase electrical machines. There are many advantages of these machines such as improved reliability, higher power capability, lower current stress per phase and better fault tolerance. Of the all the multiphase configurations, dual stator induction motors are known as one of the best for high performance drive.

A dual stator induction motor consists of two independent sets of three phase stator windings in the same machine frame separated by an electrical angle. This arrangement allows for sharing of the electromagnetic load between the two windings which results in improved torque production, lower current ratings per phase and reduced harmonic content. Thus, the machine can obtain higher power density and better efficiency with the dynamic characteristics. The d-q reference frame model is commonly used for analysis and control of such machines. The dynamic behaviour of the motor can be defined in an easy way by changing the machine variables into a rotating coordinate system [1]. Field oriented control uses this model to control separately the flux producing current and torque producing current components. Hence the induction motor has control characteristics similar to a separately excited D.C. motor which allows fast torque response, accurate speed regulation and improved overall drive performance.

The benefits of the dual stator induction motor make it especially suitable for electric vehicle propulsion and precision motion-control applications. The applications require fast acceleration, smooth deceleration, high torque capacity and stable operation under changing load. To meet these demands the control system should efficiently synchronize

the two stator winding sets taking into account the effects of electromagnetic coupling and the transient behaviour of the machine. Thus, it is important to develop an accurate mathematical model and an effective control strategy for high-performance operation.

The objective of this thesis is to study the control of the acceleration and deceleration of dual stator induction motor based on a control approach of the d-q axis. The work is mainly focused on modelling the dynamics of the machine, designing a suitable control structure and evaluating the transient response of the motor during speed variations and load disturbances. The proposed thesis is aimed to evaluate the feasibility of dual stator induction motor for electric vehicle and applications through detailed simulation and performance analysis.

1.1 General

Requirements of Electric Vehicles during acceleration and deceleration:

The driving performance of an electric vehicle is mainly affected by the characteristics of traction drive system, control strategy and energy storage unit. Effective acceleration and deceleration are required to keep the vehicle responsive, keep the passengers comfortable, the operations safe and to use the available energy efficiently. Therefore, the electric motor and the related control system must be able to provide the required torque and speed under different operating conditions.

Electric Vehicles Acceleration Requirements:

Acceleration is the process of changing the vehicle speed from one operation point to another. During this time, the traction motor has to provide enough torque to overcome the vehicle inertia, road resistance, and external disturbances. The main requirements for an acceptable acceleration performance are given below.

1. High Torque at Low RPM

A significant amount of torque is required at the vehicle start-up and low speed operation, to start motion and to ensure a smooth vehicle launch. Therefore, traction motors in EVs are designed to provide a high amount of torque even at low speeds.

2. Fast Torque Development

The drive system should be capable of developing the required torque with minimum delay possible. Fast dynamic response can help the vehicle to accelerate as fast as

possible, improve the vehicle operation and improve performance when the speed changes suddenly or the vehicle overtakes.

3. Wide speed operation

An EV traction motor is expected to operate smoothly from zero to its maximum operating speed. The stable performance over a wide range of speeds reduces the need for complex transmission systems and improve the overall vehicle operation.

4. High power to weight ratio

In order to improve the efficiency of the vehicle and to reduce the total weight, the motor should be small in size and output power should be high. The vehicle performs better for the higher power density. It uses the energy better.

5. Superior Speed & Torque Control

Nowadays, EVs use sophisticated control strategies to precisely regulate motor torque and speed. With Field-Oriented Control (FOC) strategies, the torque and flux components can be controlled independently to get smooth acceleration and accurate speed tracking.

6. Adequate Power Supply from the Battery

The battery pack has to be able to supply the high current needed during acceleration, but without excessive voltage fluctuation, thermal stress or decline of battery performance.

Electric Vehicles Deceleration Requirements:

Deceleration is the gradual decrease in speed of a vehicle for safety and comfortable ride. In electric cars, we have both regenerative brakes and mechanical brakes to slow you down.

1. Gradual torque reduction

The motor control system should gradually reduce the developed torque, to provide comfortable braking and avoid sudden jerks that may affect the passenger's comfort and the vehicle stability.

2. Regenerative energy recovery

One of the main benefits of EVs is the ability to recover some of the kinetic energy of the vehicle during braking. In regenerative mode the traction motor becomes a generator and

converts the mechanical energy into electrical energy which is fed back to the battery for further use.

3. Quick Braking Response

The drive system must be able to respond rapidly to a braking command to decelerate at the desired rate. It also makes our driving safer, and with a rapid drop in torque we will have more control over the car.

4. Vehicle Stability Management

When we apply brake, we want to keep the tires on the road and not allow the wheels to lock up or slip too much. Well-coordinated braking system and motor controller will help to provide stable vehicle behaviour under different road conditions.

5. Good heat performance

The frequent accelerations and decelerations heat the battery system, inverter and motor. Good thermal management is needed to prevent the components from overheating and to ensure reliable operation.

6. How to Make the Most of Day's Energy

Reducing the energy losses in acceleration and deceleration is necessary to extend the vehicle range. An effective design of regenerative braking strategy can improve the overall efficiency of the system.

Nowadays, advanced control methods such as indirect vector control are widely used in electric vehicle drive systems to attain accurate torque control, smooth speed variation and energy efficiency. Such control strategies improve the performance of the acceleration and deceleration, which improves the overall dynamic behaviour of the vehicle.

1.2 State of art

The focus on sustainable transport has increased the adoption of electric vehicles across the world. Concerns about the greenhouse gas emissions, increasing fuel consumption and the limited availability of conventional energy resources led to the development of effective electric propulsion systems. The traction motor is an important component in an electric vehicle, as it has direct impact on vehicle performance, energy usage, acceleration

capability, and the driving characteristics. Hence, a lot of research efforts have been dedicated to the selection and control of suitable motor drives for EV applications.

Different motor technologies have been used for electric vehicle propulsion systems including Permanent Magnet Synchronous Motors (PMSMs), Brushless DC (BLDC) motors, Switched Reluctance Motors (SRMs) and Induction Motor Drives (IMDs). For each type of motor there are advantages and limitations that determine suitability for specific operating conditions of EVs.

Permanent Magnet Synchronous Motors are mostly used in modern electric vehicles due to their high efficiency, better torque to weight ratio, and compact design. These features of PMSMs allow for higher performance and lower energy consumption. However, PMSMs use permanent magnets that are made from rare-earth materials, which increases the manufacturing cost and raises concerns about material availability. Also, the magnetic properties of these materials can degrade at elevated temperature conditions.

Brushless DC motors have also been used in electric mobility systems because of their efficient operation and comparatively simple maintenance requirements. Mechanical brushes are eliminated, reliability is improved and maintenance needs are also reduced. However, BLDC motors need electronic commutation schemes and exhibit torque pulsations. These may negatively influence smooth operation of the EVs and increase the complexity of the controller.

Switched Reluctance Motors are also considered because of their rugged structure, simple rotor design and their ability to operate under fault conditions. They are also easy to make. But, one of the main challenges is the presence of a large torque ripple and acoustic noise, especially in applications where the smooth operation of the vehicle is needed.

Amongst all the available traction motor technologies, the Induction Motor Drive is one of the promising candidates for electric vehicle propulsion. Its rugged construction, low cost and the lack of permanent magnets make it more popular. Induction motors can be used under harsh environmental conditions and usually require less maintenance during their service life and are more reliable in harsh environment. They also have good overload capability and wide range of efficient operation which make them suitable for a variety of EV operating situations. The use of advanced control techniques should be used because of the inherent coupling between motor variables and the nonlinear nature of the machine.

In order to overcome these difficulties and to achieve high performance operation, vector control methods have been widely developed and used. The Indirect Vector Control (IVC) also known as Field-Oriented Control (FOC) is one of the most common techniques used in the induction motor drives among all the different techniques. This method transforms the motor variables to a rotating reference frame, allowing independent control of the flux and torque components of the machine. This decoupled control strategy makes the induction motor behave like a separately excited DC motor, which provides better torque response, accurate speed control and improved dynamic performance.

Research in this area is still enhancing the performance of induction motor drives by means of better control algorithms, optimization methods and intelligent control strategies used for EVs. The focus is placed on improving the efficiency, increasing the system robustness and on achieving a faster transient response under varying operating conditions. Therefore, the research on the indirect vector-controlled induction motor drives is still an important research topic for present and future electric vehicle technologies.

1.3 Scope of the work

The importance of sustainable transportation has increased over the years and electric vehicles are more widely accepted and used these days. The concerns about greenhouse gas emissions, increase in fuel consumption and reduced availability of conventional energy resources have led to the development of competent electric propulsion systems. Traction motor is the most important part of electric vehicle, and it can directly affect the performance of vehicle, energy consumption, acceleration ability and general drive features. Hence, the research efforts have been increased and dedicated to the selection and control of suitable motor drives for EV applications.

The EV propulsion systems have used different motor technologies such as Permanent Magnet Synchronous Motors (PMSMs), Brushless DC (BLDC) motors, Switched Reluctance Motors (SRMs) and Induction Motor Drives (IMDs). Each motor type has its advantages and disadvantages and those are the determining factor for the motor and whether the motor is suitable to certain operating conditions or not.

Permanent magnet synchronous motors (PMSMs) are widely used in modern electric vehicles due to their high efficiency, good torque to weight ratio and compact design. These features allow better performance and lower energy consumption. However, the

dependency on rare earth materials of the permanent magnets in PMSMs leads to higher production costs and raise questions on the availability of material. Also, high temperature environments and situations can deteriorate the magnetic properties of these materials.

Efficiency and comparatively low maintenance make the brushless DC motor an ideal motor for electric vehicle systems. Because of this the reliability is increased and less maintenance is required as mechanical brushes are eliminated. However, BLDC motors need electronic commutation schemes and often have torque pulsations which can affect smooth operation of the EVs and increases controller complexity.

Switched reluctance motors (SRMs) have gained attention due to their robust construction, simple rotor design, and the possibility of operation under faulty conditions. They can also be made cheaply. However, the presence of high torque ripple and acoustic noise is a big challenge especially for applications needing smooth vehicle operation.

Induction Motor Drive is one of the promising traction motor technologies for electric vehicle propulsion system. Its popularity is due to its durable construction, cost-effectiveness, and lack of permanent magnets. Induction motors can be operated reliably in harsh environmental conditions and usually require less maintenance during their service life and are reliable. They also have a decent overload capability. They can be operated effectively within a wide speed range, which is suitable for different EV working situations. However, because of the inherent coupling between the motor variables and nonlinear nature of the machine, advanced control techniques are needed.

Vector control techniques are widely developed to overcome these challenges and achieve high performance operation. Among all the techniques, Indirect Vector Control (IVC), also known as Field Oriented Control (FOC), is one of the most popular methods for induction motor drives control. This technique changes the motor variables to a rotating reference frame, allowing independent control of flux and torque components of the machine. The decoupled control makes the induction motor behave as a separately excited dc motor with improved torque response, good speed regulation and better dynamic performance.

In this field, for better performance of induction motor drives, further improvement of control algorithms, optimization methods and intelligent control strategies are ongoing researches. Special attention is given to improving efficiency, system robustness and transient response under various operating conditions and scenarios. Hence the research

work on the indirect vector-controlled induction motor drives still remains one of the important parts of the current and future electric vehicle technologies.

This research focuses on the modelling, control and performance evaluation of a Dual-Stator Induction Motor (DSIM) drive for electric vehicle propulsion system. The motivation for study is the increasing demand for the efficient and reliable electric drive system which can provide smooth acceleration and deceleration of the electric vehicle with high dynamic performance.

The objective of the work is to create a mathematical model of the DSIM and to implement a suitable control strategy to manage its performance in different speed situations. The DSIM is a single machine with two sets of three phase stator windings each and it has the advantages over the conventional induction motors in terms of the improved torque capability, better power distribution and the increased operational flexibility. The interaction between the winding sets creates an additional complexity that should be compensated by a suitable control technique.

On the platform MATLAB/Simulink, a full simulation model of the electric drive system is developed. The model contains the electrical and mechanical dynamics of the motor and the inverter-fed drive structure and the vector control system required for the efficient control of torque and flux. To improve the dynamic behaviour of the machine, the focus is dedicated to the application of indirect vector control for the decoupled control of electromagnetic torque and flux.

The proposed electric drive system is checked under various operating conditions of interest for electric vehicle applications. The acceleration behaviour is estimated by applying step increases of the reference speed, and the deceleration behaviour is assessed by applying controlled reductions in the speed command. The system response is calculated by observing the main performance variables such as motor speed, electromagnetic torque, stator currents characteristics.

The ability of the controller to provide smooth speed tracking, balanced current distribution between the stator winding sets and stable operation under the load disturbances is examined together with other features. The dynamic performance index like rise time, settling time, overshoot and steady state accuracy are used for the evaluation of the performance of the control scheme.

The results of this study give an understanding into the suitability of dual-stator induction motor drives for electric vehicle applications. The developed simulation framework can also be used as a basis for future work on regenerative braking strategies, intelligent control methods, optimization processes and experimental implementation on real-time hardware platforms.

1.4 Objectives of the Thesis

The main goal of this thesis is to develop and evaluate an acceleration and deceleration control strategy for a dual-stator induction motor (DSIM) suitable for electric vehicles.

The specific objectives are:

1. Construction of a Dynamic Model of the DSIM

To develop a complete mathematical model of the Dual-Stator Induction Motor in the synchronous d-q frame. The model answer for the electrical behaviour of both stator winding sets, rotor dynamics, flux linkage relationships, electromagnetic torque generation, as well as the mechanical characteristics which govern motor operations.

2. Design of Vector Control Strategy

To develop a vector-control strategy to coordinate the control of the two sets of stator windings. The controller is designed to provide independent control of flux and torque, ensure balanced current distribution between the stator windings and smooth acceleration and deceleration with minimum torque fluctuations and reduced electrical and mechanical stresses.

3. Simulation and performance validation

To develop a full DSIM drive model in the MATLAB/Simulink environment and to study its performance over a wide range of operating conditions. The analysis includes speed tracking capability, response to load disturbances and behaviour during acceleration and deceleration. The performance of the proposed control strategy is evaluated with the help of simulation results and comparison with established principles of motor control reported in the literature.

1.5 Organization of Thesis

The thesis is divided in six chapters, each chapter deals with a particular aspect of the research work related to modelling, control and performance evaluation of a Dual-Stator Induction Motor (DSIM) for electric vehicle applications.

Chapter 1 Introduction

In the first chapter, the basic concepts of electric vehicle propulsion system and the significance of induction motor drives in modern EV applications are presented. The motivation for the investigation of dual-stator induction motors and the advantages of multiphase machine configurations is discussed. A brief description of the popular types of traction motors, such as PMSM, BLDC, SRM and induction motors, with their salient features is presented. The chapter also outlines the research problem, objectives, scope of the study and overall structure of the thesis.

Chapter 2: Review of Literature

This chapter presents a comprehensive review of the previous researches related to dual-stator and multiphase induction machines. The discussion includes machine modelling techniques, electromagnetic coupling effects, vector control approaches and the application of induction motor drives in electric vehicles. Relevant studies on field-oriented control, current sharing strategies and simulation-based analysis are reviewed. The existing research gaps are identified from the reviewed literature and the need for the present investigation is established.

Chapter 3: Mathematical Model of the Dual-Stator Induction Motor

In this chapter, the mathematical framework that describes the dynamic behaviour of DSIM is developed. A detailed derivation of the machine equations in the synchronous d-q reference frame is presented. The chapter contains the voltage equations of the two stator winding sets, the equations of the rotor, the flux linkage relations, the formulation of the electromagnetic torque and the mechanical dynamics of the motor. The effect of mutual leakage inductance between the stator windings is also considered. The developed model is used as the basis for controller design and simulation studies.

Chapter 4: Vector Control Strategy of DSIM

The fourth chapter presents the development of the control methodology used for the regulation of the DSIM drive. An indirect field-oriented control scheme is developed for independent control of torque and flux. The chapter explains the working principle of the controller, speed regulation and current control structure. Particular attention is paid to smooth acceleration and deceleration, as well as stable operation and balanced performance of the dual-stator system.

