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# Simulation of Various Faults in Electric Machines

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## Dedecation

الحمد لله حمدًا كثيرًا طيبًا مباركًا فيه، ما سلكنا البدايات إلا بتيسيره، وما بلغنا النهايات إلا بتوفيقه وعونه.

أُهدي ثمرة هذا الجهد المتواضع إلى من كان لهم الفضل بعد الله في كل خطوة، إلى من منحوني الحب والدعم بلا شروط، إلى من دعَوا لي في صمتٍ وساندوني في كل حين

إلى نبض قلبي، إلى من سهرا الليالي من أجلي وتحملاني في كل المراحل، إلى أمي وأبي العزيزين، أنتما النور الذي يضيء طريقي والظل الذي أستظل به عند الشدائد، فلكما مني كل الحب والامتنان والدعاء.

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.

GUERMOUZ Mohamed Amine

# Dedecation

قال تعالى:
*﴿ يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنكُمْ وَالَّذِينَ أُوتُوا الْعِلْمَ دَرَجَاتٍ﴾*

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ESSID Abderrahmane

## Abstract

The performance and dependability of three-phase induction motors are integral to the continuing operations of many industrial processes. However, all machines are susceptible to electrical or mechanical faults such as a broken rotor bar, short circuit in the stator, and voltage unbalance, which can rapidly lead to damaging consequences and expensive downtime. The SKD factory, which is an integral portion of this study had not adopted an advanced motor testing or fault diagnostic approach, but a means of detecting and classifying faults would be a significant improvement when working with three-phase induction motors. This work provides results from a MATLAB/Simulink environment simulation approach of typical motor faults which analyses how the faults behaved dynamically when processed through current signals. A Fast Fourier Transform (FFT) was applied to extract key frequency signatures that represented the faults. This work serves as an example to convey potential opportunities for detecting faults. Unlike in-line motor tests, this study demonstrated how spectral analysis could be applied in a non-invasive nature, to provide motor fault diagnostics with the aim of developing predictive maintenance and improved reliability for the industry.



**Keywords:** Induction motor, Fault diagnosis, FFT, MATLAB/Simulink, Broken rotor bar, Stator fault, Simulation, Predictive maintenance, Vibration analysis, Current spectrum.



## Résumé

La fiabilité et la performance des moteurs asynchrones triphasés est essentielle pour un bon fonctionnement des processus industriels. Malheureusement, ces machines sont encore exposées à un certain nombre de défauts électriques ou mécaniques tels que la rupture d'une barre de rotor, un court-circuit du stator ou un déséquilibre de tension…, pouvant rapidement conduire à des conséquences graves et des arrêts de production coûteux. L'usine SKD, qui constitue une partie importante de cette étude, n'a pas encore mis en œuvre un moyen de test ou de diagnostic avancé des moteurs, et le déroulement d'un système de détection et de classification des défauts a représenté un niveau supérieur de gestion des moteurs asynchrones triphasés. Ce travail présente les résultats d'une démarche de simulation dans l'environnement MATLAB/Simulink des défauts typiques rencontrés par des moteurs en analysant leur comportement dynamique par les signaux de courant, la Transformée de Fourier Rapide (FFT) ayant été appliquée dans l'analyse pour en extraire les signatures fréquentielles essentielles des défauts. Ce travail montre ainsi les enjeux possibles pour la détection des pannes. Contrairement aux tests moteurs en ligne classiques, ce travail montre que l'analyse spectrale peut être une méthode de non-intrusive pour le diagnostic des défauts moteurs.



**Mots-clés :** Moteur asynchrone, Diagnostic des défauts, FFT, MATLAB/Simulink, Barre de rotor cassée, Défaut du stator, Simulation, Maintenance prédictive, Analyse vibratoire, Spectre de courant.



## الملخص

تُعد موثوقية وأداء المحركات غير المتزامنة ثلاثية الطور أمرًا أساسيًا لضمان سير العمليات الصناعية بشكل جيد. ومع ذلك، لا تزال هذه الآلات معرضة لعدد من الأعطال الكهربائية أو الميكانيكية مثل كسر قضيب في الدوار، أو قصر كهربائي في الجزء الثابت، أو عدم توازن في الجهد...، مما قد يؤدي بسرعة إلى عواقب وخيمة وتوقفات مكلفة في الإنتاج. مصنعSKD ، الذي يُشكل جزءًا مهمًا من هذه الدراسة، لم يطبق بعد وسائل متقدمة لاختبار أو تشخيص المحركات، وقد شكّل تطوير نظام لاكتشاف وتصنيف الأعطال مستوى أعلى في إدارة المحركات غير المتزامنة ثلاثية الطور. يعرض هذا العمل نتائج نهج محاكاة في بيئة MATLAB/Simulink للأعطال الشائعة التي تواجه المحركات، من خلال تحليل سلوكها الديناميكي باستخدام إشارات التيار، حيث تم تطبيق تحويل فورييه السريع (FFT) لاستخراج التواقيع الترددية الأساسية لتلك الأعطال.

يُظهر هذا العمل بذلك الأهمية المحتملة للكشف عن الأعطال. وعلى عكس اختبارات المحركات التقليدية أثناء التشغيل، يُبيّن هذا العمل أن التحليل الطيفي يمكن أن يكون طريقة غير تدخلية لتشخيص أعطال المحركات.

**الكلمات المفتاحية** :محرك غير متزامن، تشخيص الأعطال، تحويل فورييه السريع(FFT) ، MATLAB/Simulink، كسر في قضيب الدوار، عطل في الجزء الثابت، محاكاة، صيانة تنبؤية، تحليل اهتزازي، طيف التيار.

## List of Abbreviations

| Abbreviation | Full Meaning |
|---|---|
| **FFT** | Fast Fourier Transform |
| **ITSC** | Inter-Turn Short Circuit |
| **BRB** | Broken Rotor Bar |
| **MCSA** | Motor Current Signature Analysis |
| **DWT** | Discrete Wavelet Transform |
| **abc** | Three-phase coordinate system |
| **dq** | Direct-Quadrature rotating reference frame |
| **fs** | Supply Frequency |
| **rpm** | Revolutions Per Minute |
| **Rs** | Stator Resistance |
| **Rr** | Rotor Resistance |
| **Ls** | Stator Inductance |
| **Lr** | Rotor Inductance |
| **Lm** | Magnetizing Inductance |
| **SKD** | Société de Production d'Électricité de Skikda (SKD Power Plant) |

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# 1 CHAPTER 1: Theoretical Study of Faults in Electrical Machines

## 1.1 General Introduction to Electrical Machines

Electric machines are essential for converting electrical energy into mechanical energy and vice versa. They can be classified into three main types: DC machines; synchronous machines; and asynchronous (induction) machines, with several specific applications for each of them. Induction machines are the most commonly used above all others in industry due to their simple design and robust construction. Having a clear understanding of their operation is important to guarantee system reliability and prepare for effective fault detection and simulation.

### 1.1.1 Identification and Functional Description of Electrical Machine Components

1.Stator

Stator Frame: The outer static frame which gives it support and protection. Stator Core: Lamination of silicon steel sheets that is used to reduce eddy current and hysteresis losses; the core has slots machined into the inner perimeter to house the stator windings. Stator Winding: The three-phase insulated copper windings in the slots in the stator and connected in a star or delta configuration; once energized from the AC supply the stator windings produces the rotating magnetic field.

2.Rotor

Rotor Core: A laminated cylindrical shape with slots cut into its exterior for the rotor conductors. The laminated construction helps minimize losses.

Rotor Winding: Either: Squirrel Cage Rotor: Shorted by end rings copper or aluminum bars to form a simple and reliable design structure.

Wound Rotor (Slip Ring Rotor): Contains three-phase windings on its rotor; the slip rings allow the phase windings to be controlled with external resistances in order to control starting torque needed.

Rotor Shaft: The rotor core is fixed onto the rotating shaft called the rotor shaft.

