

REPUBLIQUE ALGERIENNE DEMOCRATIQUE ET POPULAIRE

الجمهورية الجزائرية الديمقراطية الشعبية

MINISTRY OF HIGHER EDUCATION
AND SCIENTIFIC RESEARCH

HIGHER SCHOOL IN APPLIED SCIENCES
-T L E M C E N-



المدرسة العليا في العلوم التطبيقية
École Supérieure en
Sciences Appliquées

وزارة التعليم العالي والبحث العلمي

المدرسة العليا في العلوم التطبيقية
- تلمسان -

Graduation Thesis

For the attainment of the master's degree

Field: Electronics

Major: Industrial Computing

Presented by: Iyad ATIG

Thesis Title

**Diagnosis and Physical Modeling of Faults
in a Three-Phase Induction Motor**

Publicly defended, on 23/06/2026, before the jury composed of:

Ms Nadia BENAHMED	Professor	ESSA-Tlemcen	President
Mr Mohammed MESSIRDI	Adjunct Professor	ESSA-Tlemcen	Supervisor
Mr Farid OUDJAMA	MCB	ESSA-Tlemcen	Co-supervisor
Ms Asmaa BELAID	MCB	ESSA-Tlemcen	Examiner 1
Ms Kadaoui ELAÏDI	MCB	ESSA-Tlemcen	Examiner 2
Mr Choukri KOUANI	Engineer	INATEL	Examiner 3

Academic year : 2025/2026

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

DEDICATION

*I dedicate this thesis to my dear father, **BenAbdellah**, and to my beloved mother, **B. Assia**, whose love, prayers, sacrifices, and trust have been a constant source of strength. Their support gave me the courage to continue, the patience to overcome difficulties, and the confidence to complete this work. I also dedicate it to my brother, **Ihab**, and to my sisters, **Iness**, **Alaa**, and **Insaf**, for their affection, encouragement, and presence throughout this journey.*

To my supervisors

*I dedicate this work with deep respect and sincere gratitude to my supervisors, **Mr. Mohammed MESSIRDI** and **Mr. Farid OUDJAMA**, for their guidance, patience, scientific advice, and the time they devoted to this thesis. Their support helped me improve the quality of this work and guided me through an important stage of my academic formation.*

To my family, friends, and colleagues

I am also grateful to everyone who encouraged me with a word, a prayer, or a gesture of support during the preparation of this project.

ACKNOWLEDGMENT

First and foremost, I thank **Allah**, the Most Merciful, for giving me the strength, patience, health, and guidance to complete this thesis.

I express my deepest gratitude to my supervisors, **Mr. Mohammed MES-SIRDI** and **Mr. Farid OUDJAMA**, for their guidance, availability, scientific advice, and continuous support throughout this work.

I sincerely thank the members of the jury for the time and attention devoted to reading and evaluating this thesis.

I also extend my respectful thanks to **Mr. Boucherit ROUISSAT**, Director of the school, for his leadership and for supporting an academic environment that encourages serious work and excellence.

Finally, I thank my family, friends, classmates, and colleagues for their encouragement, prayers, and support during the preparation of this project.

ABSTRACT

This thesis develops a simulation-based diagnostic study for a three-phase squirrel-cage induction motor, supported by experimental parameter identification on a Siemens 1LA7096-4AA10 1.5 kW laboratory machine. A documented 500 W benchmark motor is first used to establish the power-invariant synchronous- dq formulation, the inductance reconstruction procedure, and the analytical-versus-Simscape validation workflow. The Siemens motor is then identified from a phase-to-neutral stator-resistance measurement, no-load, blocked-rotor, load, and coast-down tests; its inertia is taken from the model-specific Siemens datasheet, while the viscous-friction coefficient is derived from the measured decay ratio. Using these identified Siemens parameters, a healthy 1.5 kW analytical model is validated against an independent Simscape implementation, a measured 8.5 Nm torque-speed operating point, and manufacturer rated data. The validated Siemens model is then used to generate and interpret deterministic simulation datasets for supply-voltage unbalance, incipient inter-turn short circuit, a BPFO bearing-torque surrogate, and broken-rotor-bar rotor asymmetry. The results show that several diagnostic indicators are strongly load-dependent: negative-sequence current factors, 100 Hz torque components, BPFO sideband indices, and BRB slip sidebands cannot be interpreted through fixed thresholds without load context. The work is therefore positioned as a physically grounded modeling and dataset-construction stage, not as a hardware fault campaign or a deployed classifier.