Chapter 5 Performance Analysis

The implementation of the proposed DSIM drive system in the MATLAB/Simulink environment is presented in this chapter. Simulation studies are conducted for different operating scenarios such as acceleration, deceleration, steady-state operation and different load conditions. The obtained results are analysed through the performance indicators such as speed response, electromagnetic torque, stator currents and transient characteristics. The effectiveness of the proposed control strategy is assessed by detailed discussion of the simulation outcomes.

Chapter 6 Conclusion and Future Work

The last chapter summarizes key findings and contributions of the research. The proposed acceleration and deceleration control scheme for the dual-stator induction motor is evaluated in terms of electric vehicle requirements. Moreover, potential improvements and possible extensions of the present work are discussed. Future research recommendations including advanced control techniques, regenerative braking integration and experimental validation are also presented.

CHAPTER 2 LITERATURE SURVEY

2.1 Introduction

Induction motors are widely used for many industrial and traction applications because of their rugged, simple, low cost, and suitable characteristics. For high-performance drive systems a conventional three-phase machine has limitations in torque sharing, thermal loading, and fault tolerance, which has provided motivation for research on multiphase and dual-stator structures.

Dual stator and multiphase machines are more attractive because they can split the electrical power among more than one winding set, reduce current stress per phase, and improve the operational reliability. In the literature, this idea is presented as one of the main advantages of dual stator and six-phase machines over conventional three-phase drives. [1], [3]

2.2 Dual Stator Induction Motors (DSIMs)

Correct modelling is important for dual-stator induction motors because the two stator winding sets are magnetically coupled. The impact of stator mutual leakage inductance on the dynamic and steady-state behaviour of a dual-three-phase induction motor is studied in the literature and showed that this coupling must be included in the model for accurate transient prediction. Their works compares two d-q models, one neglecting mutual leakage and the other including it, and concludes that the model without mutual leakage is not recommended for transient operation. [1]

The previously mentioned study also shows that the dual three-phase structure can reduce rotor harmonic currents and lower current per phase without increasing phase voltage. This is one of the main technical reasons dual-stator structures are considered suitable for high-power electric drive applications. [1]

The modelling paper further discusses that the two stator winding sets are generally displaced by 30 electrical degrees and that this displacement improves the electromagnetic torque characteristic and also eliminates some torque harmonics on the same time. This makes the topology better than a conventional single-stator machine for high-torque applications. [1]

2.3 Multiphase Induction Machines

The multiphase literature supports the use of more than one stator winding set like 6 phase or n-phase for reducing phase current and improving power handling capabilities. One of the literatures compared a six-phase induction motor with a conventional three-phase machine and found that the six-phase motor requires less current to produce the same electromagnetic torque and also showing lower harmonic distortion and reduced slip characteristics. These results support the idea that distributing the load over more windings which improves machine performance. [3]

The study also shows that the six-phase machine has better efficiency and shorter settling time than the three-phase machine under the same loading conditions. This is relevant for electric vehicle propulsion systems because EV drives need fast torque response, reduced thermal stress, and smooth speed tracking. [3]

The six-phase literature records that multiphase machines increase reliability because the loss of one phase does not necessarily stop the machine from operating. That same fault tolerant idea applies to dual-stator machine structures, where one stator winding set can still operate if the other set is weakened or reconfigured. [3]

2.4 Control strategies for Multiphase Induction Machines

For control, indirect field-oriented control is one of the most common and widely used approach for dual stator induction motor drives. An indirect rotor-field-oriented control strategy based on a d-q model and two independently current-controlled voltage sources were developed. Their study shows that this structure removes the unbalanced current sharing between the two stator winding sets because the two sets are regulated separately. [2]

The same work also shows that the DSIM can be modelled with a d-q mixed representation that includes mutual leakage inductance and a given displacement between the two three-phase sets. This is important because control accuracy depends on the quality of the machine model, especially in the case when the two winding sets are not perfectly symmetrical. [2]

In general, field-oriented control is used because it separates flux and torque control of the machine. In a rotating d-q reference frame, the current components can be represented as flux-producing and torque-producing quantities, which makes the induction motor

behave in a way similar to a DC motor from the control point of view. This decoupling supports better dynamic response and simpler speed regulation of the electric drive. [5]

2.5 Research gap and motivation for the thesis

The studied literature shows that the dual-stator machines have strong advantages in torque sharing, harmonic reduction, and fault tolerance. It also shows that accurate d-q modelling must include mutual leakage inductance and that indirect field-oriented control is effective for balancing the two stator winding sets of the machine. [1], [2], [3]

However, most of the available work focuses on modelling accuracy, current balancing, or general speed control of the machine. There is still room for a thesis that specifically studies acceleration and deceleration control of DSIM for EV applications, with focus on smooth transient response, controlled torque sharing, and practical Simulink implementation. [1], [2], [5]

Simulation-based modelling is important because it helps the control strategy to be tested before any hardware implementation. A Simulink implementation of an induction machine model in which each block represents different parts of the machine equations connected to each other simplifies the machine. Their model transforms three-phase variables into the d-q frame, evaluates current and flux dynamics, and outputs torque and rotor speed, making it suitable for control design and further evaluations. [5]

The same paper emphasizes that Simulink models are easier to understand than black-box machine models because the internal parameters of the machine remain accessible. This is useful for developing indirect vector control schemes and for analysing transient behaviour under speed changes, load changes, and braking conditions. [5]

The dual-stator control paper also shows simulation results for torque, speed, stator current, and flux under step changes in load and speed inversion. The close tracking between reference and simulated values settles that indirect field-oriented control is effective for dynamic operation of DSIM drives. [2]

Dual-stator technology is not limited to motor drives only. One of the literatures shows that a dual stator induction generator can be used as a three-port network for soft coupling of distribution feeders and wind energy harvesting. Even though this is a generator application, it shows the broader flexibility of the dual-stator concept in power transfer and multiport energy systems. [4]

This wider use of dual-stator structures makes the case for DSIM in electric vehicle drives stronger. If the machine can support flexible power routing and independent winding control in generator applications then the same structural features are useful for torque sharing, smooth acceleration, and controlled deceleration in traction systems also. [4]

Based on the studies reviewed, the dual-stator induction motor is a promising candidate for high-performance electric drive applications. Its dual winding structure supports torque sharing and fault tolerance while d-q based field-oriented control enables independent regulation of flux and torque in the machine. Therefore, the next chapters present the mathematical model of the DSIM and the control strategy used for acceleration and deceleration in EV applications using Vector Control.

CHAPTER 3 MATHEMATICAL MODELLING OF DSIM

3.1 General

A Dual-Stator Induction Motor (DSIM) is a different type of induction machine which contains two separate three-phase stator winding systems within a single motor structure. Both the windings are electrically isolated from each other and they share a common squirrel-cage rotor. The two stator windings in most practical designs are placed at a fixed electrical phase displacement from each other, often about 30 electrical degrees. This helps for better power distribution and better machine performance than a conventional induction motor drive. In this model, we are keeping the stator windings at 60 electrical degrees.

The DSIM is represented in a synchronous d-q reference frame for analytical and control purposes, with each stator winding set modelled separately and their electromagnetic interaction shown through the common magnetic circuit. This modelling approach provides a comprehensive description of the machine dynamics and can be used for different winding displacement angles. Therefore, it is a good basis for the study of the steady-state and transient behaviour of dual-stator induction motor drive systems and its modelling is shown further.

3.2 Mathematical Modelling

The mathematical Modelling of DSIM is done in d-q frame for easier control and modelling. The machine model subsystem is based on the current equations discussed in this chapters and Torque and Speed equations are used to create the Torque and Speed subsystem and all the three subsystems are connected in the same manner as represented by equations relating them to each other.

3.2.1 Stator and Rotor Flux Linkages

The flux linkage equations for the DSIM, including the mutual leakage inductance between the two stator winding sets, are given below:

$$\lambda_{qs1} = L_{s1}i_{qs1} + l_{sm}i_{qs1} + l_{sm}i_{qs2} + L_m i_{qs2} + L_m i_{qr} \quad (3.1)$$

$$\lambda_{qs2} = L_{s2}i_{qs2} + l_{sm}i_{qs2} + l_{sm}i_{qs1} + L_m i_{qs1} + L_m i_{qr} \quad (3.2)$$

$$\lambda_{ds1} = L_{s1}i_{ds1} + l_{sm}i_{ds1} + l_{sm}i_{ds2} + L_m i_{ds2} + L_m i_{dr} \quad (3.3)$$

$$\lambda_{ds2} = L_{s1}i_{ds2} + l_{sm}i_{ds2} + l_{sm}i_{ds1} + L_m i_{ds1} + L_m i_{dr} \quad (3.4)$$

$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs} \quad (3.5)$$

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds} \quad (3.6)$$

3.2.2 Stator and Rotor Voltage Equations

Voltage equations for stator and rotor windings are derived using Resistive voltage drops, Induced EMF, Flux derivatives.

The stator Voltage equations for the two winding sets is given below:

$$V_{qs1} = R_s i_{qs1} + \frac{d\lambda_{qs1}}{dt} + \omega_e \lambda_{ds1} \quad (3.7)$$

$$V_{ds1} = R_s i_{ds1} + \frac{d\lambda_{ds1}}{dt} - \omega_e \lambda_{qs1} \quad (3.8)$$

$$V_{qs2} = R_s i_{qs2} + \frac{d\lambda_{qs2}}{dt} + \omega_e \lambda_{ds2} \quad (3.9)$$

$$V_{ds2} = R_s i_{ds2} + \frac{d\lambda_{ds2}}{dt} - \omega_e \lambda_{qs2} \quad (3.10)$$

$$0 = R_r i_{qr} + \frac{d\lambda_{qr}}{dt} + (\omega_e - \omega_r) \lambda_{dr} \quad (3.11)$$

$$0 = R_r i_{dr} + \frac{d\lambda_{dr}}{dt} - (\omega_e - \omega_r) \lambda_{qr} \quad (3.12)$$

3.2.3 Stator Current Equations

The stator current equations are derived by integrating derivatives of stator currents. The equations below are derived by putting values of stator flux linkages and its derivatives in stator Voltage equations mentioned above and by solving that we will get the equations given below:

$$\frac{di_{ds1}}{dt} = (1 / (L_{s1} + L_{sm})) \left[V_{ds1} - R_s i_{ds1} - (L_{sm} + L_m) \left(\frac{di_{ds2}}{dt} \right) - L_m \left(\frac{di_{dr}}{dt} \right) + \omega_e \{ (L_{s1} + L_{sm}) i_{qs1} + (L_{sm} + L_m) i_{qs2} + L_m i_{qr} \} \right] \quad (3.13)$$

$$\frac{di_{qs1}}{dt} = (1 / (L_{s1} + L_{sm})) \left[V_{qs1} - R_s i_{qs1} - (L_{sm} + L_m) \left(\frac{di_{qs2}}{dt} \right) - L_m \left(\frac{di_{qr}}{dt} \right) - \omega_e \{ (L_{s1} + L_{sm}) i_{ds1} + (L_{sm} + L_m) i_{ds2} + L_m i_{dr} \} \right] \quad (3.14)$$

$$\frac{di_{ds2}}{dt} = (1 / (L_{s2} + L_{sm})) \left[V_{ds2} - R_s i_{ds2} - (L_{sm} + L_m) \left(\frac{di_{ds1}}{dt} \right) - L_m \left(\frac{di_{dr}}{dt} \right) + \omega_e \{ (L_{s2} + L_{sm}) i_{qs2} + (L_{sm} + L_m) i_{qs1} + L_m i_{qr} \} \right] \quad (3.15)$$

$$\frac{di_{qs2}}{dt} = (1 / (L_{s2} + L_{sm})) \left[V_{qs2} - R_s i_{qs2} - (L_{sm} + L_m) \left(\frac{di_{qs1}}{dt} \right) - L_m \left(\frac{di_{qr}}{dt} \right) - \omega_e \{ (L_{s2} + L_{sm}) i_{ds2} + (L_{sm} + L_m) i_{ds1} + L_m i_{dr} \} \right] \quad (3.16)$$

3.2.4 Rotor Current Equations

The rotor current equations are derived in the similar manner as the stator current, in this also we will put the value of rotor flux linkages and its derivatives in the rotor voltage equations to get the rotor current derivatives as shown below, by integrating this we will get respective rotor current.

$$\frac{di_{qr}}{dt} = (1 / L_r) \left[V_{qr} - R_r i_{qr} - L_m \left(\frac{di_{qs1}}{dt} \right) - L_m \left(\frac{di_{qs2}}{dt} \right) - (\omega_e - \omega_r) \{ L_r i_{dr} + L_m i_{ds1} + L_m i_{ds2} \} \right] \quad (3.17)$$

$$\frac{di_{dr}}{dt} = (1 / L_r) \left[V_{dr} - R_r i_{dr} - L_m \left(\frac{di_{ds1}}{dt} \right) - L_m \left(\frac{di_{ds2}}{dt} \right) + (\omega_e - \omega_r) \{ L_r i_{qr} + L_m i_{qs1} + L_m i_{qs2} \} \right] \quad (3.18)$$

3.2.5 Electromagnetic Torque Equation

The electromagnetic torque produced by the DSIM is the sum of the torque contributions from both stator winding sets acting on the same rotor. The torque equation in terms of d-q quantities is given below:

$$T_{em} = \frac{3}{2} * \frac{P}{2} * L_m \left[i_{dr} (i_{qs1} + i_{qs2}) - i_{qr} (i_{ds1} + i_{ds2}) \right] \quad (3.19)$$

3.2.6 Mechanical Equation

The mechanical dynamics of the DSIM are given by the same equation as a conventional induction motor, because the two stator sets are acting on the same rotor. The mechanical equation is:

$$J \frac{d\omega_{rm}}{dx} = T_{em} - T_l - B\omega_{rm} \quad (3.20)$$

Where J is the moment of inertia, T_l is the load Torque, B is the friction Coefficient and ω_{rm} is the mechanical rotor speed, related to the electrical rotor speed by

$$\omega_r = \frac{P}{2} \omega_{rm} \quad (3.21)$$

3.3 Parameters and specifications of the machine

For the mathematical Modelling of the DSIM, certain assumptions are made to develop the mathematical model of the DSIM in the d-q reference frame. The assumptions are given below:

- The windings are sinusoidally distributed along the air gap.
- Core losses and Magnetic Saturation are neglected
- The air gap is uniform
- Both the windings have identical parameters.
- The rotor is squirrel-cage type

Table 3.1: Parameters of DSIM

Parameters	Values
$R_{s1} = R_{s2} = R_s (\Omega)$	0.8
$R_r (\Omega)$	0.6
$L_{s1} = L_{s2} (\text{Henry})$	0.085
$L_m (\text{Henry})$	0.082

L_r (Henry)	0.085
l_{sm} (Henry)	0.000178
J (Kg.m ²)	0.033
B (Nms/rad)	0.00825
P (No. of Poles)	4
ω_e (rad/s)	2*pi*50
T_l (Load Torque)	26.5

Table 3.2 Specifications of DSIM

Specification	Value
Nominal Power	4 kW
Voltage (L-L)	440 V
Rated Speed	1500 rpm
Frequency	50 Hz

3.4 Conclusion

The developed mathematical model properly models the dynamic behaviour of the Dual-Stator Induction Motor drive. The electromagnetic coupling between the two-stator winding sets is included in the modelling through mutual leakage inductance. This modelling approach allows a detailed study of the electrical and mechanical characteristics of the machine for different operating conditions. For the practical realization of field-oriented control, the rotational speed of the reference frame is selected to be equal to the synchronous angular speed which allows the effective decoupling of torque and flux components of the machine and simplifies the control strategy. The d-q modelling of the 6 phase induction motor is done in this chapter and as discussed earlier vector control strategies are more suitable to control and evaluate the dynamic behaviour of induction motors and is discussed in the next chapter.

CHAPTER 4 VECTOR CONTROL OF DSIM

4.1 General

This chapter discusses the vector control approach adopted for the Dual-Stator Induction Motor (DSIM) for electric vehicle and applications. The proposed method employs Indirect Field Oriented Control (IFOC) which is a recognized method for high performance operation of induction motor drives.

The basic principle of IFOC is to decouple the torque and flux producing current components which allows independent control of electromagnetic torque and rotor flux of the machine. Because of this the dynamic performance of the control decoupled is improved, the speed regulation is improved and the smooth operation over a wide range of operating conditions is allowed.