3.Air Gap

The "air gap" (usually 0.4 mm to 4 mm) or space between the stator and rotor that allows relative motion and magnetic coupling.[1]

4.Magnetic field

A magnetic field in electrical machines is a force field generated by moving electric charges or currents that applies magnetic forces onto other charges and materials, thus able to induce voltages, currents, and produce torque.[2]

### 1.1.2 Classification of machines (asynchronous, synchronous, direct current)

| Type | Principles | Characteristics | Applications |
|---|---|---|---|
| **DC Motors [3][4][5]** | Driven by direct current feeding the rotor windings. The induced magnetic field in the rotor interacts with the | - Fine control of speed and torque<br>- High starting torque<br>- Requires brushes and commutators | Electric vehicles, power tools, cranes, winches, fine speed control applications |

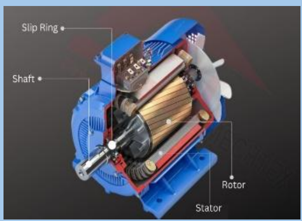
| | | | |
|---|---|---|---|
|  | stator’s field, producing torque. | (in brushed types)<br>- Brushless types use electronic commutation for reliability | |
| **Synchronous Motors (AC)[4][5][6][7]**<br><br> | Rotor rotates at the same speed as the stator’s rotating magnetic field, which is proportional to the supply frequency. | - Constant speed under load<br>- High efficiency and power factor<br>- Rotor excited by magnets or DC source<br>- Complex design, higher cost<br>- Used for power factor correction | Precision machinery, robotics, large fans, pumps, compressors, electric vehicles |
| **Asynchronous Motors (Induction)[4][5][6][8]**<br> | Rotor rotates slightly slower than stator’s magnetic field. Slip induces current in the rotor to generate torque. | - Simple and rugged<br>- Widely used in industry<br>- Speed varies slightly with load<br>- Minimal starting controls required | Industrial drives, pumps, fans, compressors, home appliances |

*Tableau 1.1 : Classification of machines*

## 1.2 Basics of Defects

Due to the important tasks that induction motors perform and their duty of continuous use, induction motors are often considered stressed under operation. The mechanical, electrical, and thermal stresses which occur over time can adversely affect the performance of the motor. Because of this, these motors can develop many types of defects and faults. Understanding the nature and root cause of these problems is critical to maintain reliability and avoid unexpected downtime.

### 1.2.1 Definition of a defect

An electrical motor defect is any defect, any damage, or condition occurring to the motor that prevents the motor from performing properly. The mechanism for defects could be due as a result of insulation (e.g., electrical) breakdown, mechanical damage (e.g., wear), other types of electrical contamination, improper assembly, electrical imbalances, or excessive heat. There are several common types of defects that may occur in electrical motors these include insulation faults (such as turn-to-turn shorts), bearing failures (due to contamination or lubrication), rotor bars damage, stator shape deformation (deformed mechanical mounting supports), air spaces (variations Gleason taps and shaft runouts) etc. There are also common modes of an anomaly, like overheating, physical vibrations, strange or unusual noise, electrical failures - these typically result in motor failure or malfunction.[9]

### 1.2.2 Typical causes of faults

| Cause | definition |
|---|---|
| **Aging** | While aging contributes to motor failure, it accounts for less than 20% of failures. Over time, insulation deteriorates, and mechanical parts wear out, but most failures are due to other stresses rather than just old age. |
| **Overvoltages and Electrical Issues** | Voltage fluctuations, overvoltages, or incorrect wiring can cause insulation breakdown, winding failures, and loss of motor power. Incorrect wiring configurations (e.g., star vs delta) can also lead to motor damage. |
| **Overloads** | When a motor is pushed over its rated load, it will draw excessive current, which can cause overheating, insulation failure, and forcing mechanical components to stress levels above their designed limits. Overloading is one of the most common causes of motor failure and burnout. |
| **Environmental Factors** | Extreme environments play a large role in motor failures. These are: High Temperatures and Overheating: Excess heat increases the rate of insulation break down thereby reducing the lifespan of the motor. A 10°C rise in temperature can result in halving the insulation life.<br><br>Moisture and Humidity: Moisture can promote corrosion and cause insulation failure that can lead to damage if the motor is not properly sealed or protected from moisture ingress.<br><br>Contamination (Dust, Dirt Debris): Contamination can block ventilation and create overheating, while damaging bearings and windings. Vibration and Mechanical Stresses: There are numerous mechanical failures that can occur because of vibration (equipment alignment, bearing wear, mechanical impact damage). |
| **Vibration and Mechanical Stress** | Misalignment, wear on bearings, and physical damage from vibration causes mechanical failure. [10] [11][12] [13] [14] |

*Tableau 1.2 : Typical causes of faults*

### 1.2.3 Consequences on the electrical system

| **Consequences** | |
|---|---|
| ***Production Shutdowns*** | An unexpected motor failure can lead to the sudden or unforeseen shut down of crucial equipment. At this point, some product may have been completed, while a vast loss of production output has been incurred as a production line ceases operations. When the production schedule is compromised, it results in a disengagement from agreed commitments that often leads to production delays in customer deliveries, resulting in even larger losses in productivity |

| | |
|---|---|
| ***Maintenance and Replacement*** | An imperfect motor makes for an expensive repair, and in some cases, it must be completely replaced. Additionally, the specialization of some motors makes it time consuming and expensive to replace, further straining the company's balance sheet |
| ***Safety*** | Faults on the electrical side of motors can lead to electric shocks from faulty wiring, arc flashes, fires and explosions. Safety breaches submit workers to unnecessary risk. Electric shocks may lead to injuries from falls or fatalities. Added to the potential trauma from a fatality, the subsequent legal and compensation claims are both costly and lengthy and further detracts from productive time |
| ***Motor Characteristic Failures*** | Individual motor faults like overheating, contamination, or vibration may lead to changes in available energy output. Disregarding small faults ultimately leads to increased energy use, decreased motor efficiency and lifespan, and unwarranted maintenance visits. |
| ***Interdependency*** | Motors are often vital components driving major processes, and in most cases the interdependency of motors in industrial processes is not obvious. Thus, the failure of one component can lead to other types of resolved or possibly unrecognized failure leading to lost production outputs and ultimately a potentially considerable loss across the plant. |
| ***Damage / Increased Cost (from the incident)*** | If motors have poorly functioning management systems, or frequent or serious incidents of failure, dependability may drop significantly, especially when the failure at one source of production causes problems between equipment at different points of production. Loss of dependence on motor resolution will affect current customers and suppliers/vendor relationships and could jeopardise future business.[15][16] |

*Tableau 1.3 : Consequences on the electric system*

### 1.2.4 Types of Frequent Faults in Electrical Machines

| | | |
|---|---|---|
| **Electrical Faults** | ***Stator Winding Faults*** | Insulation failure, short circuiting between turns, open circuits, phase-to-phase short circuits are all common electrical faults, in particular asychronous and synchronous machines. Common causes of stator winding faults include thermal stress, electrical stress (from inverter drives), ageing of insulation, pattern of contamination.[17][18][19] |

| | | |
|---|---|---|
| | ***Rotor Faults*** | Common rotor faults in induction motors include broken or cracked rotor bars, rotor winding open circuits (where rotor windings are used), and rotor eccentricity (uneven air gap). Rotor faults generate torque pulsations, vibration, and starting difficulties.[18] |
| | ***Power Supply Issues*** | Power supply issues including voltage imbalance, low voltage, and surges in voltage may also cause inefficient operation, component overheating, and premature failure of motor components.[19][20] |
| **Mechanical Faults** | ***Brush and Commutator Faults (DC Machines)*** | Brush commutation faults include open circuits, short circuits, defective brushes, dirty and\or roughened commutators, and inadequate brush contact. Faults within brush and commutation can lead to unstable output voltage, sparking, and heat generation.[21] |
| | ***Bearing Failures*** | Bearings may experience wear, lack of lubrication, overheating, and misalignment. Bearing failures are one of the causes of motor failures, they create and cause excessive vibration, noise, and mechanical stress.[18][20] |
| | ***Eccentricity*** | Any misalignment between rotor and stator that creates varying air gaps within the motor assembly will create vibration, noise, and additional mechanical stress on the motor. [18] |

| | | |
|---|---|---|
| | ***Shaft and/or coupling*** | A bent shaft, a shaft coupling, or mechanical overload and misalignment can cause excessive vibration, extreme noise, or damage to the rotor and/or its connected machinery.[21][22]<br>- Unbalanced Rotor: A rotor can be either statically out of balance or dynamically out of balance, either way, the mechanical impacts of imbalance will create excessive vibration, and significantly reduce bearing life.[21] |
| **Thermal Faults** | ***Overheating*** | Overloading, insufficient ventilation, or malfunctioning electrical components can generate excessive heat, which can degrade insulation and damage windings while decreasing machine life.[20][21] |
| | ***Hot Spots*** | Localized overheating can develop due to shorted turns or poor cooling and cause insulation breakdown and winding damage.[17] |

