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THEME

Fault-Tolerant Control of PMSM Based on Second-Order Sliding Mode

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☞ I thank **Allah** for the strength He gave me to complete this work.

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✎... *Mohamed BENSAOUCHA*

Univ. Mohamed BOUDIAF M'SILA

Dedication

I dedicate this work:

To my beloved Mother,

To my cherished Father,

To my supportive Brothers,

To my dear Sisters,

To my Relatives,

And to all my Esteemed Teachers and Colleagues.

✎... *Mohamed BENSAOUCHA*

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12-06-2024

Abstract

Permanent Magnet Synchronous Motors (PMSMs) are renowned for their efficiency, power density, and reliability, but they are prone to faults that can degrade performance. This thesis studies Fault-Tolerant Control (FTC) using Sliding Mode Control (SMC) to mitigate the effects of faults. SMC offers robustness but is hindered by the chattering phenomenon. Second-Order Sliding Mode Control (SOSMC) mitigates chattering, providing smoother control and enhanced fault tolerance. Finally, a second-order sliding mode observer (SOSMO) is constructed to estimate and reconstruct the faults. We will explores the integration of SOSMC for PMSMs to improve robustness and reliability. It encompasses fault diagnostics, PMSM modeling, passive FTC, and active FTC using SOSMC with a SOSMO.

Keywords: Fault-Tolerant Control (FTC), Passive FTC, Active FTC, sliding mode control (SMC),Second order sliding mode control and observer (SOSMC and SMO), Permanent Magnet Synchronous Motors (PMSM)

Résumé:

Les moteurs synchrones à aimants permanents (PMSM) sont réputés pour leur efficacité, leur densité de puissance et leur fiabilité, mais ils sont sujets à des pannes qui peuvent dégrader leurs performances. Cette thèse étudie le contrôle tolérant aux pannes (FTC) utilisant la commande par mode glissant (SMC) pour atténuer les effets des pannes. La SMC offre une robustesse mais est entravée par le phénomène de chattering. La commande par mode glissant du second ordre (SOSMC) atténue le chattering, offrant un contrôle plus fluide et une tolérance aux pannes améliorée. Enfin, un observateur par mode glissant du second ordre (SOSMO) est construit pour estimer et reconstruire les pannes. Nous allons explorer l'intégration de la SOSMC pour les PMSM afin d'améliorer la robustesse et la fiabilité. Elle englobe le diagnostic des pannes, la modélisation des PMSM, le FTC passif et le FTC actif utilisant la SOSMC avec un SOSMO.

Mots-clés : Contrôle Tolérant aux Pannes (FTC), FTC Passif, FTC Actif, Commande par Mode Glissant(SMC), Commande et Observateur par Mode Glissant d’ordre deux (SOSMC et SOMO), Moteurs Synchrones à Aimants Permanents (PMSM)

ملخص: تشتهر المحركات المتزامنة ذات المغناطيس الدائم (PMSMs) بكفاءتها وكثافة قدرتها وموثوقيتها، لكنها عرضة للأعطال التي يمكن أن تدهور الأداء . تدرس هذه الرسالة التحكم المتسامح مع الأعطال (FTC) باستخدام التحكم الانزلاقي (SMC) لتخفيف تأثيرات الأعطال. يوفر SMC المتانة ولكنه يعاني من ظاهرة التشتت. يخفف التحكم بطريقة الانزلاق من الدرجة الثانية (SOSMC) من التشتت، مما يوفر تحكمًا أكثر سلاسة وقدرة محسنة على تحمل الأعطال. أخيرًا، يتم إنشاء المراقب الانزلاقي من الدرجة الثانية (SOSMO) لتقدير وإعادة بناء الأعطال. سوف نقوم باكتشاف دمج SOSMC للمحركات المتزامنة ذات المغناطيس الدائم لتحسين المتانة والموثوقية. وتشمل تشخيص الأعطال ونمذجة PMSM و FTC السلبي و FTC النشط باستخدام SOSMC مع SOSMO.

الكلمات المفتاحية: التحكم المتسامح مع الأعطال (FTC)، FTC السلبي، FTC النشط، التحكم الانزلاقي (SMC), التحكم والمراقب الانزلاقي من الدرجة الثانية (SOSMC وSOSMO)، المحركات المتزامنة ذات المغناطيس الدائم (PMSM)

Contents

List of abbreviations

FTC	Fault-Tolerant Control
PFTC	Passive fault tolerant control
AFTC	Active fault tolerant control
FD	Faults Detection and diagnosis
PMSM	Permanent Magnet Synchronous Motor
PMSMs	Permanent Magnet Synchronous Motors
FOC	Field-Oriented Control
PI	Proportional-Integral
SMC	Sliding Mode Control
FOSMC:	First-order Sliding Mode Control
SOSMC	Second-Order Sliding Mode Control
SMO	Sliding Mode observer
SOSMO	Second-Order Sliding Mode observer
AI	Artificial Intelligence
MCSA	Motor Current Signature Analysis

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General Introduction

Permanent Magnet Synchronous Motors (PMSMs) are highly regarded in various industrial applications for their efficiency, power density, and reliability. Despite these advantages, PMSMs are vulnerable to a range of faults that can compromise performance or cause system failures. To mitigate these issues, fault-tolerant control (FTC) systems are critical, ensuring that PMSM drives continue to operate reliably even when faults occur [1][2][3].

A common control strategy for PMSMs is Field-Oriented Control (FOC). FOC is effective in decoupling torque and flux control, leading to excellent dynamic performance. This technique is usually implemented using a proportional-integral (PI) controller. However, (PI) controller have disadvantages, particularly in their limited robustness to parameter variations and external disturbances. Furthermore, they face difficulty to deal with nonlinearity and complexities in the motor's behavior in faulty conditions, which can hinder performance [4][5].

Sliding Mode Control (SMC) presents a robust alternative due to its resilience against system uncertainties and disturbances. First-order sliding mode control (SMC) is known for its robustness, but it suffers from a significant drawback: the chattering phenomenon, which is primarily a result of the control laws switching property. This can lead to excessive wear and tear on mechanical components and result in suboptimal performance [6-8].

To address these challenges, we are going to introduced a second-order sliding mode control which improves upon first-order SMC by using higher-order derivatives of the sliding surface, and significantly reduces chattering and ensures smoother control actions, thereby improving the fault tolerance and overall performance of PMSM drives [1-3] [9][10].

In our work, we will focus particularly on this method, as second-order sliding mode control offers a more effective solution to the previously mentioned problems. By integrating SOSMC, we aim to achieve a highly robust and reliable control strategy for PMSMs that can maintain optimal performance even under fault conditions.

This thesis is organized as follows:

Chapter 1 provides a comprehensive overview of fault-tolerant control systems and fault diagnostics. It discusses the importance of FTC in maintaining the reliability and performance of electrical machines, particularly PMSMs. Various fault types and diagnostic techniques are explored, setting the stage for the subsequent chapters.

Chapter 2 delves into the specifics of PMSM, including their construction, operating principles, advantages and disadvantages. Detailed modeling of PMSMs is presented, covering both mathematical and simulation models that are essential for developing effective control strategies.

Chapter 3 focuses on Passive Fault-Tolerant Control strategies for PMSMs. PFTC techniques do not require real-time fault detection and diagnosis; instead, they rely on robust control designs that can handle certain faults inherently. The chapter discusses the strengths and limitations of PFTC and its applicability to PMSM drives.

Chapter 4 introduces Active Fault-Tolerant Control strategies, emphasizing the use of second-order sliding mode control with a second order sliding mode observer SOSMO. AFTC involves real-time fault detection, diagnosis, and reconfiguration to maintain optimal system performance. The chapter explores this technique design and implementation, demonstrating its effectiveness in enhancing the fault tolerance of PMSM systems.

We conclude this thesis with a general conclusion.

Chapitre 1

Introduction to Fault and FTC diagnosis in Electrical Motor

1.1 Introduction

Fault-Tolerant Control (FTC) is a control strategy designed to maintain the desired performance and operational safety of a system under predefined conditions, even in the presence of faults. FTC also aims to protect healthy components from degradation. Its concept is to ensure system stability and satisfactory performance after sustaining a fault by automatically compensating for faults and failures in the system components.

Especially in safety-critical and high-cost applications, FTC is essential for improving the reliability and availability of advanced control systems while minimizing downtime and maintenance costs. These include nuclear reactors, aerospace systems, and autonomous vehicles. An appropriate FTC action would ensure a safe shutdown in case of emergency and avert a significant economic losses and human casualties [10-12].

1.2 Importance of Fault-Tolerant Control

Through a series of case studies, it highlights instances where the absence of FTC led to major disasters. These instances underscore the pivotal nature of FTC in upholding system dependability and safety. This is especially critical in industries where failure ramifications can be dire. For instance, there have been numerous cases where undetected faults led to major catastrophes, which highlight the need for FTC. We can mention [1-8]:

- **Chernobyl Disaster (April 1986):** An outdated defective technology coupled with lack of fault management mechanisms caused a massive explosion and reactor meltdown (Figure 1.1 (a)).

- **Ethiopian Airlines Flight 302 crash (March 2019):** The crash was caused by erroneous sensor data from one of the aircraft's angle of attack (AOA) sensors, which triggered the Maneuvering Characteristics Augmentation System (MCAS) to automatically push the nose of the aircraft down repeatedly. The pilots were unable to counteract this automated system. The Boeing 737 MAX 8 aircraft crashed shortly after takeoff, claiming the life of all 157 passengers and crew on board. (Figure 1.1(b)).

- **SpaceX starship sn8 test launch landing explosion (December 2020):** SpaceX's Starship SN8 prototype suffered a hard landing and subsequent explosion due to a fault in the fuel header tank pressure sensor. The sensor provided incorrect data, leading to insufficient thrust during the landing burn and the vehicle's destruction upon impact (Figure 1.1(c))

(a) (b) (c)

Figure 1.1: Catastrophic accidents caused by undetected faults: Chernobyl nuclear disaster (a), Ethiopian Airlines Flight crash (b) and SpaceX starship explosion (c)

By deriving lessons from these incidents, engineers can create control systems that are more robust and resilient, thus improving the safety and effectiveness of complex systems.

1.3 Fault-Tolerant Control Notions

Let’s start by clarifying the definitions of a few key notions related to FTC [14] [15]:

- **Fault**: A fault is an unacceptable deviation of at least one property or characteristic parameter of the system from acceptable or (and) standard conditions. It can range from minor performance degradation to total failure under certain conditions if appropriate measures are not taken.

- **Failure**: A failure is the alteration or interruption of a system's ability to perform its required function(s) properly under specified operational conditions.

- **Breakdown**: A breakdown is a state where the system is incapable of performing its required function(s) due to a failure.

- **Residue**: A residue is a signal designed to indicate a functional or behavioral abnormality.

- **Hardware redundancy**: it refers to the inclusion of duplicate or backup hardware components within a system to ensure its continued operation in the event of a component failure

- **Real-Time Monitoring**: FTC often relies on real-time monitoring of system variables to detect faults and make necessary adjustments.

1.4 Faults in Control Systems

In control systems, faults can arise in different components and can have varying effects on system behavior. As shown in Figure 2, the common types of faults encountered in control systems are: Actuator faults, sensor faults, system Faults [15] [17].

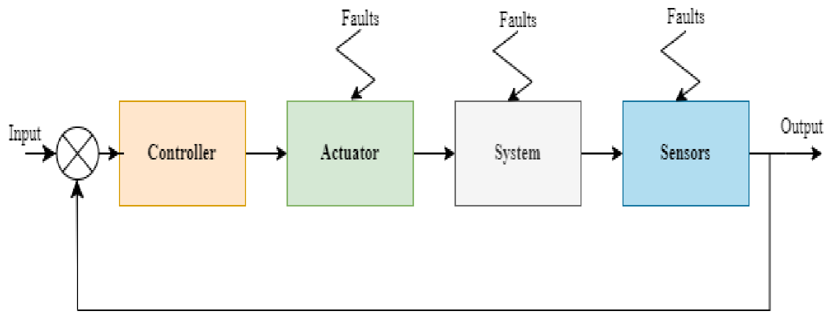


Figure 1. 2 - Faults in Control Systems

Actuator Faults: Actuator faults occur when there are problems with the components responsible for controlling the system's output. These faults include:

- Stuck actuators: Actuators that are jammed or stuck in a particular position, preventing them from responding to control signals.
- Partial actuator failure: Actuators that operate with reduced effectiveness or precision, leading to inaccuracies in system control
- Actuator saturation: Occurs when actuators reach their maximum or minimum limits, limiting the control authority of the system.

Sensor Faults: Sensor faults involve issues with the components responsible for measuring system variables and providing feedback to the controller. These faults include:

- Sensor drift: Gradual changes in sensor readings over time, leading to inaccuracies in feedback signals.
- Sensor bias: Systematic errors in sensor measurements, resulting in consistent deviations from the true values.
- Sensor noise: Random fluctuations or interference in sensor readings, making it difficult to discern the true system state.

System Faults: System faults encompass broader issues affecting the overall operation of the control system. These faults include:

- Parameter variations: Changes in system parameters (e.g., mass, inertia, damping) due to external factors or wear and tear, affecting system dynamics.
- Model uncertainties: Discrepancies between the mathematical model used for control design and the actual behavior of the system, leading to performance degradation.
- External disturbances: Unpredictable inputs or disturbances acting on the system from the environment, affecting system response and stability.
- Actuator/sensor misalignment: Mismatches between the physical locations or orientations of actuators and sensors, leading to discrepancies in feedback signals.

Communication Faults: Communication faults involve problems with data transmission between different components of the control system [16]. These faults include:

- Packet loss or corruption: Errors in data transmission resulting in loss or corruption of control signals.
- Communication delays: Delays in data transmission between components, affecting the timeliness of control actions.
- Network congestion: Overloaded communication channels leading to delays or packet loss, impacting system performance.

These common types of faults can have significant impacts on the performance, stability, and reliability of control systems, and appropriate fault detection, isolation, and mitigation strategies are often necessary to ensure proper system operation.

1.5 Classification of faults based on severity

Faults are categorized into three primary categories depending on their severity as follow [15-18]:

1.5.1 Intermittent fault:

An intermittent fault manifests irregularly at a random interval with a short duration. However, this type of malfunction can still lead to a long-lasting effect, such as actuator saturation due to excessive loads. It is typically triggered by improper electrical connections or temporary sensor failures. The unpredictable nature of this fault makes it difficult to detect.

1.5.2 Drift-like faults:

A drift like faults usually develops slowly over time. Their gradual nature make them challenging to detect due to their small effects on residuals, but also provides opportunities for preventive maintenance and mitigation. They are caused from actuator, sensor inaccuracies or partial failures.

1.5.3 Permanent faults:

These faults persist and do not resolve on their own, indicating hardware failures, such as short circuits, intense vibrations, or metal flakes separating. These faults progress rapidly due to the sudden changes that occur within the system properties, rendering them challenging to monitor relying on residuals.

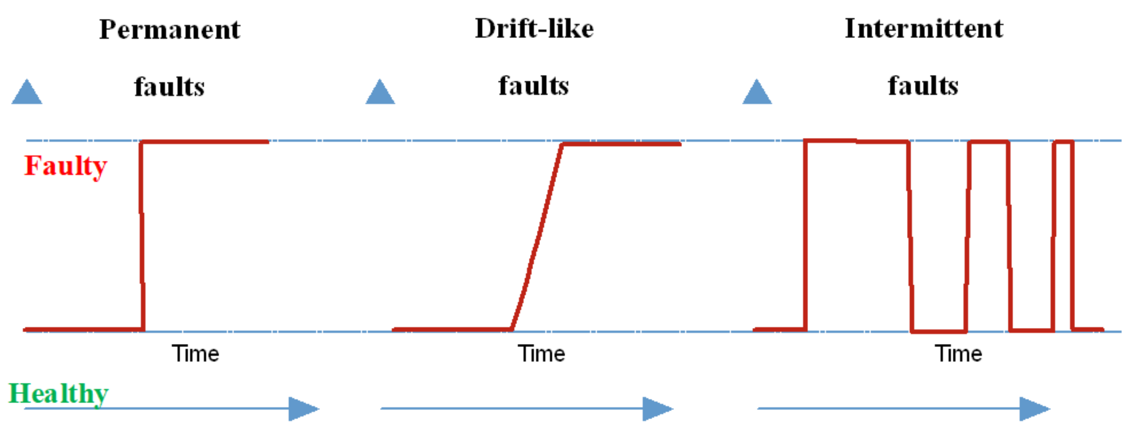


Figure 1.3 - Classification of faults based on severity

1.6 Classification of faults based on their influence on the system

Depending on how they affect the system, the faults mentioned previously can be classified in two main ways: additive and multiplicative [19][20].

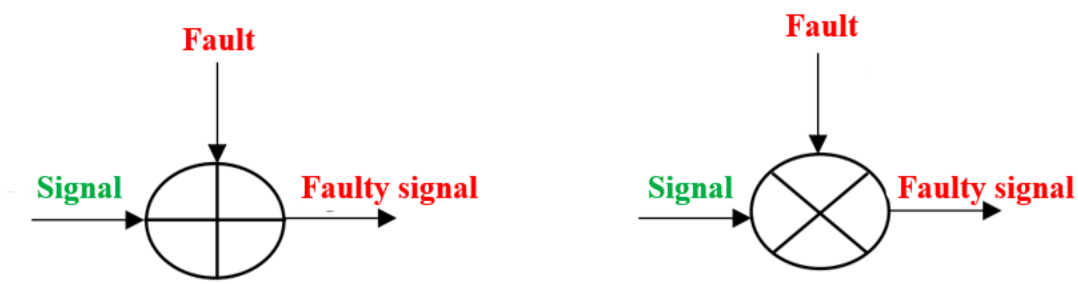


Figure 1. 4 - Classification of faults. (left) additive faults, (right) multiplicative faults

1.6.1 Additive Faults

Additive faults introduce a constant change in the system, independent of the system's state or its inputs. For example, sensor and actuator biases are considered an additive faults because they adds a constant value to the actual measurements.

1.6.2 Multiplicative Faults:

Multiplicative faults alter the system proportionally to the system's state or its inputs. For example, a sensor fault that causes a measurement error proportional to the measured value is considered a multiplicative fault because it affects the measurement proportionally to the actual value.

The distinction between additive and multiplicative faults is important for the design of fault detection and diagnosis strategies. Additive and multiplicative faults often require different detection and correction approaches to minimize their impact on the system.

1.7 Diagnosis Methods for electrical machines

Fault Diagnosis (FD) is a procedure used to detect, isolate, and identify faults or failures within a system. It is designed to ensure the operational reliability and functional performance of the system by providing data that allows remedial measures to be applied [10][13] [15] . FD involves three key steps:

- **Fault Detection:** The first step involves detecting the presence of a fault or malfunction within the system and the time of detection.

- **Fault Isolation:** After detecting a fault, the next step is to determine the fault type and location.

- **Fault Identification:** The final step is to identify the fault characteristic, including its severity, influence, and time pattern.