For a Dual-Stator Induction Motor, the control system has to deal with additional problems because of the presence of two three-phase stator winding sets. In addition to torque and flux control, the controller must also properly coordinate the two stator windings in order to provide balanced current distribution and stable operation of the machine. Good current sharing between the winding sets avoids uneven loading and results in better drive performance.

The proposed control strategy is developed to assure smooth acceleration and deceleration with minimum torque fluctuations and transient disturbances. Therefore, the DSIM drive can achieve reliable speed tracking and stable operation, suitable for electric vehicle propulsion systems and precise motion control applications.

4.2 Principle of field-Oriented Control for DSIM

Field-Oriented Control (FOC) functions by changing the stator current components from the stationary reference frame to a rotating d-q reference frame which is synchronized with the rotor flux. This transformation makes the induction motor easier to control by separating the responsibilities of flux generation and torque production in the machine.

The d-axis current component in this rotating reference frame is responsible for establishing and maintaining the rotor flux while the q-axis current component produces electromagnetic torque in the machine. This allows the induction motor to be controlled like a separately excited DC motor in which torque and flux can be controlled separately.

This decoupled control structure provides better dynamic performance, accurate speed regulation and faster torque response.

The same control concept is applied in Dual-Stator Induction Motor. However, since the machine has two independent three-phase stator winding sets, the flux-producing and torque-producing current components must be properly shared between them. The two winding sets are coordinated appropriately such that the current distribution is balanced, the torque production is stable and the operation is smooth in steady-state situations as well as in transient conditions.

. The IFOC scheme for DSIM works as follows:

- The rotor flux is aligned with the d-axis, so $\lambda_{qr} = 0$.
- The d-axis currents i_{ds1} and i_{ds2} together control the rotor flux.
- The q-axis currents i_{qs} and i_{qs2} together control the torque.
- The two stator winding sets are independently controlled to keep balanced current sharing. [2]

The slip frequency is calculated as:

$$\omega = \frac{L_m}{L_r} \frac{R_r}{\lambda_{dr}} (i_{qs1} + i_{qs2}) \quad (4.1)$$

where L_m is the magnetizing inductance, L_r is the rotor inductance, R_r is the rotor resistance, and λ_{dr} is the d-axis rotor flux. [2]

The synchronous speed is obtained by adding the rotor speed and slip speed:

$$\omega_e = \omega_r + \omega \quad (4.2)$$

4.2.1 Overall Control Structure

The proposed control structure for acceleration and deceleration of the DSIM consists of a vector control loop with reference speed as the input given to the ACIM reference control which generates the reference d-q currents which are further use to get the angle

theta and ω_e for controlling the induction motor model. V_d and V_q are generated by giving reference current to the feedforward control models.

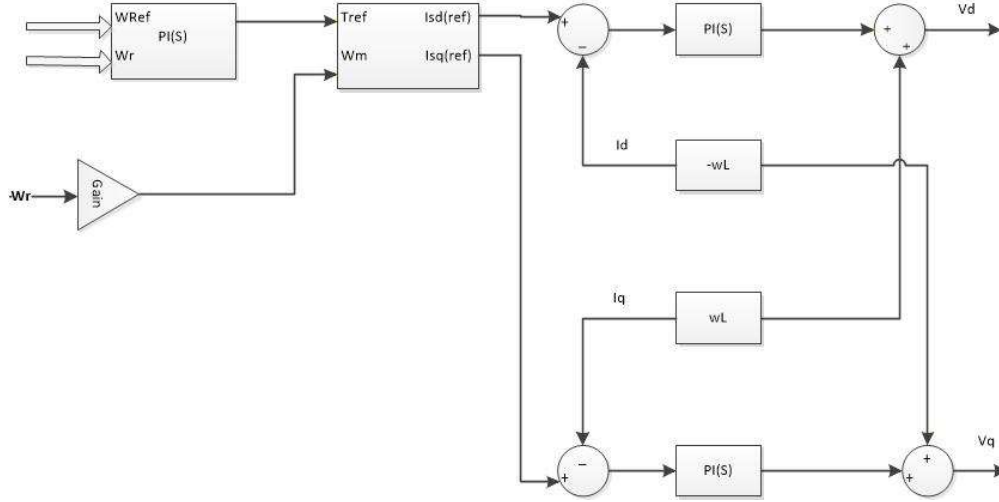


Figure 4.1 Control Strategy for DSIIM

4.2.2 Speed Controller Loop Design

The speed controller compares the reference speed ω_{ref} with the actual rotor speed ω_r and produces the torque reference command. A proportional-integral (PI) controller is used for speed regulation:

$$T_{ref} = K_p (\omega_{ref} - \omega_r) + K_i \int (\omega_{ref} - \omega_r) dt \quad (4.3)$$

Where K_p and K_i are the proportional and integral gains of the speed controller. In the speed controller loop the reference speed has been given by two methods. In the first method a constant speed reference is given to the speed controller and Torque, current and speed responses are analysed and in the second method reference speed is given through a signal editor which gives similar reference speed as an electric drive for different time periods.

4.2.3 Current Controller Loop Design

The inner current control loop controls the d-q currents of both stator winding sets independently using PI controllers.

The inverter equations in d-q transform are as follows:

$$L \frac{di_{ds}}{dt} + Ri_{ds} - \omega_e Li_{qs} = u_{ds} \quad (4.4)$$

$$L \frac{di_{qs}}{dt} + Ri_{qs} + \omega_e Li_{ds} = u_{qs} \quad (4.5)$$

The stator voltage equations with feedforward decoupling compensation are:

$$L \frac{di_{ds}}{dt} + Ri_{ds} = \left[K_p + \frac{K_i}{s} \right] (i_{ds}^* - i_{ds}) \quad (4.6)$$

$$L \frac{di_{qs}}{dt} + Ri_{qs} = \left[K_p + \frac{K_i}{s} \right] (i_{qs}^* - i_{qs}) \quad (4.7)$$

$$u_{ds} = \left[K_p + \frac{K_i}{s} \right] (i_{ds}^* - i_{ds}) - \omega_e Li_{qs} \quad (4.8)$$

$$u_{qs} = \left[K_p + \frac{K_i}{s} \right] (i_{qs}^* - i_{qs}) + \omega_e Li_{ds} \quad (4.9)$$

4.3 Conclusion

In this chapter the control strategy developed for controlling the acceleration and deceleration of the Dual-Stator Induction Motor by using an Indirect Field-Oriented Control (IFOC) technique was explained. The proposed control structure makes use of a hierarchical structure of the speed and current control loops for better regulation of the motor drive system.

The main focus was given to the independent control of the two sets of stator winding which allows proper coordination between them during the operation. The control scheme is developed to produce smooth electromagnetic torque, to keep the current balance between the two stator windings and to give the machine stability at different working conditions.

The proposed strategy decouples the torque and flux control which improves the dynamic response of the drive, and allows accurate tracking of the desired speed commands. Thus, the DSIM can implement reliable accelerating and decelerating features and is very suitable for electric vehicle and motion control applications of the machine.

CHAPTER 5 PERFORMANCE ANALYSIS

5.1 General

This chapter presents the performance analysis of the Dual-Stator Induction Motor (DSIM) drive system with different operating conditions. The aim is to evaluate the effectiveness of the proposed control strategy and study the dynamic behaviour of the motor during different modes of operation.

The analysis includes the motor response to acceleration and deceleration, changes in the speed and its steady-state performance under different load. Special attention is paid to the current sharing between the two-stator winding sets in order to achieve balanced operation and optimum utilization of the machine. Also, the influence of the mutual leakage inductance on the dynamic characteristics and the total control accuracy of the DSIM is considered.

The simulation results give an idea of the speed response, the torque characteristics, the current behaviour and the stability of the drive system and hence show the suitability of the proposed DSIM control scheme for electric vehicle applications.

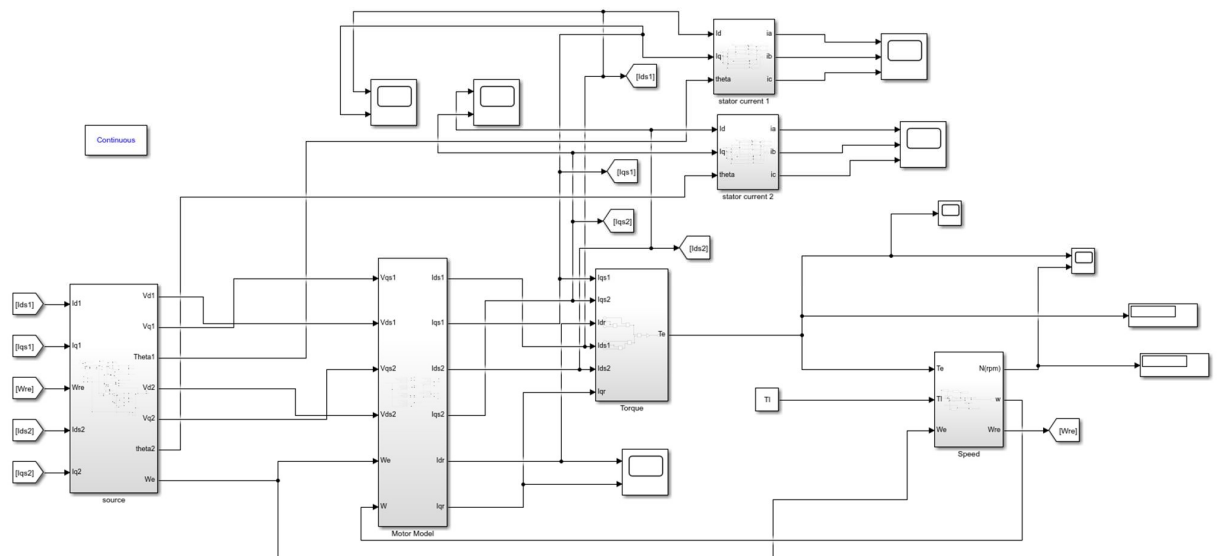


Figure 5.1: MATLAB Model

5.2 Performance Evaluation Under Constant Reference Speed

One of the main advantages of the Dual-Stator Induction Motor (DSIMs) is its better fault tolerance capability than a conventional three phase induction motor. The machine has two independent three-phase stator winding sets so even if a fault occurs in one phase or one winding set the machine can still operate. But, a conventional three-phase induction motor cannot normally start with a phase loss due to an open-circuit condition. The capability to operate under fault conditions increases system reliability and makes the DSIM specifically appealing for electric vehicle propulsion systems which require safety and uninterrupted operation.

For evaluating the dynamic performance of the proposed drive system, the behaviour of the motor is studied for no-load, full-load operating conditions and on varying load conditions. The corresponding speed and electromagnetic torque responses are shown in the next figures. These results provide understanding of the acceleration and deceleration characteristics of the DSIM and demonstrate the effectiveness of the control strategy in maintaining stable and reliable operation under different load conditions. The speed and torque with respect to time for full load and no-load and varying load conditions are given below.

Constant reference Speed with increasing load torque

Input Conditions:

$$\text{Reference Speed (N}_{\text{ref}}) = 150 \text{ rad/s} = 150 \times \frac{30}{\pi} = 1432.39 \text{ rpm}$$

Increasing Load Torques given to the system are:

Table 5.1 Load Torque values

Load Torque (Nm)	Time(sec)
5	0-2
10	2-3
26.5	10

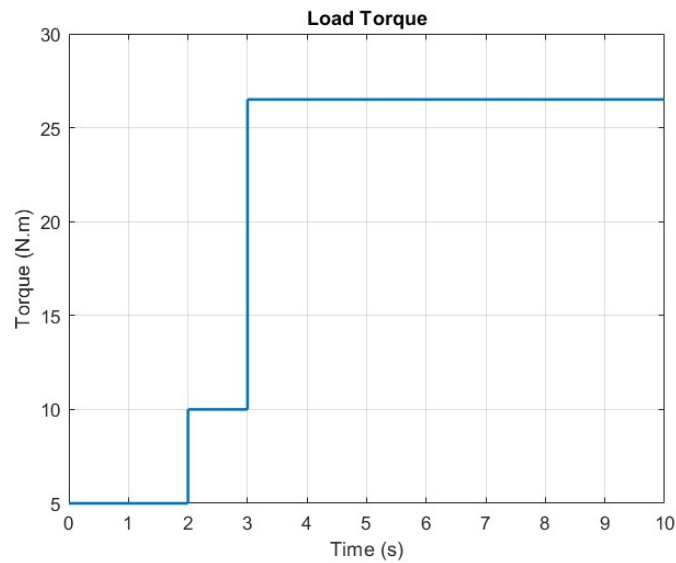


Figure 5.2 Increasing Load Torque

Speed Response Analysis

The motor speed tracks the reference quickly.

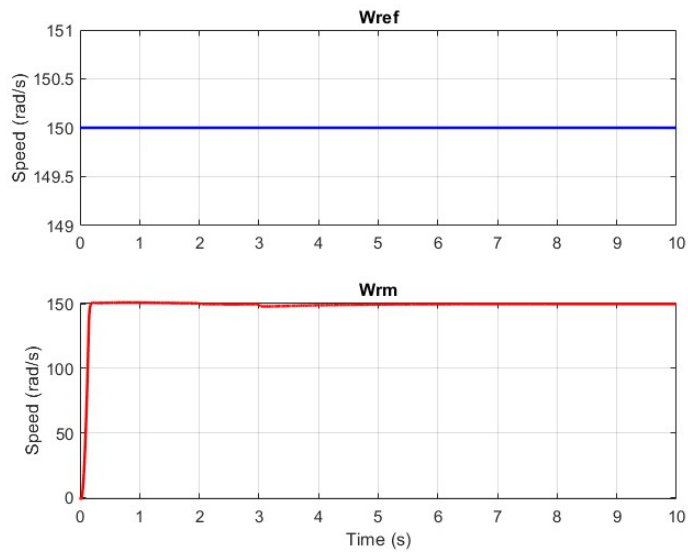


Figure 5.3 Reference Speed and Motor speed

1) Steady state speed:

$$N=1432 \text{ rpm}$$

Steady state error

$$e= N_{\text{ref}} - N= 1432.39-1432= 0.39 \text{ rpm}$$

$$\text{percentage error} = \frac{0.39}{1432.39} \times 100 = 0.027\%$$

Steady-state error is almost zero. This proves better speed regulation.

2) Rise Time Calculation:

Speed at 10% = $0.1 * N_{ref} = 143.239$ rpm

Speed at 90% = $0.9 * N_{ref} = 1289.15$ rpm

The time for speed at 10% = 0.0612 sec

The time for speed at 90% = 0.1492 sec

So, the rise time $t_r = t_{90} - t_{10} = 0.1492 - 0.0612 = 0.0880$ sec

The calculated rise time shows that proposed vector controlled DSIM drive have a fast dynamic response and it is capable of reaching the desired operating speed rapidly.

3) Peak Time:

Peak time is the time at which the response reaches to its maximum value for the first time.

$$t_p = t(N_{peak})$$

From the simulation $N_{peak} = 1443.1$ and it occurs at $t_p = 0.7947$ sec.

4) Maximum Overshoot:

$N_{ref} = 1432.39$ rpm

$N_{peak} = 1443.1$ rpm

Overshoot is given by

$$\frac{N_{peak} - N_{ref}}{N_{ref}} \times 100 = 0.748\%$$

The calculated overshoot is less than 1% which shows that the speed controller is properly tuned and the proposed model shows good damping characteristics with minimum oscillations.

5) Startup Settling Time:

The time required for the response to enter a specified tolerance band around its final value and remain in the band after that is called settling time.

$N_{ref} = 1432.39$ rpm

For a $\pm 2\%$ band:

Upper limit = $1.02 * N_{ref} = 1461.04$ rpm

Lower limit = $0.98 * N_{ref} = 1403.74$ rpm

The response is considered settled when:

$$1461.04 \leq N \leq 1403.74$$

The motor settling time during start up is 0.1672 seconds.