*Tableau 1.4 Types of Frequent Faults in Electrical Machines*

### 1.2.5 Methods of Defect Detection and Diagnosis

Defect detection is the process that identifies defects and anomalies in one or more products or systems to assess the quality, safety and reliability of products. The defects can be surface defects like spots, pits, scratches, or color differences and any other deviation from the specifications supplied to the manufacturer. Defect detection is more than an ordinary detection of defects: it can be done manually or through automation, which may include specified machine vision and image processing technologies (digital image processing, and/or deep learning) in a systematic effort to improve detection, cost and efficiency. In its simplest perspective, machine vision systems can compare a product's or workpiece's image against quality standards using sensors and artificial intelligence algorithms to detect and locate defects. Moreover, industrial engineers realize the inherent value of identifying and reducing defects in the early stages of production to increase quality, save costs and improve production efficiencies.[23]

Defect diagnosis refers to the step that follows defect detection, in which the nature, cause and extent of the defect requiring further understanding and analysis. Diagnostics to determine root-cause analysis, is necessary to identify an action plan to resolve a defect when it occurs and to mitigate the possibility of reoccurring defects. Diagnostics provides valuable information for the intelligent maintenance of processes necessary for quality assurance, especially when it comes to manufacturing processes where defects occur because of environmental factors as well operational constraints.[24]

| Category | Method | Principle / Description | Key Features | Typical Use Cases |
|---|---|---|---|---|
| **Classical** | Frequency Analysis (FFT, Current Spectrum)[25] | Converts time-domain signals (vibration, sound, current) into the frequency domain to identify fault-related frequency shifts. | - Detects component shifts<br>- Effective for rotating machinery<br>- Current spectrum analysis complements vibration data | Motors, rotating equipment, structural analysis |
| **Classical** | Time Analysis[26] | Analyzes signal changes directly over time, focusing on transients and waveform abnormalities. | - Captures timing issues<br>- Useful for transient analysis<br>- Signature waveforms compare normal vs. fault behavior | Integrated circuits, transient-sensitive systems |
| **Advanced** | Machine Learning (ML)[27][28] | Uses data-driven models to automatically detect fault patterns without human supervision. | - Algorithms: SVM, Logistic Regression, CatBoost<br>- Handles complex/noisy data<br>- Integrates with simulation tools (e.g., ETAP) | Power systems, predictive maintenance, large industrial datasets |
| **Advanced** | Neural Networks (NN)[29] | Deep learning (e.g., transformers, PINNs) combines data from multiple sensors and physics knowledge for high-accuracy fault detection. | - >98% accuracy in complex systems<br>- Excellent at nonlinear relationships<br>- Sensor fusion enhances performance | Inverter-driven motors, sensor-rich environments |
| **Advanced** | Fuzzy Logic[30] | Uses approximate reasoning to handle ambiguity and uncertainty in fault detection scenarios. | - Good for ambiguous or overlapping fault symptoms<br>- Works well with AI techniques<br>- Supports gradual fault severity evaluation | Fault-prone, imprecise environments, hybrid AI systems |

*Tableau 1.5 : Methods of Defect Detection and Diagnosis*

## 1.3 Importance of Simulation for Fault Study

Simulation is instrumental for being part of the investigation and diagnosis of faults within electrical machines, while providing a safe and controlled environment to study an infinite number of possible faults in electrical machines, without exposing any real equipment to potential risk or damage. Simulation allows faults to be applied, observed, and studied extensively, which in turn allows us to have a greater understanding of the fault behavior and progression. The faults can also help in the investigation and application of verification of defective diagnostic methods and treatments of defects as well, and should ultimately increase the reliability and efficiency of real systems. Furthermore, simulation serves to improve the cost and time of using a real system to validate observations and findings; therefore, simulation is fundamentally valuable to research and investigations and has a wide variety of useful applications in industry.

Now we will mention its importance:

-Early Fault Detection and Diagnosis: Simulation allows for and provides various electrical machine faults including the loss of a phase, rotor bar faults, short circuits, supply interruption and more to be modeled and reproduced without damage to the machine. The engineer can then analyze the fault signatures and create diagnostic algorithms without a real machine fault.[31][32]

-Efficiency and Accuracy: Virtual simulation methods again offer a level of efficiency and accurate diagnosis of a fault compared to manual methods. For example, some fault diagnosis systems operate based on virtual simulation and have had diagnosis times of under 30 seconds and higher accuracy then manual diagnostic also improve maintenance efficiency or fleet downtime.[33][34]

-Cost and Time Savings: Simulating the fault digitally avoids expensive physical prototypes and destructive tests, third-party verification and qualification is often not required. The number of physical iterations is reduced thereby saving time and money in both the design and test phases.[35]

-Predictive Maintenance and Reliability Improvement: Simulations support predictive maintenance with the ability to forecast defects and incorporate condition monitoring. Networks of prediction and condition monitoring sensors improve the reliability, functionality and life of the machine by enabling preventative or corrective maintenance actions before major failures occur.[36][37]

-Detailed Analysis of Complex Phenomena: Students and engineers can simulate many transient electrical or mechanical phenomena such as switch-on currents, electromagnetic skating, mechanical vibration and noise. This allows the dynamic behavior of the machine under fault or faulty conditions to be studied and the design optimized to minimize the consequences.[38][39]

-Safe, Controlled Environment: Simulating faults utilises a safe, controlled environment to study dangerous or hazardous fault conditions which may be impractical or unsafe to reproduce physically. This is particularly useful for training and or to design or troubleshoot a system.[33]

-Whole Systems Connection: Simulations can include the whole electrical machine system including the controllers and power electronics. Simulating both machine faults and effects on system performance can then help to assess fault detection and remedial strategies for the overall system.[38]

**Conclusion**

In this chapter we have covered an overview of electrical machines, the nature and causes of the common faults associated with electrical machines, and a brief exposure to some of the diagnostic methods available. We put emphasis on simulation as a safe and convenient means of understanding fault behavior, establishing the basis for the investigation of practical investigation in the following chapter.

# 2 CHAPTER 2: Fault Simulation Using Matlab/Simulink

In this chapter, the simulation of electrical faults in asynchronous machines with Matlab/Simulink is presented. Once a three-phase motor was modeled and validated in a healthy condition, different faults were injected to analyze the effects these faults had on electrical and mechanical quantities. This helped not only the understand the behavior of the machines under fault conditions, but also gave insight to the engineer as to how to analyze or detect the faults.

## 2.1 Simulation Environment

### 2.1.1 Presentation of Matlab/Simulink

Simulink is a graphical extension for MATLAB providing a modeling, simulation and design of dynamic systems for the use of block diagrams. Simulink is commonly used in control engineering, signal processing, power systems, and embedded systems.

### 2.1.2 Useful libraries (SimPowerSystems, Simscape Electrical)

| Library | Description |
| --- | --- |
| **SimPowerSystems[40][41]** | Developed at Hydro-Québec, this toolbox models AC, DC, and hybrid systems. Includes components like transformers, machines, power electronics, and FACTS devices. Features phasor and discrete simulations, load flow analysis, and mechanical-thermal domain coupling. |
| **Simscape Electrical[42]** | Built on Simscape technology for modeling electromechanical systems. Offers libraries for power systems and mechatronics, custom nonlinear modeling (Simscape language), HIL testing support, and tools like powergui for steady-state and frequency-domain analysis. |

*Tableau 2.1 : Useful libraries (SimPowerSystems, Simscape Electrical)*

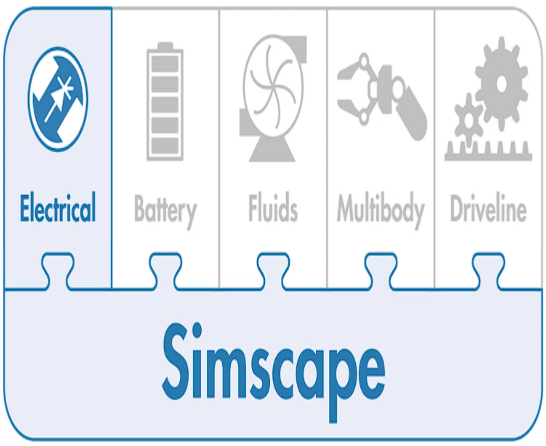



*Figure 2.1 : Simscape Domains in MATLAB Simulink*

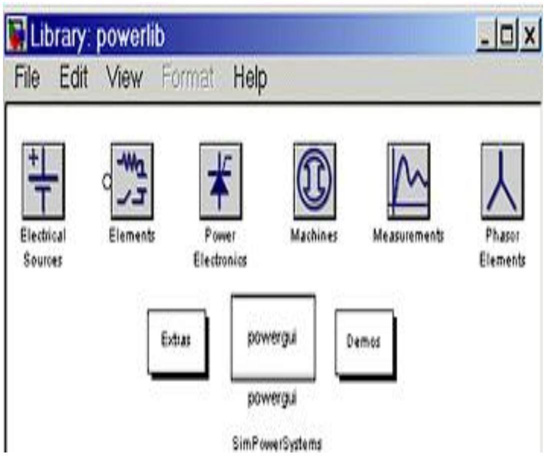



*Figure 2.2 : SimpowerSystems (powelib) Library in matlab*

## 2.2 General diagram of an electrical machine model

The standard electrical machine model (block diagram form) consists of Electrical circuits of the stator and rotor windings both with voltage and current time depending dynamic behaviours

- Mechanical rotor dynamics with instantaneous angular velocity and torque.
- Electromechanical energy transfer (conversion).
- Measurement and control blocks for the designer to monitor and evaluate the performance of the machine.