Keywords: induction motor, parameter identification, dq modeling, Simscape validation, fault diagnosis, load dependence.

RÉSUMÉ

Ce mémoire développe une étude de diagnostic par simulation d'un moteur asynchrone triphasé à cage, appuyée par l'identification expérimentale des paramètres d'une machine de laboratoire Siemens 1LA7096-4AA10 de 1.5 kW. Un moteur de référence de 500 W est d'abord utilisé pour établir la formulation synchrone dq invariante en puissance, la reconstruction des inductances et la démarche de validation entre le modèle analytique et Simscape. Le moteur Siemens est ensuite identifié par mesure de la résistance statorique phase-neutre à température ambiante, essai à vide, essai rotor bloqué, essai en charge et essai de décélération; son inertie est retenue depuis la fiche technique Siemens du modèle, tandis que le coefficient de frottement visqueux est déduit du rapport de décroissance mesuré. A partir de ces paramètres, le modèle sain Siemens de 1.5 kW est validé par comparaison avec une implémentation Simscape indépendante, avec le point expérimental couple-vitesse à 8.5 N m et avec les données nominales du constructeur. Ce modèle validé sert ensuite à produire et interpréter des jeux de données de simulation pour le déséquilibre de tension d'alimentation, le court-circuit inter-spires naissant, un substitut de défaut de roulement BPFO par couple perturbateur et une asymétrie rotorique de type barre cassée. Les résultats montrent que plusieurs indicateurs diagnostiques dépendent fortement de la charge: composantes de séquence négative, couple à 100 Hz, indices de bandes latérales BPFO et bandes latérales BRB ne doivent pas être interprétés par seuil fixe sans contexte de charge. Le travail est donc positionné comme une étape de modélisation physique et de construction de jeux de données, et non comme une campagne expérimentale de défauts ni comme un classifieur industriel déployé.

Mots-clés : moteur asynchrone, identification paramétrique, modélisation dq , validation Simscape, diagnostic de défauts, dépendance à la charge.

الملخص

تطوّر هذه المذكرة دراسة تشخيصية قائمة على المحاكاة لمحرك حثي ثلاثي الأطوار ذي قفص سنجابي، مدعومة بتحديد تجريبي لمعاملات محرك مخبري من نوع Siemens 1LA7096-4AA10 بقدرة 1.5 kW . استُخدم أولاً محرك مرجعي موثق بقدرة 500 W لتثبيت صياغة النموذج المتزامن dq المحافظة على القدرة، ومنهجية إعادة بناء المحاثات، ومسار المقارنة بين النموذج التحليلي وبيئة Simscape . بعد ذلك حُددت معاملات محرك سيمنس اعتماداً على اختبارات المقاومة المستمرة، واللاحمل، والدوار المحجوز، والحمل، والتباطؤ الحر؛ حيث أخذ عزم القصور الذاتي من ورقة البيانات الخاصة بالنموذج، بينما استُنتج معامل الاحتكاك اللزج من نسبة التناقص المقاسة.

باستخدام معاملات سيمنس المحددة، تم التحقق من النموذج السليم بقدرة 1.5 kW بالمقارنة مع تنفيذ مستقل في Simscape ، ومع نقطة تشغيل مخبرية عند 8.5 Nm ، ومع القيم الاسمية للشركة المصنعة. ثم استُخدم النموذج المتحقق منه لإنتاج وتحليل مجموعات بيانات محاكاة حتمية لحالات عدم توازن جهد التغذية، والقصر الناشئ بين اللفات ITSC ، واضطراب عزم يمثل عطل الحمل الخارجي BPFO ، ولا تماثل الدوار المرتبط بكسر قضبان الدوار BRB . بينت النتائج أن عدداً من المؤشرات التشخيصية يعتمد بقوة على مستوى الحمل، مثل عامل التيار ذي التابع السالب، ومركبة العزم عند 100 Hz ، ومؤشرات الحزم الجانبية لكل من BPFO و BRB . لذلك توضع هذه المذكرة كمرحلة نموذجية فيزيائية وبناء موثق للبيانات، وليست كحزمة تجريبية لأعطال حقيقية أو كمصنف صناعي منشور.

الكلمات المفتاحية: محرك حثي، تحديد المعاملات، نمذجة dq ، التحقق باستعمال Simscape ، تشخيص الأعطال، تأثير الحمل.