6) Steady-state Error analysis at Maximum Load:

$$N_{\text{ref}} = 1432.39 \text{ rpm}$$

$$T_l = 26.5 \text{ Nm}$$

$$\text{Measured Speed} = 1432.365 \text{ rpm}$$

$$\text{Steady State error} = 1432.39 - 1432.365 = 0.0248 \text{ rpm}$$

Taking the magnitude the error % can be calculated as:

$$\frac{0.0248}{1432.39} \times 100 = 0.0017\%$$

7) Disturbance Rejection Analysis:

In practical electric-drive applications load torque is rarely constant. Variations in mechanical load creates disturbances that reduces the rotor speed. The ability of a controller to maintain the desired speed in spite of such disturbances is called as disturbance rejection capability.

A good vector-control strategy should quickly compensate for load variations by increasing the torque and restoring the motor speed to its desired value. Thus, disturbance rejection performance is evaluated by evaluating the speed response immediately after each load-torque change.

The load is changed at 2 second and 3 second.

The first load change occurs from 5 Nm to 10 Nm at $t = 2 \text{ sec}$

$$\text{The disturbance in Torque} = 10 - 5 = 5 \text{ Nm}$$

The load increase at $t = 2 \text{ sec}$, the minimum speed reached after the disturbance = 1430.31

The minimum speed occurs at $t = 2.5282 \text{ sec}$

Disturbance rejection at $t = 2 \text{ sec}$:

At $t = 2 \text{ second}$ load changes from 5 to 10 Nm

The minimum speed dip= 1430.31 rpm

Speed dip= 1432.39- 1430.31= 2.08 rpm

$$\text{Percentage dip} = \frac{2.08}{1432.39} \times 100 = 0.145\%$$

Since the dip remains within the band $\pm 2\%$ the disturbance does not violate the criterion.

So, the drive maintains acceptable regulation during the 5 to 10 Nm transition.

Disturbance Rejection at $t = 3$ sec

At $t = 3$ second load changes from 10 to 26.5 Nm. The load increases by 16.5 Nm

The minimum speed dip = 1414.6 rpm at $t_{\min} = 3.0842$ sec

Speed dip= 1432.39-1414.6= 17.79 rpm

$$\text{Percentage dip} = \frac{17.79}{1432.39} \times 100 = 1.24\%$$

The disturbance response time

$$t_{\text{dip}} = 3.0842 - 3 = 0.0842 \text{ sec}$$

The controller successfully limits the speed deviation and stops excessive decline in speed performance even under severe loading conditions. Even under the full-load torque application, the speed remains inside the tolerance band. This shows strong disturbance rejection capability.

8) Speed Regulation Analysis

Speed regulation is an important performance indicator of electric drive system because it measures the ability of the motor to maintain the desired operating speed at varying load torque values.

Speed regulation analysis is performed to assess the effectiveness of the proposed vector control system in keeping speed stability under varying load conditions. conventional speed regulation calculations use No-load speed and Full-load speed. But, in the simulation the lowest available load torque is 5 Nm. So the speed corresponding to 5 Nm is taken as the minimum-load operating speed and not the real no-load speed.

Average Speed during the interval corresponding to the 5 Nm load condition =1438.42 rpm. At a load torque of 5 Nm the motor operates a little above the reference speed. The observed speed shows that the controller maintains the motor speed close to the desired operating value.

the average speed during the 10 Nm load interval = 1430.42 rpm

The increase in load torque creates a small reduction in speed. But the speed remains very close to the reference value which shows effective compensation by the vector control system.

The average speed during the full-load operating area = 1432.37

Even at the highest load condition taken the motor speed remains almost same to the reference speed. This shows the effectiveness of the controller in keeping speed stability at heavy load conditions. Speed regulation is defined as the percentage change in speed from the minimum load and maximum load operating conditions.

$$N_{\min \text{ load}} = 1438.42 \text{ rpm}$$

$$N_{\text{full load}} = 1432.37$$

$$\text{Speed Regulation} = \frac{N_{\min \text{ load}} - N_{\text{full load}}}{N_{\text{full load}}} \times 100 = 0.42\%$$

The measured speed regulation is less than 5% even with the increase in load torque from 5 Nm to 26.5 Nm. This shows that the motor speed changes only a little over the entire load range. The speed remains near to the reference value through the operating range. The largest deviation from the reference speed happens at the 5 Nm operating condition while the full load operating speed is almost same to the reference speed. This behaviour shows that the proposed vector control system is effectively compensating for the changes in load torque.

The speed regulation analysis shows that the proposed vector controlled DSIM keeps stable operation under changing load conditions. The speed values are averages taken over selected ranges. Since the load intervals are short (specifically the 10 Nm region).

9) Speed Ripple

In addition to preserving the average speed close to the reference value a high-performance drive system should also reduce speed instabilities during steady state operation.

Even after the transient response becomes stable small fluctuations may exist around the average speed because of controller dynamics, electromagnetic torque changes and machine nonlinearities. These oscillations are referred as speed ripple. A smaller speed ripple shows smoother motor operation and better speed stability.

The speed ripple is measured separately for each load condition.

Speed ripple is defined as the ratio of the peak to peak speed variation to the average operating speed of the given load range.

The percentage speed ripple is calculated using

$$\text{Speed Ripple} = \frac{N_{max} - N_{min}}{N_{avg}} \times 100$$

where N_{max} is the maximum speed within the selected operating interval, N_{min} is the minimum speed within the selected operating interval and N_{avg} is the average speed within the same interval.

Speed ripple at 5 Nm is

$$\frac{1439.6 - 1437.4}{1438.4} \times 100 = 0.153\%$$

Speed ripple at 10 Nm is

$$\frac{1430.6 - 1430.3}{1430.4} \times 100 = 0.0209\%$$

Speed ripple at 26.5 Nm is

$$\frac{1432.42 - 1432.405}{1432.4} \times 100 = 0.001\%$$

The results show a progressive reduction in speed ripple as the load torque increases. which shows excellent steady state speed stability, low speed ripple is desirable because it improves speed smoothness, reduces mechanical vibration, enhances drive stability, improves the quality of speed regulation. The extremely small ripple values measured in

this study shows that the proposed vector control system maintains a nearly constant speed under varying load conditions. The ripple values measured in this section are based on the averaging ranges selected during MATLAB analysis. The speed ripple analysis shows that the proposed vector controlled DSIM shows highly stable steady state operation.

Electromagnetic Torque Analysis

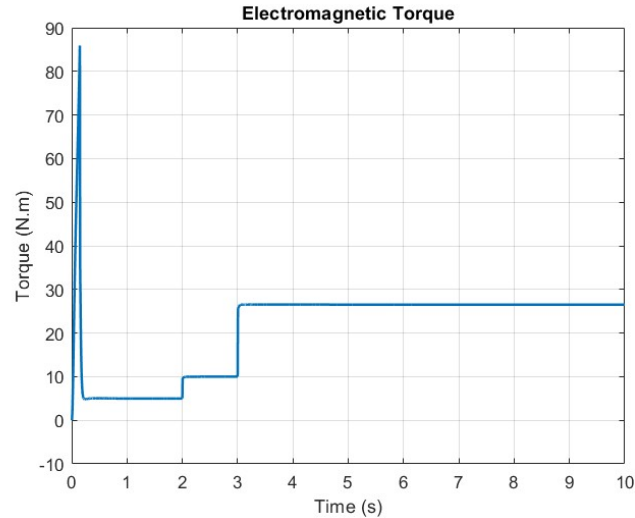


Figure 5.3 Electromagnetic Torque for Constant Reference Speed

Electromagnetic torque is the main parameter responsible for converting electrical energy into mechanical energy in an induction motor. In a vector-controlled drive torque regulation is mainly important because the controller should regularly adjust the electromagnetic torque to fulfil changing load requirements while keeping the desired speed.

The torque response provides valuable information regarding Acceleration capability, Load carrying capability, Disturbance rejection performance, Torque tracking accuracy, Dynamic performance of the controller of the system.

That's why the electromagnetic torque response of the proposed DSIM is evaluated in terms of rated torque, peak torque, overload capability, torque tracking performance, and torque ripple.

1) Rated Torque Calculation

The rated torque denotes the torque corresponding to the rated operating condition of the machine. It is taken as the reference value against which the peak torque capability of the controller is measured. The rated Power is 4kW

The rated motor speed is

$$N_{rated}=1450 \text{ rpm}$$

The corresponding mechanical angular speed is

$$\omega_{rated} = \frac{2\pi N_{rated}}{60} = 151.84 \text{ rad/s}$$

$$\text{Rated Torque } T_{rated} = \frac{P_{rated}}{\omega_{rated}} = 26.5 \text{ Nm}$$

The rated torque of 26.5 Nm signifies the continuous torque capability of the machine at rated operating conditions. This value gives a useful standard for evaluating the transient torque capability of the proposed controller.

2) Peak Torque

From the MATLAB simulation results, the maximum electromagnetic torque is

$$T_{peak} = 85.923 \text{ Nm}$$

We get the peak torque at $t = 0.1477 \text{ sec}$

3) Torque Overload Factor

The torque overload factor shows the number of times the motor torque exceeds its rated value during transient operation.

The torque overload factor is

$$\frac{T_{peak}}{T_{rated}} = 3.24$$

The motor develops approximately 3.24 times its rated torque at startup. This shows strong transient torque capability and describes the short rise time obtained during startup analysis.

4) Torque Tracking Capability

Torque tracking estimates how accurately the electromagnetic torque follows the load torque which is applied during steady state operation.

The measured electromagnetic torque is 4.9762 Nm for the 5 Nm operating condition.

The applied load torque is 5 Nm

The torque tracking error = $5 - 4.9762 = 0.0238$ Nm

The electromagnetic torque almost matches the load torque. This shows accurate torque control at low load operation.

The measured electromagnetic torque for the 10 Nm operating condition is 10.0032 Nm

The torque tracking error = $10 - 10.0032 = -0.0032$ Nm

The torque error is almost zero. The controller accurately produces the torque required by the load.

the measured electromagnetic torque for the 26.5 Nm operating condition is 26.5001 Nm

The torque tracking error = $26.5 - 26.5001 = -0.0001$ Nm

The torques generated by the controller is almost identical to the applied load torque.

This shows excellent torque regulation during full-load operation.

5) Torque Ripple Analysis

The variation of electromagnetic torque around its average value during steady state operation is torque ripple

Unnecessary torque ripple may produce, mechanical vibration, acoustic noise, reduced drive smoothness.

From the full-load operating region,

$$\text{Torque Ripple} = \frac{T_{\max} - T_{\min}}{T_{\text{avg}}} \times 100$$

$$\text{Torque Ripple} = 0.00024\%$$

The torque ripple is very small and it can be considered insignificant for practical purposes.

The result shows smooth torque production and stable vector control operation. The torque analysis establishes that the proposed vector controlled DSIM possesses excellent torque generation capability.

Stator Current Analysis

One of the most common issues in Dual-Stator Induction Motor drive system is unbalanced current distribution among two sets of stator windings of the machine. This phenomenon is mainly caused by practical differences in machine and drive parameters such as variations in stator resistance, leakage inductance, manufacturing tolerances and inverter voltage characteristics etc. When using voltage-controlled methods, these parameter mismatches can lead to one winding set to carry more current than the other, which causes uneven heating, increased losses, and reduced overall drive efficiency.

The control strategy used in this study is an effective solution for this problem by Indirect Field Oriented Control (IFOC). Each stator winding set is given its own current regulation loop that enable independent control of the d-axis and q-axis current components. As a result, the measured currents are continuously forced to follow their respective reference values which reduces the effect of parameter variations and system asymmetries.

The simulation results indicate that the two-stator winding sets equally share the electric load in the entire operation range. The good agreement between the responses of the two winding sets in the current confirms the success of the proposed control strategy in avoiding current imbalance and therefore enhancing system reliability, thermal performance and overall operational characteristics of the electric drive.

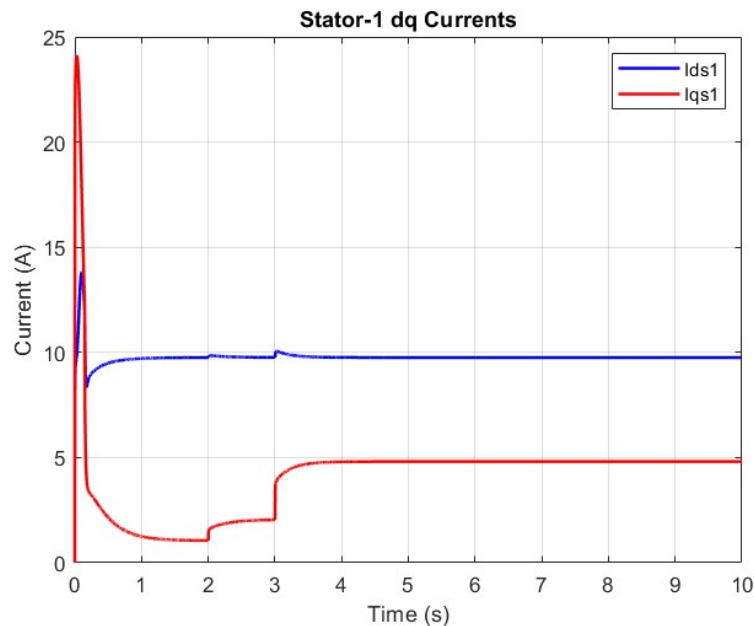


Figure 4.5 d-q current of stator 1

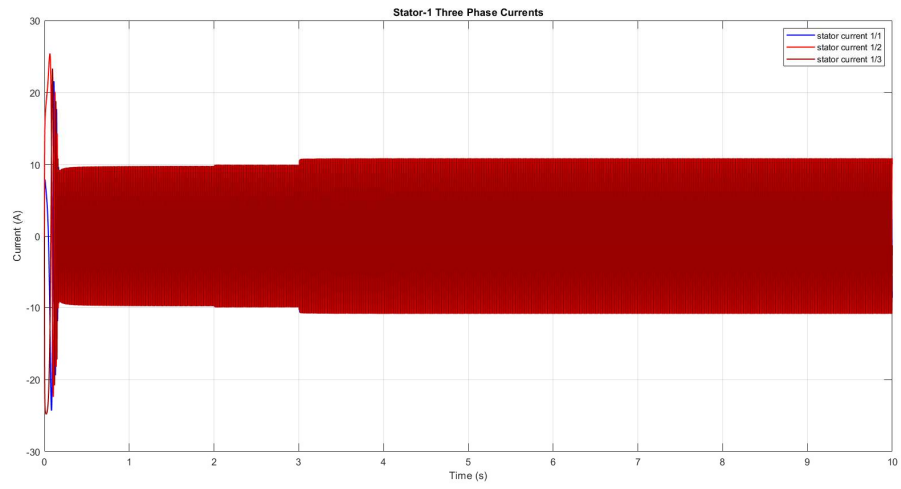


Figure 5.5 Three Phase Stator Current of Stator 1

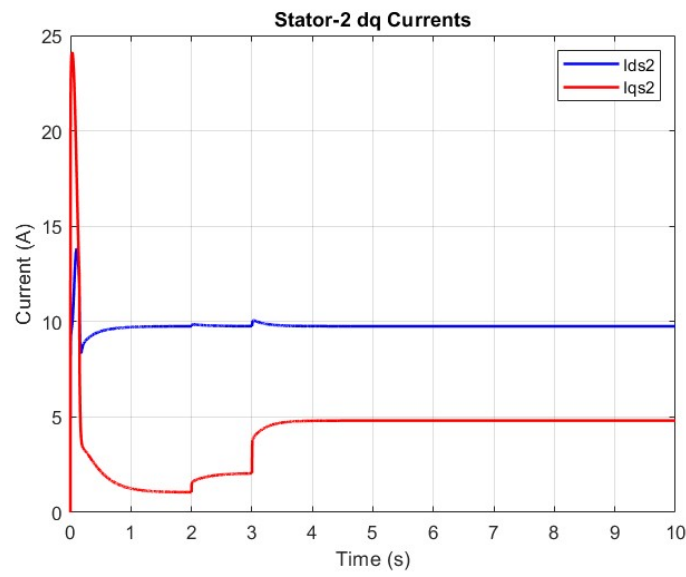


Figure 5.6 d-q current of Stator 2

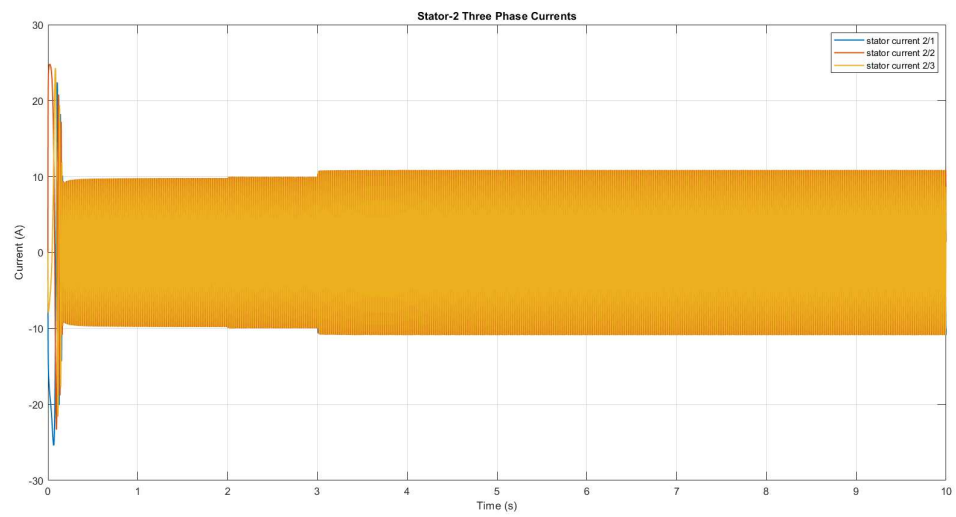


Figure 5.7 Stator 2 three phase Current

From the MATLAB results,

the average d-axis current of Stator-1 is 9.7561 A

the average d-axis current of Stator-2 is 9.7561 A

the average q-axis current of Stator-1 is 4.8079 A

the average q-axis current of Stator-2 is 4.8079 A

the peak d-axis current of Stator-1 is 13.8429 A

the peak d-axis current of Stator-2 is 13.8429 A

the peak q-axis current of Stator-1 is 24.1265A

the peak q-axis current of Stator-2 is 24.1265 A

5.3 Performance Evaluation Under Trapezoidal Reference Speed with increasing load torque

The performance of the proposed vector-controlled Dual Stator Induction Motor (DSIM) drive was evaluated under a trapezoidal reference speed profile with increasing load torque conditions. The objective of this test is to investigate the ability of the controller to provide smooth acceleration, accurate speed tracking, stable cruising operation, controlled deceleration, and effective disturbance rejection during propulsion operation.