The modular structure of the model makes it possible to simulate various types of machines (DC, synchronous, induction) and operating conditions and assess the machine's variables such as power, torque, speed, losses, and efficiency in a single system.

## 2.3 Modeling an Electrical Machine – Case of the Three-Phase Asynchronous Motor

The three-phase asynchronous motor has been most prevalent in industry, with over 80% of installed electric motors are asynchronous motors. This motor design is robust, inexpensive, and reliable; however, it can also be sensitive to faults associated with the rotor, stator, and power supply maximising options for diagnostic study. In addition, with the availability of pre-built libraries in MATLAB/Simulink such as Simscape Electrical, the motor design can also be conveniently modelled, simulated and studied.

### 2.3.1 Fundamental Speed Relationships in Asynchronous Motors

#### 2.3.1.1 Synchronous Speed (Ns)

The synchronous speed is that of rotating magnetic field produced by the stator, which has a function of supply frequency and number of poles:

$$Ns = \frac{120 \times f}{P} \quad (1)$$

Where:
Ns: synchronous speed in revolutions per minute (RPM)
f: supply frequency (50hz)
P: number of poles

#### *2.3.1.2 Rotor Speed (Nr)*

The rotor speed is below synchronous speed because slip occurs, which is defined as:

$$Nr = (1 - s) \times Ns \quad (2)$$

Where:

s: slip
Nr: rotor speed in RPM
Ns: stator speed in RPM

#### *2.3.1.3 Slip (s)*

Slip is the relative difference between synchronous speed and rotor speed expressed as a percentage of synchronous speed. Slip does occur, in the motor, because slip is needed to produce torque.

$$s = \frac{Ns-Nr}{Ns} \quad (3)$$

or expressed as a percentage:

$$s(\%) = (\frac{Ns-Nr}{Ns}) \times 100 \quad (4)$$

### 2.3.2 the motor equations on the coordinates system (dq) are set as

## Flux

Stator

$$\frac{d\lambda sd}{dt} = vsd - Rs\ isd - \omega da\lambda sq \quad (5)$$

$$\frac{d\lambda sq}{dt} = vsq - Rs\ isq + \omega da\lambda sd \quad (6)$$

Rotor

$$\frac{d\lambda rd}{dt} = vrd - Rr\ ird - \omega dA\lambda rq \quad (7)$$

$$\frac{d\lambda rq}{dt} = vrq - Rr\ irq + \omega dA\lambda rd \quad (8)$$

## Flux linkage expressions

$$\lambda sd = Ls\ isd + Lm\ ird \quad (9)$$

$$\lambda sq = Ls\ isq + Lm\ irq \quad (10)$$

$$\lambda rd = Lm\ isd + Lr\ ird \quad (11)$$

$$\lambda rq = Lm\ isq + Lr\ irq \quad (12)$$

## current equation

$$isd = \frac{1}{\frac{Lm^2}{Lr} - Ls}(-Lr\lambda sd + Lm\lambda rd) \quad (13)$$

$$isq = \frac{1}{\frac{Lm^2}{Lr} - Ls}(-Lr\lambda sq + Lm\lambda rq) \quad (14)$$

$$ird = \frac{1}{\left(\frac{Lm^2}{Lr} - Ls\right)}(Lm\lambda sd - Ls\lambda rd) \quad (15)$$

$$irq = \frac{1}{\frac{Lm^2}{Lr} - Ls}(Lm\lambda sq - Ls\lambda rq) \quad (16)$$

## Inductances

$$Ls = Lls + Lm \quad (17)$$

$$Lr = Llr + Lm \quad (18)$$

## Electromagnetic Torque

$$Te = PLm(isqird - isdirq) \quad (19)$$

## Current (dq → abc)

$$\begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta da & -\sin\theta da \\ \cos\left(\theta da - \frac{2\pi}{3}\right) & -\sin\left(\theta da - \frac{2\pi}{3}\right) \\ \cos\left(\theta da + \frac{2\pi}{3}\right) & -\sin\left(\theta da + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} isd \\ isq \end{bmatrix} \quad (20)$$

| Symbol | Description |
|---|---|
| **ωm** | Angular velocity of the rotor (rad/s) |
| **ωem** | Electrical rotor speed (rad/s) |
| **ωslip** | Electrical rotor slip speed (rad/s) |
| **ωsyn** | Synchronous rotor speed (rad/s) |
| **ωda** | dq stator electrical speed with respect to the stator a-axis (rad/s) |
| **ωdA** | dq stator electrical speed with respect to the rotor A-axis (rad/s) |
| **Θda** | dq stator electrical angle with respect to the stator a-axis (rad) |
| **ΘdA** | dq stator electrical angle with respect to the rotor A-axis (rad) |
| **Lq, Ld** | q- and d-axis inductances (H) |
| **Ls** | Stator inductance (H) |
| **Lr** | Rotor inductance (H) |
| **Lm** | Magnetizing inductance (H) |
| **Lls** | Stator leakage inductance (H) |

| | |
|---|---|
| **Llr** | Rotor leakage inductance (H) |
| **vsq, vsd** | Stator q- and d-axis voltages (V) |
| **isq, isd** | Stator q- and d-axis currents (A) |
| **λsq, λsd** | Stator q- and d-axis flux (Wb) |
| **irq, ird** | Rotor q- and d-axis currents (A) |
| **λrq, λrd** | Rotor q- and d-axis flux (Wb) |
| **va, vb, vc** | Stator voltage phases a, b, c (V) |
| **ia, ib, ic** | Stator currents phases a, b, c (A) |
| **Rs** | Resistance of the stator windings (Ohm) |
| **Rr** | Resistance of the rotor windings (Ohm) |
| **P** | Number of pole pairs |
| **Te** | Electromagnetic torque (Nm) |

*Tableau 2.2 : Definition of Variables Used in the Induction Motor dq Model*

### 2.3.3 Typical technical characteristics of the engine used

| Parameter | Value |
|---|---|
| **Type** | Three-phase squirrel-cage asynchronous motor |
| **Nominal Power** | 3 kW |
| **Supply Voltage** | 400 V three-phase, 50 Hz |
| **Nominal Speed** | 1460 rpm (typical 4% slip) |
| **Number of Poles** | 4 |
| **Stator Resistance (Rs)** | 1.4050 Ω |
| **Rotor Resistance (Rr)** | 1.3950 Ω |
| **Leakage Inductance (Ls, Lr)** | 178 MH |
| **Mutual Inductance** | 172.2 MH |
| **Moment of Inertia** | 0.0131 kg·m² (approximate value) |
| **Load Type** | Constant load (constant torque) or torque proportional to speed |