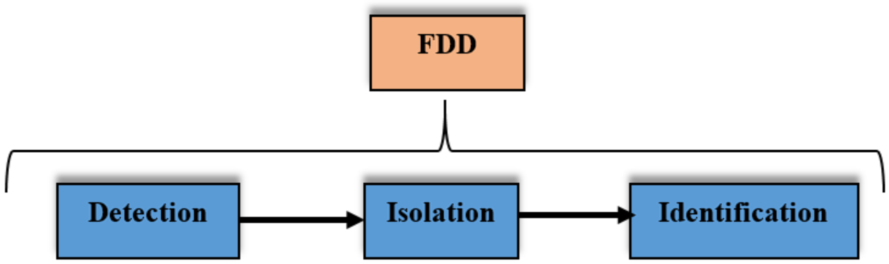


Figure 1.5 - Diagnosis steps

Several diagnostic methods have been developed to monitor the condition of electrical machines and identify potential faults. These methods can be broadly classified into three categories are Model-based techniques, AI-based techniques, Signal-based techniques [3] [13-15] [20]:

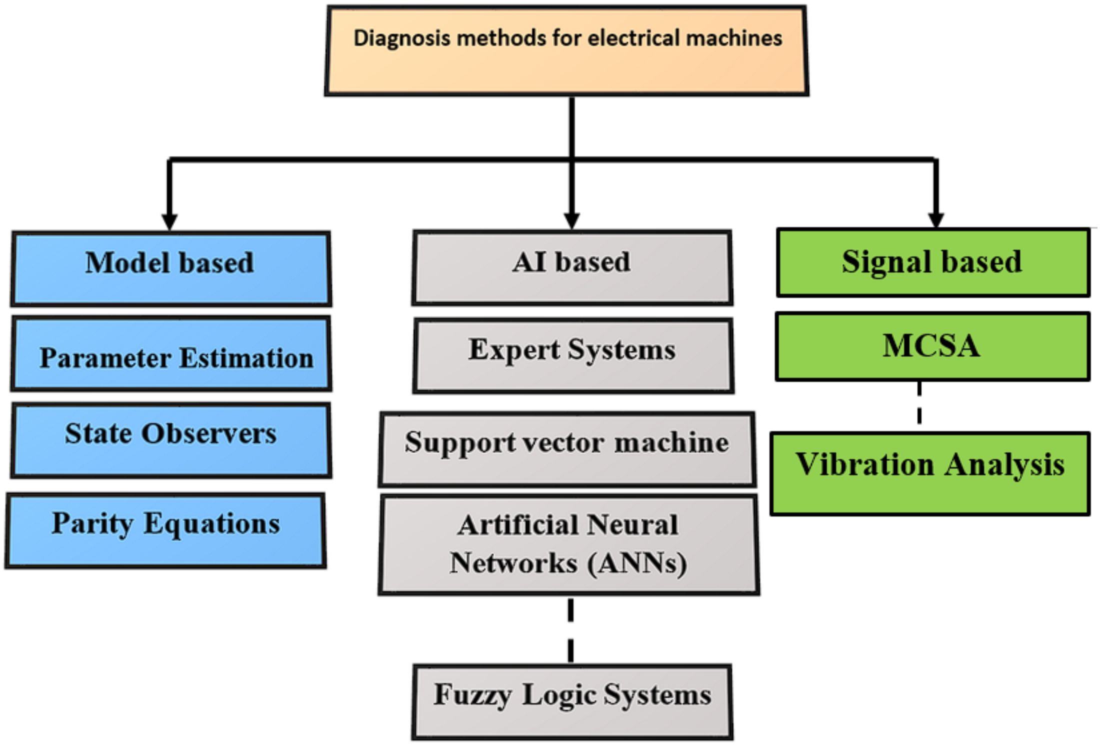


Figure 1.6 - Diagnosis methods for electrical machines

1.7.1 Model-Based Techniques

Model-based techniques rely on mathematical models that describe the behavior of the electrical machine under healthy and faulty conditions. These techniques involve comparing the actual machine behavior with the expected behavior predicted by the model, and any deviations can be attributed to potential faults. Some commonly used model-based techniques include:

1.7.1.1 Parameter Estimation

This approach involves estimating the parameters of the electrical machine model, such as resistances, inductances, or time constants, from measured data. Deviations in the estimated parameters from their expected values can indicate the presence of faults.

1.7.1.2 State Observers

State observers are utilized to estimate the internal states of the electrical machine based on measured inputs and outputs. The estimated states can be compared with the actual measured states, and any discrepancies can indicate the presence of faults.

1.7.1.3 Parity Equations

Parity equations are derived from the mathematical model of the electrical machine, which relates the measured inputs and outputs. Any violation of these equations can serve as an indicator of faults in the system.

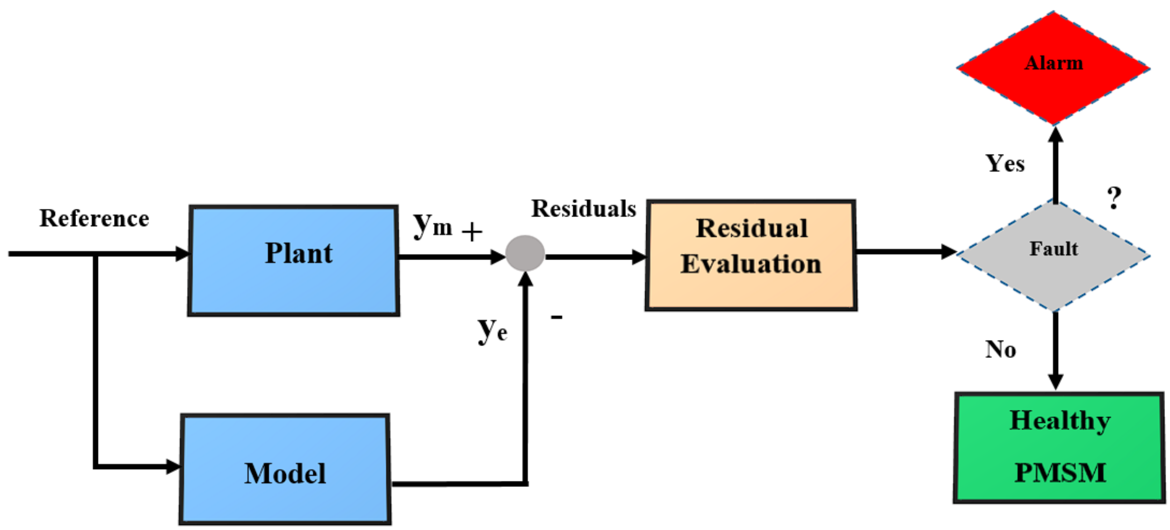


Figure 1.7 - Model-Based Techniques architecture

1.7.2 AI-Based Techniques

AI-based techniques leverage expert knowledge and historical data to diagnose faults in electrical machines. These techniques often employ artificial intelligence and machine learning algorithms to analyze complex data patterns and make decisions. Some commonly used knowledge-based techniques include:

- Expert Systems;
- Support vector machine;

- Artificial Neural Networks (ANNs);
- Fuzzy Logic Systems

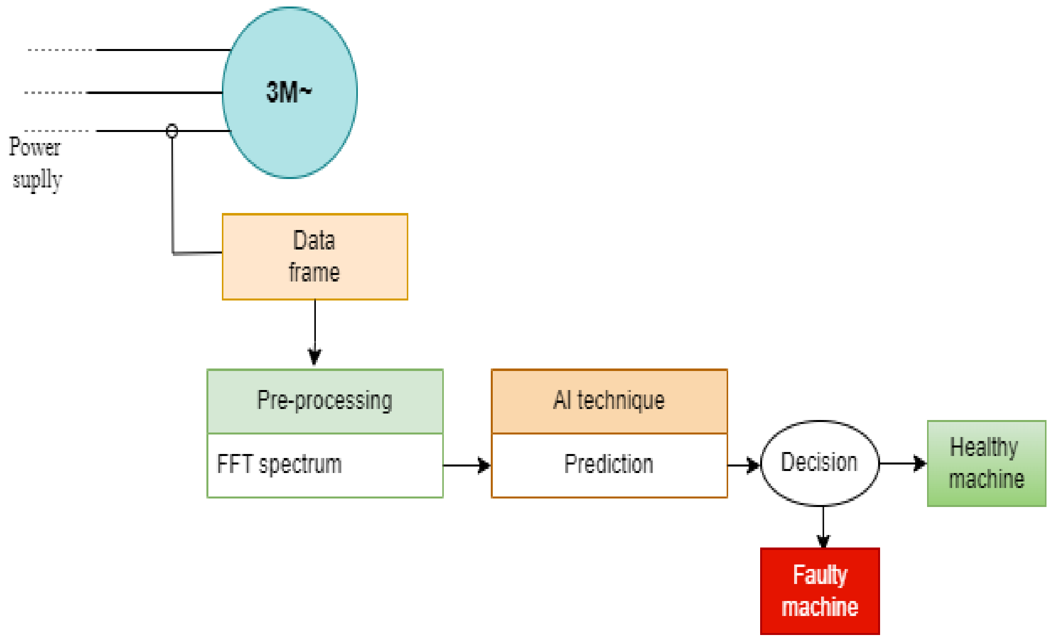


Figure 1.8 - AI-based fault detection method

1.7.3 Signal-based techniques

Signal-based techniques rely on the analysis of signals obtained from the electrical machine or its associated systems. These signals can be electrical (currents, voltages, power), mechanical (vibration, acoustic emissions), or thermal (temperature). Some commonly used signal-based techniques include:

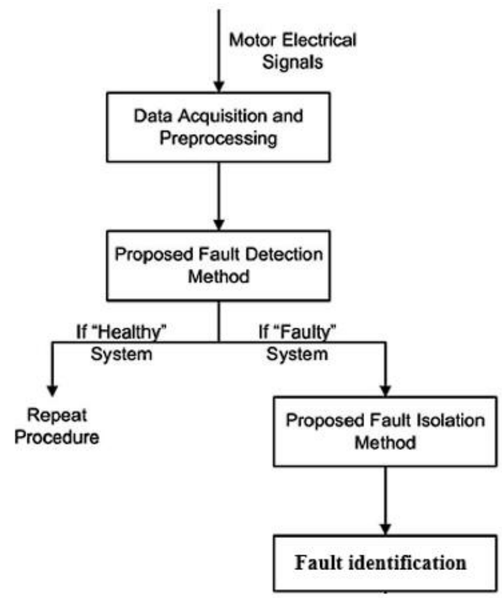


Figure 1.9 - Signal- fault detection method

1.7.3.1 Motor Current Signature Analysis (MCSA):

This technique involves analyzing the stator current signals of the electrical machine to detect various faults, such as air-gap eccentricity, broken rotor bars, and bearing faults. The presence of faults introduces characteristic frequencies or patterns in the current spectrum, which can be identified and analyzed [20].

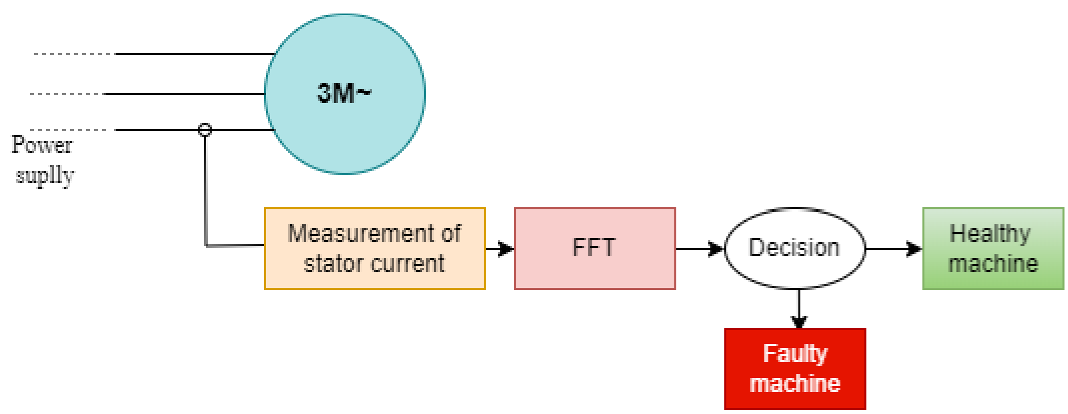


Figure 1.10 - Signal-Based Fault Detection Method based on MCSA technique

1.7.3.2 Vibration Analysis:

Vibration signals from the electrical machine are analyzed to detect faults related to mechanical components, such as bearings, gears, or shaft misalignment. Various signal processing techniques, including time-domain analysis, frequency-domain analysis, and time-frequency analysis, can be employed to extract fault-related features from the vibration data. This technique is widely used to diagnose mechanical faults such as bearing faults.

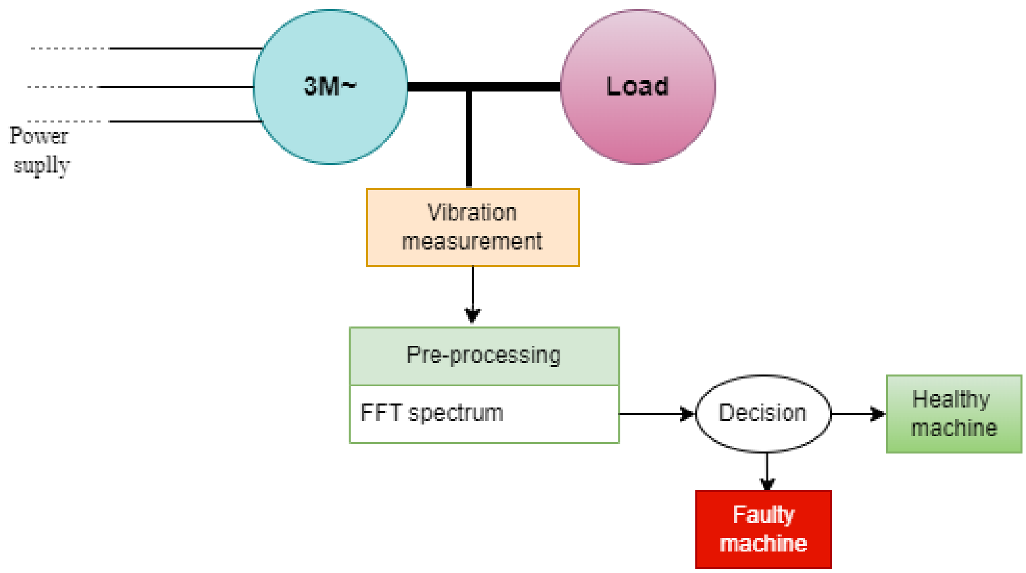


Figure 1.11 - Signal-Based Fault Detection Method based on Vibration Spectrum

1.8 General overview of FTC

Fault-Tolerant Control (FTC) is a control strategy designed to maintain the desired performance and operational safety of a system under predefined conditions, even in the presence of faults. FTC also aims to protect healthy components from degradation, preventing minor faults from escalating into critical failures. [12] [13][15]

1.8.1 Classification of FTC Systems:

FTC systems can be divided into two main classes: active and passive. The fundamental difference lies in their approach to fault handling and their reliance on fault information. Passive FTC systems do not depend on fault information; instead depend on the robustness of the controller to deal with a predetermined set of faults. Conversely, active FTC systems use fault detection and diagnostic (FDD) systems to detect faults and then use a monitoring system to modify control structures and settings to mitigate the effects of the faults. [13][15]

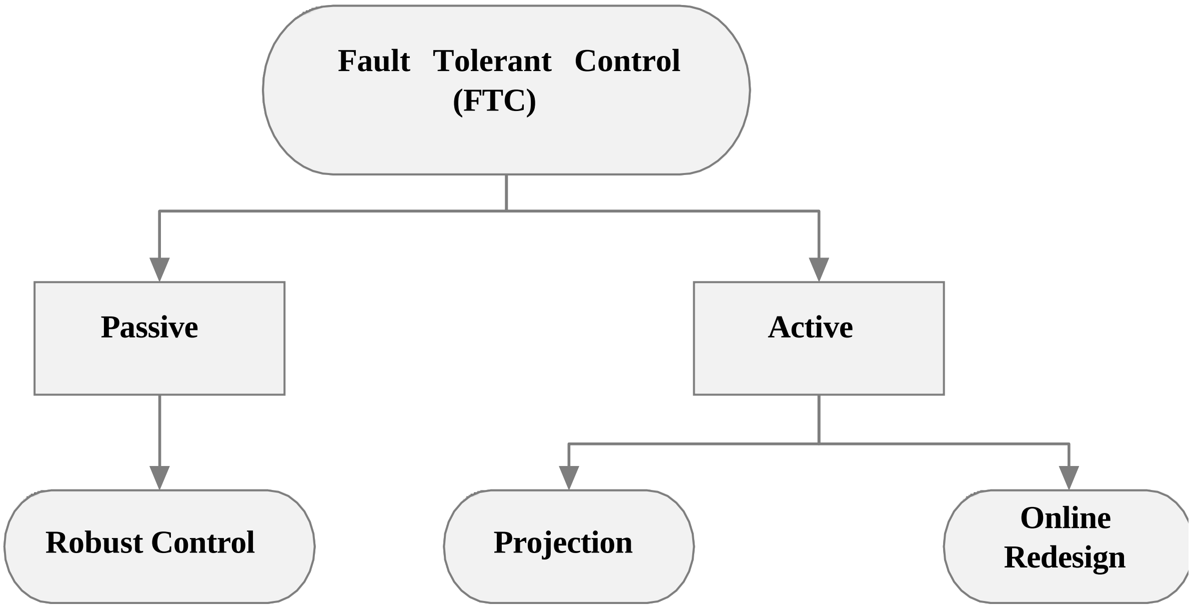


Figure 1.12 - Classification of FTC systems.

1.8.1.1 Passive FTC:

Passive Fault-Tolerant Control (PFTC) systems are based on robust control designs aimed at stability and resilience against certain faults and disturbances. PFTC does not require fault feedback, fault detection mechanisms, or a reconfiguration block for the control law, which indicates that no additional action or decision is needed from the control system, as shown in Figure 1.13.However, its fault tolerance capability is limited to a small number of failures. The fundamental concept of this method is to ensure that the closed-loop system remains unaffected by certain known uncertainties and disturbances, while maintaining system stability and satisfactory performance with the same control structure without any re-adjustment.

Passive fault-tolerant control relies on the robustness of the control model itself. The most popular robust control methodologies developed include H∞ [21] and Sliding Mode Control (SMC) [17]. They have emerged as the most advanced methods of multivariable control, with numerous applications due to their simplicity, fast response to faults, and cost-effectiveness. Despite these advantages and its ease of implementation, its practical use remains relatively limited.

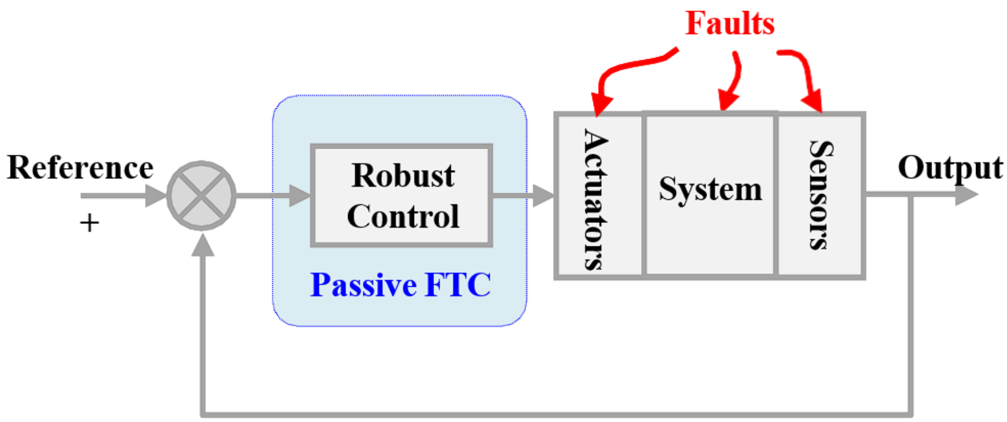


Figure 1.14 - Schematic diagram for passive FTC systems

The applicability of PFTC is very limited due to its significant drawbacks and constraints:

- Performance tradeoffs: to achieve fault tolerance, passive systems often require design compromises that can lead to reduced performance or efficiency under normal conditions. Since faults occur relatively rarely, which could be unreasonable to degrade the system's nominal performance merely to gain insensitivity to a limited set of faults.

- Inability to handle severe faults: Passive methods may not be able to maintain system stability and performance in the presence of multiple or severe faults.

1.8.1.2 Active FTC:

Active Fault-Tolerant Control (AFTC) systems rely on controller reconfiguration or the selection of a few predesigned controllers. This approach requires a fault detection and diagnosis (FDD) system to detect and localize faults. The structure of an AFTC system with an FDD unit is illustrated in Figure 1.15:

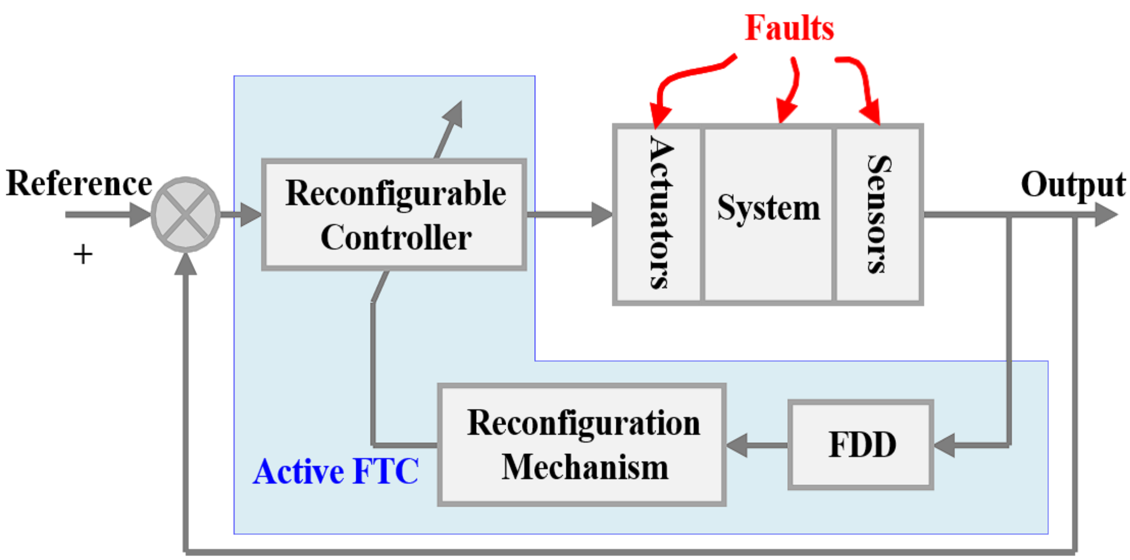


Figure 1.15 - Schematic diagram for active FTC systems

The FDD block uses input-output measurements from the system to detect and localize faults. After that, the identified faults are transmitted to a reconfiguration mechanism, which adjusts the parameters and structure of the controller to ensure acceptable system performance in the presence of fault. AFTC systems utilize dedicated detectors or specialized state or parameter observers to identify failure occurrence. The selection of the fault-tolerant control algorithm depends on the system requirements and the employed components. We distinguish two main categories of active strategies: The projection-based technique and the online redesign technique:

- **The projection-based technique:** it involves precomputing a set of control laws designed to accommodate all potential faults or failures within a system [22]. The projected control will only be active when the relevant fault or failure occurs. Upon fault detection, this technique selects the most suitable control law from the predefined control laws that can handle the corresponding fault. This technique is illustrated in Figure 1.16.