Unlike constant-speed operation, the trapezoidal speed profile simultaneously evaluates both steady-state and transient performance. Consequently, this test provides a more realistic assessment of propulsion-drive behaviour.

Input Conditions:

$$\text{Reference Speed (N}_{\text{ref}}) = 150 \text{ rad/s} = 150 \times \frac{30}{\pi} = 1432.39 \text{ rpm}$$

Trapezoidal Reference Speed Response Analysis

The motor speed tracks the reference quickly.

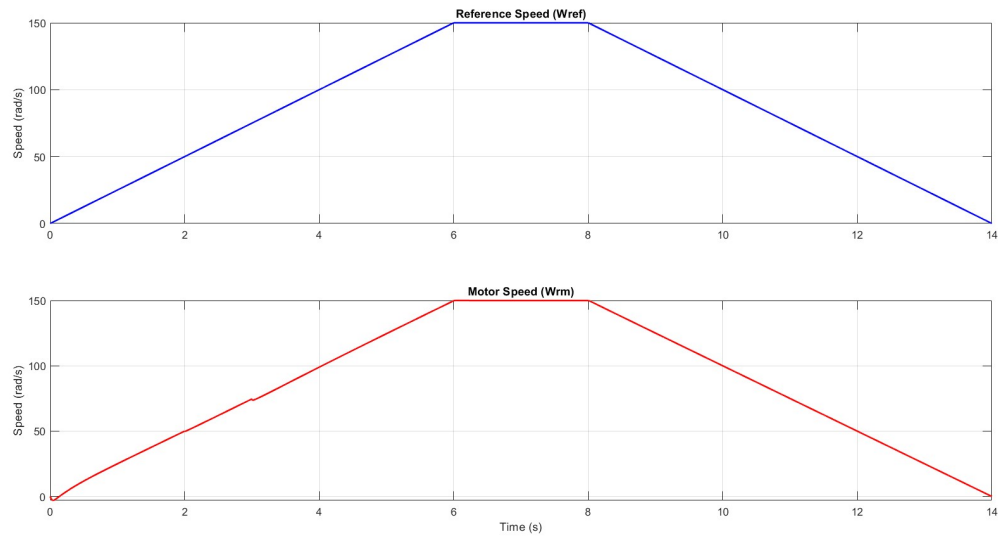


Figure 5.8 Reference Speed and Motor Speed

The trapezoidal speed profile consists of three operating regions.

The acceleration region $0.000003 \leq t \leq 5.9996 \text{ sec}$

The constant region $5.9961 \leq t \leq 8.0041 \text{ sec}$

The deceleration region $7.9996 \leq t \leq 13.9996 \text{ sec}$

During this interval, the controller reduces the motor speed according to the prescribed trapezoidal trajectory.

Acceleration Performance Analysis

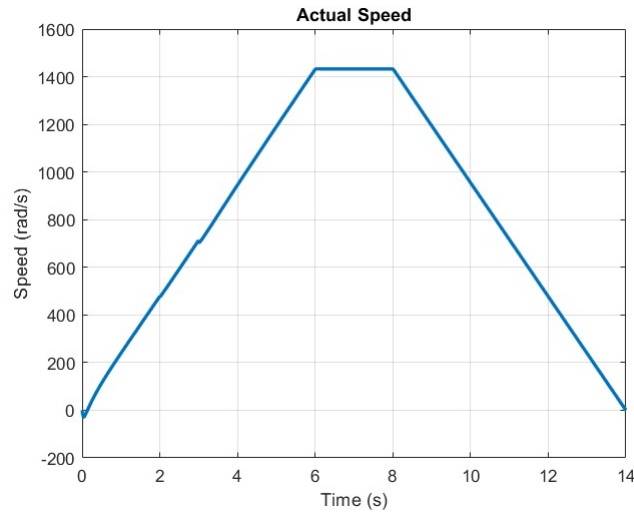


Figure 5.9 Speed graph

The acceleration region evaluates the capability of the DSIM to follow the increasing reference speed while compensating for increasing load torque.

The acceleration region $0.3942 \leq t \leq 3.6052 \text{ sec}$

the acceleration duration = 5.9996 sec, during this interval the reference speed increases from zero to its maximum value of 150 rad/s i.e. 1432.39 rpm

$$a_{avg} = \frac{N_f - N_i}{t_f - t_i} = 238.75 \text{ rpm/s}$$

This value represents the average rate at which the motor speed increases during the acceleration interval.

Load Disturbance Analysis During Acceleration

Two load disturbances were applied during the acceleration interval.

The load is changed at 2 second and 3 second.

The first load change occurs from 5 Nm to 10 Nm at $t = 2$ sec

The disturbance in Torque = $10 - 5 = 5$ Nm

At $t = 3$ second load changes from 10 to 26.5 Nm. The load increases by 16.5 Nm

The motor continued accelerating successfully after both load disturbances, indicating that the controller maintained sufficient torque reserve to satisfy the increased load demand.

Deacceleration Performance analysis

$$a_{dec} = \frac{N_f - N_i}{t_f - t_i} = -238.75 \text{ rpm/s}$$

Torque Analysis

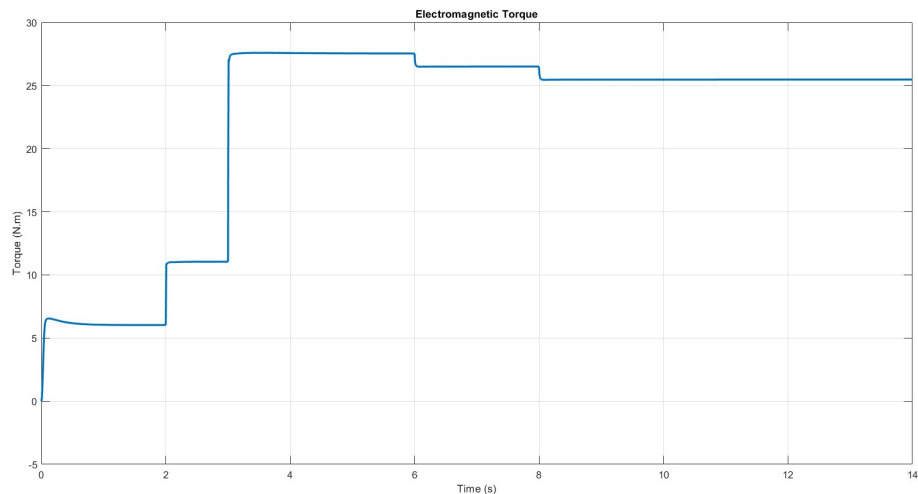


Figure 5.10 Electromagnetic Torque

The Peak Torque is 27.5883 Nm

$$\text{Torque Ripple} = \frac{T_{\max} - T_{\min}}{T_{\text{avg}}} \times 100 = 5.9542 \%$$

Stator Current Analysis

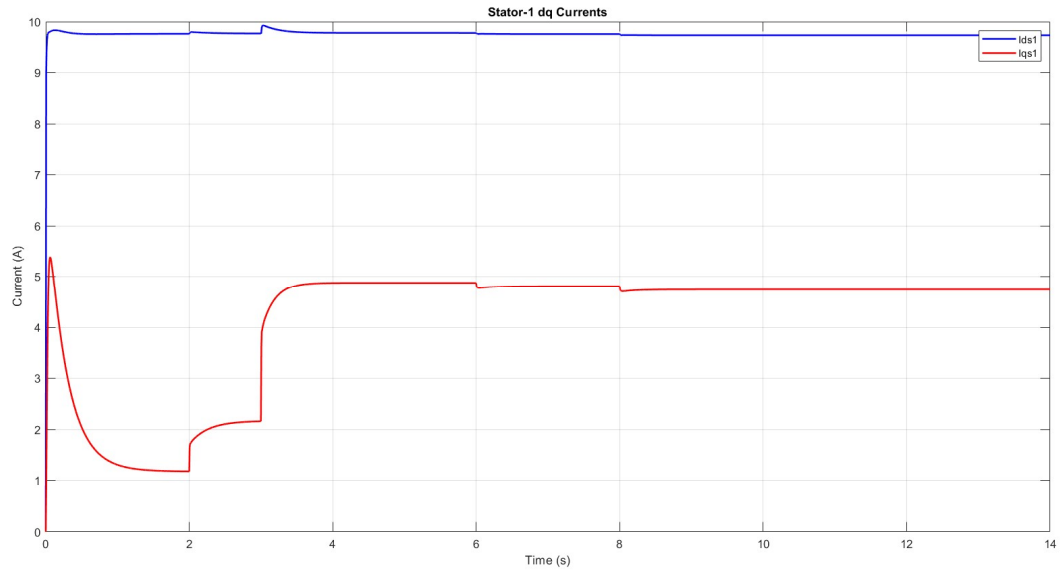


Figure 5.11 d-q axis current of stator 1

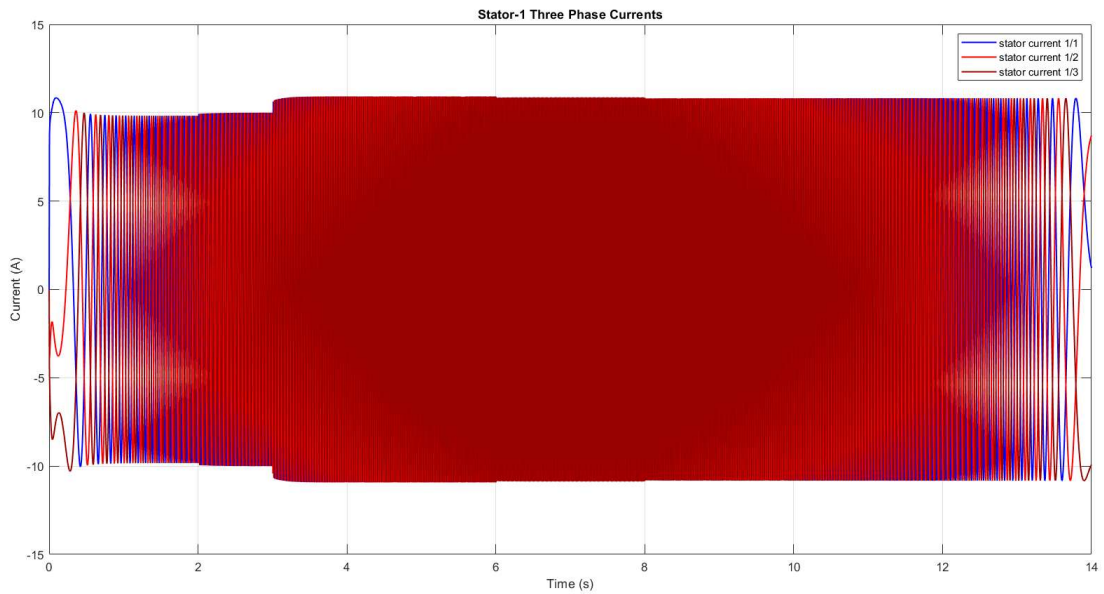


Figure 5.12 Stator 2 three Phase Current

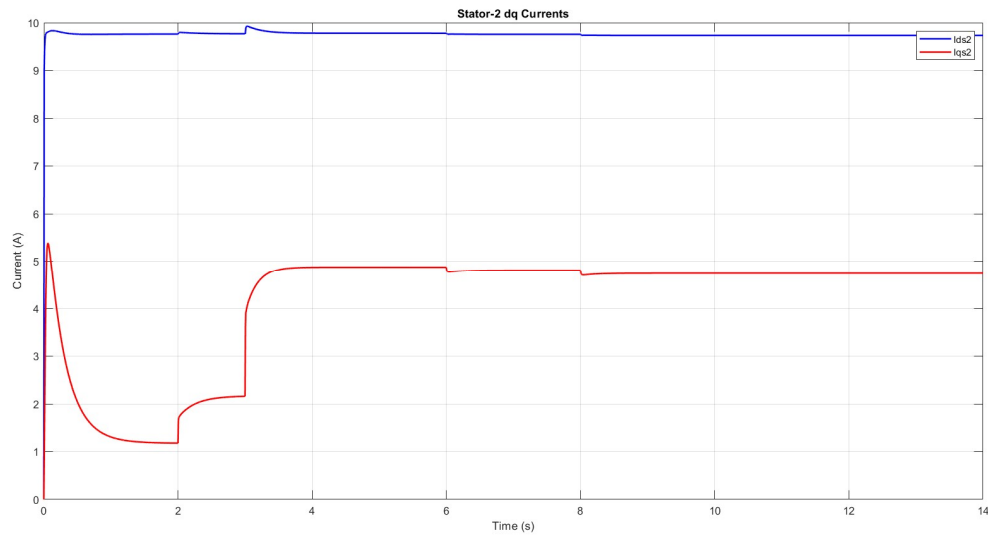


Figure 5.13 d-q axis current of Stator 2

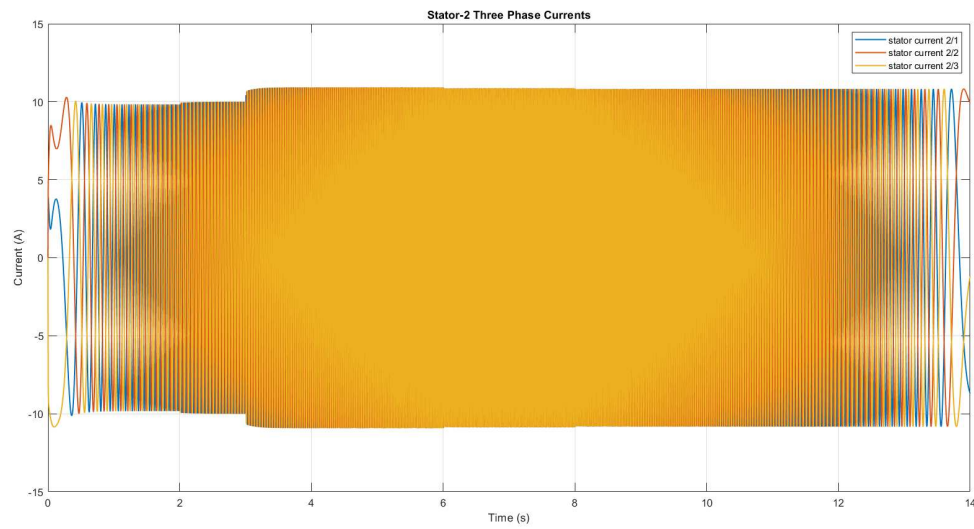


Figure 5.14 stator 2 three phase Current

From the MATLAB results,

the average d-axis current of Stator-1 is 9.7522 A

the average d-axis current of Stator-2 is 9.7522 A

the average q-axis current of Stator-1 is 4.0437 A

the average q-axis current of Stator-2 is 4.0437 A

the peak d-axis current of Stator-1 is 10.0418 A.

the peak d-axis current of Stator-2 is 10.0418 A.

the peak q-axis current of Stator-1 is 4.8264 A.

the peak q-axis current of Stator-2 is 4.8264 A.