Contents

Dedication	i
Acknowledgment	ii
Abstract	iii
Résumé	iv
Arabic Abstract	v
List of Figures	x
List of Tables	xii
Abbreviations	xiii
General Introduction	1
1 State of the Art on Induction-Motor Fault Diagnosis	4
1.1 State of the Art	4
1.2 Induction-Motor Operating Principle	5
1.3 Fault Families and Contextual Mechanisms Discussed in the Thesis .	6
1.4 Electrical Faults	6
1.5 Rotor and Mechanical Faults	7
1.6 Thermal and Environmental Effects	7
1.7 Diagnostic-Method Literature Review	8
1.7.1 Signal-Based Methods	8
1.7.2 Model-Based Methods	8

1.7.3	Data-Driven and AI-Based Methods	9
1.8	Chapter Summary	9
2	Experimental Identification and Physical Modeling	10
2.1	Experimental Parameter Identification of the Siemens 1.5 kW Motor .	10
2.1.1	Role of Parameter Identification in the Thesis	10
2.1.2	Laboratory Motor and Nameplate Data	11
2.1.3	Laboratory Instruments and Measured Quantities	12
2.1.4	Electrical Parameter Calculations	14
2.1.5	Load and Mechanical Parameter Calculations	16
2.1.6	Final Identified Siemens Parameters	17
2.2	Healthy 500 W Benchmark Model in the Transformed Reference Frame	18
2.3	State Representation and Simulation Architecture of the 500 W Bench- mark	20
2.4	Numerical Validation of the 500 W Benchmark Model	24
2.5	Stator and Supply-Related Fault Modeling	29
2.6	Rotor and Bearing Extensions	31
2.7	Chapter Summary	33
3	Calibration of the Siemens Model and Cross-Machine Transfer- ability	34
3.1	Cross-Rating Transferability with the 500 W Benchmark Motor . . .	34
3.2	Healthy 1.5 kW Siemens Model	36
3.3	Analytical Healthy Results	36
3.4	Analytical–Simscape Cross-Validation	37
3.5	Validation Against Laboratory and Manufacturer Data	39
3.6	Transient Interpretation	40
3.7	Chapter Summary	40
4	Diagnostic Methods and Techniques	42
4.1	Retained Diagnostic Paradigms	42
4.2	Feature Chain Used in the Thesis	43
4.3	Sequence Components for Electrical Asymmetry	43
4.4	Spectral Estimators Retained for the Final Results	44
4.5	Rotor and Bearing Spectral Indicators	45
4.6	Model-Supported Interpretation	45
4.7	Dataset Rules for Later Classification	46
4.8	Chapter Summary	46

5	Simulation, Validation, and Results	47
5.1	Simulation Environment and Retained Operating Cases	47
5.2	Healthy 1.5 kW Baseline	48
5.3	Supply-Voltage Unbalance Results	48
5.4	Incipient ITSC Results	51
5.5	Bearing BPFO Surrogate Results	52
5.6	Broken-Rotor-Bar Rotor-Asymmetry Results	53
5.7	Synthesis of Diagnostic Significance	55
5.8	Chapter Summary	55
	 Conclusion and Future Work	 56
A	Reproducibility and Dataset Documentation	58
A.1	Benchmark 500 W Simulation Parameters	58
A.2	Siemens 1LA7096-4AA10 Parameter Set	59
A.3	Numerical Post-Processing Rules	59
A.4	Dataset Inventory	60
A.5	Manuscript Figure Inventory	61
A.6	Dataset Consolidation Rules	61
A.7	Model Scope	62
	 Bibliography	 63

List of Figures

1.1	Compact taxonomy of the simulated fault families and the thermal contextual branch retained for future extension.	6
2.1	Nameplate of the Siemens 1LA7096-4AA10 laboratory induction motor.	11
2.2	Terminal-board plate of the Siemens laboratory motor showing the 230/400 V, 1.5 kW ratings.	12
2.3	Retained healthy 500 W benchmark analytical-model architecture: balanced phase source, direct Park transformation, five-state motor block, feedback integration, and inverse Park reconstruction.	21
2.4	Detailed Simulink implementation of the retained healthy 500 W benchmark analytical model.	21
2.5	Independent Simscape Electrical implementation used for numerical cross-validation of the healthy 500 W benchmark model.	24
2.6	Direct/inverse Park reconstruction test for the retained power-invariant convention.	25
2.7	Final no-load startup response of the retained healthy analytical model.	26
2.8	Loaded response of the retained healthy analytical model with a 1.6 N m load step at $t = 1$ s.	27
2.9	Analytical and Simscape comparison using RMS current and electromechanical response indicators.	28
2.10	Relative steady-state differences between analytical and Simscape implementations.	28
3.1	Analytical no-load response of the identified Siemens 1.5 kW model. .	38
3.2	Analytical response at the 8.5 N m experimental operating point. . . .	38
3.3	Analytical response at the 10.1 N m rated-load operating point. . . .	41
4.1	Signal-feature chain used for the Siemens fault-simulation datasets. .	43
5.1	Supply-unbalance severity trends at the 8.5 N m operating point. . . .	49
5.2	Time-domain validation example for 2% VUF at the 8.5 N m operating point.	50