- **Online redesign technique:** the concept of this approach involves synthesizing a new control law for a plant subject to an occurring fault, without using any prior knowledge of the plant's model in real-time. In contrast to the projection-based method, this approach focus on system dynamics rather than predefined trajectories. Therefore, it offers a more flexible and adaptive strategy.

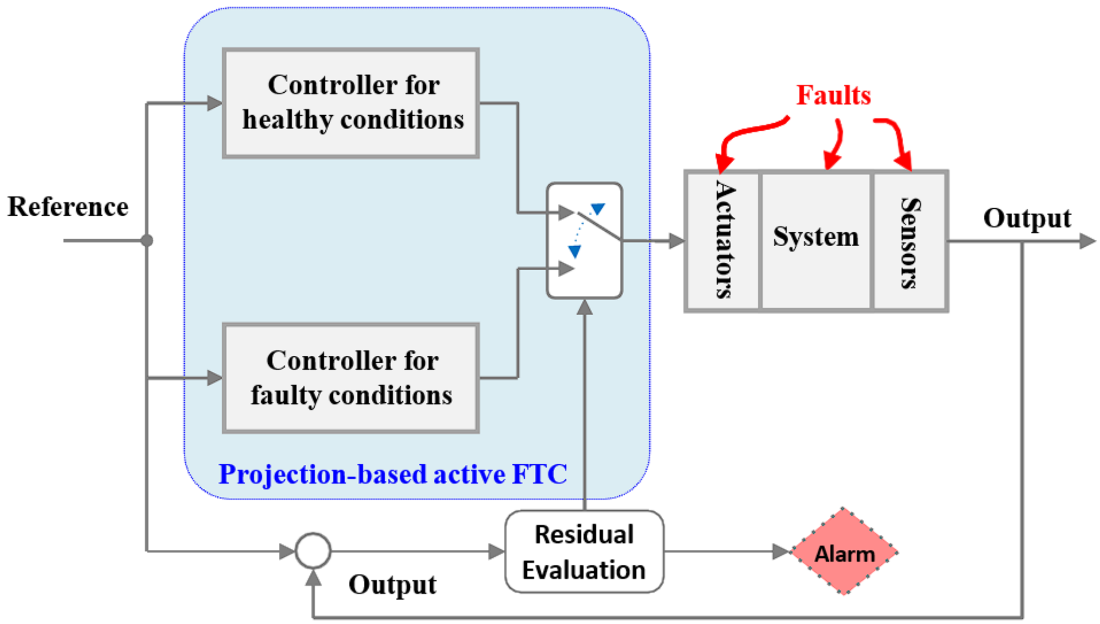


Figure 1.16 - Schematic diagram for projection-based active FTC systems.

1.9 Conclusion

In this chapter, we explored in detail the concepts of Fault Detection and Diagnosis (FDD) and Fault-Tolerant Control (FTC) in control systems. Fault detection and diagnosis is a crucial step in identifying and diagnosing anomalies that may occur in a system, thus maintaining system performance and reliability. We examined various fault detection methods, including model-based, data-driven, and observer-based techniques. Each method has specific advantages and limitations depending on the type of system and the faults being detected.

Fault-Tolerant Control (FTC) aims to ensure that the system continues to operate correctly despite the presence of faults. We discussed both passive and active FTC strategies. Passive strategies are designed to be robust against a predefined range of faults without requiring reconfiguration, while active strategies involve dynamically reconfiguring the controller in response to fault detection.

By effectively combining FDD and FTC techniques (AFTC), it is possible to develop control systems that not only detect faults early but also adapt to maintain optimal performance. This combination is essential in critical applications where safety, reliability, and continuity of operations are paramount, such as in aerospace, automotive, and complex industrial systems.

This chapter has provided a solid foundation for understanding the principles and techniques of fault detection and fault-tolerant control. The following sections will delve into specific case studies and practical applications to illustrate the implementation of the discussed.

Chapitre 2

Modeling of Permanent Magnet Synchronous Motors

2.1 Introduction

Permanent Magnet Synchronous Motors (PMSMs) are a type of synchronous motor that utilize permanent magnets to generate the magnetic field instead of relying on field windings. This design offers several advantages, including higher efficiency, compact size, and superior performance. PMSMs are characterized by their ability to maintain synchronous speed, which is directly related to the frequency of the supplied voltage [1] [2].

This chapter aims to provide an understanding of permanent magnet synchronous motors (PMSM) with their essential concepts, construction and operating principles. Additionally, it seeks to establish a mathematical representation by deriving and presenting the equations governing voltage, flux linkage and torque.

2.2 Importance and Applications of PMSMs

PMSMs are highly valued across numerous industries due to their efficiency, reliability, and superior performance characteristics [5] [20] [23]. They are extensively used in:

- **Electric Vehicles:** PMSMs are the preferred choice for propulsion systems in electric vehicles due to their ability to deliver high torque density and efficient operation, enabling extended driving range and improved performance.

- **Automation and Manufacturing:** PMSMs are essential components in robotic systems, computer numerical control (CNC) machines, and conveyor systems within industrial settings. Their precise speed and position control capabilities are crucial for accurate and efficient manufacturing operations.

- **Renewable Energy Generation:** The efficient performance of PMSMs under varying load conditions makes them well-suited for use in wind turbines and other renewable energy applications, contributing to sustainable energy production.

- **Energy-Efficient Appliances:** High-efficiency household appliances, such as washing machines and air conditioners, incorporate PMSMs to achieve better performance and energy savings, aligning with energy conservation initiatives.

- **Aerospace and Maritime Applications:** The high power-to-weight ratio of PMSMs makes them suitable for weight-sensitive applications in the aerospace industry, including aircraft actuators and drone propulsion systems, as well as marine propulsion systems for ships and vessels.

2.3 Structure and components of PMSM

PMSM consist of several key components that work together to produce efficient and precise rotational motion. The major components of a PMSM are [23][24] :

2.3.1 Stator:

The stator is the stationary part of the motor (Figure 2.1), consisting of a laminated steel core with evenly spaced slots. These slots accommodate the stator windings, which are typically made of copper wire. The stator windings, when energized, create a rotating magnetic field.

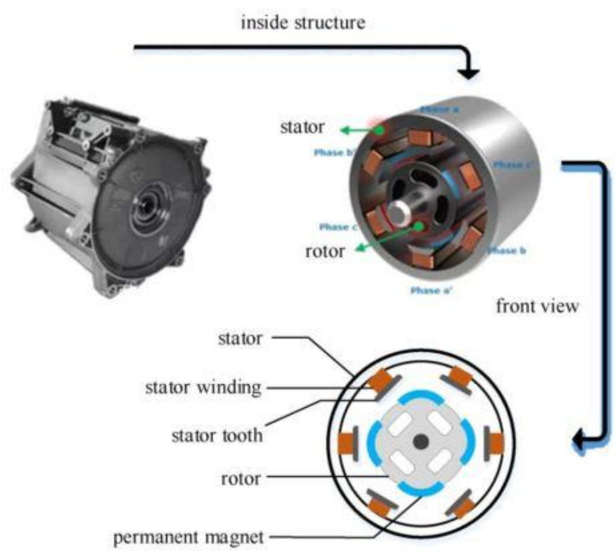


Figure 2.1 - Stator of PMSM

2.3.2 Rotor:

The rotor is the rotating part of the motor (Figure 2.2). In a PMSM, the rotor is composed of permanent magnets. These permanent magnets are mounted on the rotor surface or buried inside the rotor core, creating a constant magnetic field.

Figure 2.2 - Rotor of PMSM

2.3.3 Bearings:

Bearings (Figure 2.3) support the rotor shaft and allow smooth rotation with minimal friction. Common bearing types used in PMSMs include ball bearings and sleeve bearings.

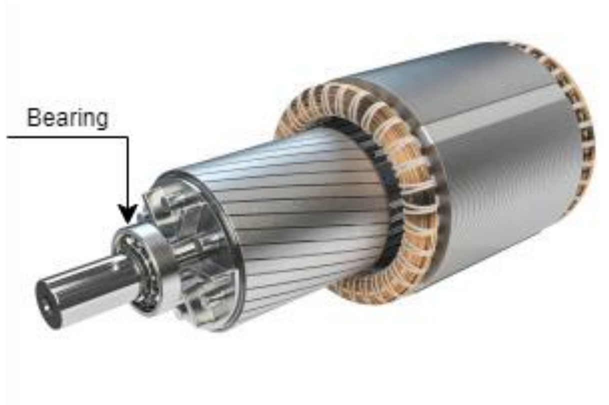


Figure 2.3 - Bearing on PMSM

2.4 Types of PMSMs

PMSMs can be classified into different types (Figure 2.4) based on their rotor design and the arrangement of permanent magnets [25]:

2.4.1 Surface mounted magnets type

In this case, the magnets are affixed to the rotor surface using strong glue or binding, ensuring a uniform gap. The inductances do not depend on the rotor position. In addition, this type has a non-salient pole design, which means that the inductance of the direct axis is equal to that of the quadrature axis. Because of the same flux paths in d and q axis, the reluctance torque disappears. This type of rotor is the most popular. On the other hand, the magnets are subjected to a demagnetising field. In addition, they are affected by the centrifuge forces, which can lead to detachment of the rotor.

2.4.2 Inset magnets type

Inset magnets are mounted on the surface of the rotor and the spaces between the magnets are filled with iron. This arrangement creates a saliency effect, resulting in a slight difference in inductance between the d-axis and the q-axis.

2.4.3 Interior magnets type

The permanent magnets are buried or embedded inside the rotor core. This makes the motor a salient pole type with anisotropic magnetism. In this design, the inductance varies with the rotor position, providing greater mechanical durability and robustness at high speeds. However, it also increases production costs and control complexity.

2.4.4 Flux concentrating type

The magnets are deeply placed in the rotor’s body. The magnets and their axes are radial. This configuration offers the advantage of concentrating the flux generated by the permanent magnets within the rotor, resulting in a stronger magnetic induction in the air gap. This type of machine exhibits a saliency effect. However, surface permanent magnet synchronous motors and interior permanent magnet synchronous motors are more utilized in the industry.

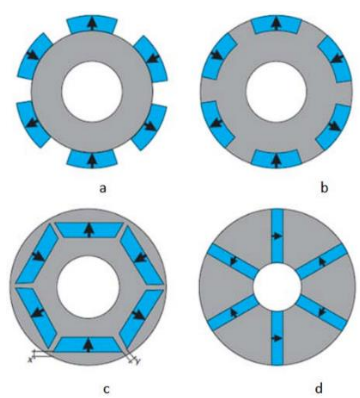


Figure 2.4 - Different types of PMSM. a) surface PMSM, b) inset PMSM, c) interior PMSM, d) flux concentrating PMSM

PMSMs can be classified into two categories based on rotor design: salient and non-salient.

- **Salient rotor PMSMs** also known as Interior PMSMs (IPMSMs), have magnets embedded within the rotor, providing high torque and mechanical robustness. The inductance aren't equal $L_d \neq L_q$

- **Non-salient rotor PMSMs: or Surface-Mounted PMSMs (SPMSMs),** have magnets mounted on the rotor's surface, offering high efficiency and power density. These machines cannot be used for high-speed applications (higher than 3000 rpm), due to their lack of mechanical robustness. The inductance are equal $L_d = L_q$.

The choice of PMSM type depends on factors such as the desired performance characteristics, speed range, torque requirements, and the specific application. Each type has its own advantages and trade-offs in terms of cost, efficiency, torque density, and manufacturing complexity [26].

2.5 Working principle of PMSM

The working principle of PMSMs revolves around the interaction between the rotating magnetic field created by the energized stator windings and the constant magnetic field generated by the permanent magnets on the rotor. When the stator windings are supplied with alternating current, a rotating magnetic field is produced, causing the rotor's permanent magnets to experience a torque that aligns their magnetic field with the stator's rotating field. As a result, the rotor rotates synchronously with the stator's rotating magnetic field at the same speed, generating a continuous torque that drives the rotation of the rotor shaft [26].

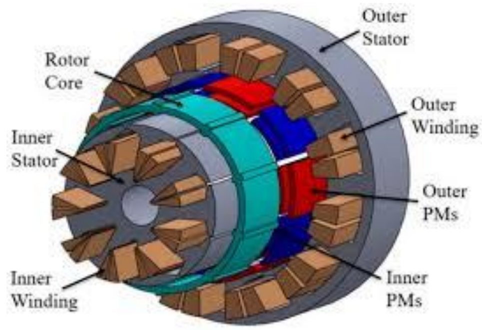


Figure 17 - Working principle of PMSM

2.6 Common Faults in PMSMs

PMSMs can experience various faults, including electrical faults, mechanical faults, and magnetic faults [27] [28] [29].

2.6.1 Electrical faults:

Electrical faults primarily include issues like incorrect motor winding connections, grounding errors, stator phase winding short circuits, and complete phase open circuits. Stator faults account for 38% of all motor faults, with inter-turn short circuits in the stator windings being the most prevalent in Permanent Magnet Synchronous Motors (PMSM). With prolonged operation, insulation wear, overheating, or overloading can lead to breakdowns in the motor's stator winding insulation system, causing short circuits between stator turns.

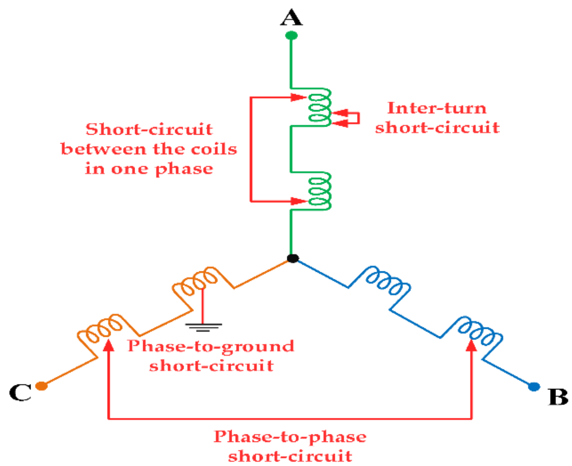


Figure 18 – Stator faults of PMSM

2.6.2 Mechanical faults:

Mechanical faults in motors primarily include magnet damage, shaft bending, bolt loosening, bearing faults, and air gap eccentricity.

Bearing faults, which account for almost 40–50% of all motor faults, occur due to environmental mechanical vibrations, shaft misalignment, poor lubrication, overload, corrosion, and other factors. Bearings inevitably experience fatigue, even during normal operation. This can lead to bearing damage and failure, which can manifest as cage faults, inner race faults, outer race faults, and ball Eccentricity faults involve an inconsistent air gap between the rotor and the stator, often caused by improper installation, lack of bolts, shaft misalignment, or rotor imbalance. Eccentricity faults can be static, dynamic or mixed faults.

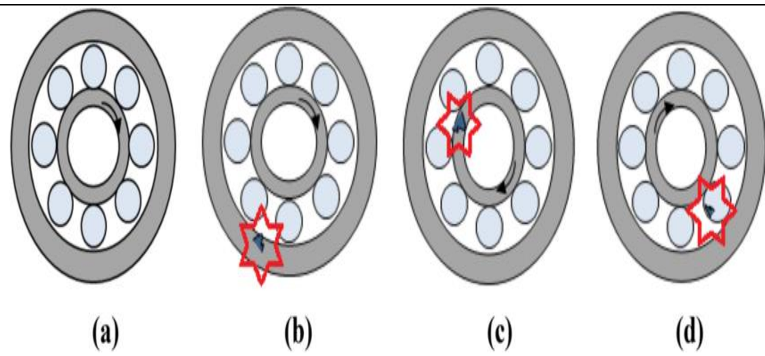


Figure 19 – Fault Location Schematic for Bearing Components. a) healthy bearing, b) outer race fault, c) inner race fault, and d) ball fault.

2.6.3 Magnetic faults:

The demagnetization fault is a specific issue encountered in PMSMs. Permanent magnets within the PMSM can lose their magnetization due to various factors such as physical damage, high temperatures, excessive stator currents, large short-circuit currents caused by inverters or stator faults, and the natural aging of the magnet itself.

Detecting and diagnosing these faults early is crucial for preventing further damage and ensuring the efficient and safe operation of the motor.

2.7 Causes of Faults in PMSM

Faults in PMSMs can arise from various sources, including **[27] [28]:**

- High temperatures and excessive currents;
- Insulation breakdown, overheating, or mechanical stress in the stator windings;
- Mechanical stress or manufacturing defects in the rotor;
- Wear, misalignment, inadequate lubrication, or environmental conditions;
- Excessive vibrations, moisture, dust, or temperature variations impacting overall motor performance.

2.8 PMSM Fault Frequency Spectrum

In PMSMs, most electrical and magnetic faults produce distinct harmonics in motor current signature analysis [30].

The frequencies corresponding to these faults can be described as follows:

$$f_d = \left[1 \pm \frac{k}{n_p}\right] f_s$$

Where k represents an integer constant, and n_p indicates the number of pole pairs in the motor, f_s denotes the supply frequency.

2.8.1 Motor Current Signature Analysis (MCSA) for PMSM Fault Detection

Motor Current Signature Analysis (MCSA) is a powerful and non-invasive diagnostic technique used for detecting faults in PMSM. MCSA involves analyzing the current signal of the motor to identify characteristic patterns and anomalies indicative of various types of faults. MCSA detects faults by examining the frequency components of the motor's current signal [31] [32].

2.8.2 Advantages of MCSA:

Some of the key advantages of MCSA include [31] [32]:

- **Non-Invasive:** Does not require motor disassembly, allowing for real-time monitoring without interrupting operations;
- **Cost-Effective:** Uses readily available current sensors and signal processing techniques;
- **Comprehensive:** Capable of detecting a wide range of electrical and mechanical faults.

2.8.3 MCSA Methodology:

The methodology of MCSA involves several key steps [31] [32]:

- **Data Acquisition:** Motor current signals are measured using current sensors.
- **Signal Processing:** Techniques such as Fast Fourier Transform (FFT) are applied to convert time-domain signals into the frequency domain.
- **Fault Diagnosis:** The resulting frequency spectrum is analyzed to identify characteristic fault frequencies and patterns.

2.8.4 Practical Implementation of MCSA:

Implementing Motor Current Signature Analysis (MCSA) in a practical setting involves several steps:

- **Sensor Placement:** Current sensors are placed on the motor's power supply lines.
- **Signal Analysis:** Advanced software tools are used to perform FFT and other signal processing techniques.
- **Fault Identification:** Diagnostic algorithms compare the frequency spectrum with known fault signatures to determine the presence and type of faults.

2.9 PMSMs Healthy Model

Putting PMSM models into state form allows the latter simulate in the dq-frame, with stator currents and mechanical speed as state variables, and the stator voltages as control vectors and the resistive torque Tl as the disturbance.