The nearly identical values indicate balanced transient torque production by both stators.

5.4 Performance Evaluation Under S-curve Reference Speed with increasing load torque

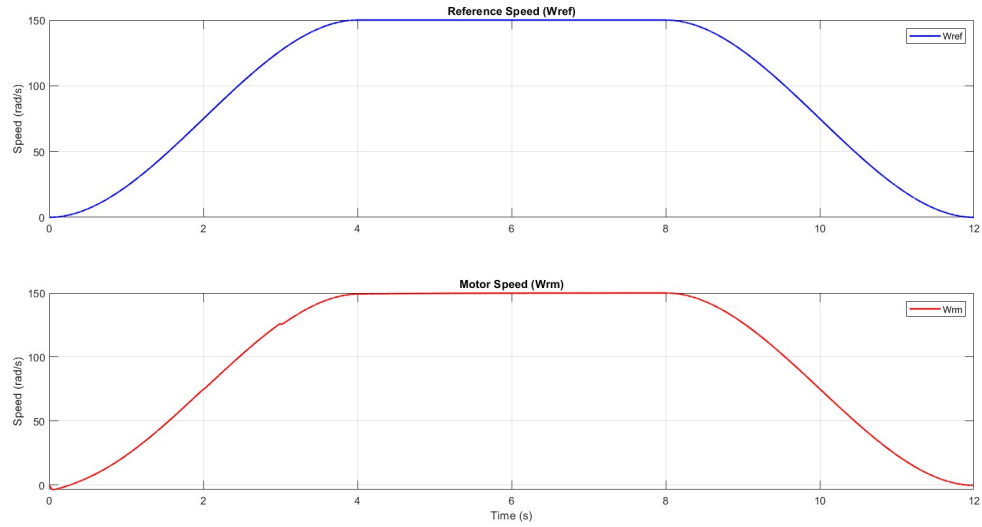


Figure 5.15 Reference speed and motor speed comparison

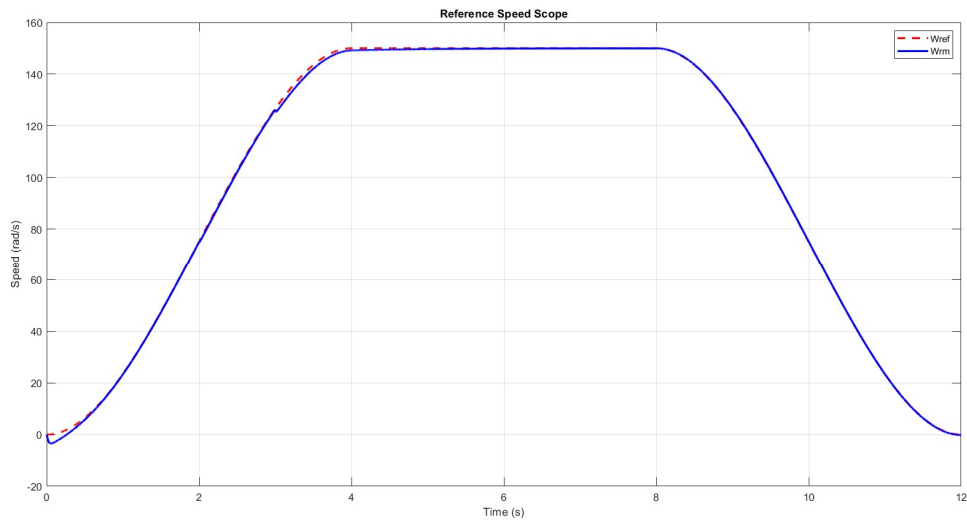


Figure 5.16 Speed graph

Speed Ripple Analysis

The speed ripple is measured separately for each load condition.

Speed ripple is defined as the ratio of the peak to peak speed variation to the average operating speed of the given load range.

$$N_{\max}=1432.2 \text{ rpm } N_{\min}=1424.6 \text{ rpm } N_{\text{avg}}=1430.4 \text{ rpm}$$

The percentage speed ripple is calculated using

$$\text{Speed Ripple} = \frac{N_{\max} - N_{\min}}{N_{\text{avg}}} \times 100 = 0.536\%$$

The ripple remains below 1%, indicating stable speed regulation.

Average Acceleration Analysis

The average acceleration during the S-shaped acceleration interval is calculated using

From the simulation N_f is 1432.3 rpm and N_i is -25.65 rpm and duration of acceleration is 4 sec

$$a_{\text{avg}} = \frac{N_f - N_i}{t_f - t_i} = 364.46 \text{ rpm/s}$$

The acceleration profile is smooth due to the S-curve trajectory, resulting in reduced mechanical stress and smoother propulsion dynamics compared with a conventional trapezoidal profile.

Average Deceleration Analysis

The average deceleration is calculated using

$$a_{\text{dec}} = \frac{N_f - N_i}{t_f - t_i} = -358.49 \text{ rpm/s}$$

Steady State Error Analysis

The steady-state error is calculated using

$$e = N_{\text{ref}} - N_{\text{avg}} = 1432.4 - 1430.4 = 2 \text{ rpm}$$

$$\text{percentage error} = \frac{2}{1432.4} \times 100 = 0.13\%$$

The very small percentage error demonstrates excellent speed regulation.

Torque Ripple Analysis

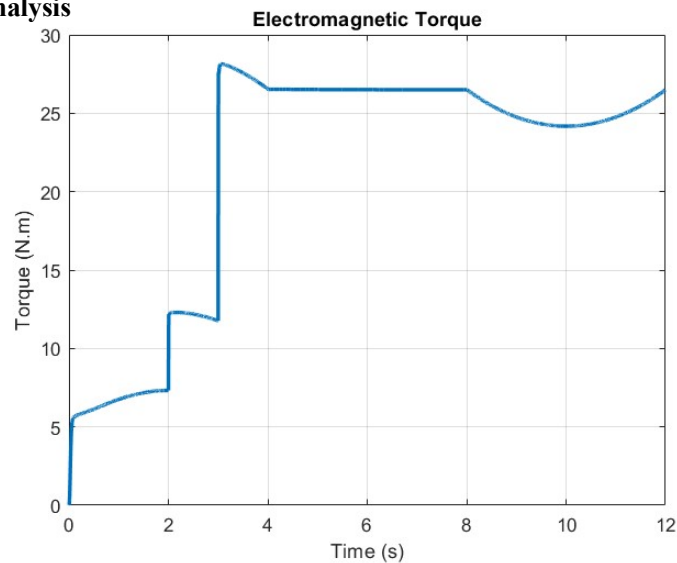


Figure 5.17 Electromagnetic Torque graph

$$T_{\max}=26.5459 \text{ Nm } T_{\min}=26.5006 \text{ Nm } T_{\text{avg}}=26.5083 \text{ Nm}$$

$$\text{Torque Ripple} = \frac{T_{\max} - T_{\min}}{T_{\text{avg}}} \times 100 = 0.1706 \%$$

The extremely low torque ripple demonstrates smooth electromagnetic torque production.

Stator Current Analysis

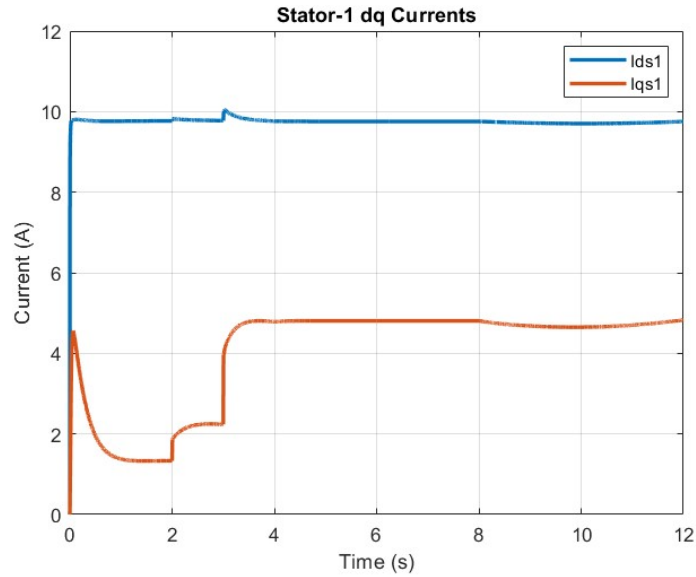


Figure 5.18 d-q axis stator 1 current

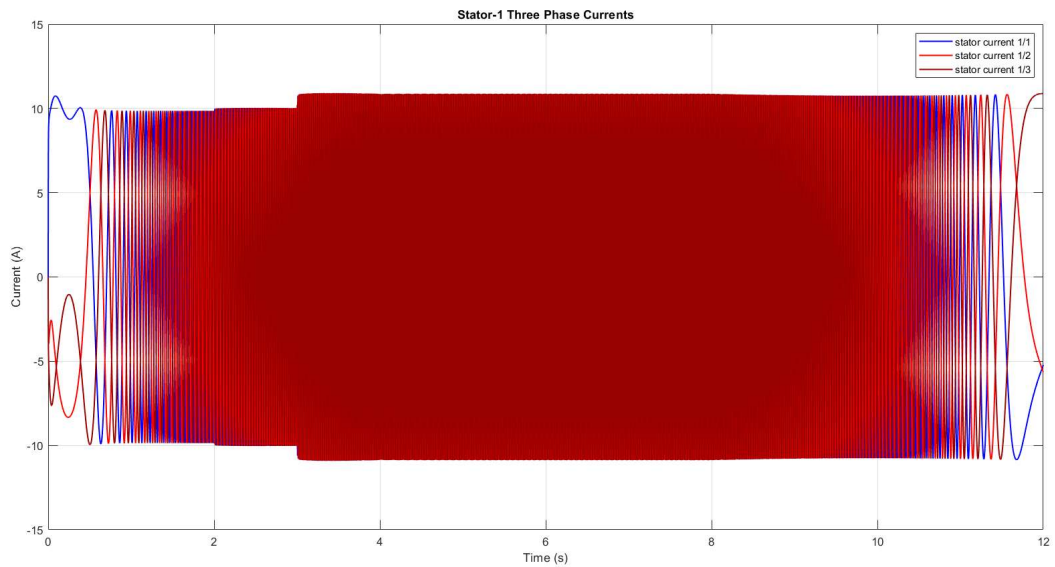


Figure 5.19 Stator 1 three phase Current

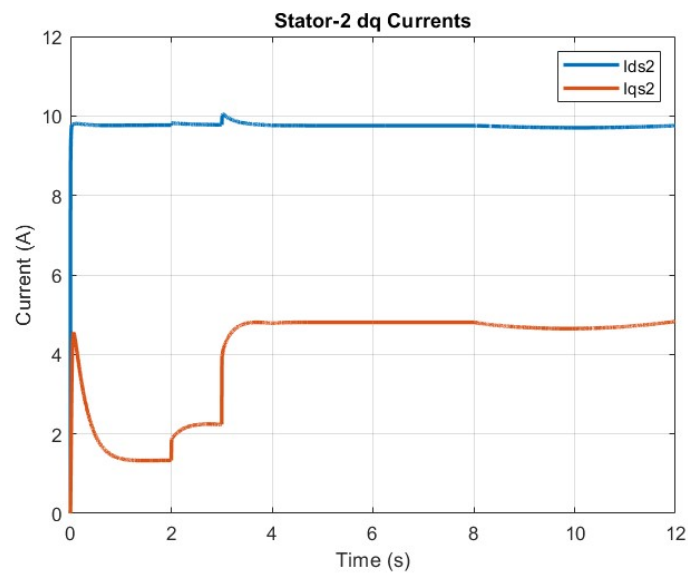


Figure 5.20 d-q axis stator 2 current

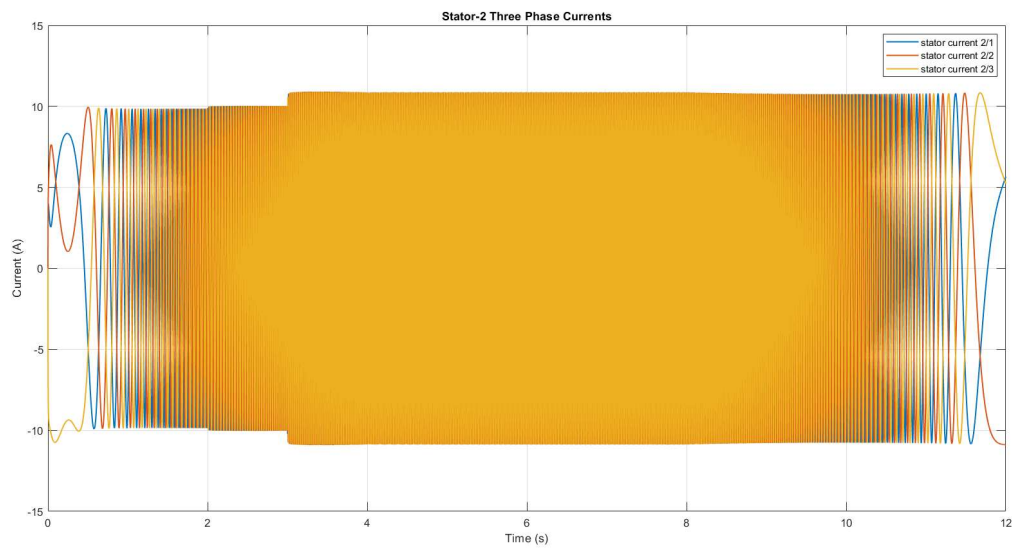


Figure 5.21 stator 2 three phase Current

From the MATLAB results,

the average d-axis current of Stator-1 is 9.7522 A

the average d-axis current of Stator-2 is 9.7522 A

the average q-axis current of Stator-1 is 4.0437 A

the average q-axis current of Stator-2 is 4.0437 A

the peak d-axis current of Stator-1 is 10.0418 A.

the peak d-axis current of Stator-2 is 10.0418 A.

the peak q-axis current of Stator-1 is 4.8264 A.

the peak q-axis current of Stator-2 is 4.8264 A.