*Tableau 2.3 : Typical technical characteristics of the engine used*

## 2.4 Validation of the model in normal operation

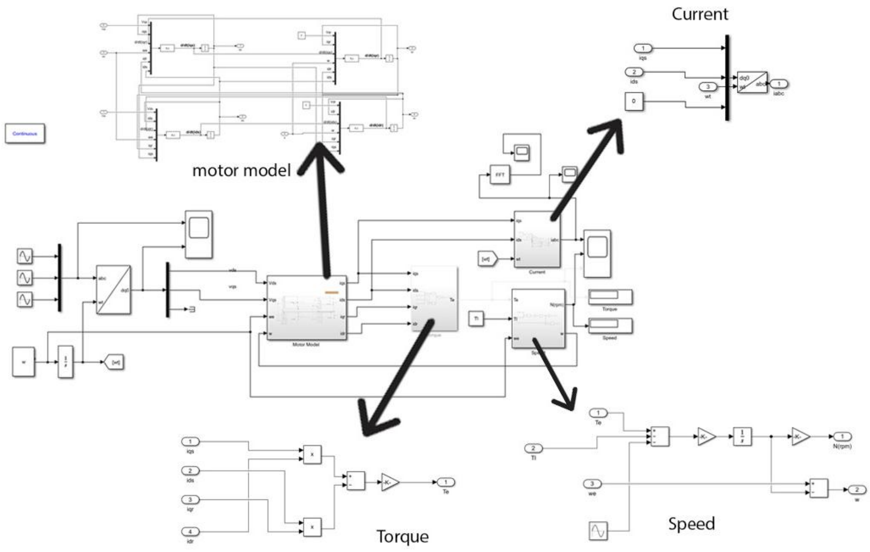



*Figure 2.3 : model in normal operation*

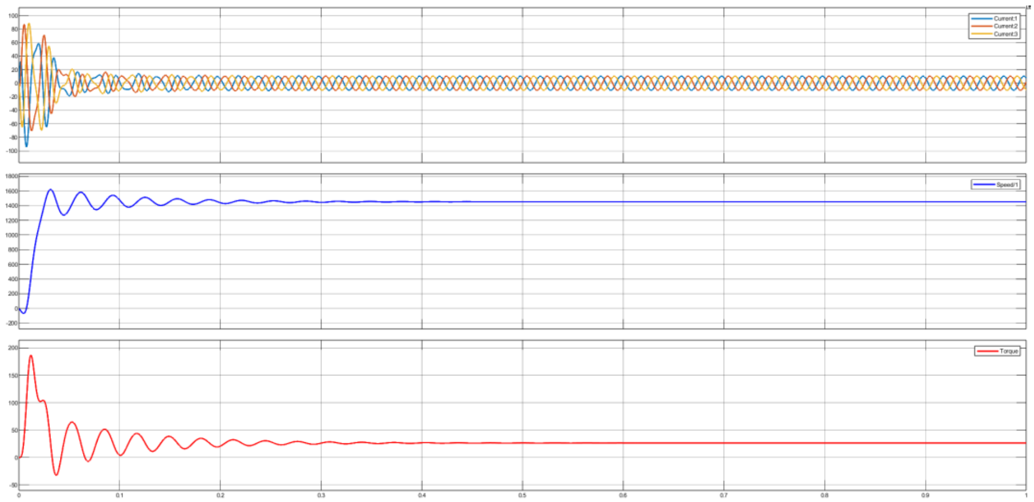


*Figure 2.4 : results in normal operation*

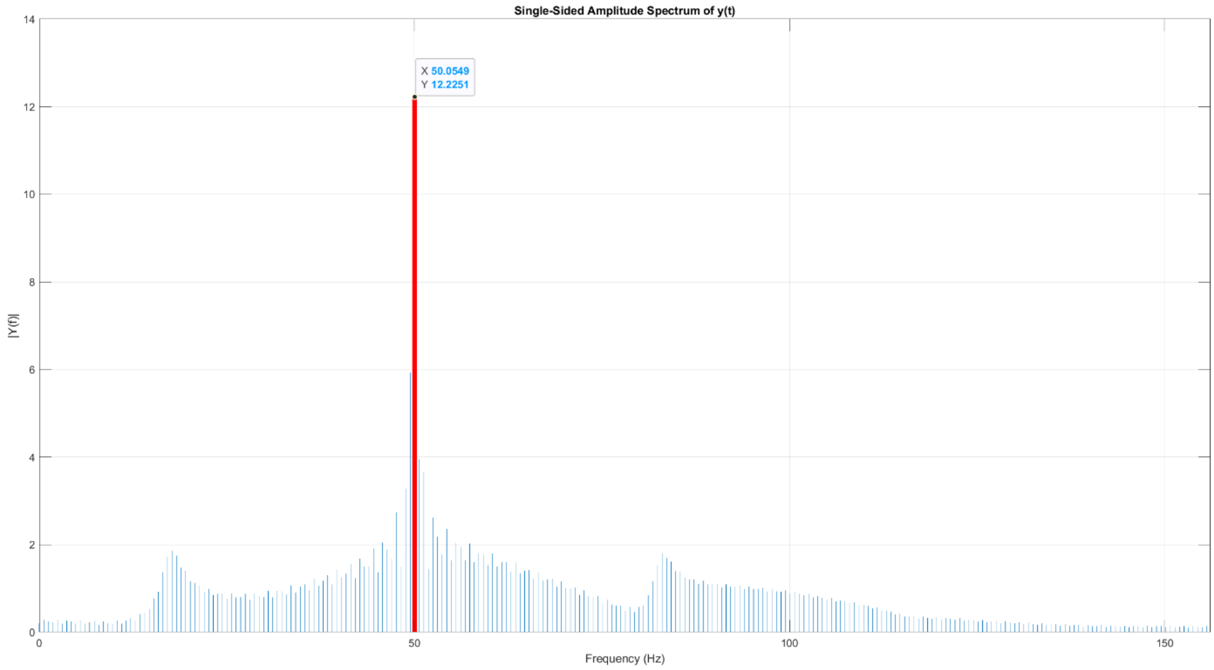



*Figure 2.5 : results of fft in healthy conditions*

As shown in the figure 2.5 the FFT spectrum given indicates a good operating condition of the system which can be characterized by the major peak at 50.05 Hz which corresponds to the fundamental frequency (50 Hz) of a regular power supply. The FFT spectrum doesn't indicate any significant harmonic components above that of the fundamental frequency or sidebands, or any symmetrically about the fundamental frequency. Therefore, the electrical and mechanical components of the machine are operating in a stable configuration. Further, the low amplitude of the other frequency indicates minimal levels of noise, again confirmational of there being no commonly associated faults like broken rotor bars, stator short circuits (inter-turn shorts), or unbalance, all indicative of the motor operating well with no issues present.

### 2.4.1 Results and Interpretation

The first graph of the Figure 2.2 shows the phase currents Ia, Ib, Ic. Upon start-up we see a significant transient state: the currents had large amplitudes in an erratic fluctuating shape. This is typical of the first currents drawn by an asynchronous motor, which is normally several time the nominal current (this is called the "starting current"). The transient response is due to the fact an initial magnetic flux was not provided and the rotating field had time to create. After about 0.15 seconds the currents became sinusoidal and thought to be balanced and 120° out of phase; at this point we confirm the motor is at steady state.

The second graph represents the rotor speed. Immediately after power-up, the speed is zero, then it increases rapidly. During the ramp-up, oscillations (or "transient ripples") appear, due to the rotor's inertia and fluctuating electromagnetic forces. These oscillations are gradually damped thanks to mechanical resistance and internal losses. The speed eventually stabilizes around 1450 rpm, which corresponds to normal slip for a supply frequency of 50 Hz (synchronous speed of 1500 rpm). This rapid stabilization confirms the good dynamic behavior of the model.

The third graph corresponds to the evolution of the electromagnetic torque. It is possible to see that very high initial peak that corresponds to the starting torque. This torque is necessary because it needs to overcome the inertia of the rotor to allow for rotation to begin. Following the peak there is very quick oscillations about mean value that indicate the dynamic interactions between the stator and rotor fields, that attenuates and experiences damping until reaching a constant torque once the speed is reached. The behaviour that we see is reflective of the real behaviour of a squirrel-cage asynchronous motor.

The FFT spectrum given indicates a good operating condition of the system which can be characterized by the major peak at 50.05 Hz which corresponds to the fundamental frequency (50 Hz) of a regular power supply. The FFT spectrum doesn't indicate any significant harmonic components above that of the fundamental frequency or sidebands, or any symmetrically about the fundamental frequency. Therefore, the electrical and mechanical components of the machine are operating in a stable configuration. Further, the low amplitude of the other frequency indicates minimal levels of noise, again confirmational of there being no commonly associated faults like broken rotor bars, stator short circuits (inter-turn shorts), or unbalance, all indicative of the motor operating well with no issues present.

Thus, all the results confirm that the asynchronous motor model correctly simulates normal operating conditions, both in transient and steady state. This model is therefore considered reliable for the study and simulation of faults that will be addressed in the rest of the work.

## 2.5 Injection and Simulation of Faults

### *2.5.1* Simulation (expremental/Simulation Setup)

#### *2.5.1.1 Rotor Bar Fault Simulation*

In an induction motor, a rotor bar fault occurs when one or more of the rotor bars are broken or fractured, thereby interrupting the current path in those bars. This condition usually occurs as a result of excessive starts, heavy loads, and thermal and mechanical stresses. A broken rotor bar results in rotor circuit asymmetry, which causes a reverse rotating magnetic field and certain frequency components in the stator current, especially frequencies such as (1±2s) f, where s is the slip and f is the supply frequency. This results in torque and speed oscillations, and ultimately lowers the efficiency and reliability of the motor.[43] The equation for rotor bar fault in induction motors is often based on the observation of frequency components in the spectrum of the stator current that occur because of broken rotor bars. The following is a typical equation for the frequencies of the fault signatures in the stator current due to broken rotor bars:[45]

$$f_{brb} = f_s(1 \pm 2sk) \quad (5)$$

where:
$f_{brb}$: are the characteristic fault frequencies
$f_s$: is the supply frequency (50hz)
s: is the slip of the motor
k=1,2, 3… (harmonic index).