In the field oriented frame dq, the field vector is forced to line up with the d axis $(\varphi_q = \dot{\varphi}_q = 0)$. The healthy model of the machine in this frame is given by the following state equation [1] [13] [17]:

$$\dot{x} = f\left(x\right) + Bu + DCr \tag{2.1}$$

The state vector x, the input matrix B and the vector D are given by:

$$x=\begin{pmatrix}x_1\\x_2\\x_3\end{pmatrix}=\begin{pmatrix}i_d\\i_q\\\omega_r\end{pmatrix};u=\begin{pmatrix}u_d\\u_q\end{pmatrix}=\begin{pmatrix}V_{sd}\\V_{sq}\end{pmatrix};B=\begin{pmatrix}b_1&0\\0&b_2\\0&0\end{pmatrix};D=\begin{pmatrix}0\\0\\d\end{pmatrix} \tag{2.2}$$

With the following expression for the field vector f(x):

$$\begin{pmatrix}f_1(x)\\f_2(x)\\f_3(x)\end{pmatrix}=\begin{pmatrix}a_1x_1+a_2x_2x_3\\a_3x_2+a_4x_3+a_5x_1x_3\\a_6x_2+a_7x_3+a_8x_1x_2\end{pmatrix} \tag{2.3}$$

The components of this vector are expressed in terms of the PMSM parameters:

Where:

i_{dq} : dq-axis components of the stator current;

V_{dq} : Stator voltages;

R_s : Stator resistance;

L_{dq} : Stator inductances;

φ_f : Magnetic flux linkage;

ω_r : Rotor speed;

f : Friction coefficient;

J : Inertia constant

2.10 Modeling of PMSMs in presence of disturbance

The PMSM parameters are subject to additional signals referred to as unknown inputs (disturbances and noise) resulting from different operating conditions, along with modeling uncertainties For instance, the stator resistance R_s varies directly with the temperature fluctuations of the machine, while the variations in L_q are related to magnetic saturation phenomena. An unknown but always limited term $\delta(x, \delta ai)$ is added to the models (2.1), which then take the following form: [33]

$$\dot{x} = f(x) + B \cdot u + d \cdot C_r + \delta(x, \delta a_i) \tag{2.4}$$

One way to simulate the effect of parametric variations on the machine's behavior is to induce a random change in the system coefficients at a given moment [34].

The parametric variations is expressed as follows:

$$\begin{cases} R_s \quad \to R_s^0 + \delta R_s; \quad L_q \quad \to L_q^0 + \delta L_q; \quad L_d \quad \to L_d^0 + \delta L_d \\ \varphi_f \quad \to \varphi_f{}^0 + \delta\varphi_f; \quad f \quad \to f^0 + \delta f; \quad j \quad \to j^0 + \delta j \end{cases}$$

This results in the following variations in the coefficients of the model (2.1):

$$a_i \to a_i^0 + \delta a_i; \quad b_i \to b_i^0 + \delta b_i; \quad d \to d^0 + \delta d$$

The expression for the variations of these coefficients is obtained using the formula for the exact total differential of a function with multiple variables. Let A be a function from .The exact total differential of $A(x, y, \ldots, z)$, the image of $(x, y, \ldots, z)$ is given by:

$$dA = \delta A = \frac{\partial A}{\partial x} \cdot dx + \frac{\partial A}{\partial y} \cdot dy + \cdots + \frac{\partial A}{\partial z} \cdot dz \tag{2.4}$$

According to (2.1) and (2.4), the disturbances $\delta(x, \delta a_i)$ in the case of the PMSM will take the following form:

$$\delta(x, \delta a_i) = \begin{pmatrix} \delta_1(x) \\ \delta_2(x) \\ \delta_3(x) \end{pmatrix} = \begin{pmatrix} \delta\, a_1 x_1 + \delta b_1 u_d \\ \delta\, a_3 x_2 + \delta\, a_4 x_3 + \delta b_2 u_q \\ \delta a_6 x_2 + \delta a_7 x_3 + \delta d T_L \end{pmatrix} \tag{2.5}$$

Thus, we obtain the variations of the components (a_i, b_i and d):

$$\begin{cases} \delta a_1 = \frac{R_s}{L_d}\left(\frac{\delta L_d}{L_d} - \frac{\delta R_S}{R_S}\right); \delta a_3 = \frac{R_s}{L_q}\left(\frac{\delta L_q}{L_q} - \frac{\delta R_S}{R_S}\right); \delta a_4 = \frac{\varphi_f}{L_d}\left(\frac{\delta L_d}{L_d} - \frac{\delta \varphi_f}{\varphi_f}\right); \delta d = \frac{n_p}{J}\left(\frac{\delta J}{J}\right) \\ \delta a_6 = -\frac{n_p^2 \varphi_f}{J}\left(\frac{\delta J}{J} - \frac{\delta \varphi_f}{\varphi_f}\right); \delta a_7 = -\frac{f}{J}\left(\frac{\delta f}{f} - \frac{\delta J}{J}\right); \delta b_1 = -\frac{1}{L_d}\left(\frac{\delta L_d}{L_d}\right); \delta b_2 = \frac{1}{L_q}\left(\frac{\delta L_q}{L_q}\right) \end{cases}$$

Based on these results, the new model of the PMSM in presence of parametric disturbances is:

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{pmatrix} = \begin{pmatrix} a_1 x_1 + a_2 x_2 x_3 + b_1 u_d + \delta_1(x) \\ a_3 x_2 + a_4 x_3 + a_5 x_1 x_3 + b_2 u_q + \delta_2(x) \\ a_6 x_2 + a_7 x_3 + dC_r + \delta_3(x) \end{pmatrix} \quad (2.6)$$

2.11 Modelled Faults in the PMSM Model

Faults create asymmetries in the machine, generating harmonics (sinusoidal components) in the stator currents. In the case, the dq-frame currents thus take the following form:

$$\begin{cases} i_d \rightarrow i_d + \sum_{n_f}^{i} A_i \sin(\omega_i t + \theta_i) \\ i_q \rightarrow i_q + \sum_{n_f}^{i} A_i \cos(\omega_i t + \theta_i) \\ \omega_i = 2\pi.(F_{fault} + F_s) \\ i = 1, \ldots, n_f \end{cases} \quad (2.7)$$

Where:

nf : The number of harmonics produced by the faults,

Fs : The fundamental frequency;

F_{fault} : The characteristic frequency of the fault.

With the unknown amplitude Ai and the phase parameters θi that describe the initial condition of the fault.

We note that The MCSA method is utilized to detect and subsequently analyze faults frequency.

The following exosystem is able to model the previous faults [5] [11]:

$$\dot{z} = S \cdot z \tag{2.8}$$

Where:

$$\begin{cases} S = diag(S_i) \\ S_i = \begin{bmatrix} 0 & \omega_i \\ -\omega_i & 0 \end{bmatrix} \\ i = 1, 2, \dots, n_f \end{cases}$$

And

$$\begin{cases} size(S) = 2n_f \times 2n_f \\ size(z) = 2n_f \times 1 \end{cases}$$

After this, we can rewrite the dq-frame currents equation (2.1) with the perturbing terms into the next form:

$$\begin{pmatrix} i_{sd} \to i_{sd}^0 + Q_d z \\ i_{sq} \to i_{sq}^0 + Q_q z \end{pmatrix} \tag{2.9}$$

Where:

$$\begin{pmatrix} Q_d = (1 \quad 0 \quad 1 \quad 0 \quad \dots \quad 1 \quad 0) \\ Q_q = (0 \quad 1 \quad 0 \quad 1 \quad \dots \quad 0 \quad 1) \end{pmatrix}$$

With: $size(Q_d) = size(Q_q) = n_f \times 1$

Using the exosystem, we get the dq-frame currents in the following form:

$$\begin{pmatrix} i_{sd} \to i_{sd}^0 + Q_d Sz \\ i_{sq} \to i_{sq}^0 + Q_q Sz \end{pmatrix} \tag{2.10}$$

After developing (2.10), we get the new current dynamics in the presence of modelled faults:

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} a_1 x_1 + a_2 x_2 x_3 + b_1 u_d - (a_1 Q_d + a_2 Q_q x_3 + Q_d S) z \\ a_3 x_2 + a_4 x_3 + a_5 x_1 x_3 + b_2 u_q - (a_3 Q_d + a_4 Q_q x_3 + Q_d S) z \end{pmatrix} \quad (2.11)$$

Using (2.11) yield the new model of the SMPM in the form:

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{pmatrix} = \begin{pmatrix} a_1 x_1 + a_2 x_2 x_3 + b_1 u_d + \Gamma_d z \\ a_3 x_2 + a_4 x_3 + a_5 x_1 x_3 + b_2 u_q + \Gamma_d z \\ a_6 x_2 + a_7 x_3 + dC_r \end{pmatrix} \quad (2.12)$$

Where:

$$\begin{pmatrix} \Gamma_d \\ \Gamma_q \end{pmatrix} = \begin{pmatrix} a_1 Q_d + a_2 Q_q x_3 + Q_d S \\ a_3 Q_d + a_4 Q_q x_3 + Q_d S \end{pmatrix}$$

2.12 Simulation results:

After completing the model preparation process to simulate the PMSM, we will present below the simulation results of the PMSM, showing the evaluation of its measurable quantities: rotor speed (ωr), electromagnetic torque (Te), and stator currents (id, iq).

First, a machine simulation will be presented for a healthy machine without load. Subsequently, the machine is simulated under normal conditions with a load of 0.05Nm, followed by the machine under load 0.05 Nm with varying Rs (+50%) parameters. Table (2.1) shows the machine parameters used in the simulation in the MATLAB environment.

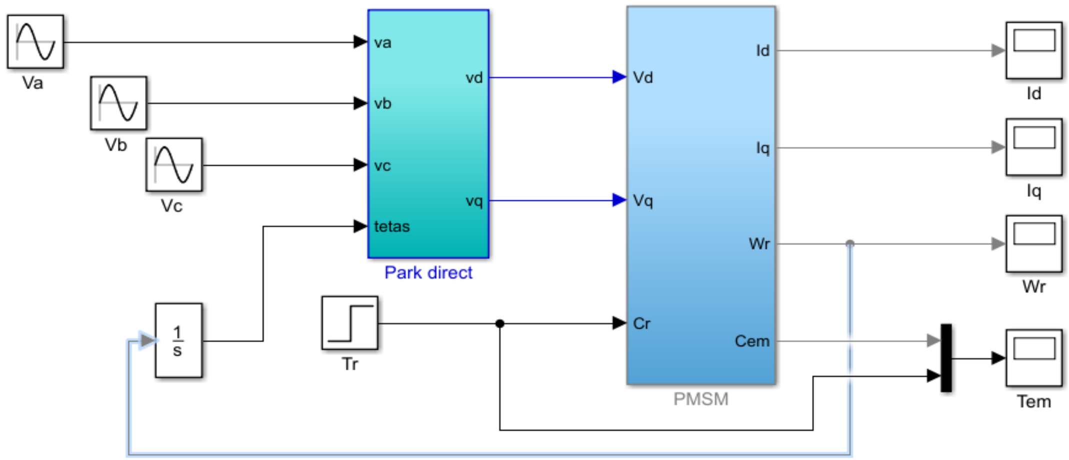


Figure 20 – MATLAB Simulink of PMSM in open loop

The table 2.1 contains the parameters and their nominal numerical values of the studied machine. As showed in Table 2.1, we are working on a surface PMSM, which mean that L_d=L_q. in this case (a8 = 0).

Table 2.1 - PMSM parameters

Parameter Value	**Parameter Value**
Rated output power (Prated)	22 W
Rated speed (nrated)	1500 rpm
Rated torque (Trated)	0.05 Nm
Rated voltage (Vrated)	220 V
Pole pairs (np)	2
Stator resistance (Rs)	3.4 Ohm
Stator inductance (Ld)	0.0121 mH
Rotor inductance (Lq)	0.0121 mH
PM flux-linkage (ϕf)	0.013 Wb
Inertia constant (J)	0.0001 Kg × m2
Viscous friction (f)	0.00005 Kg × m2/s

2.12.1Healthy PMSM without load

In this case, we simulate the machine without load for a healthy state. Figure 1 shows the evolution of the rotor speed, the electromagnetic torque, the id current, and the iq current, respectively. In the steady state, we notice that the speed stabilizes at 314 rad/s, the machine torque approaches zero, the id current stabilizes at 6A, and the iq current approaches zero.

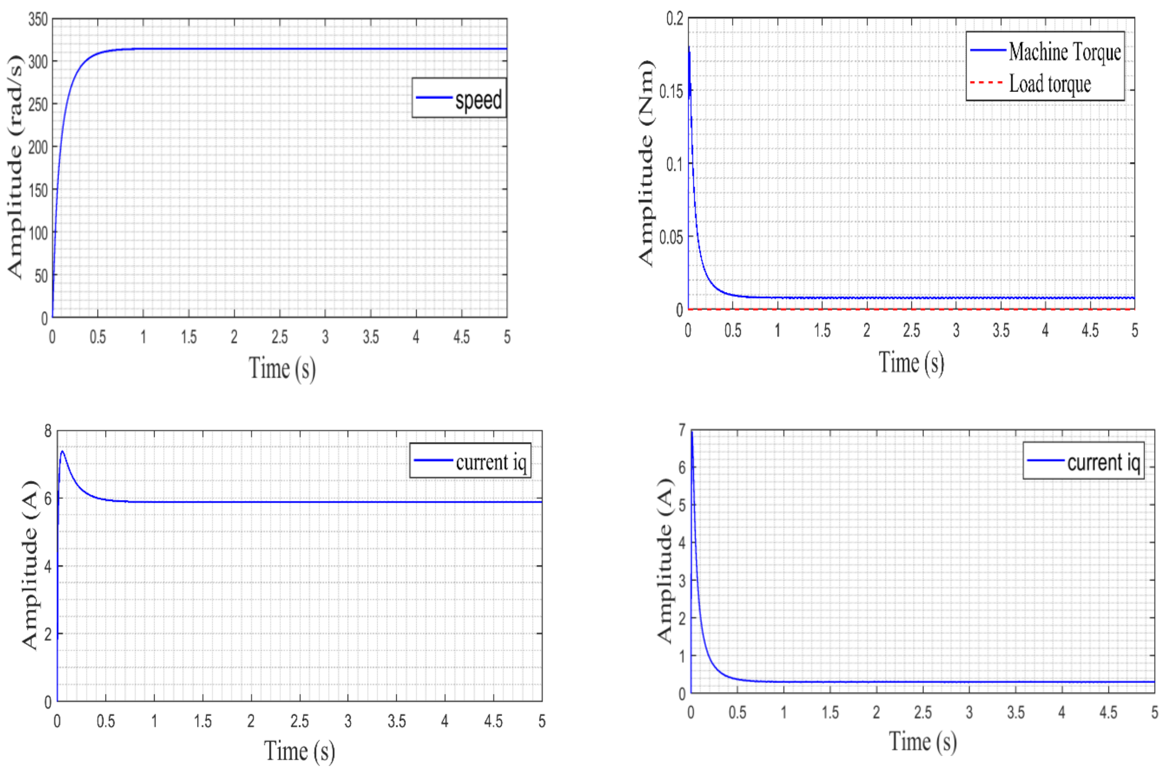


Figure 21 – Simulation of PMSM in a healthy state without load torque.

2.12.2Healthy PMSM under load

In this case, we start the machine without load and apply a load of 0.05 Nm at t = 1s. In the steady state, following the application of the load, we observe a decrease in speed to 200 rad/s, an increase in machine torque of 0.05 Nm, stabilization of the id current at 7A, and the iq current approaching 2A.

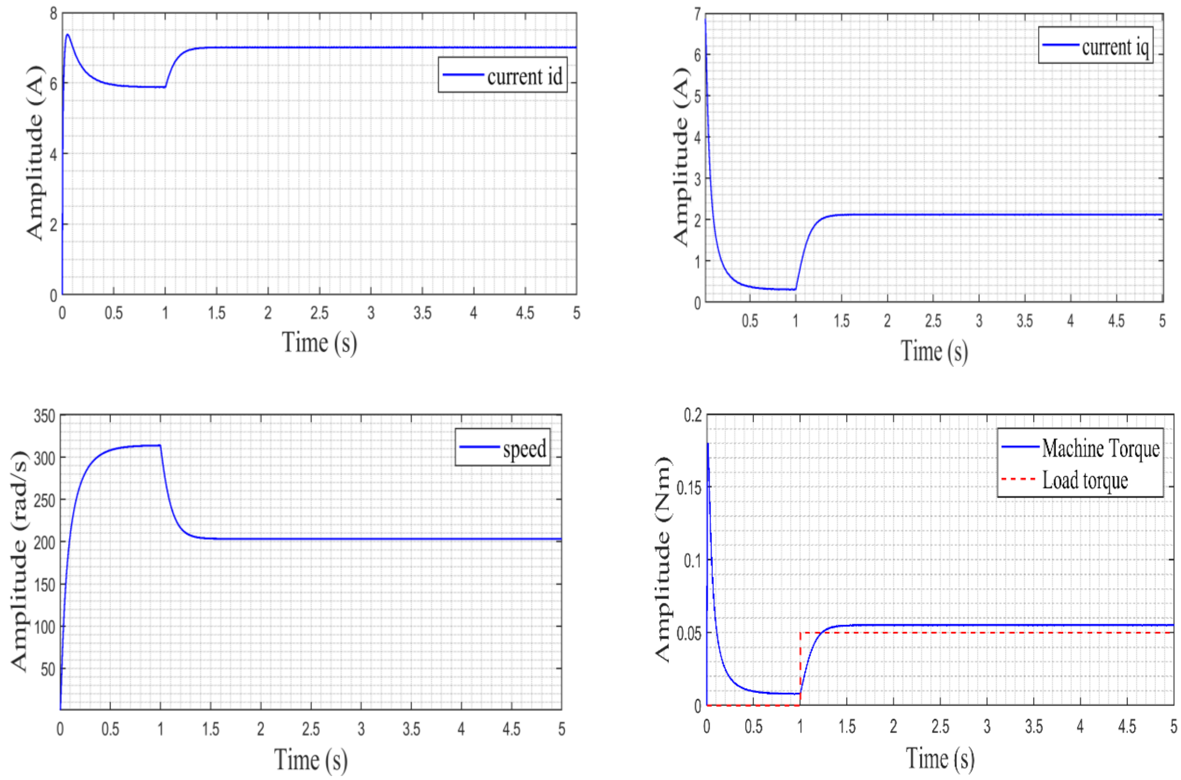


Figure 22 – Simulation of PMSM in a healthy state under a load torque of 0.05 Nm

2.12.3PMSM under stator resistance variation

In this case, we start the machine with a load of 0.05 Nm. At t = 2s, we increase the Rs value to 1.5Rs. Figure 2.11 shows the simulation results.

After the increase in Rs, we notice that the speed increases to 210 rad/s and the id current decreases to 4.5A.

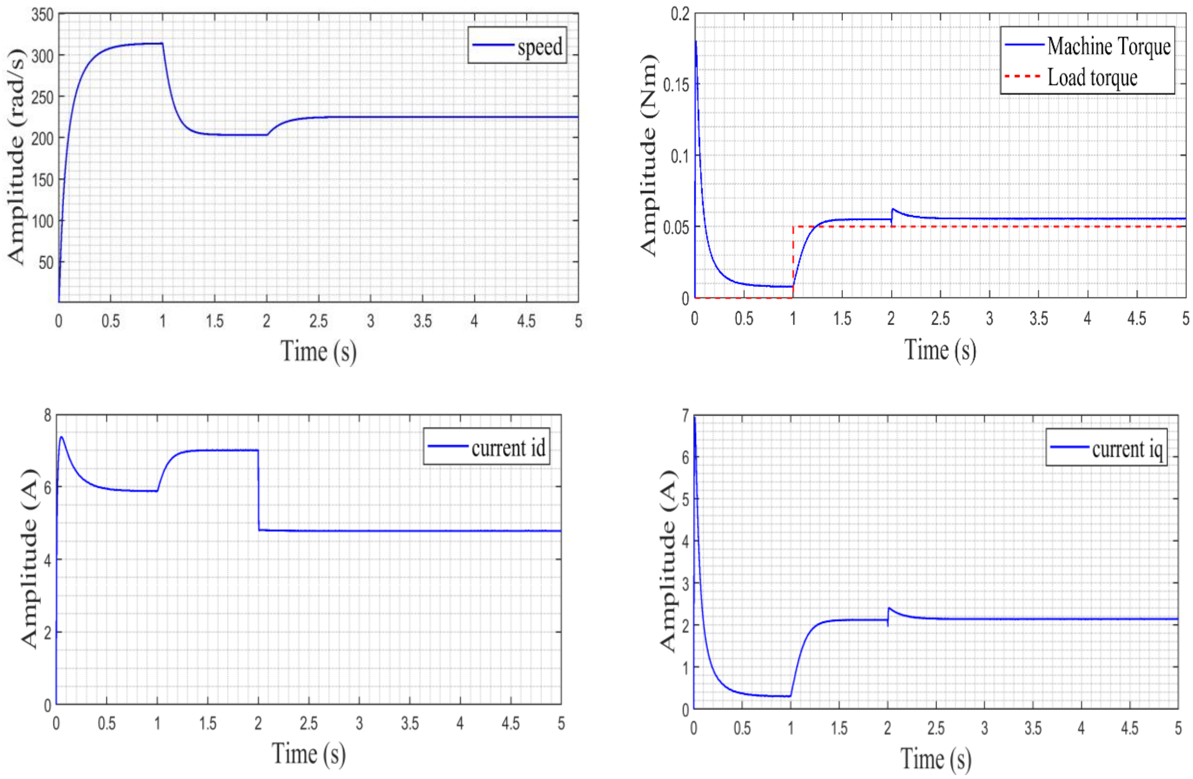
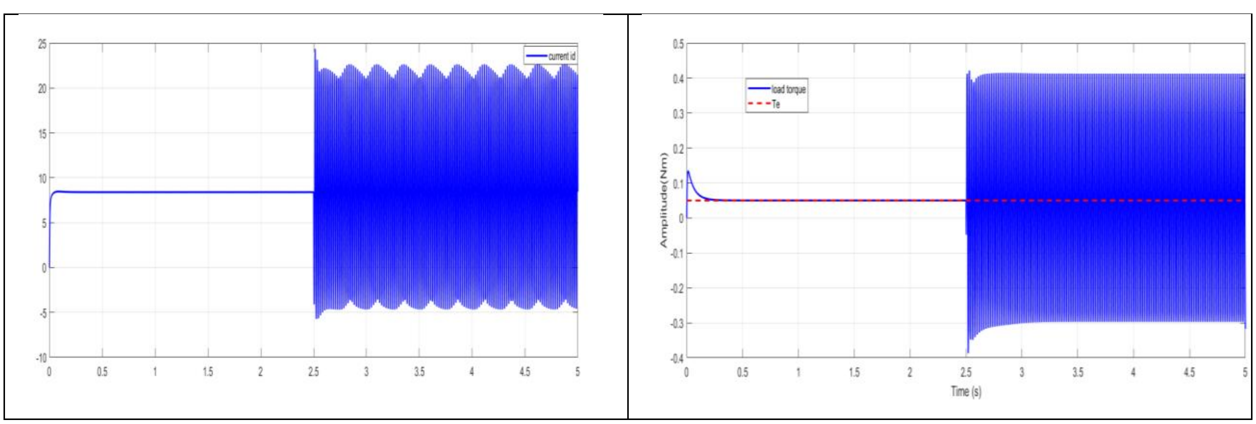


Figure 23 – Simulation of PMSM under parameter variation with Rs = 1.5Rs

2.12.4 PMSM under stator fault

In this scenario, we inject a stator fault at t = 2.5s. The simulation results are depicted in Figure 4, showing that the presence of faults increases the ripple in all signals.