5.5 Performance Evaluation Under Step Input Reference Speed with increasing load torque

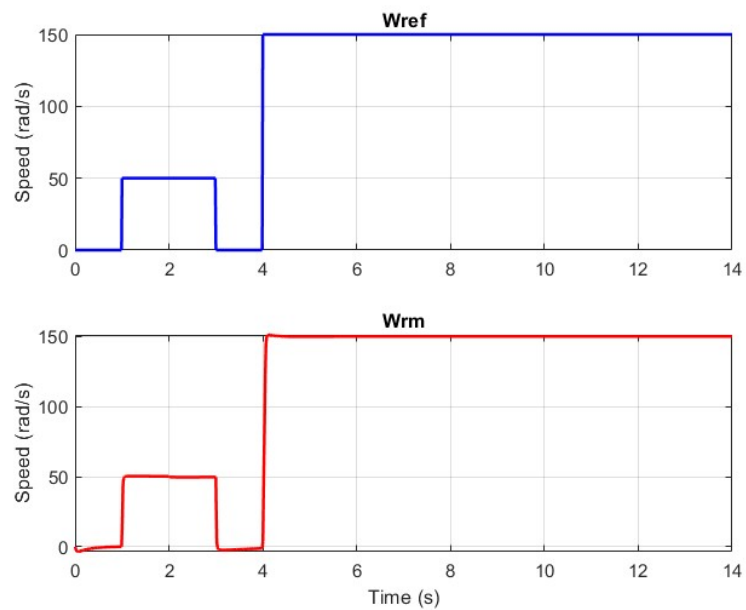


Figure 5.22 Comparison of Reference Speed and Motor Speed

Speed Analysis

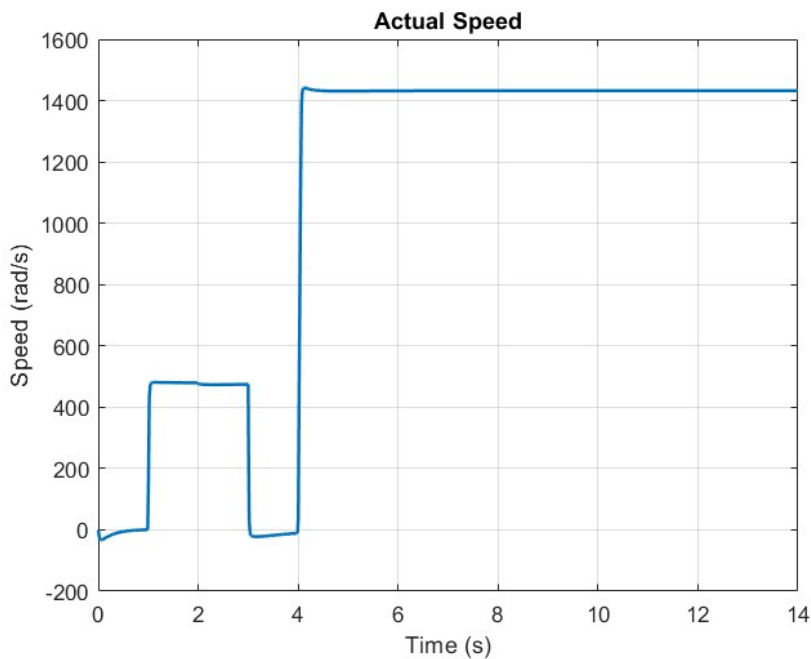


Figure 5.23 Speed Graph

1) Steady state speed:

$$N=1432.39 \text{ rpm}$$

Steady state error

$$e= N_{\text{ref}} - N= 1432.39-1432.39= 0\text{rpm}$$

$$\text{percentage error} = 0\%$$

Steady-state error is almost zero. This proves better speed regulation.

2) Rise Time Calculation:

$$\text{Speed at } 10\% = 0.1 * N_{\text{ref}} = 143.239 \text{ rpm}$$

$$\text{Speed at } 90\% = 0.9 * N_{\text{ref}} = 1289.15 \text{ rpm}$$

$$\text{The time for speed at } 10\% = 4.0059 \text{ sec}$$

$$\text{The time for speed at } 90\% = 4.0579 \text{ sec}$$

$$\text{So, the rise time } t_r = t_{90} - t_{10} = 4.0579 - 4.0059 = 0.052 \text{ sec}$$

The calculated rise time shows that proposed vector controlled DSIM drive have a fast dynamic response and it is capable of reaching the desired operating speed rapidly.

3) Peak Time:

Peak time is the time at which the response reaches to its maximum value for the first time.

$$t_p = t(N_{\text{peak}})$$

From the simulation $N_{\text{peak}}=1442.5$ and it occurs at $t_p= 4.1154 \text{ sec}$.

4) Maximum Overshoot:

$$N_{\text{ref}}=1432.39 \text{ rpm}$$

$$N_{\text{peak}}=1442.5 \text{ rpm}$$

Overshoot is given by

$$\frac{N_{\text{peak}} - N_{\text{ref}}}{N_{\text{ref}}} \times 100 = 0.705 \%$$

The calculated overshoot is less than 1% which shows that the speed controller is properly tuned and the proposed model shows good damping characteristics with minimum oscillations.

Torque Ripple Analysis

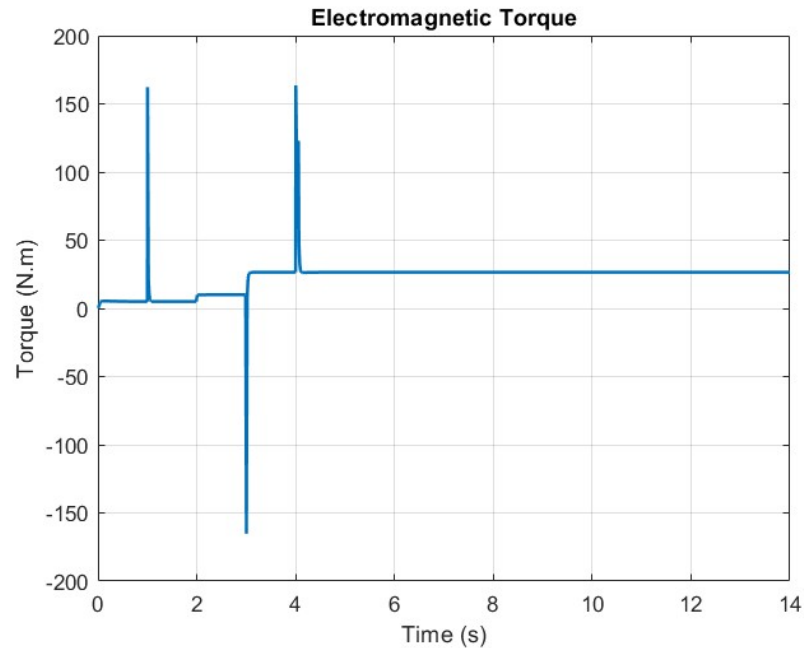


Figure 5.24 Electromagnetic torque response

$$T_{\max}=26.5001 \text{ Nm} \quad T_{\min}=26.5 \text{ Nm} \quad T_{\text{avg}}=26.5001 \text{ Nm}$$

$$\text{Torque Ripple} = \frac{T_{\max} - T_{\min}}{T_{\text{avg}}} \times 100 = 0.00038 \%$$

The extremely low torque ripple demonstrates smooth electromagnetic torque production.