**Model modification:**
- Increasing the resistance in the rotor circuit model.
- In the equivalent circuit, we need to modify the rotor resistance dynamically.
- Simulating **asymmetry** in the rotor resistance of a wound rotor or squirrel-cage motor.
Changes: Increasing Rr (rotor resistance)

#### *2.5.1.2 Simulation of a Stator Turn Short Circuit (inter_turns)*

A turn-to-turn short circuit in the stator winding occurs if one (or more) turns of the stator winding are short-circuited. These turn-to-turn shorts on stator winding happen due to insulation breakdown caused by heat, mechanical damage, or overvoltage. The occurrence is modeled by an additional short circuit resistance branch in the stator circuit. The short requires at least one of the three stator phase currents to be larger and also affects the stator voltage equations, resulting in higher current in the shorted turns, with a steady progressive limiting of power in the windings.[44]

When a stator turn short circuit (inter-turn short circuit) occurs in an induction motor, the failure signature can usually be seen as a distinct harmonic in the stator current spectrum. This frequency results from fault-generated negative sequence currents that, when combined with the rotor currents, produces torque pulsations at two times the supply frequency. The primary frequency component associated with a stator turn short circuit fault in the stator current write is:

$$f_{sc} = 2 \times f_s \qquad (6)$$

where fs is the supply frequency. This frequency component is a consistent signature of inter-turn short circuits of the stator winding and is utilized for fault detection and diagnosis techniques.[46]

**Model modification**
- Modify the stator winding model to create a **shorted turn** using a low-resistance path.
- Reduce insulation resistance between phases turns.
- Changes: decrease Rs

#### *2.5.1.3 C. Simulation of a Voltage Unbalance*

Voltage unbalance in an electric motor occurs when the voltages applied to the various phases of the stator have different magnitudes or phase angles. The occurrence of voltage unbalance may originate from faults in the electric power supply network, faults in the stator (such as turn-to-turn short circuit faults), or from mechanical asymmetries. An unbalanced voltage source will produce an unbalanced current source, which has ramifications of additional losses, caused vibrations, and shorter motor life.[44]

The characteristic frequency components associated with unbalanced supply voltage in three-phase induction motor can be expressed as:

$$f_{unv} = (1 \pm 2k)fs \qquad (7)$$

where:
funv:is the frequency of the unbalance voltage fault component
fs: is the supply (fundamental) frequency (50hz)
k=1,2,3,.. is the harmonic order.

Thus, unbalanced voltage produces sideband frequencies at odd multiples of the supply frequency; fs,3fs,5fs, etc. The most important component usually seen is the third harmonic frequency 3fs (150 Hz in the case when fs=50 Hz); this harmonic component is the clearest indicator of voltage unbalance in the motor current spectrum.[47]

**Model modification**

-Supply different voltages to each phase (simulate an unbalanced three-phase system).

### 2.5.2 Results and Interpretation

#### 2.5.2.1 Rotor Bar Fault Simulation

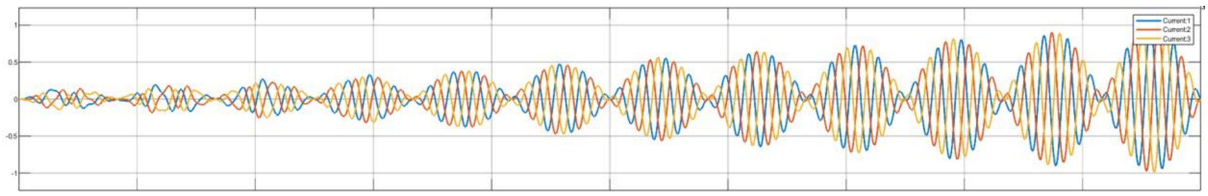


*Figure 2.6 : stator curren in broken bar fault*

The three-phase currents demonstrate amplitude modulation patterns in the time domain indicating non-stationary behaviour. Modulation patterns are generally diagnostic of rotor asymmetry, in particular broken rotor bars. Additionally, some evidence of phase imbalance and sideband frequencies also provides supporting evidence for the diagnosis.

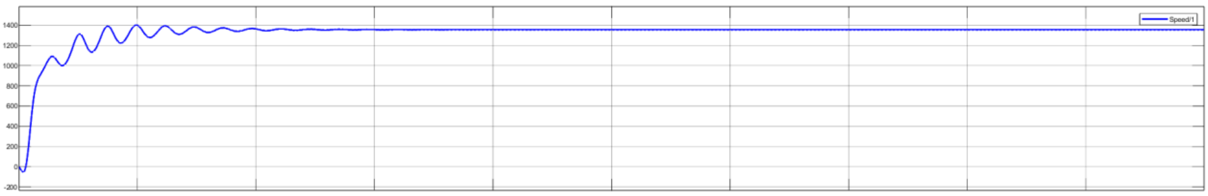


*Figure 2.7 : Rotor speed in broken bar fault*

The rotor speed quickly rises with a minor drift before settling to a stable value 1357 rpm. It oscillates during the transient period just like the torque response, which diminishes quickly but has a small persistent oscillation in the steady-state.

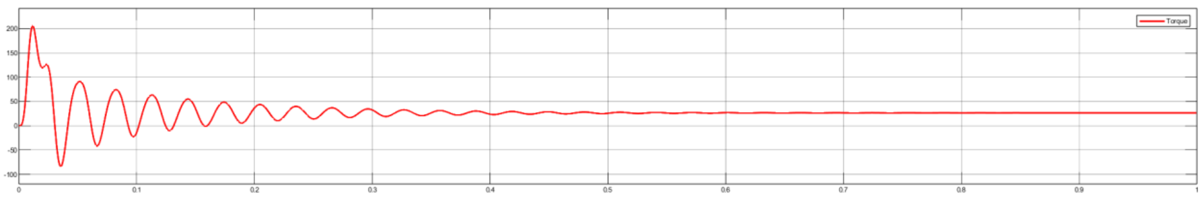


*Figure 2.8 : torque in broken bar fault*

The torque waveform levels fluctuate at startup with high peak with overshoot and settling characteristics with obvious ripples that originate and damp out over time. The torque stabilizes at about 0.5 seconds, but at lower level and still with ripples remaining.

**conclusion**

The stator currents show distinct evidence of broken rotor bars: Explain what sort of amplitude modulation is most likely caused by rotor slot harmonics, including significant first oscillations and normalized settling time indicating mechanical imbalance or asymmetry in the rotor's magnetic fields, both of which are hallmarks of broken rotor bar fault. Additionally, the emergence of startup oscillations, including a minimal alteration in speed (what is commonly called ripples) conforms to torque pulsations ordinarily caused by rotor bars in a fictitious way. The motor does eventually settle and reaches a steady state, but the ripples indicate a constant disturbance due to periodic behavior caused by rotor asymmetry, complementing the diagnosis.

### *2.5.2.2 Simulation of a Stator Turn Short Circuit*

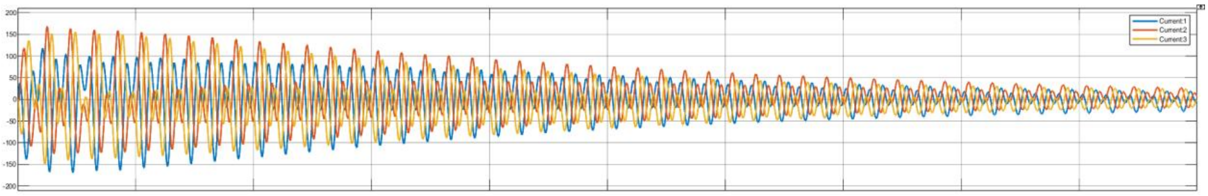



*Figure 2.9 : stator current in short circuit fault*

The stator currents (Current1, Current2, and Current3) are grossly distorted and unbalanced with varying amplitude and harmonic distortion indicating the presence of a stator winding fault. This may be an inter-turn short circuit, which may lead to magnetic asymmetry and unbalanced currents.