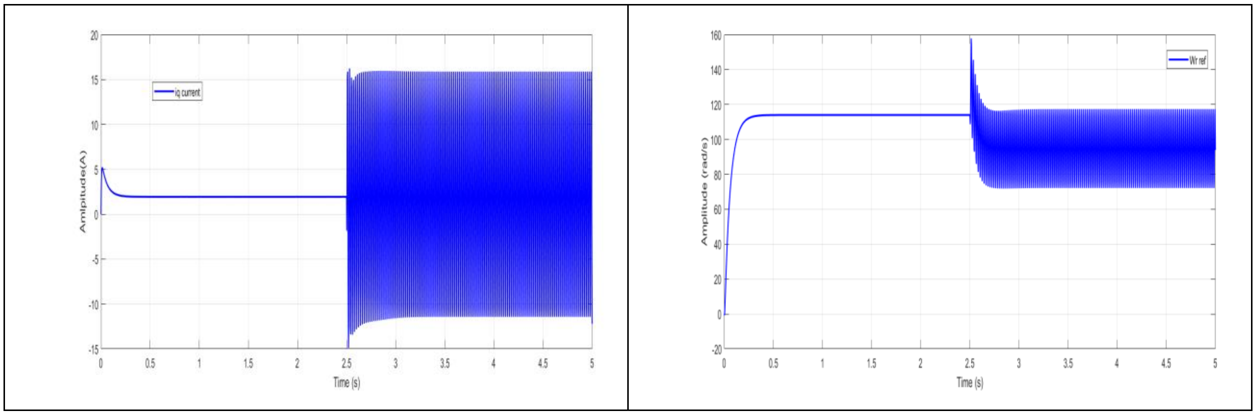


Figure 2.12: Simulation of PMSM under stator fault

2.13 Conclusion

In this chapter, we provided an overview of PMSMs and their faults, along with the methods used for their detection. Following this, we presented a mathematical model that allows for simulating the machine in both a healthy and faulty state. The simulation results in open loop illustrated the behavior of the machine in these states. Thus, it is possible to use this model in the following chapters in order to develop an FTC based on sliding mode control.

Chapitre 3

Passive fault-tolerant control of PMSM

3.1 Introduction

The Permanent Magnet Synchronous Motor (PMSM) have many recognized features. However, PMSMs are vulnerable to faults and parameter variations, which have the potential to greatly affect their performance and safety. To solve these issues, fault-tolerant control (FTC) strategies are deployed to guarantee uninterrupted operation even under faulty conditions, accounting for disturbances and parameter variations. This chapter focuses on the implementation of PFTC for PMSMs using a first order SMC then a second order SMC. Furthermore. The efficacy of the proposed control scheme will be demonstrated through simulations.

3.2 Sliding Mode Control (SMC)

3.2.1 Generalities and principles:

SMC is a robust control strategy widely used in various engineering applications. It is particularly effective in systems where uncertainties, disturbances, and nonlinearities are present. The key concept behind SMC is to force the system states to converge to a predefined sliding surface and remain on it, resulting in robust and stable control [6] [7][35]. We distinguish three parts in the phase plane as showed in Figure 3.1:

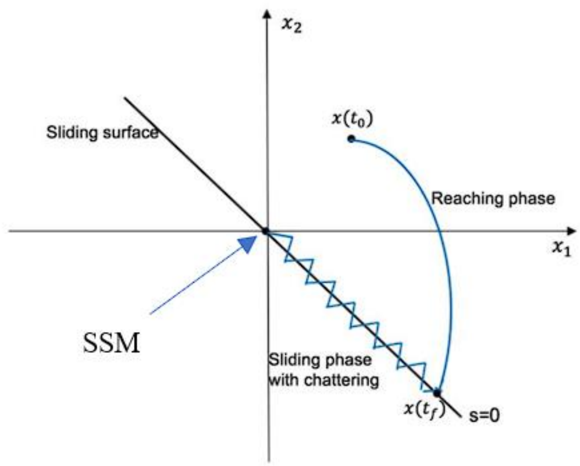


Figure 3.1: Different trajectory modes in the phase plane

- Reaching phase or convergence mode (CM): This is the mode during which the variable to be regulated moves from any initial point in the phase plane and tends towards the switching surface S(x)=0. This mode is characterized by the control law and convergence criterion.

- Sliding Mode (SM): This is the mode during which the state variable has reached the sliding surface and tends towards the origin of the phase plane. The dynamics of this mode are characterized by the choice of the sliding surface S(x) =0.

- Steady-State Mode (SSM): This mode is added to study the system's response around its equilibrium point (origin of the phase plane). It is characterized by the quality and performance of the control.

3.2.2 Ideal sliding mode regime

The ideal sliding mode regime refers to the theoretical case where the system dynamics are perfectly constrained to a predetermined sliding surface (S=0). Under this regime, the system would show continuous and smooth transition over different operating points, demonstrating high stability and robustness against disturbances and uncertainties.

3.2.3 Real sliding mode regime

The Real Sliding Mode is the practical implementation of the sliding mode strategy. It comprises system dynamics affected by model uncertainties, measurement noises, and actuator nonlinearities. It is characterized by the continuous switching of different operating points, which cause chattering.

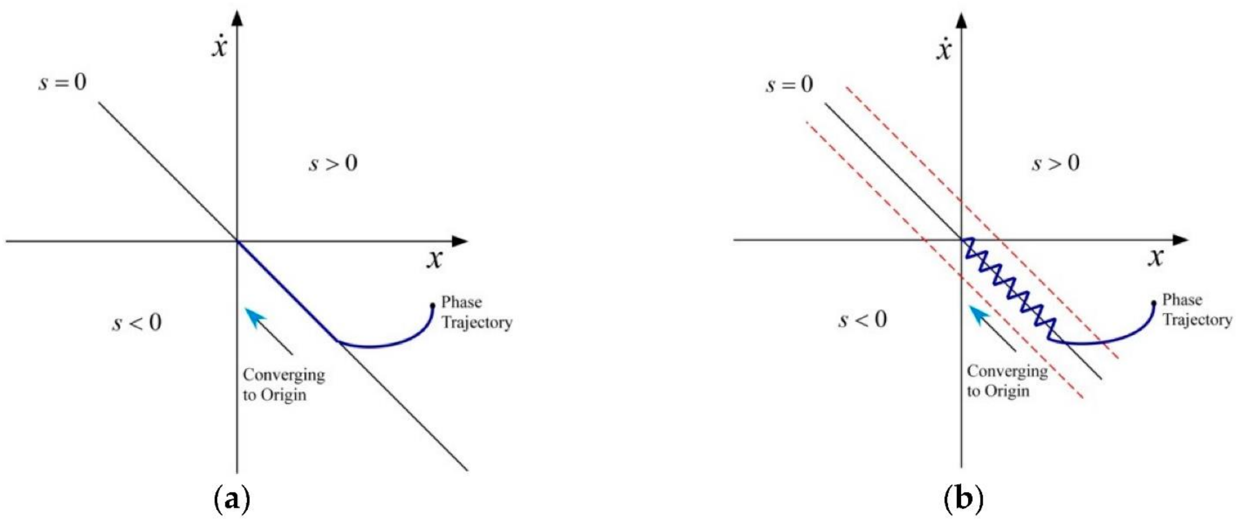


Figure 3.2-Sliding mode regimes: (a) Ideal sliding mode regime, (b) Real sliding mode regime

3.3 Design of the SMC Control

The design of sliding mode control carefully considers stability and performance aspects. Generally, implementing this type of control requires following three key steps.

3.3.1 Selecting the sliding surface:

The frequently adopted surface for achieving sliding mode, ensuring the state converges to its reference as outlined by Slotine (Slotine, 1984)[36], is defined by:

$$S(x) = (\frac{d}{dt} + \lambda)^{r-1} e(x) \tag{3.1}$$

Where λ, r and, $e(x) = (x_{ref} - x)$ represent a positive constant, the relative degree, and the deviation between the variable to be controlled and its reference.

3.3.2 Convergence and Existence Conditions:

The criteria for existence and convergence are the conditions that enable the various system dynamics to converge to the sliding surface and remain there, regardless of disturbances. Two considerations ensure the convergence mode.

3.3.3 Switching Control Law:

This is the initial proposed and studied convergence condition by (Emelyanov, 1967) and (Utkin, 1977). It involves giving the surface dynamics that converge to zero, defined as:

$$S(x)\dot{S}(x) < 0 \tag{3.2}$$

3.3.4 Lyapunov Function:

This condition is the second for convergence. The Lyapunov function, a positive scalar function (V(x) > 0) for the system's state variables, is defined as:

$$V(x) = \frac{1}{2} S^2(x) \tag{3.3}$$

The derivative of this function is:

$$\dot{V}(x) = S(x)\dot{S}(x) \tag{3.4}$$

To ensure the function V(x) decreases and converges to zero, its derivative must be negative $\left(V^{\cdot}(x) \ < \ 0\right)$. This condition holds only if (3.2) is satisfied.

3.3.5 Control Synthesis:

Achieving a sliding mode necessitates a discontinuous control. The sliding surface should be attractive from both sides. Therefore, while this discontinuous control is essential, it does not preclude adding a continuous component to it. The continuous component aims to minimize the amplitude of the discontinuous part. In the presence of disturbances, the discontinuous part primarily verifies the attractiveness conditions. To compel the system to track the prescribed trajectory, it suffices to make S = 0.

To achieve this, a control U_{at} is added to the equivalent control Ueq in the form:

$$U = U_{eq} + U_{at} \tag{3.5}$$

The requisite condition for the system states to follow the trajectory defined by the sliding surfaces is $S = 0 \Rightarrow \dot{S} = 0$, which necessitates defining the equivalent control Ueq.

Meanwhile, the control law ensuring attractiveness U_{at} is given by:

$$U_{at} = -k\,sign(S) \tag{3.6}$$

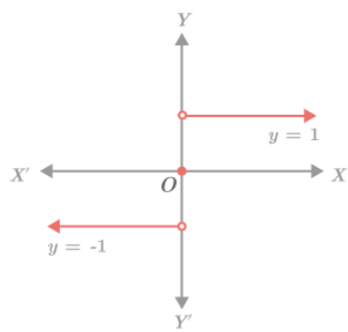


Figure 3.3-Sign function

We could attune the chattering by replacing the sign function with a sigmoid function, which is defined in the following form:

$$F = \frac{s}{|s| + m} \tag{3.7}$$

Where |s| >> $m>0$.

3.3.6 Advantages:

SMC offers various advantages:

- **Resilience to Parametric Variations:** SMC excels in its ability to maintain performance despite changes in system parameters.
- **Disturbance Rejection:** SMC effectively minimizes the impact of disturbances on system operation.
- **Simplicity in Design:** SMC is recognized for its straightforward design process.
- **Ease of Practical Implementation:** SMC is easily implemented in practical applications.

3.4 Application of first SMC to PMSM

Our aim is to design a PFTC for the PMSM that ensures the speed Ω and flux φd follow their desired references Ω* and φd* despite the load torque Cr and parametric disturbances. This control strategy should be robust, eliminating the need for fault detection or control reconfiguration. The PFTC method uses a fixed controller and considers faults as uncertainties in the control law design. A robust sliding mode control (SMC) stability in the presence of faults [12] [36] [37].

Let's consider the results presented in the previous, the PMSM model is.

$$\begin{pmatrix} \dot{i}_d \\ \dot{i}_q \\ \dot{\omega}_r \end{pmatrix} = \begin{pmatrix} a_1 i_d + a_2 i_q \omega_r + b_1 u_d \\ a_3 i_q + a_4 \omega_r + a_5 i_d \omega_r + b_2 u_q \\ a_6 i_q + a_7 \omega_r + dC_r \end{pmatrix} \tag{3.8}$$

In designing an SMC strategy tailored to the PMSM, the following sliding surfaces are selected:

$$\begin{pmatrix} S_1(t) = \omega_r - \omega_r^{ref} \\ S_2(t) = i_q - i_q^{ref} \\ S_3(t) = i_d - i_d^{ref} \end{pmatrix} \tag{3.9}$$

Where ωr_{ref}, id_{ref}, and iq_{ref} represent the reference speed and currents.

3.4.1 Speed regulator

Applying the sliding mode theorem (Utkin, 1977), the required condition for the system states to track the desired trajectories is S1 (t) = 0:

$$\dot{S}_1(t) = (\dot{\omega}_r - \dot{\omega}_r^{ref}) = 0 \tag{3.10}$$

In this case, the equivalent control is given by:

$$i_q^{eq} = \frac{1}{a_6}(-a_7\omega_r - dC_r + \dot{\omega}_r^{ref}) \tag{3.11}$$

The control law ensuring attractiveness is given by:

$$i_q^{at} = -k_1 sign(S_1) \qquad k_1 > 0 \tag{3.12}$$

As a result, the speed regulator (SMC):

$$i_q^{eq} = \frac{1}{a_6}(-a_7\omega_r - dC_r + \dot{\omega}_r^{ref}) - K_1 sign(S_1) \tag{3.13}$$

3.4.2 Current Regulators

In this case, the necessary conditions for the states to follow the desired trajectory are S2 (t) = 0 and S3 (t) = 0. Therefore, we have:

$$\begin{pmatrix} \dot{S}_2(t) = \dot{i}_q - \dot{i}_q^{ref} = 0 \\ \dot{S}_3(t) = \dot{i}_d - \dot{i}_d^{ref} = 0 \end{pmatrix} \tag{3.14}$$

Using the derivative of the current surfaces, we can generate u_q^{eq} and u_d^{eq} in the following manner:

$$\begin{cases} u_q^{eq} = \dfrac{1}{b_2}(\dot{i}_q^{ref} - a_3 i_q - a_4\omega_r - a_5 i_d \omega_r) \\ u_d^{eq} = \dfrac{1}{b_1}(\dot{i}_d^{ref} - a_1 i_d - a_2 i_q \omega_r) \end{cases} \tag{3.15}$$

The control law ensuring attractiveness is given by:

$$\begin{pmatrix} u_q^{at} & = -k_2 sign(S_2) \\ u_d^{at} & = -k_3 sign(S_3) \end{pmatrix} \qquad k_2, k_3 > 0 \tag{3.16}$$

The global form of the SMC law will be as follows:

$$\begin{cases} u_q^{nom} = \dfrac{1}{b_2}(i_q^{ref} - a_3 i_q - a_4 \omega_r - a_5 i_d \omega_r) - k_2 sign(\mathrm{S}_2) \\ u_d^{nom} = \dfrac{1}{b_1}(i_d^{ref} - a_1 i_d - a_2 i_q \omega_r) - k_3 sign(\mathrm{S}_3) \end{cases} \tag{3.17}$$

3.4.3 Stability analysis

The control objective is to compel the speed to track its reference ($\omega_r \rightarrow \omega_{ref}$) and concurrently maintain $i_d \rightarrow 0$ despite parametric variations and load torque effects. If e_d, e_q, and e_ω represent the errors in currents and speed, then their dynamics can be described as:

$$\begin{pmatrix} \dot{e}_d & = a_1 i_d + a_2 i_q \omega_r + b_1 u_d - \dot{i}_d^{ref} \\ \dot{e}_q & = a_3 i_q + a_4 \omega_r + a_5 i_d \omega_r + b_2 u_q - \dot{i}_q^{ref} \\ \dot{e}_\omega & = a_6 i_q + a_7 \omega_r + a_8 i_d i_q + dC_r - \dot{\omega}_r^{ref} \end{pmatrix} \tag{3.18}$$

Let's consider: $k_1 = \dfrac{k_\omega}{a_6}; k_2 = \dfrac{k_q}{b_2}; k_3 = \dfrac{k_d}{b_1}$

We obtain:

$$\begin{cases} \dot{e}_d = -k_d sign(S_3) \\ \dot{e}_q = -k_q sign(S_2) \\ \dot{e}_\omega = -k_\omega sign(S_1) \end{cases} \tag{3.19}$$