Stator Current Analysis

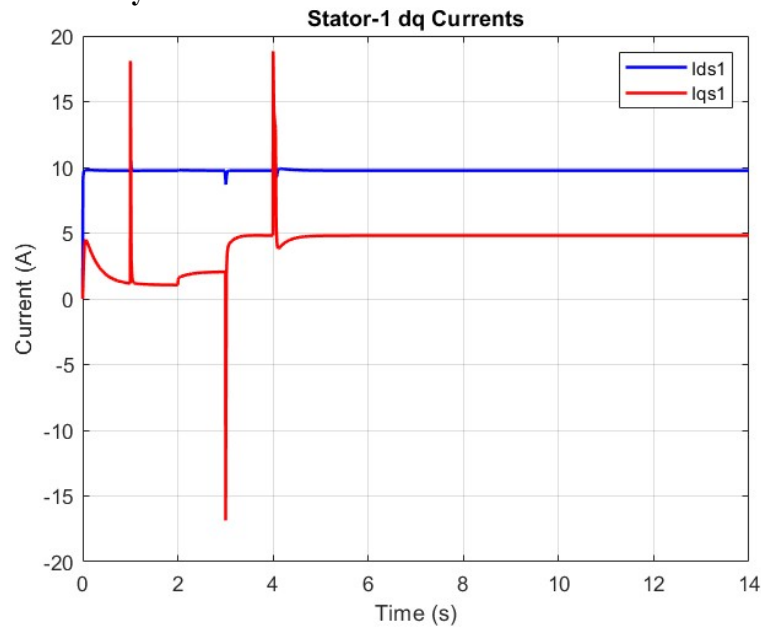


Figure 5.25 Stator 1 d-q Current

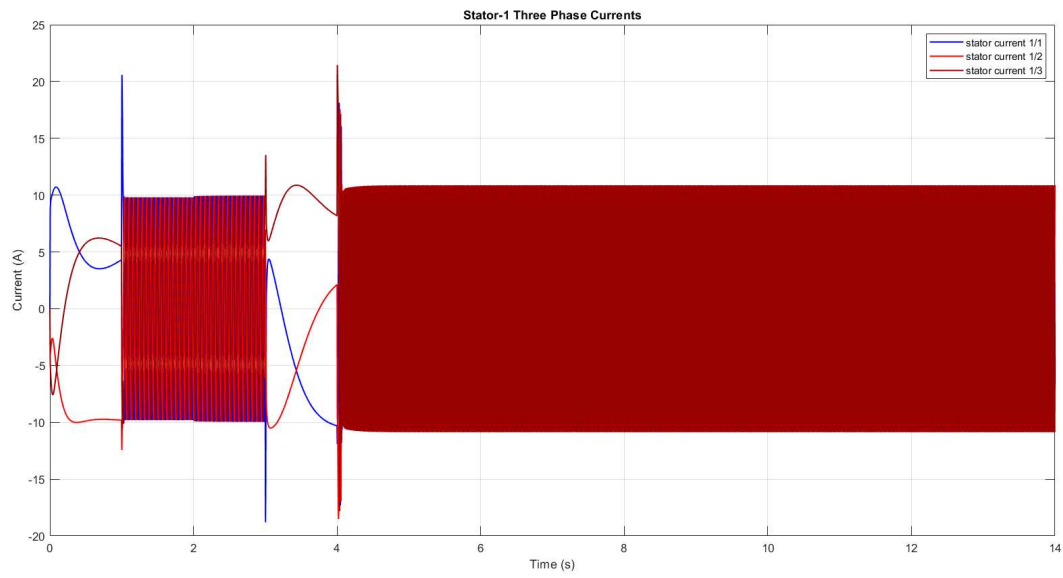


Figure 5.26 Stator 1 Three Phase Current

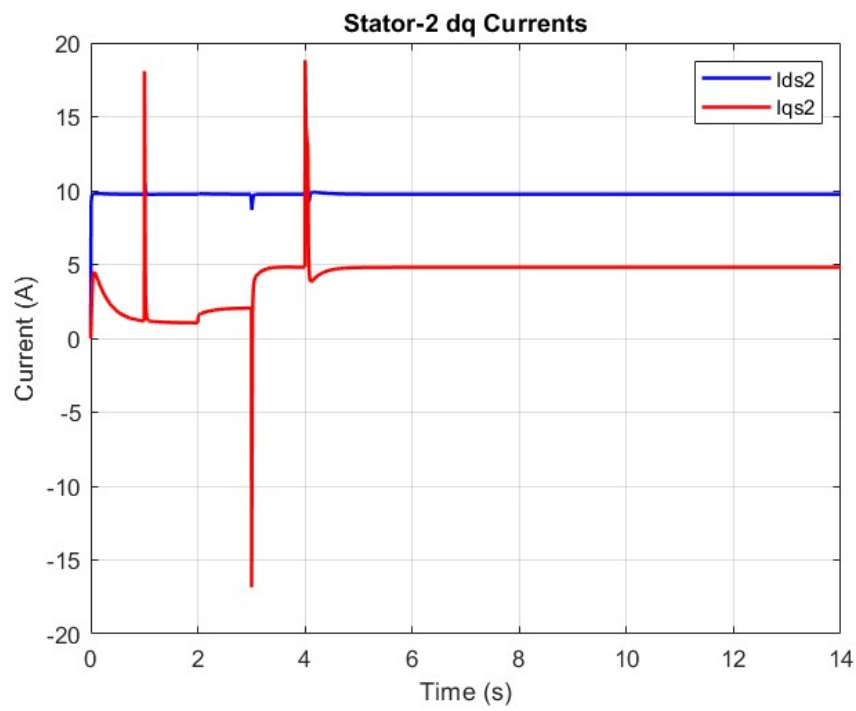


Figure 27 Stator 2 d-q Current

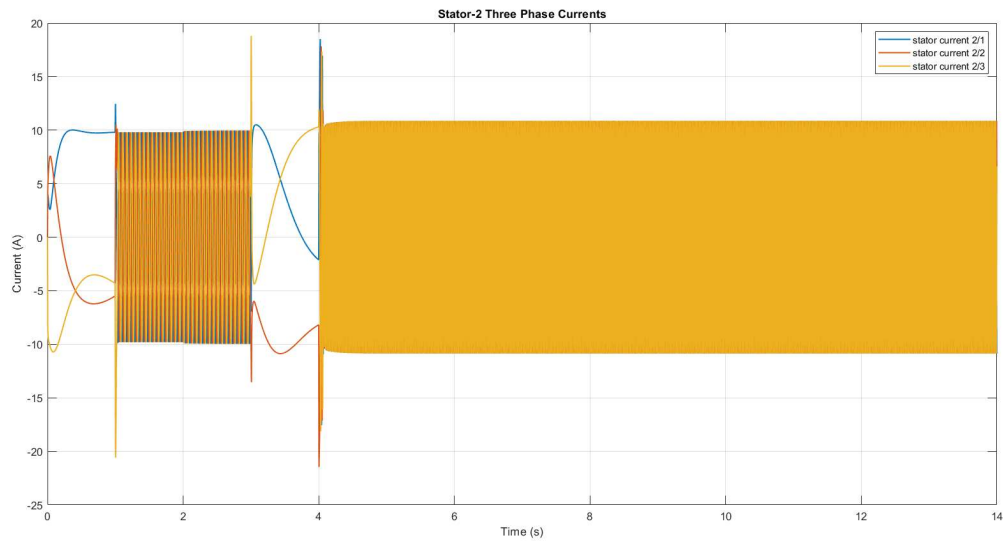


Figure 5.28 Stator 2 Three Phase Current

From the MATLAB results,

the average d-axis current of Stator-1 is 9.7652 A

the average d-axis current of Stator-2 is 9.7652 A

the average q-axis current of Stator-1 is 3.9085 A

the average q-axis current of Stator-2 is 3.9085 A

the peak d-axis current of Stator-1 is 11.9947 A

the peak d-axis current of Stator-2 is 11.9947 A

the peak q-axis current of Stator-1 is 18.8363 A

the peak q-axis current of Stator-2 is 18.8286 A

5.6 Performance Evaluation Under Speed Reversal Reference with increasing load torque

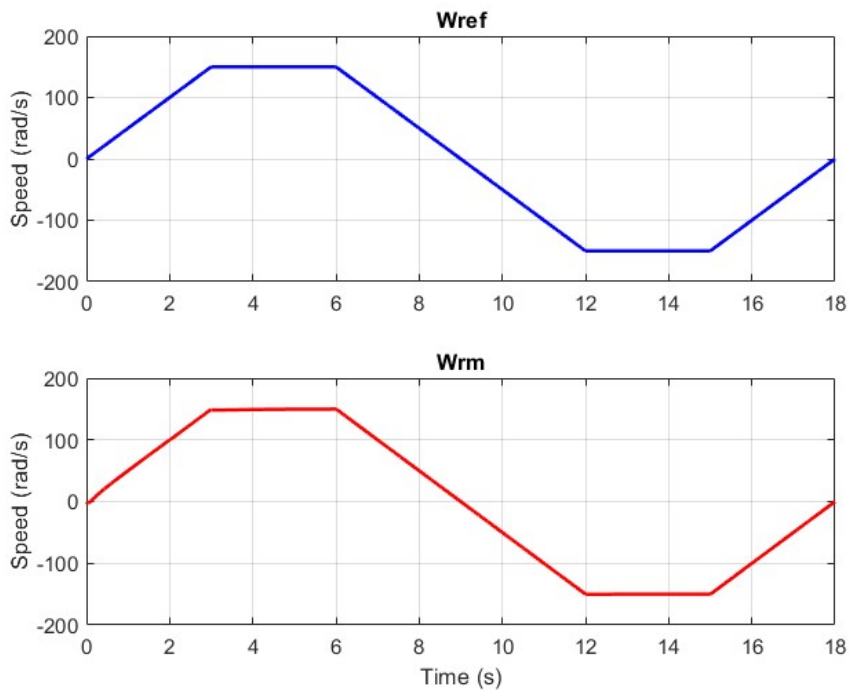


Figure 5.29 Comparison Between Reference Speed and Motor Speed

Speed Tracking Performance

$N_{\max} = 1431.23 \text{ rpm}$

$N_{\min} = -1431.23 \text{ rpm}$

Speed Reversal Capability

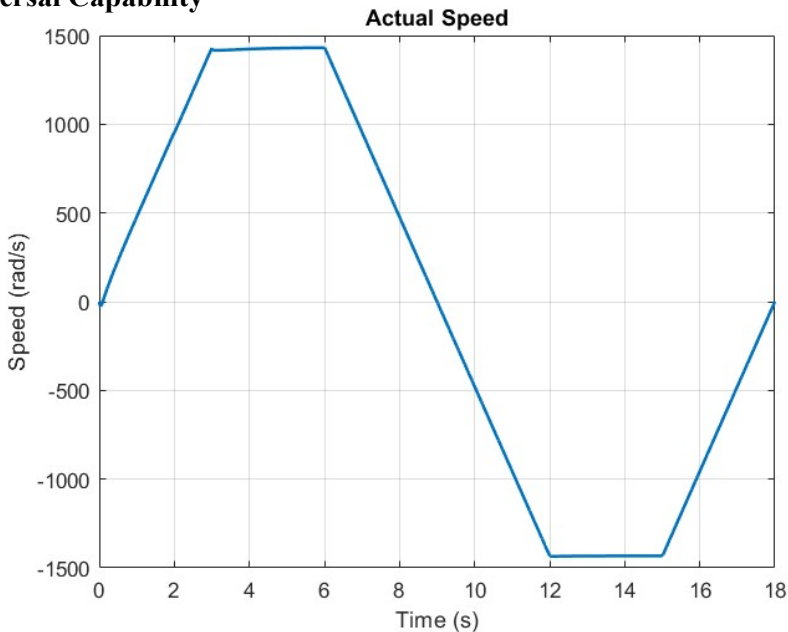


Figure 5.30 Speed Graph

The motor reverses successfully from 1431.23 rpm to -1431.23 rpm

The reversal occurs between t= 6 sec and 12 sec

Torque Ripple Analysis

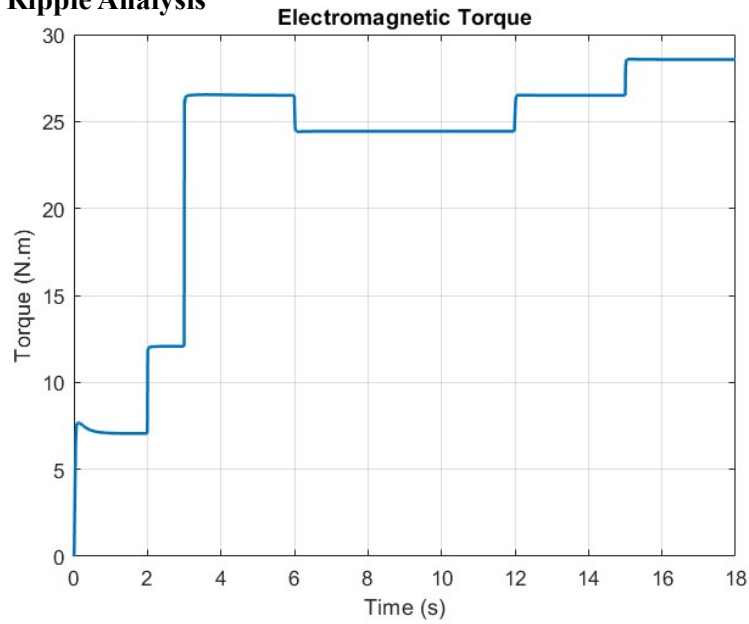


Figure 5.31 Electromagnetic Torque

$$T_{\max} = 28.5634 \text{ Nm} \quad T_{\min} = 28.5631 \text{ Nm} \quad T_{\text{avg}} = 28.5632 \text{ Nm}$$

$$\text{Torque Ripple} = \frac{T_{\max} - T_{\min}}{T_{\text{avg}}} \times 100 = 0.001334 \%$$

The extremely low torque ripple demonstrates smooth electromagnetic torque production.

Stator Current Analysis

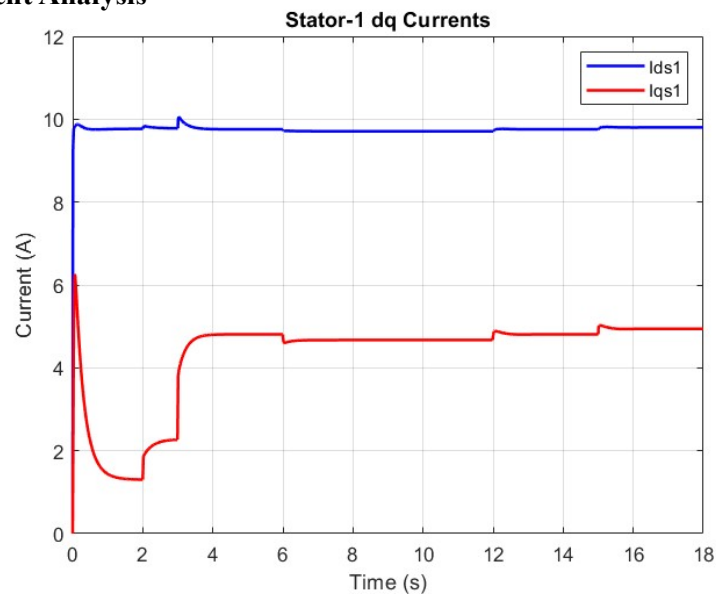


Figure 5.32 stator 1 d-q Current

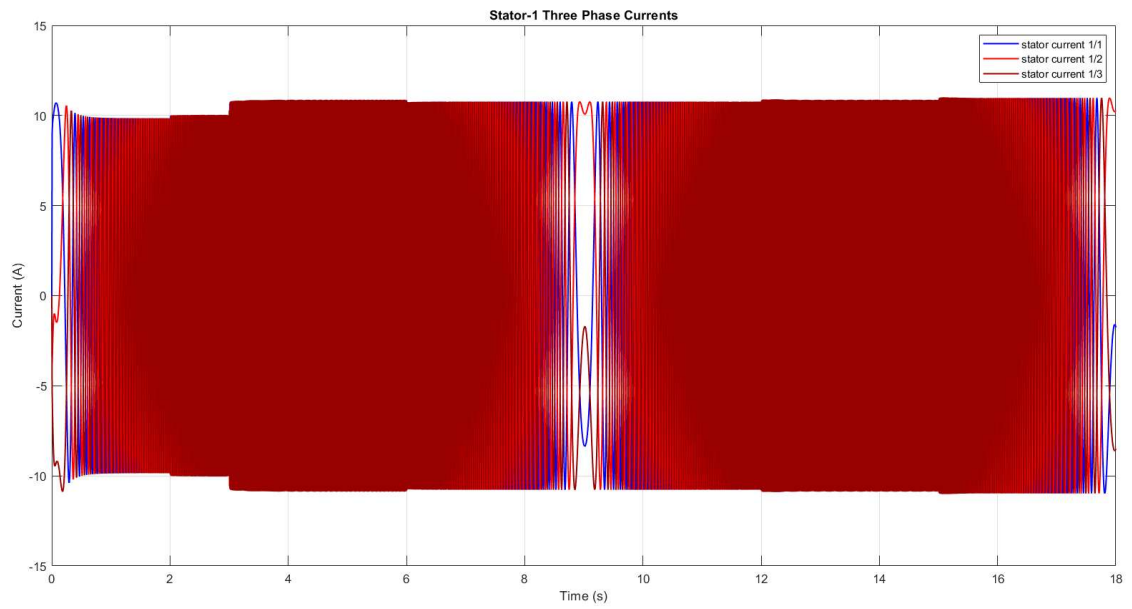


Figure 5.33 Stator 1 Three Phase Current

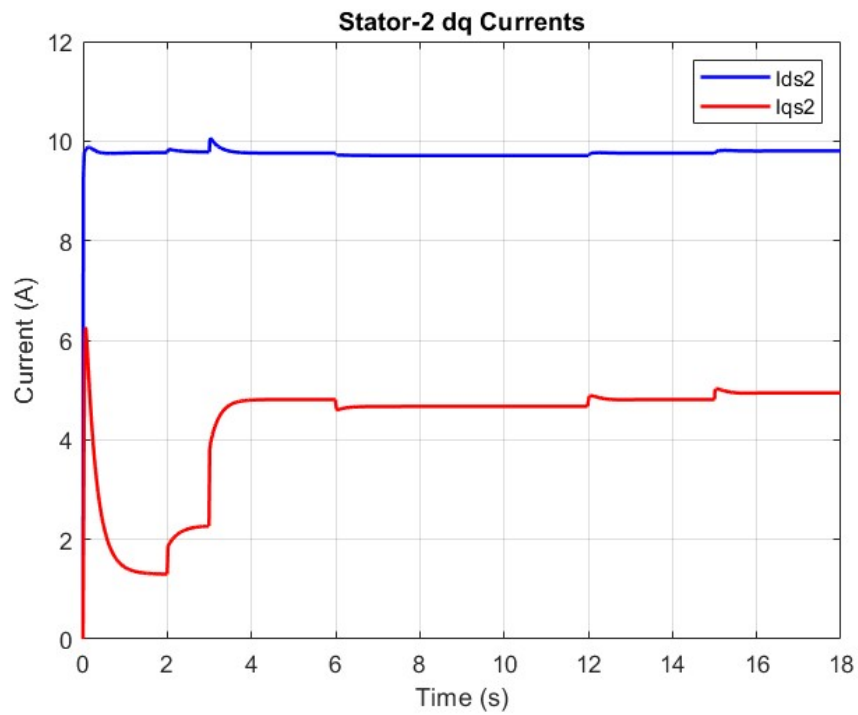


Figure 5.34 Stator 2 d-q Current

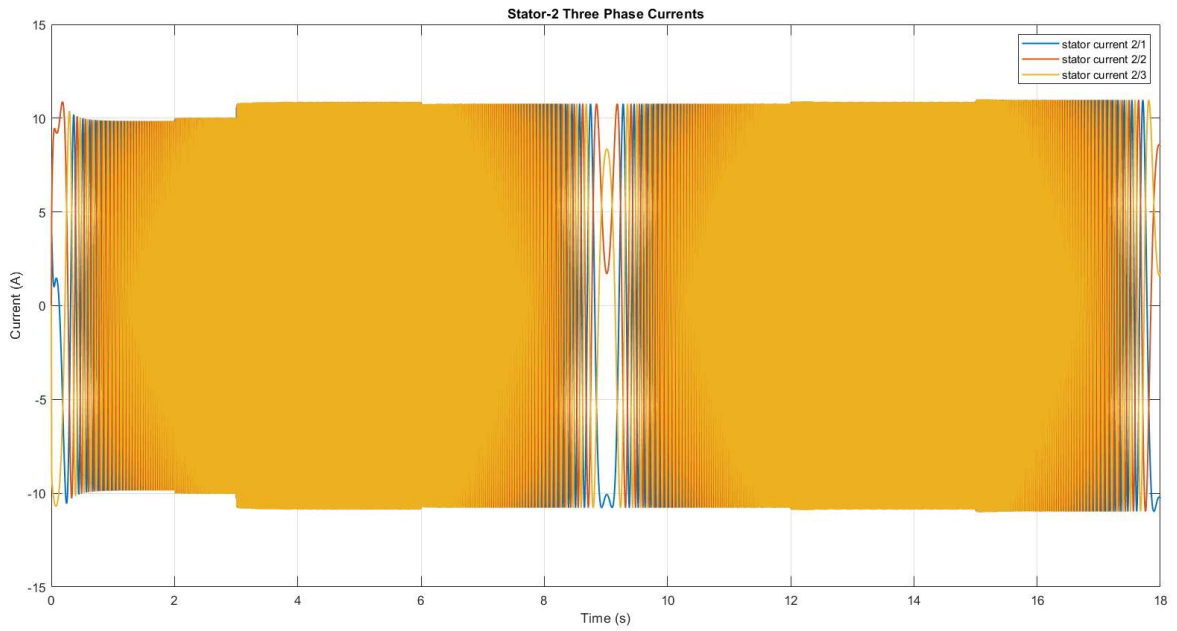


Figure 5.35 Stator 2 Three Phase Current

From the MATLAB results,

the average d-axis current of Stator-1 is 9.7535 A

the average d-axis current of Stator-2 is 9.7535 A

the average q-axis current of Stator-1 is 4.3207 A

the average q-axis current of Stator-2 is 4.3207 A

the peak d-axis current of Stator-1 is 10.0603 A

the peak d-axis current of Stator-2 is 10.0603 A

the peak q-axis current of Stator-1 is 6.2627 A

the peak q-axis current of Stator-2 is 6.2626 A

5.7 Conclusion

The results shown in this chapter show that the Dual-Stator Induction Motor drive controlled using Indirect Field-Oriented Control is appropriate for acceleration and deceleration applications of electric vehicle. The proposed control strategy provides a stable operation and almost accurate speed control under different operating conditions.

From simulation results, it is observed that the drive follows the reference speed with high accuracy, very small overshoot value and negligible steady state error. The two sets of stator windings are each separately controlled to give a balanced current distribution in operation. This solves the common problem of unbalanced current sharing in conventional voltage controlled DSIM drives and provides improved thermal balance, reduced losses and more uniform torque generation characteristics.

The developed controller also shows a good dynamic response to the load disturbances in the machine. The cascaded PI control structure allows to compensate as fast as possible the variations of load torque in order to keep the motor speed near the reference value and to reduce the transient deviations in the machine.

The study also highlights the need to consider the mutual leakage inductance in the machine model. This parameter allows a more realistic simulation of the electromagnetic interactions between the two stator winding sets and results in a better accuracy in transient conditions of the machine. These effects are neglected in simplified models which cause unrealistic fast responses and do not describe important dynamic phenomena of the machine. The mathematical model developed in this work successfully accounts for these interactions and provides a more reliable basis for performance evaluation of the model.

The deceleration analysis further confirms the ability of the DSIM drive to switch effortlessly between motoring and generating modes of the machine. The flux is maintained during the transition providing an effective regenerative operation and energy recovery without major changes to the control strategy.

In conclusion, the simulation results confirm the effectiveness of the proposed DSIM drive system and shows the potential of this configuration as a reliable and effective solution for electric vehicle propulsion applications.

CHAPTER 6 MAIN CONCLUSION AND FUTURE SCOPE OF WORK

The thesis deals with the acceleration/deceleration control of a Dual-Stator Induction Motor (DSIM) for the electric vehicle and position-control applications. This research work mainly focuses on the development of mathematical model, implementation of indirect field oriented control strategy and assessment of the drive performance under various operating conditions. The dual-stator configuration has a number of benefits including increased torque capability, enhanced reliability and the ability to share the electrical load between two independent three-phase stator winding sets.

Through simulation results it can be derived that the proposed control scheme can achieve accurate speed regulation and guarantee stable operation during acceleration, steady-state running, and deceleration. The indirect field-oriented control approach provides balanced current distribution and avoids unequal current sharing unlike conventional control methods by independently controlling the two stator winding sets. The balanced operation provide better efficiency, lesser thermal stress and smoother torque production.

The proposed acceleration and deceleration strategy is based on controlled variation of the speed reference combined with appropriate regulation of the torque producing current component. This causes smooth speed changes with a minimum current surge and torque oscillations. Thus, making the drive having good dynamic performance and reliable response when the operating conditions change.

The research also brings light to the significance of including mutual leakage inductance in the DSIM mathematical model. By the inclusion of this parameter more realistic description of the electromagnetic interaction between the stator winding sets and increases the accuracy of transient simulations, in particular for fast acceleration and braking events.

This same control architecture can be extended for position-control applications by adding an outer position control loop. This arrangement permits accurate positioning with less overshoot and an improved tracking performance. The modular MATLAB/Simulink implementation developed in this work offers a flexible environment to analyse the machine behaviour and validate the control algorithms before their practical implementation. The results of this study shows that the Dual-Stator Induction Motor is

a suitable for electric vehicle propulsion systems. The ability of sharing the torque between two sets of stator windings and to reduce the current loading on each winding and to continue operation in the event of certain faults makes it most suitable for applications where high reliability and performance is needed.

In general, the results verify that a vector controlled DSIM drive can offer smooth acceleration and deceleration, almost accurate speed regulation with minimal error, balanced current sharing and reliable operation which make it well suited for both electric vehicle and motion control applications.

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