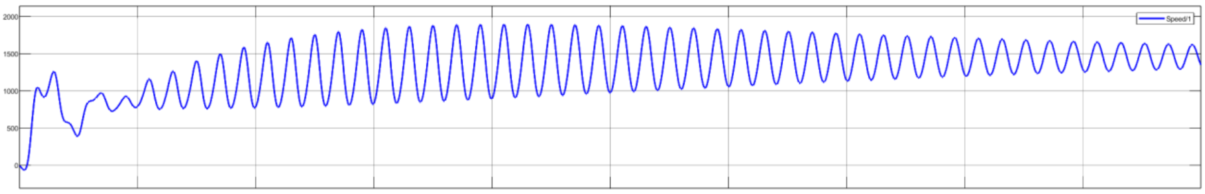



*Figure 2.10 : Rotor speed in short circuit fault*

There is rotor speed instability with sharp drops and oscillations that are often and violent in their response. This indicates infrequent torque disturbances were induced on a stator fault, so the motor does not have a consistent speed and electromagnetic performance has degraded.

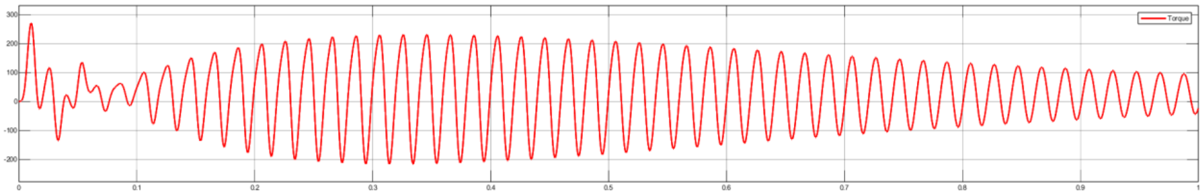


*Figure 2.11 : torque in short circuit fault*

The electromagnetic torque signal shows irregular oscillations with periodic sharp spikes and greater high-frequency components, which reflects disturbing qualities to the machine. The spikes consistently appear at fairly regular intervals, indicating some kind of faulty condition which is generally electrical asymmetry. The overall waveform is significantly different from the anticipated smooth profile expected under normal operating conditions, showing compelling transients both positive and negative of high frequency.

**conclusion**

The joint analysis of stator currents with speed and electromagnetic torque may verify a short circuit in the stator. This fault causes unbalanced and severely distorted currents, which affects the rotor's ability to increase speed and torque stability. These symptoms are clear indications of a significant failure, which could potentially affect reliability of the machine. It is essential that continuous monitoring and early detection techniques are initiated, in order to prevent total fail or irreversible damage.

#### *2.5.2.3 Simulation of a Voltage Unbalance*

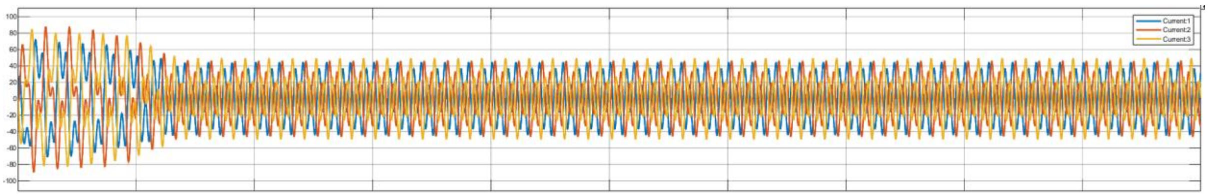


*Figure 2.12 : stator current in suply unbalance fault*

The three-phase currents (Current1, Current2, Current3) demonstrate high amplitude oscillations at the start, and then stabilize. However, even in steady state current the amplitude and waveform are asymmetrical with respect to the phase. This is a clear indicator of current unbalance.

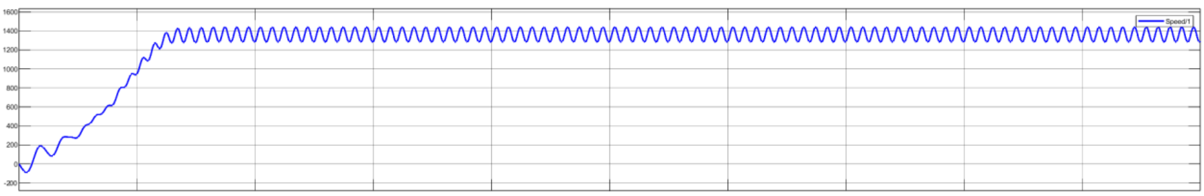


*Figure 2.13 : Rotor speed in suply unbalance fault*

The rotor speed increases in a nonlinear way during start up, with clear oscillation as the rotor accelerates to a steady state, nominal speed. The oscillation indicates that the rotor is being subjected to dynamic disturbances and electromechanical interactions typical of rotor operation during or after a fault has occurred, such as, a broken rotor bar which may cause an imbalance in torque produced by the rotor. The speed will eventually transition to a steady-state; however, steady-state will still not be completely smooth; rather, it will demonstrate periodic fluctuations of low amplitude indicating steady-state torque ripple caused by an asymmetric current distribution in the rotor. This steady-state ripple indicates an internal rotor defect, and furthersupports the mechanical and electromagnetic back-of-the-envelope malady as a result of the fault due to the broken bar.

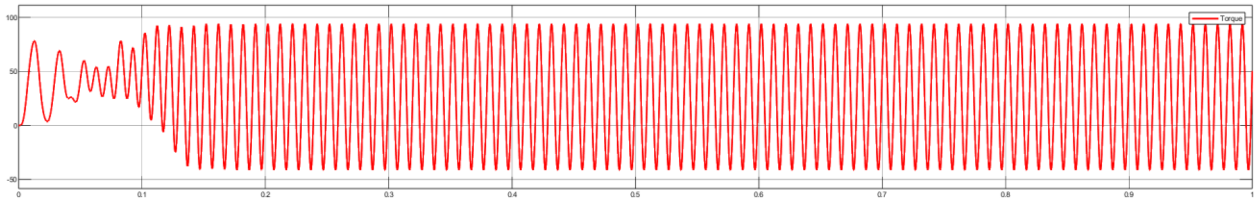


*Figure 2.14 : torque in suply unbalance fault*

The torque response demonstrates considerable fluctuations identified by high-amplitude oscillations while the motor accelerates. The early transients indicate the mechanical and electromagnetic instabilities associated with the specified fault condition—i.e., a broken rotor bar. With time, as the system reaches more or less steady operation, the torque transitions into a steady state. However, roughly consistent oscillations persist—the steady-state oscillations have a consistent alternating (AC) component added to an average torque level.

**conclusion**

The simulation shows an undeniable imbalanced motor condition. The phase currents are not symmetrical, speed shows small oscillations around the nominal speed, and torque has sustained rippling. These behaviors represent mechanical unbalance; both mechanical and electrical performances are influenced when loading periodically. An unbalanced condition can produce periodic forces. These periodic forces can not only lead to efficiency problems, but can cause long term damage to the motor condition if not remedied.

### 2.5.3 FFT results of each fault

#### **2.5.3.1** broken bar fault

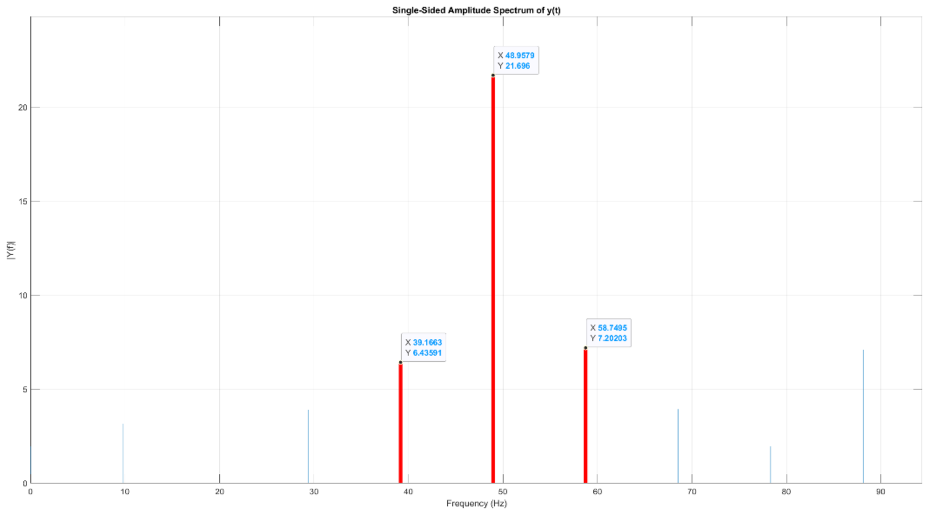



*Figure 2.15 : FFT result for broken bar fault*

The FFT spectrum of the motor current is shown in Figure 2.12, and it clearly shows a broken rotor bar fault was present. In the FFT, two sidebands occur at approximately 39.17 Hz and 58.75 Hz (around the main supply frequency peak of 48.96 Hz). The main frequency peak in the FFT shows two sidebands symmetrically spaced at approximately ±9.8 Hz from the positive frequency peak. This represents the theoretical fault signature given by f= fs±2sf s, where fs is the supply frequency and s is the slip. We can see that using the spacing, the calculated slip is around 10%, which is a typical value when the motor is subjected to load. In addition, the sidebands show relatively high amplitudes of (6.44 and 7.20). This all supports the rotor asymmetry due to broken rotor bars once again confirms the diagnosis.