Let consider the following Lyapunov function:

$$V = \frac{1}{2}e_i^2 \tag{3.20}$$

The time derivative of V is:

$$\dot{V} = e_i(-k_i sign(S_i)) \tag{3.21}$$

At t $\rightarrow \infty$, the derivative of the Lyapunov function given by (3.20) becomes:

$$V^{\bullet} < -k_i e_i^{\,2} \tag{3.22}$$

From (3.21) we confirm that $\dot{V} \leq 0$

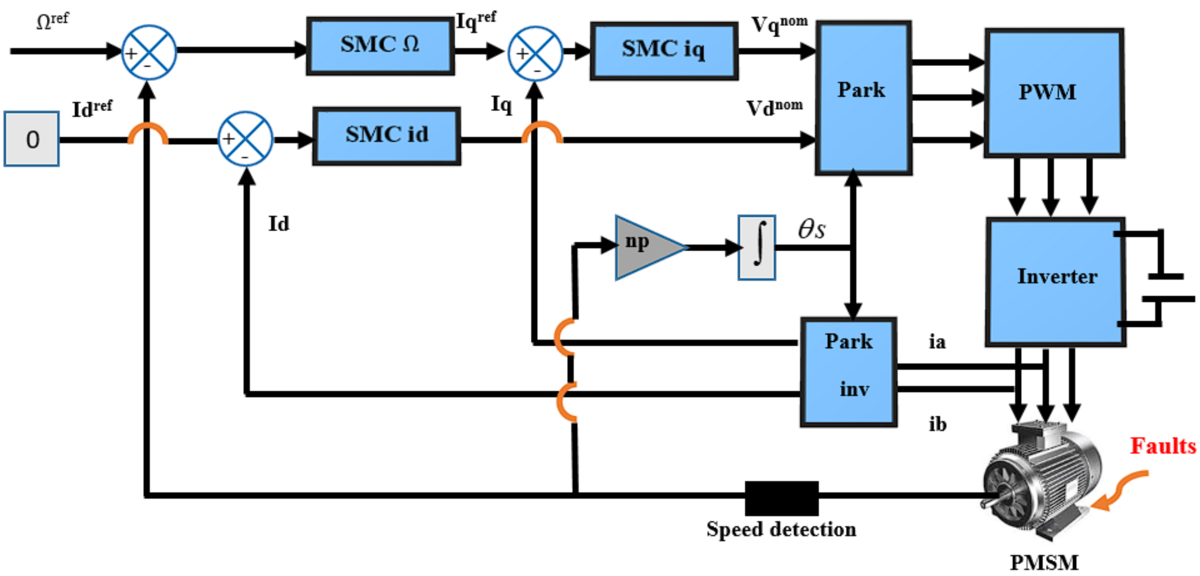


Figure 3. 4: Passive FTC based on SMC

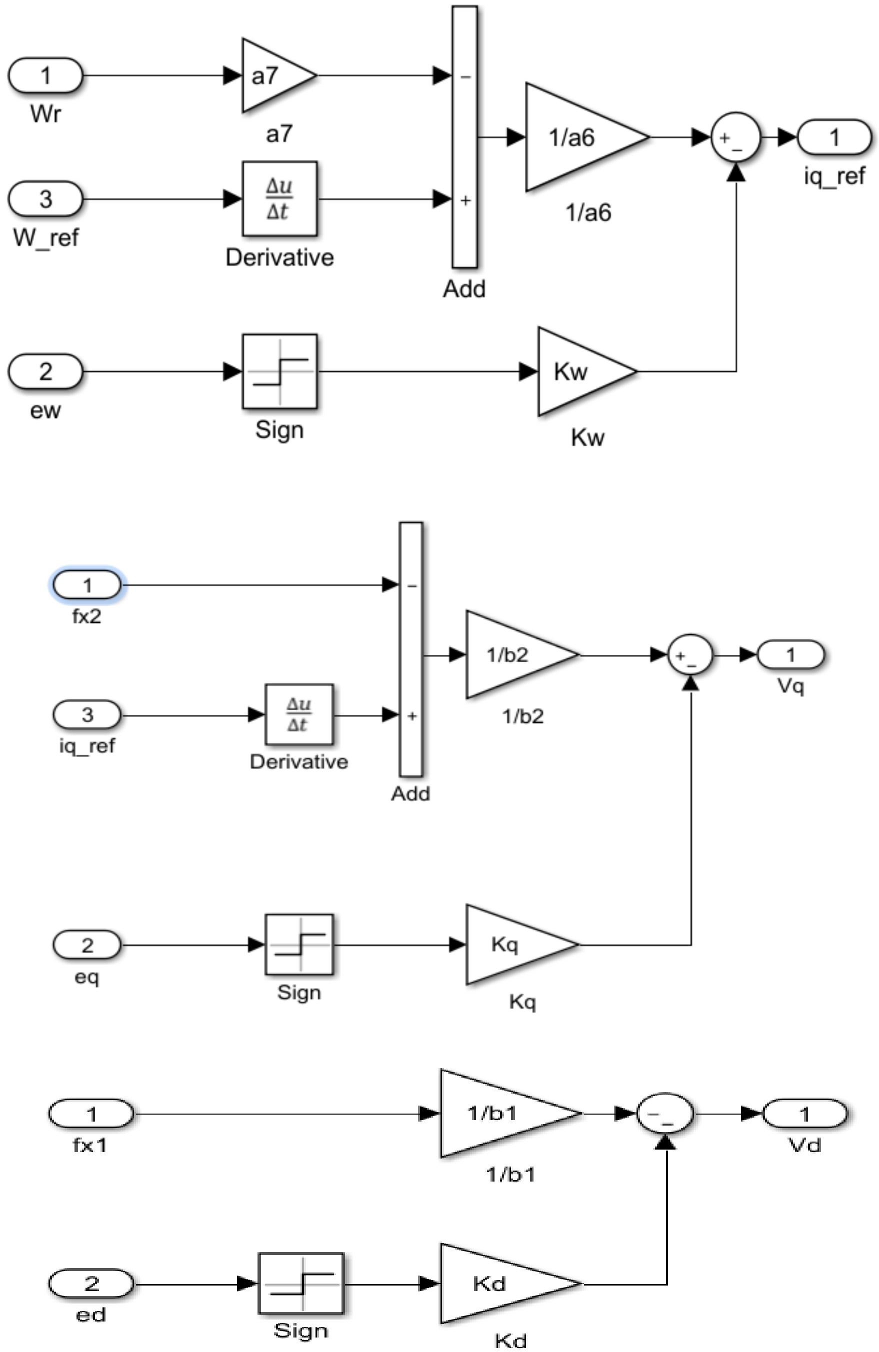


Figure 3.5: Control block structure of FOSMC in Matlab

Overall, while first-order sliding mode control has its advantages, it is important to carefully consider its limitations and suitability for a particular control application.

3.4.4 Chattering problem:

During the sliding regime of FOSMC, the control action involves discontinuities, leading to a phenomenon known as chattering. This chattering is characterized by significant oscillations of the system's trajectories around the sliding surface. The primary causes of chattering are actuator limitations and switching delays in the control. The impacts on the system include:

- **Deterioration of Control Precision:** Frequent oscillations reduce the accuracy with which the system can follow the desired trajectory.
- **Premature Wear of Mechanical Systems:** The high-frequency oscillations induce mechanical stress, leading to accelerated wear and tear of components.
- **Increased Temperature in Electrical Systems:** The rapid switching causes energy losses in the form of heat, leading to elevated temperatures and reduced efficiency.

A. Solutions to Mitigate Chattering:

Improper handling of chattering in the control design has been a significant issue for many real-world applications when implementing sliding mode control .To reduce or eliminate chattering, various solutions have been proposed in the literature. These include:

1. **Fuzzy Sliding Mode Control:** This approach combines fuzzy logic with sliding mode control to smooth the control action, thereby reducing chattering. The fuzzy logic component adjusts the control signal based on the system's state, providing a more gradual transition across the sliding surface.[38]
2. **Second-Order Sliding Modes (SOSM):** Second order sliding modes using algorithm like super twisting algorithm aim to mitigate chattering by employing control laws that involve higher-order derivatives of the sliding variable. This method smooths the control signal and reduces high-frequency oscillations.[17]

3.5 Second order sliding mode:

Second-order sliding mode (SOSM) improves the chattering phenomenon by applying the sliding mode control to higher-order derivatives. This approach mitigates the drawbacks associated with first-order sliding modes. The primary advantages of SOSM control include:

- **Retaining the Benefits of First-Order Sliding Mode:** SOSMC maintains the robustness and performance benefits inherent in first-order sliding mode control.
- **Elimination of Chattering in Most Systems:** By addressing higher-order derivatives, SOSMC significantly reduces or eliminates chattering.
- **Enhanced Control Performance in Terms of Precision:** SOSMC improves the overall accuracy and precision of the control system.

3.6 SOSMC design

The Super Twisting algorithm was developed to control systems to avoid the phenomenon of chattering. Emelyanov proposed this control law in 1990. The convergence of this algorithm is also governed by rotations around the origin of the phase diagram [39]. The goal is to generate a second-order sliding regime on a surface by canceling S itself as well as its derivative $\dot{S}$ within a finite time: ($S = \dot{S} = 0$). The Super Twisting control law is obtained by combining two terms. The first term is given by a continuous function of the sliding variable. While, the second term is defined by its derivative with respect to time:

$$u^{at} = U_1 + U_2 \tag{3.23}$$

Where

$$\begin{cases} U_1 = \begin{cases} -k_1\sqrt{|s_0|}sign(s), & \text{if } |s| > s_0, \\ -k_1\sqrt{|s|}sign(s), & \text{if } |s| \le s_0, \end{cases} \\ \dot{U}_2 = \begin{cases} -u^{at}, & \text{if } \left|u^{at}\right| > U, \\ -k_2 sign(s), & \text{if } \left|u^{at}\right| \le U, \end{cases} \end{cases} \tag{3.24}$$

Where U is the control value boundary and s_0 is a boundary layer around the sliding surface S.
With, K1 and K2 defined as positive constants
Following the same step as FOSMC and the same sliding surface (3.8), we get:

3.6.1 Speed controller:

The equivalent control is given by:

$$i_q^{eq} = \frac{1}{a_6}(-a_7\omega_r - dC_r + \dot{\omega}_r^{ref}) \tag{3.25}$$

The control law ensuring attractiveness is given by:

$$\begin{aligned} u_q{}^{at} &= U_{1\Omega} + U_{2\Omega} \\ U_{1\Omega} &= -k_{1\Omega}\sqrt{|s_1|}sign(s_1) \\ U^{\bullet}{}_{2\Omega} &= -k_{2\Omega}sign(s_1) \end{aligned} \tag{3.26}$$

As a result, the speed regulator is:

$$\begin{aligned} i_q^{ref} &= i_q^{eq} + i_q^{at} \\ i_q^{ref} &= \frac{1}{a_6}(-a_7\omega_r + \dot{\omega}_r^{ref} - dCr) - k_{1\Omega}\sqrt{|s_1|}sign(s_1) + U_{\Omega 2} \end{aligned} \tag{3.27}$$

3.6.2 Current controllers:

3.6.2.1 Id current

The equivalent control is given by:

$$u_d^{eq} = \frac{1}{b_1}(\dot{i}_d^{ref} - a_1 i_d - a_2 i_q \omega_r) \tag{3.28}$$

The control law ensuring attractiveness is given by:

$$u_d{}^{at} = U_{1d} + U_{2d}$$
$$U_{1\text{d}} = -k_{1d}\sqrt{|\text{s}_1|}sign(s_3) \tag{3.29}$$
$$\dot{U}_{2d} = -k_{2\text{d}}sign(s_3)$$

As a result, the id regulator is:

$$U_d^{nom} = u_d^{eq} + u_d^{at}$$
$$U_d{}^{nom} = \frac{1}{b_1}(\dot{i}_d^{ref} - a_1 i_d - a_2 i_q \omega_r) - k_{1d}\sqrt{|\text{s}_3|}sign(s_3) + U_{d2} \tag{3.30}$$

3.6.2.2 iq current:

The equivalent control is given by:

$$u_q^{eq} = \frac{1}{b_2}(\dot{i}_q^{ref} - a_3\dot{i}_q - a_4\omega_r - a_5 i_d \omega_r) \tag{3.31}$$

The control law ensuring attractiveness is given by:

$$u^{at} = U_{1q} + U_{2q}$$
$$U_{1\text{q}} = -k_{1q}\sqrt{|\text{s}_1|}sign(s_2) \tag{3.32}$$
$$\dot{U}_{2q} = -k_{2\text{q}}sign(s_2)$$

As a result, the iq regulator is:

$$U_q^{nom} = u_d^{eq} + u_d^{at}$$
$$U_q{}^{nom} = \frac{1}{b_2}(\dot{i}_q^{ref} - a_3\dot{i}_q - a_4\omega_r - a_5 i_d \omega_r) - k_{1q}\sqrt{|\text{s}_2|}sign(s_2) + U_{q2} \tag{3.33}$$

3.6.3 Stability analysis:

The proposed Lyapunov function for the control, as shown in [40] is:

$$V = 2k_2\,|\,s\,| + \frac{1}{2}U^2 + \frac{1}{2}(k_1\,|\,s\,|^{1/2}\ \text{sign}(s) - U)^2 \tag{3.34}$$

Additionally, the Lyapunov function can be represented in a quadratic form as follows:

$$V = \zeta TP\zeta \tag{3.35}$$

Where $\zeta^T = \left(|s|^{1/2}\ \mathrm{sign}(s) \quad U\right)$,and $P = \frac{1}{2}\begin{vmatrix} 4k_2 + k_1^2 & -k_1 \\ -k_1 & 2 \end{vmatrix}$

Taking the time derivative of (3.35) yields:

$$\dot{V} = -\frac{1}{2}k_1 |s|^{-1/2}\ \zeta^T q\zeta \tag{3.36}$$

Where

$$q = \frac{k_1}{2}\begin{bmatrix} 2k_2 + k_1^2 & -k_1 \\ -k_1 & 1 \end{bmatrix}.$$

To ensure that the derivative of the Lyapunov function is negative and thus guarantee stability, we must select control gains that satisfy the following conditions:

$$\begin{cases} k_{1\Omega} > 2\delta_\Omega \\ k_{2\Omega} > k_{1\Omega}\dfrac{5\delta_\Omega k_{1\Omega} + 4\delta_\Omega^2}{2(k_{1\Omega} - 2\delta_\Omega)} \end{cases}$$
$$\begin{cases} k_{1q} > 2\delta_q \\ k_{2q} > k_{1q}\dfrac{5\delta_q k_{1q} + 4\delta_q^2}{2(k_{1q} - 2\delta_q)} \end{cases} \tag{3.37}$$
$$\begin{cases} k_{1d} > 2\delta_d \\ k_{2d} > k_{1d}\dfrac{5\delta_d k_{1d} + 4\delta_d^2}{2(k_{1d} - 2\delta_d)} \end{cases}$$

Whereδ_Ω, δ_q, and δ_d are bounding known positive constants

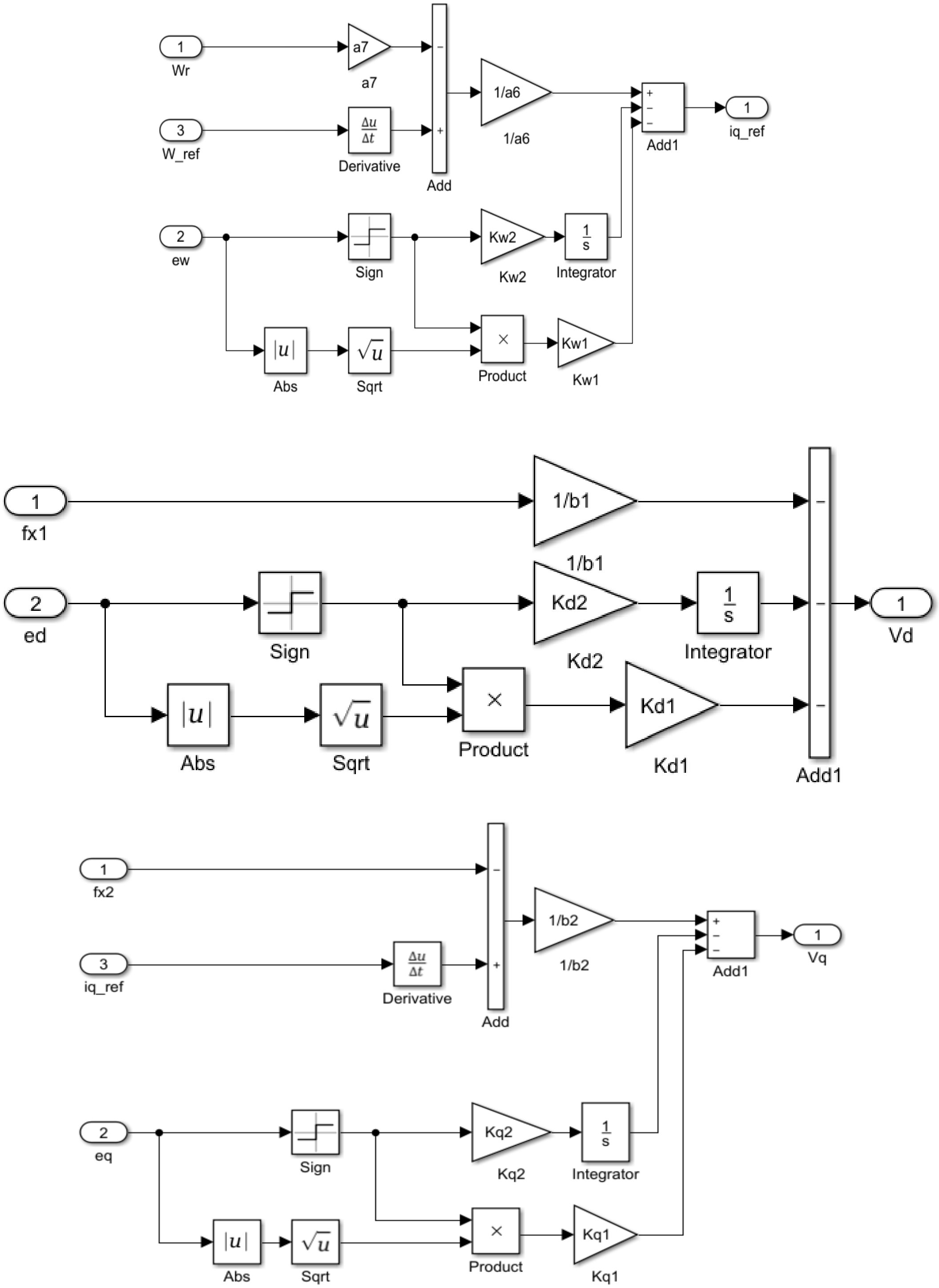


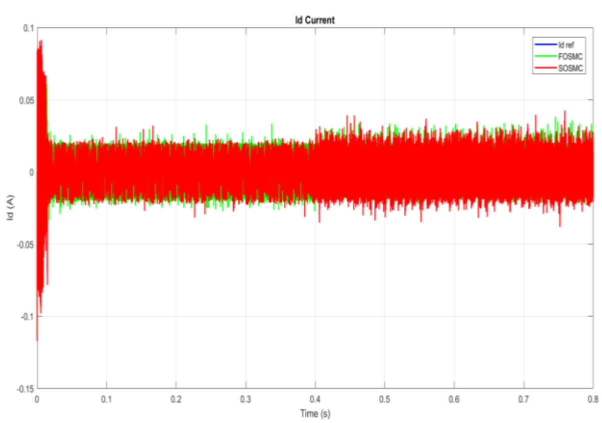
Figure 3.6: Control block structure of SOSMC in MATLAB

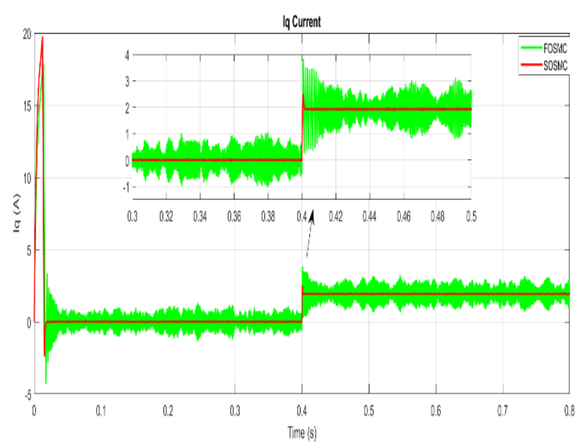
3.7 Simulation results

In our simulation we have Tl=0.05Nm in the speed test, Rs test and in presence of fault test.

- **First Test:** The simulation starts with a reference speed ωref=100 rad/s, followed by a sudden change to ωref=10 rad/sec at t=0.4 s
- **Second Test:** This simulation starts with a Tl=0Nm and a 100% increase to Tl=0.05Nm in at t=0.4
- **Third Test:** This scenario simulate a 250% increase in Rs at t=0.4s.
- **Fourth Test:** The simulation starts with a reference speed ωref=100 rad/s, Tl=0.05 Nm. In addition, with a stator fault with a 50Hz at t=0.4s.

This cumulative study compares passive fault-tolerant control using both first-order and second-order sliding mode control (SMC).





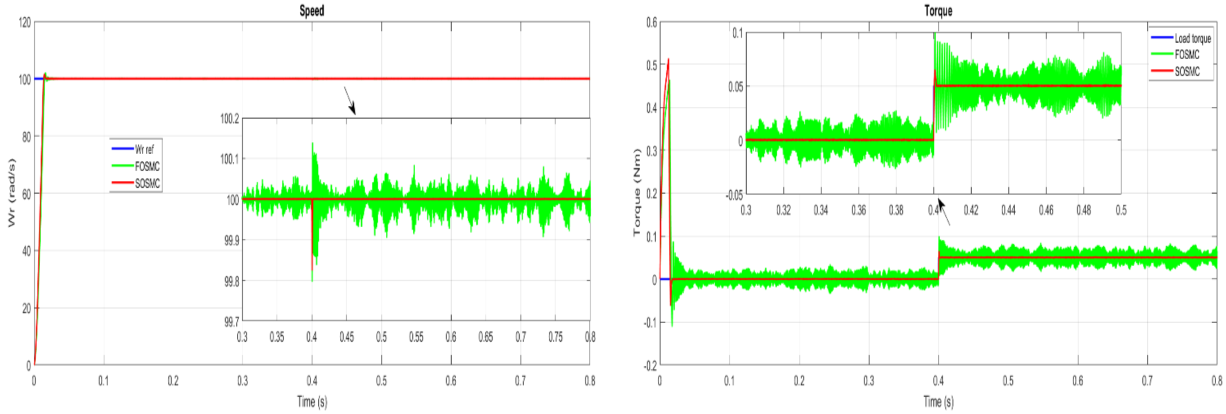
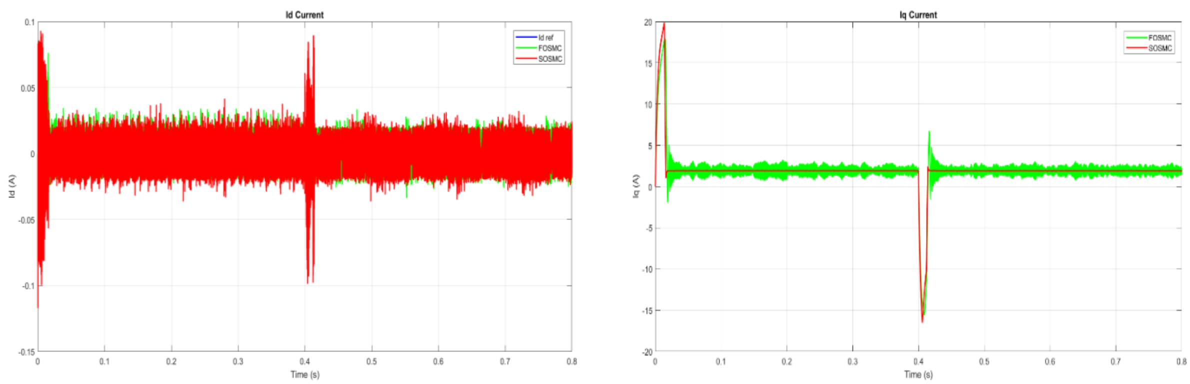


Figure 3.7 – Simulation of PMSM under variation of load.