#### 2.5.3.2 stator short circuit

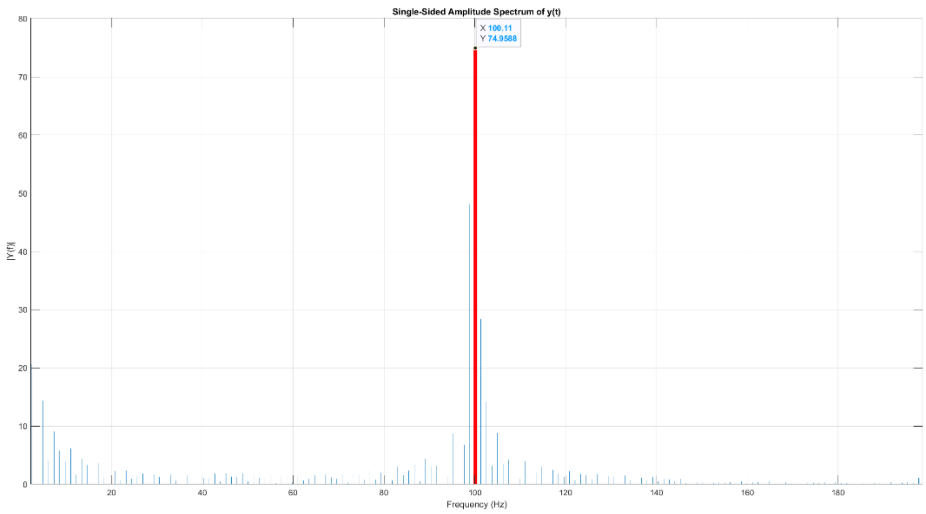



*Figure 2.16 : FFT result for short circuit fault*

In the figure 2.16 FFT results show a prominent peak at 100.11 Hz, which corresponds to two times the supply frequency (2 × fs). This third harmonic, or twice the frequency, is an identifiable baseline signature for a stator winding inter-turn short circuit fault. In a dq reference frame, an inter-turn short circuit would cause a disturbance in id and iq currents which would manifest itself in the frequency domain as a component 2fs. The presence of this harmonic in the FFT confirms the existence of a short-circuit fault, and validates the simulation.

#### 2.5.3.3 unbalance suply voltage

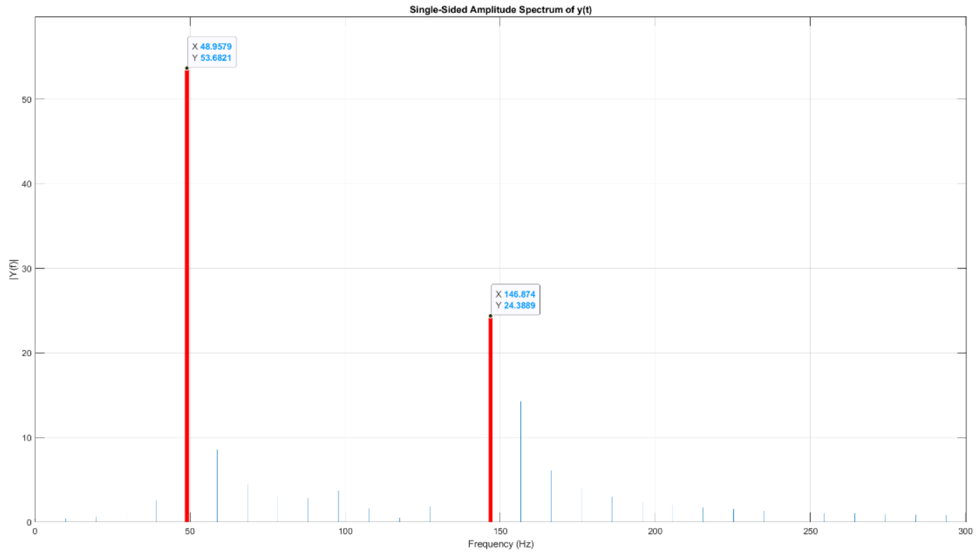



*Figure 2.17 : FFT result for unbalance suply voltage fault*

This figure illustrates the FFT spectrum of a signal when under a voltage unbalance condition in a three-phase induction motor. The peak at ~48.96 Hz is the fundamental supply frequency (fs ≈ 50 Hz). The component at ~146.87 Hz is close to the third harmonic (3fs), which is a prominent signature of unbalance voltage. From the equation Funv = (1 ± 2k)fs, take k = 1. Therefore 3fs = 150 Hz results from unbalance in the magnitude of the voltage or phase angle between the three phases. The appearance of this component in the spectrum confirms that there are unbalances supply voltage which is a reliable signature of a fault in induction motors.

## 2.6 Conclusion

In this chapter, a three-phase asynchronous motor was modeled and simulated in Matlab/Simulink, along with the discovery of faults in the electrical machines. The validated model was designed successfully under regular operating conditions and subsequently the elementary faults were injected into the model, which included rotor bar defects, stator turn short circuits and voltage unbalance. In this study, FFT provided fault signatures from the faults analysed, which demonstrated the advantage of using simulation to understand and identify anomalies in electrical machines.

# General conclusion

The objective of the work was to study and analyze the behavior and characteristics of electrical machines in fault scenarios through modeling, and simulation, of which the three-phase asynchronous motor was of primary focus. Electrical machines are a critical part of industrial systems, maintaining their reliability will guarantee production, reducing operational costs, and maintaining safety. The early detection, and accurate verification of faults is paramount to efficient maintenance processes.

The first section of this study provided a considerable theoretical exposition of electrical machines and some of the fault types they are subjected to. We presented the classification and operation of electrical machines with a focus on DC, synchronous, and asynchronous systems in the first chapter and demonstrated common faults of electrical machines attributable to broken rotor bars, stator turn short circuits, and unbalance of voltage which included descriptions of characteristics, causes and the effect on machine operation as well as the main diagnostic techniques concerning current signature analysis used in industry, vibration detriments, and use of the frequency domain in diagnosing faults such as Fast Fourier Transform (FFT) to analyze electrical machine diagnostics.

Based on this theoretical foundation, the second part of the thesis shifted focus to simulating faults in practice using the Matlab/Simulink environment. A complete dynamic model of a three-phase asynchronous motor was created and tested under normal operating conditions to validate its performance. Once the model's operation was confirmed, faults were systematically introduced into the model and the impacts of the faults were evaluated on selected physical quantities: stator current, rotor speed and electromagnetic torque. The analysis confirmed that corresponding disturbance patterns—in both the time and frequency domains—were present for each type of fault. For example, broken rotor bars produced the

sideband frequencies unique to the fault whereas stator turn short circuits boosted the second harmonic and voltage unbalance exhibited third harmonic features in the current spectrum.

The results highlighted the usefulness of simulation as a study of fault analysis. Simulation is capable of safely producing and providing repeatable fault experiments and with the developed and verified programming model, supports the development of diagnostic indicators. Simulation allows practitioners/researchers to analyse complex behaviours, without the associated cost and risk of physical testing.

There are many prospects that can be inferred from this work. First, greater variety to electrical faults can be simulated, such as bearing faults, rotor eccentricity, faulty insulating systems or thermal overloads can all be simulated. Including these cases would provide a better overall perspective of the reliability issues in machines. Second, the use of real-time simulation environments (for example, Hardware-in-the-Loop systems) would allow for greater use of physical sensors and controllers, to allow for online fault detection systems with real time experimentation. Finally, the ability to use advanced data analysis procedures, such as artificial intelligence, neural networks, or pattern recognition would allow for increased automation and precision in diagnosing faults. These tools can include simulated and experimental data to enable real-time condition monitoring and fault classification, which are two important elements of predictive maintenance that ensure reliability in modern manufacturing environments.

Overall, this thesis has shown how the combination of theoretical understanding with experimentation using simulation leads to powerful insight into the behaviour of machines with faults.Furthermore it lays the groundwork for future research and the development of intelligent, predictive diagnosis systems for future generations of electrical engineers.

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