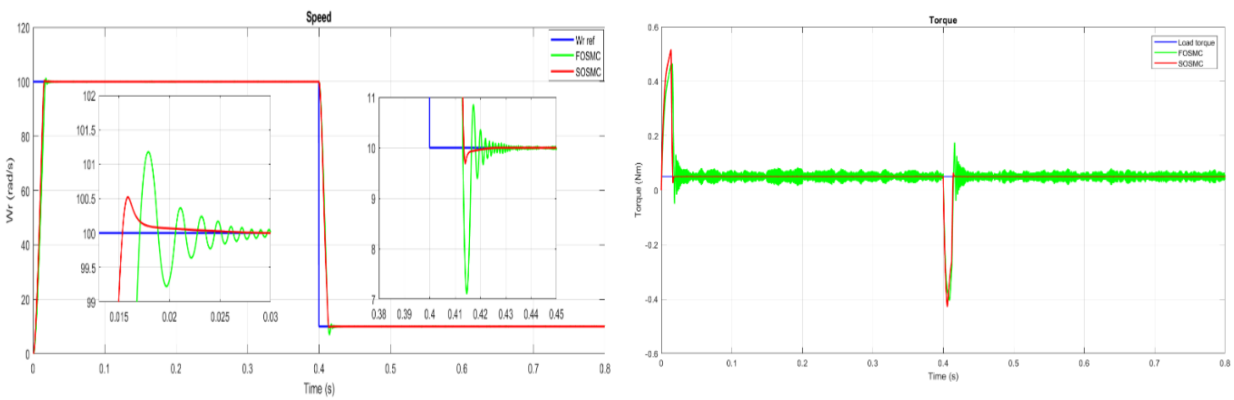
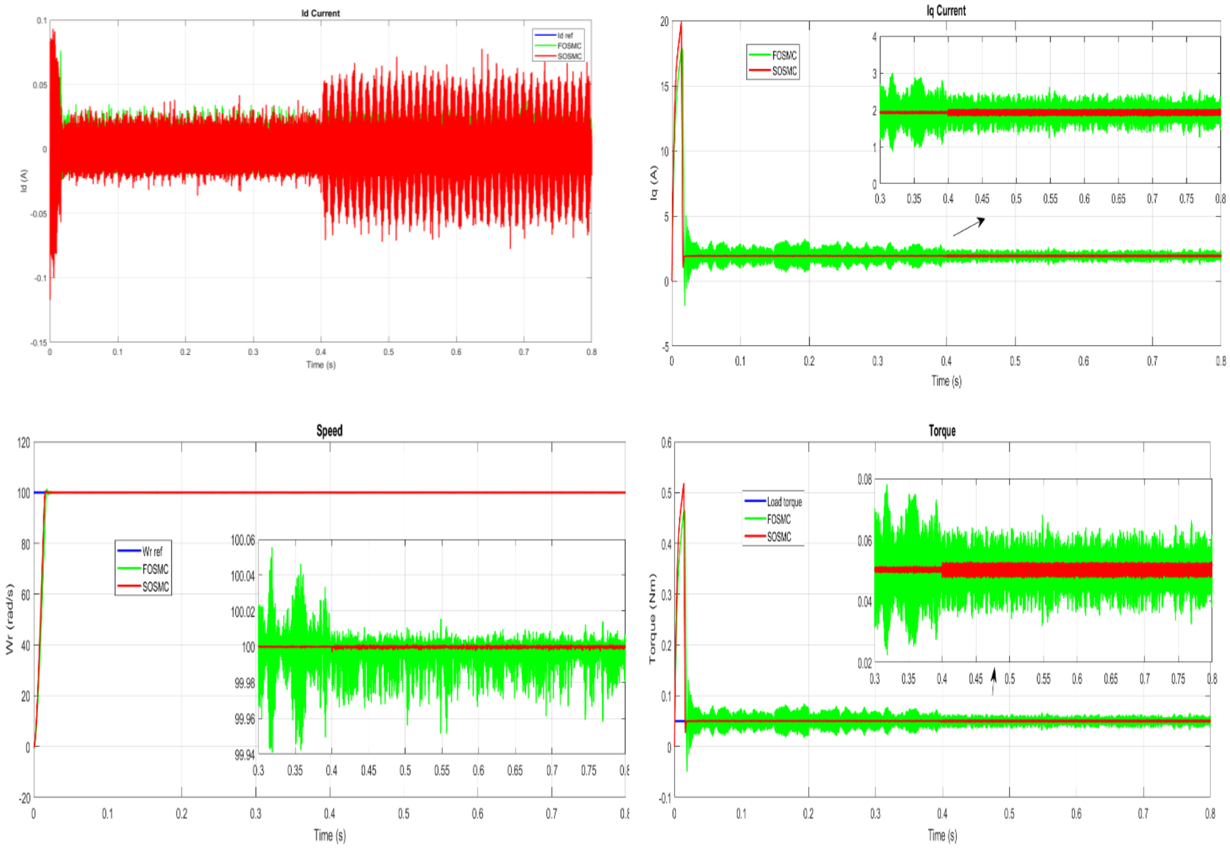


Figure 3.8 – Simulation of PMSM under variation of speed.

Figure 3.9 – Simulation of PMSM under variation of Rs.


Id Current
Id ref
FOSMC
SOSMC
Id (A)
Time (s)
Iq Current
FOSMC
SOSMC
Iq (A)
Time (s)
Speed
Wr ref
FOSMC
SOSMC
Wr (rad/s)
Time (s)
Torque
Load torque
FOSMC
SOSMC
Torque (Nm)
Time (s)

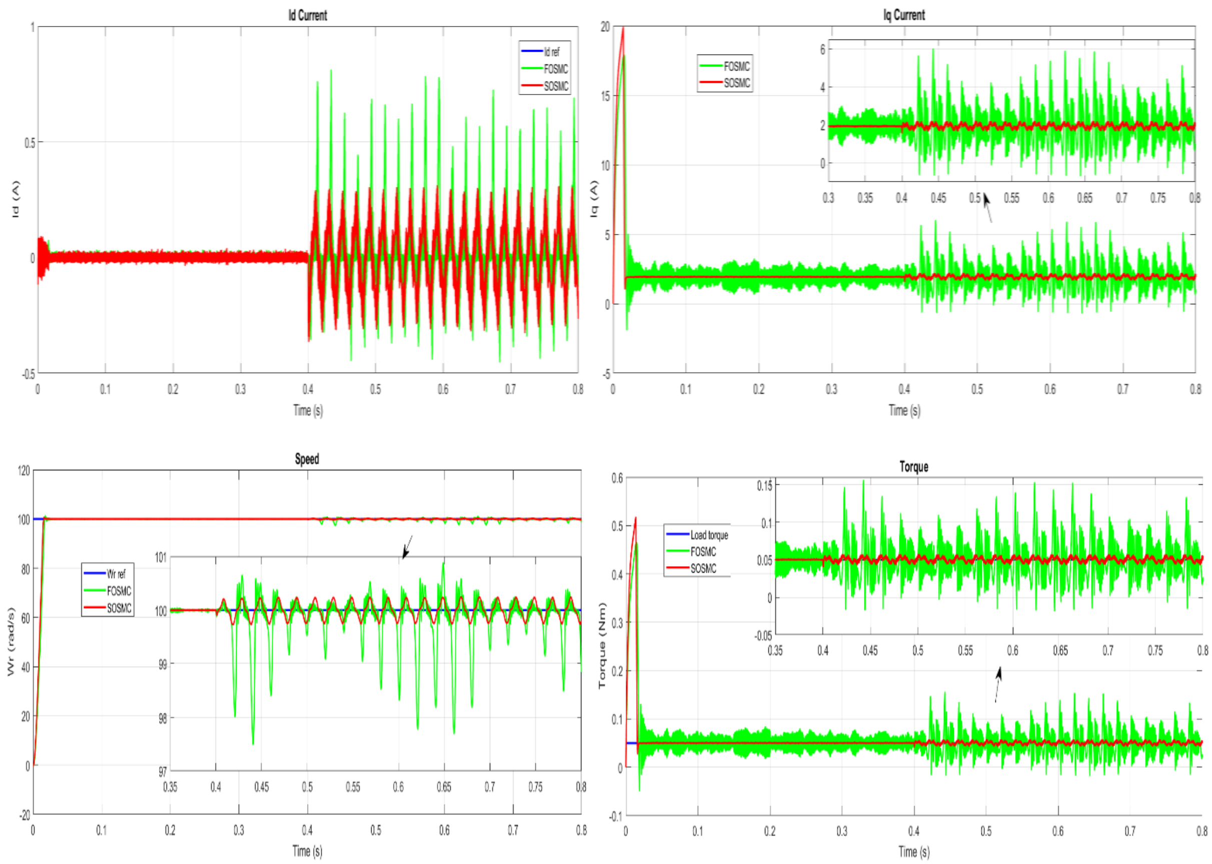


Figure 3.10 – Simulation of PMSM under stator fault.

3.7.1 Results discussion:

- **Torque variation**

First-Order SMC: The system experience a transient response due to the sudden increase in load torque. It handle the disturbance, some chattering appear, affecting the control precision.

Second-Order SMC: The second-order SMC handle the increased torque more smoothly, reducing the impact of chattering and providing a more stable response.

- **Speed variation:**

First-Order SMC: The system initially tracks the reference speed accurately, but with chattering, leading to oscillations around the new reference speed. After the change in speed, the control system stabilize after a brief transient period.

Second-Order SMC: The super-twisting algorithm in second-order SMC reduces chattering significantly. The system smoothly transition to the new reference speed with minimal oscillations and better precision.

- **Parametric Variation**

First-Order SMC: The sudden increase in stator resistance cause a minor permanent degradation in performance.

Second-Order SMC: The increased robustness of second-order SMC to parameter variations result in a more stable response. The system will adjust to the new resistancevalue with improved precision and stability.

- **Stator fault:**

First-Order SMC: First-order SMC exhibit significant chattering,. The control system maintain stability but show oscillations and reduced precision.

Second-Order SMC: The second-order SMC, provide a better response. The impact of the stator fault is mitigated more efficiently, leading to better fault tolerance.

Overall Comparison:

First-Order SMC: While effective in handling disturbances and parameter variations, first-order SMC is prone to chattering, which can degrade performance and precision, especially under sudden changes or faults.

Second-Order SMC: The super-twisting algorithm in second-order SMC significantly reduces chattering, resulting in smoother and more precise control. It enhances the system's robustness to parameter variations and faults, providing better performance in all tested scenarios.

This cumulative study demonstrates that second-order SMC offers substantial improvements over first-order SMC, particularly in reducing chattering and improving fault tolerance and control precision.

3.8 Conclusion

In this chapter, we presented the first and second order sliding mode control techniques. First, we generally presented the algorithm for designing first-order sliding mode control. In the second part, we presented the algorithms for designing second-order sliding mode control, using the Super Twisting algorithms, which is the most commonly used in the literature. Finally, we presented a comparative study between the two algorithms applied to the control of the PMSM.We found that while first-order SMC is effective and robust, second-order SMC, particularly using the super-twisting algorithm, offers significant improvements in reducing chattering and enhancing control precision.

Chapitre 4

Active FTC using a sliding mode observer

4.1 Introduction

To ensure the reliability, safety, and operational security of complex systems, and with the advancements in digital computing and the emergence of FTC systems, researchers have increasingly focused on the design and analysis of fault diagnosis and detection (FDD) using observers over the past few decades [10][12][34].

In this chapter, we synthesis a SOSMC control along with a sliding mode observer, The SOSMO observer is designed for fault detection and reconstruction, providing a significant advantage in fault detection, diagnosis, and FTC.

4.2 Fault reconstruction and observer principals:

Let's consider a nonlinear system experiencing external disturbances and/or structured uncertainties, along with faults [10] [12][17][34]:

$$\begin{cases} \dot{x}(t) = f(x(t)) + Bu(t) + \Gamma z + Dd(t) \\ y(t) = Cx(t) \end{cases} \tag{4.1}$$

Where $f(x(t))$ represents a known smooth function describing the system's nonlinear characteristics, $x \in \mathbb{R}^n$ is the state vector, $u \in \mathbb{R}^m$ is the input vector, $y \in \mathbb{R}^p$ is the output vector, z is a vector containing unknown parameters and external disturbances (faults), $d(t) \in \mathbb{R}^l$

denotes an unknown input that includes an external disturbance or a structured uncertainty with $D \in R^{n\times 1}$. $y \in \mathbb{R}^{p}$ is the output matrix, $\Gamma \in \mathbb{R}^{n\times r}$ is the distribution matrix for disturbances and parameter variations, $B \in \mathbb{R}^{n\times m}$ is the input matrix, and $C \in \mathbb{R}^{p\times n}$ is the output matrix.

The desired control law must ensure that the system tracks smooth reference signals for its outputs. This control law, denoted as:

$$U^{nom} = \alpha\left(x,\ y,\ yref\right)$$

It is designed under healthy conditions (z (t) = 0). It is formulated so that for all initial states x (0) ∈ $\mathbb{R}^n$ and for any potential external disturbances or structured uncertainties, the outputs of the closed-loop system remain bounded and approach zero as time approaches infinity:

$$lim\ t \to \infty\ |\ yi\left(t\right)\ -\ yi\ ref\ \left(t\right)|\ =\ 0.$$

To enhance performance, we adopt an approach based on the sliding mode observer (SMO). The SMO is designed to detect and reconstruct the fault signal Γz . The term $\hat{\Gamma}$z(t) should be minimized so that:

$$lim\ t \to \infty\ \hat{\Gamma}\text{z(t)-}\Gamma\text{z(t)=0}.$$

Consequently, an additional control law $u^{f}(t)$ will be generated, once the fault signal is detected and reconstructed by the SOSMO based on the criterion [10] [12] [34]:

$$\begin{cases} u^{f}(t) = 0 \ \text{ if } \ \hat{\Gamma}z\text{=0} \\ u^{f}(t) \neq 0 \ \text{ if } \ \hat{\Gamma}z \neq 0 \end{cases} \tag{4.2}$$

The overall new control law $u^{T}(t)$ will take the following form:

$$u^{T}(t) = u^{nom}(t) + u^{f}(t) \tag{4.3}$$

The additive control laws $u^f(t)$ designed to compensate for the effect of the additive fault in the system are provided by [10] [12] [34]:

$$u^f(t) = B^{-1}\hat{\Gamma}z(t) \tag{4.4}$$

So, u_d^{faulty} and u_q^{faulty} the additional control laws are taken as:

$$\begin{aligned} u_d^{faulty} &= -\frac{1}{b_1}\hat{\Gamma}_d z \\ u_q^{faulty} &= -\frac{1}{b_2}\hat{\Gamma}_q z \end{aligned} \tag{4.5}$$

4.3 Faults Detection and reconstruction:

Thanks to their robustness against uncertainties and parametric disturbances, sliding mode observers (SMOs) are widely utilized across various fields. These observers are particularly effective for detecting, reconstructing, and diagnosing faults in both linear and nonlinear systems that are susceptible to uncertainties and failures. In practical applications, some state variables may be unmeasurable, while others are accessible. In such scenarios, a fault-tolerant control (FTC) strategy utilizing a second-order sliding mode observer (SOSMO) can be implemented.SOSMOs are designed to handle systems with higher-order dynamics by applying control actions to the higher-order derivatives of the sliding variable, thereby enhancing robustness and accuracy. They provide significant advantages in fault detection and isolation.

4.3.1 Design of the second order sliding mode observer (SOSMO) for (PMSM):

Based on the research conducted by [10] [12] [34], we can formulate the SOSMO as follows:

$$\begin{cases} \dot{\hat{i}}_d = a_1\hat{i}_d + a_2 i_q\hat{\omega}_r + b_1 u_d - \eta_{d1}\sqrt{|s_d|}sign(s_d) + u_d \\ \dot{\hat{i}} = a_3\hat{i}_q + a_4\hat{\omega}_r + a_5 i_d\hat{\omega}_r + b_2 u_q - \eta_{q1}\sqrt{|s_q|}sign(s_q) + u_q \\ \dot{\hat{\omega}} = a_7\varepsilon_\omega \end{cases} \quad (4.6)$$

Where

$$\dot{u}_d = -\eta_{d2} sign(s_d)$$
$$\dot{u}_q = -\eta_{q2} sign(s_q)$$

Where $\hat{\imath}_d$ and $\hat{\imath}_q$ are the observed stator currents, where the observer sliding surfaces are:

$$s_d = \hat{i}_d - i_d$$
$$s_q = i_q - i_q$$

With $\eta_{d1}, \eta_{d2}, \eta_{q1}, \eta_{q2} > 0$

And $\hat{\omega}$ is the estimated speed.

4.3.2 Stability analysis:

With the same Lyapunov function as the SOSMO in [40], which is stated in the following form:

$$V = 2\eta_2|s_d| + \frac{1}{2}u_d^2 + \frac{1}{2}\left(\eta_1|s_d|^{1/2} sign(s_d) - u_d\right)^2 + 2\eta_2|s_q| + \frac{1}{2}u_q^2 + \frac{1}{2}\left(\eta_1|s_q|^{1/2} sign(s_q) - u_q\right)^2 \quad (4.7)$$

It can also be written in quadratic form, as follow:

$$V = \zeta_d^T P\zeta_d + \zeta_q^T P\zeta_q \quad (4.8)$$

Where

$$\begin{bmatrix} \zeta_d & \zeta_q \end{bmatrix} = \begin{bmatrix} |s_d|^{1/2} sign(s_d) & |s_q|^{1/2} sign(s_q) \\ u_d & u_q \end{bmatrix}$$
$$P = \frac{1}{2}\begin{bmatrix} 4\eta_2 + \eta_1^2 & -\eta_1 \\ -\eta_1 & 2 \end{bmatrix} \quad (4.9)$$

Taking the time derivative of Equation (4.6) results in:

$$\dot{V} = -\frac{1}{2}\eta_1 \left|s_d\right|^{-1/2} \zeta_d^T q \zeta_d - \frac{1}{2}\eta_1 \left|s_q\right|^{-1/2} \zeta_q^T q \zeta_q \tag{4.10}$$

Where

$$q = \frac{\eta_1}{2}\begin{bmatrix} 2\eta_2 + \eta_1^2 & -\eta_1 \\ -\eta_1 & 1 \end{bmatrix}$$

To ensure that $\dot{V}$ is negative, η_1 and η_2 must be chosen to meet the following conditions:

$$\begin{aligned} &\eta_1 > 2\delta_{\hat{i}_{dq}} \\ &\eta_2 > \eta_1 \frac{5\delta_{\hat{i}_{dq}}\eta_1 + 4\delta_{\hat{i}_{dq}}^2}{2\left(\eta_1 - 2\delta_{\hat{i}_{dq}}\right)} \end{aligned} \tag{4.10}$$

It is clearly noticeable that the sliding surface can be reached in finite time and maintained thereafter, that is $\dot{\varepsilon}_d = 0$ and $\dot{\varepsilon}_q = 0$

$$\begin{cases} 0 = a_1\varepsilon_d + a_2 i_q \varepsilon\hat{\omega}_r + b_1 u_d - \eta_{d1}\sqrt{|s_d|}\,sign\left(s_d\right) + u_d \\ 0 = a_3\varepsilon_q + a_4\varepsilon\hat{\omega}_r + a_5 i_d \varepsilon\hat{\omega}_r + b_2 u_q - \eta_{q1}\sqrt{|s_q|}\,sign\left(s_q\right) + u_q \\ \dot{\varepsilon}\omega = a_7\varepsilon_\omega \end{cases} \tag{4.11}$$

Where

$$\dot{u}_d = -\eta_{d2}\,sign\left(s_d\right)$$
$$\dot{u}_q = -\eta_{q2}\,sign\left(s_q\right)$$

Since a7 is negative (a7<0), it is clearly demonstrated that ε_ω tends towards zero $(\varepsilon_\omega \to 0)$ as $t\to\infty$, meaning that the faults can be estimated. Thus, from (4.11), the expression for fault estimation can be obtained:

$$\begin{aligned} \hat{\Gamma}_d z &= -\eta_{d1}\sqrt{|s_d|}\,sign\left(s_d\right) + u_d \\ \hat{\Gamma}_q z &= -\eta_{q1}\sqrt{|s_q|}\,sign\left(s_q\right) + u_q \end{aligned} \tag{4.12}$$

Where

$$\dot{u}_d = -\eta_{d2}\,sign\left(s_d\right)$$
$$\dot{u}_q = -\eta_{q2}\,sign\left(s_q\right)$$

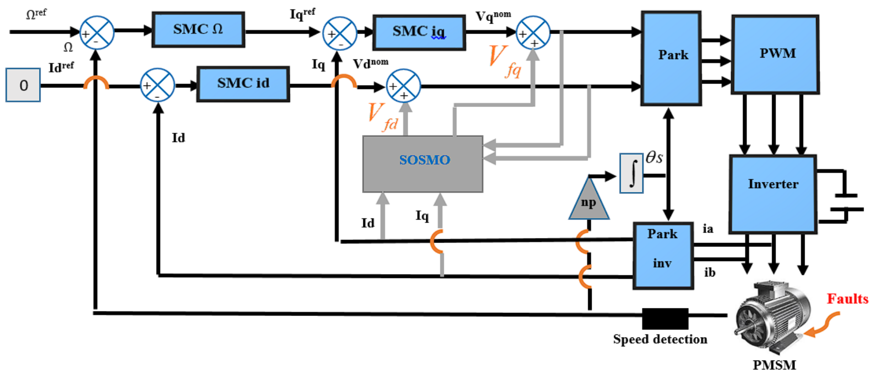


Figure 4.1: Active FTC based on SOSMC

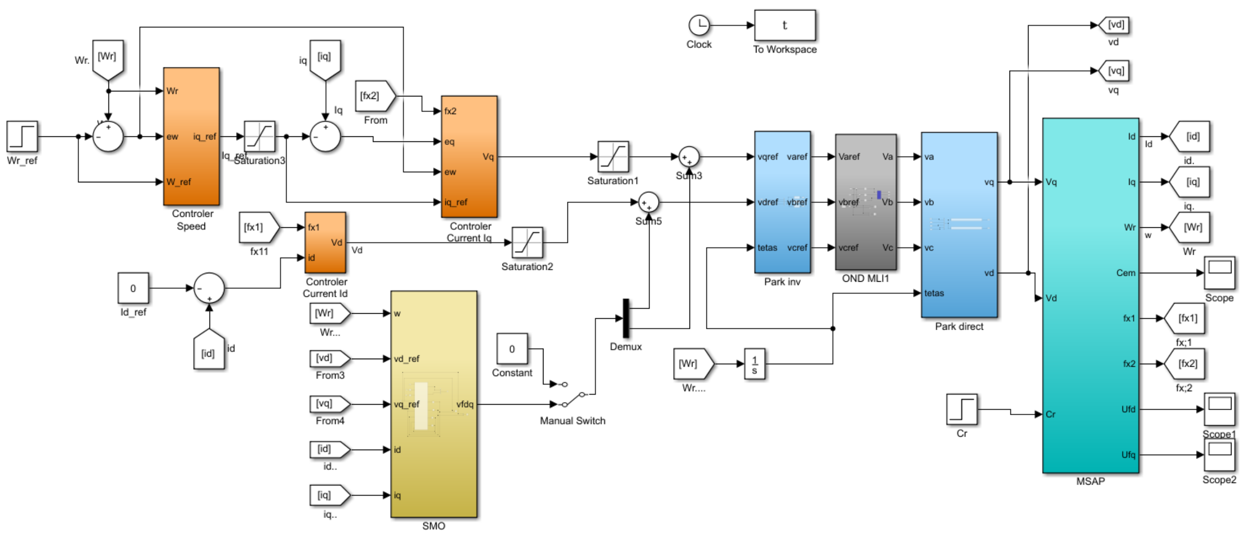


Figure 4.2: MATLAB simulation of AFTC

4.4 Simulation results:

We will do the same simulation in chapter 3 to verify the outlined approach of using SOSMC with SOSMO:

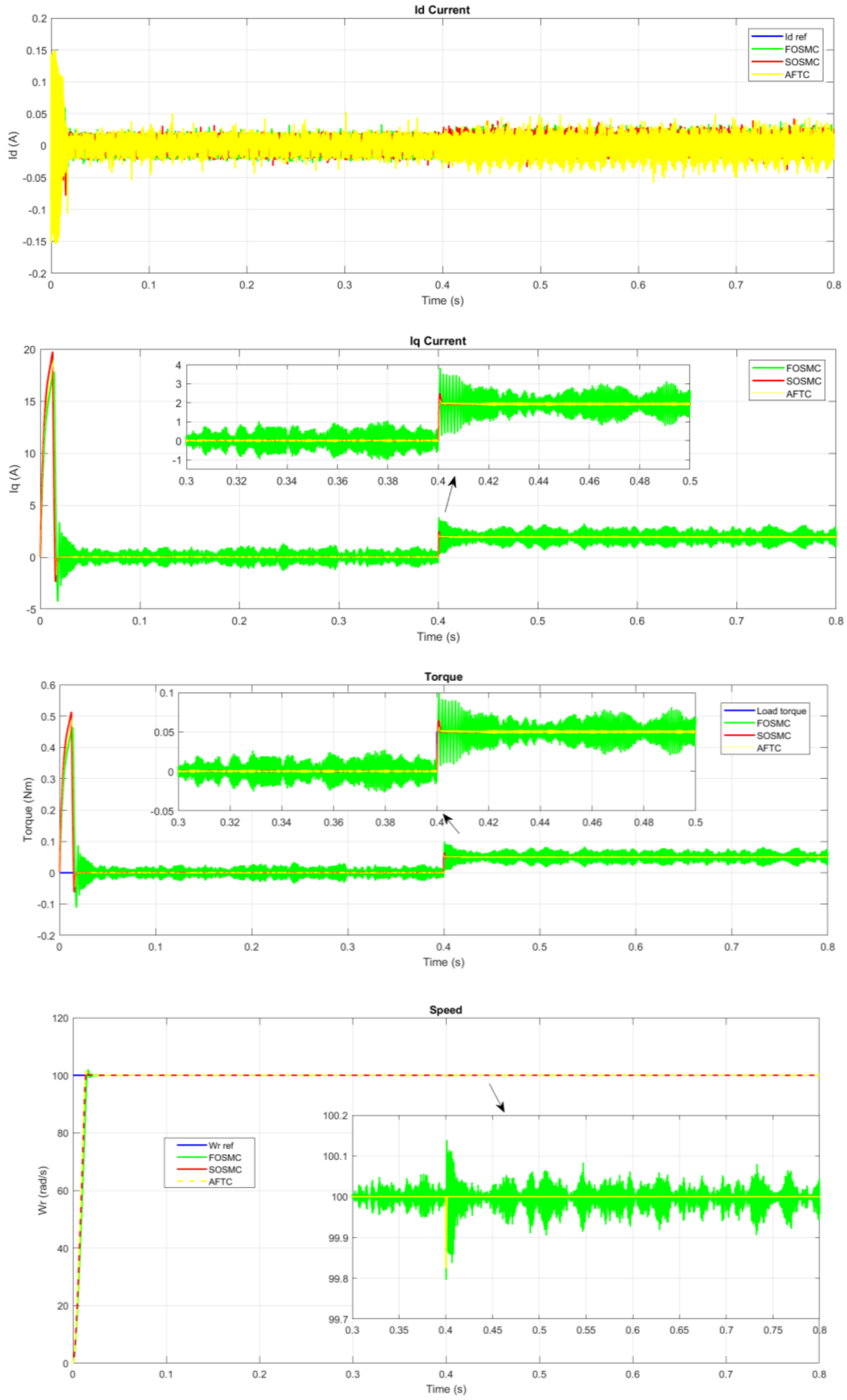


Figure 4.3 – Simulation of PMSM under variation of load.

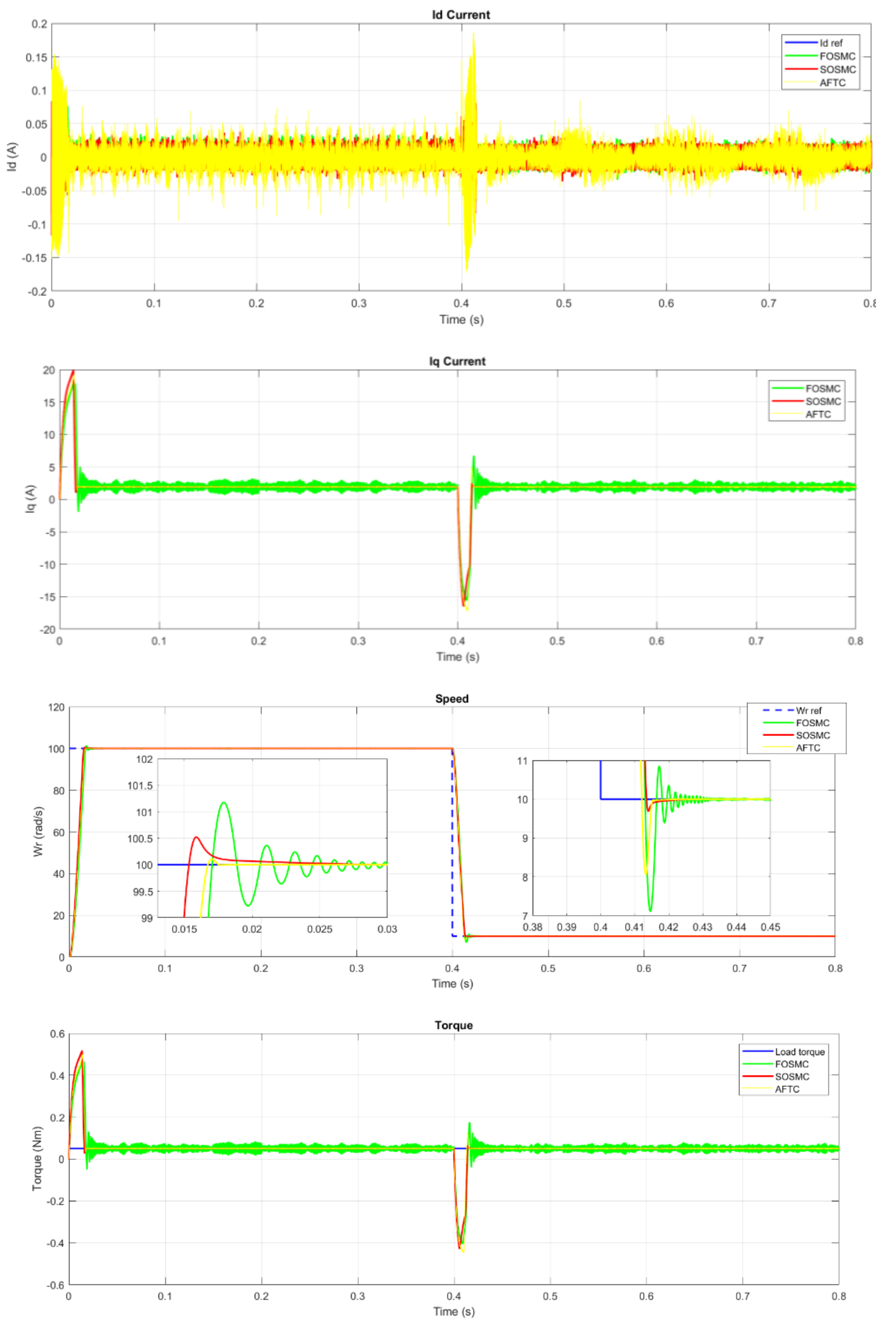


Figure 4.4 – Simulation of PMSM under variation of speed.

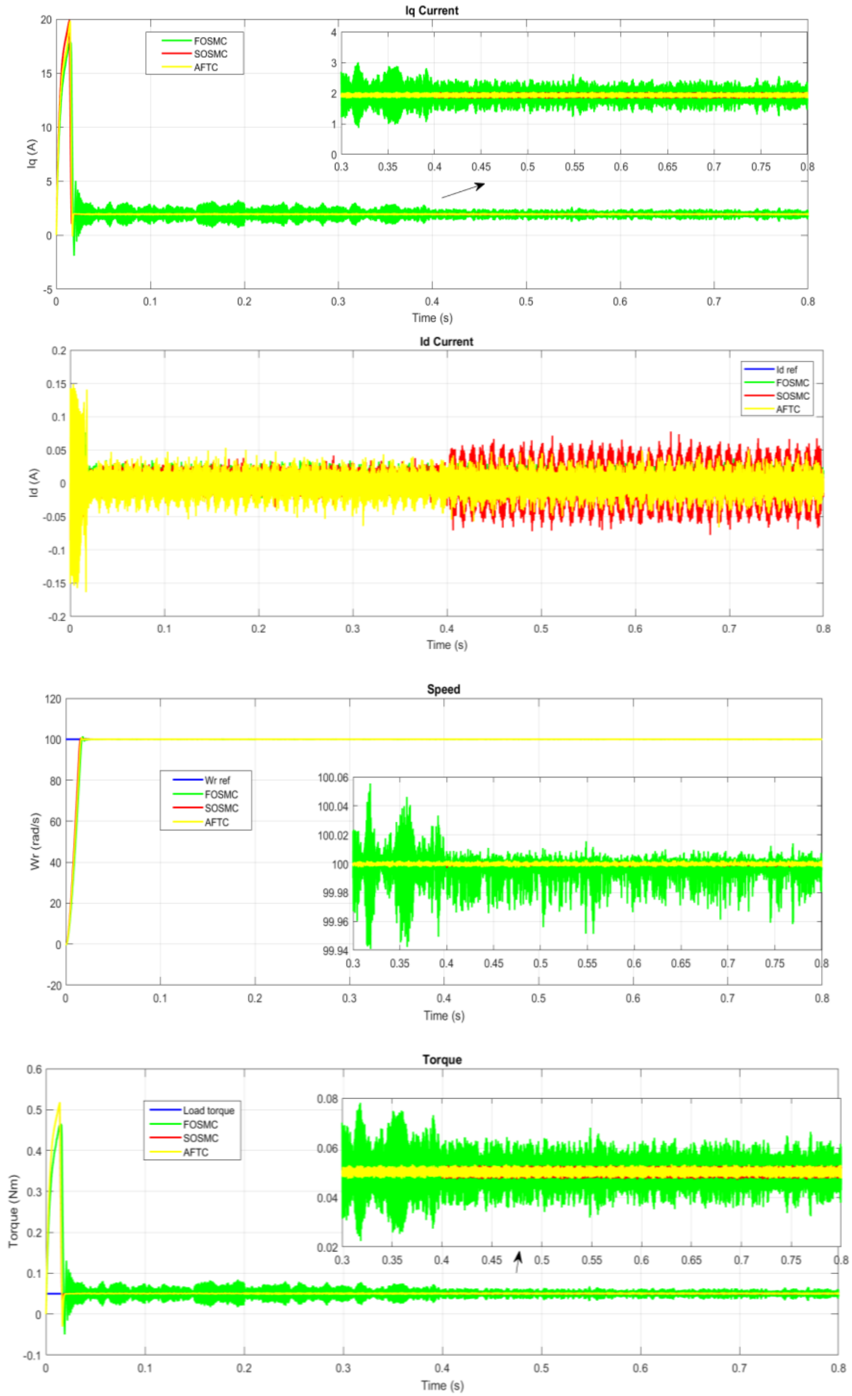


Figure 4.5 – Simulation of PMSM under variation of Rs.

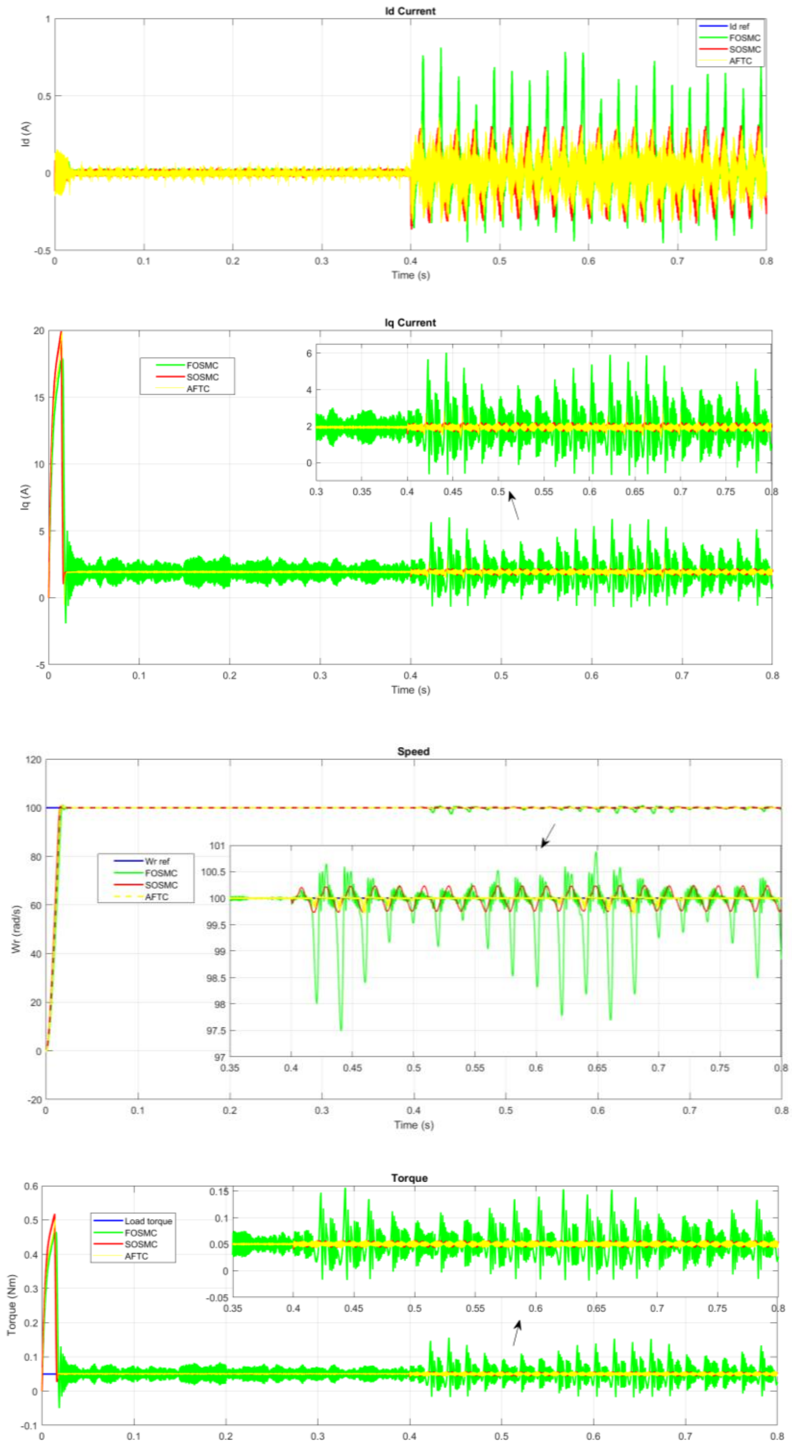


Figure 4.6 – Simulation of PMSM under fault.

4.4.1 Results discussion:

The new method provides the most effective fault tolerance, accurately estimating and compensating for the fault, ensuring optimal control performance. The advanced fault detection and isolation capabilities of the SOSMO enable the system to maintain high performance and stability despite the presence of the fault, outperforming both first-order SMC and SOSMC in terms of fault management and overall system robustness.

4.5 Conclusion:

In this chapter, we explored the application of second-order sliding mode observers (SOSMOs) for fault detection and reconstruction in (PMSMs). The focus was on exploiting the robustness and precision of SOSMOs to improve the reliability and performance of fault-tolerant control systems in the presence of faults.

General Conclusion

In conclusion, this thesis has examined the integration of Second-Order Sliding Mode Control (SOSMC) for Permanent Magnet Synchronous Motors (PMSMs) to enhance their robustness and reliability under fault conditions and to mitigate the chattering present in First-Order Sliding Mode Control (FOSMC), providing smoother control and improved fault tolerance.

The integration of SOSMC for PMSMs has been proven to be an effective solution for minimizing chattering and improving fault tolerance, reliability, and overall performance. Future research in this area may include using different diagnostic methods, such as vibration analysis or AI-based methods, or exploring different SOSMC algorithms.

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