5.3	Frequency-domain validation example for 2% VUF at the 8.5 N m operating point.	50
5.4	Incipient ITSC dataset trends for $\mu = 0$, 1%, and 2%.	51
5.5	Bearing BPFO surrogate trends using the retained current-sideband index.	53
5.6	BRB rotor-asymmetry dataset trends.	54

List of Tables

1.1	Fault families and contextual mechanisms discussed in the thesis. . .	6
2.1	Verified 50 Hz nameplate and datasheet data of the Siemens laboratory motor.	12
2.2	Laboratory instruments and retained measured quantities.	13
2.3	Laboratory measurements and retained datasheet value used for Siemens 1.5 kW motor identification.	14
2.4	Final identified Siemens 1.5 kW laboratory motor parameters.	17
2.5	Healthy-model assumptions retained after the model reconstruction. .	19
2.6	Final reconstructed 500 W benchmark parameters used in the analytical and Simscape implementations.	23
2.7	Steady-state quantitative results of the retained 500 W benchmark analytical healthy model.	27
2.8	Analytical 500 W benchmark model versus Simscape steady-state validation.	27
3.1	Benchmark and Siemens motor domains used in the thesis.	35
3.2	Siemens 1.5 kW healthy operating cases.	36
3.3	Analytical steady-state results for the identified Siemens 1.5 kW model. The efficiency column is the reduced-model electromechanical efficiency.	36
3.4	Analytical and Simscape comparison for the Siemens healthy model. .	37
4.1	Diagnostic paradigms retained at thesis level.	42
5.1	Retained Siemens simulation studies and dataset sizes.	47
5.2	Load dependence of the supply-unbalance indicators for orientation $\phi_2 = 0^\circ$	49
5.3	ITSC indicators for phase-A faults at the 8.5 N m operating point. . .	51
5.4	Load dependence of phase-A ITSC indicators at $\mu = 2\%$	52
5.5	BPFO surrogate indicators at the 8.5 N m operating point.	53
5.6	BRB indicators at the 8.5 N m operating point for the 0° asymmetry orientation.	54

5.7	BRB current sideband index by load and rotor-asymmetry coefficient for the 0° orientation.	54
5.8	Main diagnostic indicators retained from the Siemens simulation cam- paign.	55
A.1	Reconstructed 500 W benchmark parameters used for the modeling- convention validation.	58
A.2	Retained Siemens 1.5 kW parameter set.	59
A.3	Signal properties and manuscript aliases for the primary retained datasets.	60

ABBREVIATIONS

Abbreviation	Meaning
ACF	Autocorrelation Function
AI	Artificial Intelligence
BPI	Ball Pass Frequency, Inner Race
BPFO	Ball Pass Frequency, Outer Race
BRB	Broken Rotor Bar
BSF	Ball Spin Frequency
BiLSTM	Bidirectional Long Short-Term Memory
CNN	Convolutional Neural Network
DC	Direct Current
DE	Dynamic Eccentricity
EKF	Extended Kalman Filter
ESSAT	Higher School in Applied Sciences – Tlemcen
FDI	Fault Detection and Isolation
FFT	Fast Fourier Transform
FTF	Fundamental Train Frequency
GRU	Gated Recurrent Unit
ITSC	Inter-Turn Short Circuit
KVL	Kirchhoff's Voltage Law
LSTM	Long Short-Term Memory
MATLAB	Matrix Laboratory
MCSA	Motor Current Signature Analysis
MEMS	Micro-Electro-Mechanical Systems
ML	Machine Learning
MRAS	Model Reference Adaptive System
P-MRAS	Power-Based Model Reference Adaptive System
PCA	Principal Component Analysis
PDF	Portable Document Format
PI	Proportional–Integral
PSD	Power Spectral Density
RMS	Root Mean Square
SCIM	Squirrel-Cage Induction Motor
SE	Static Eccentricity
STFT	Short-Time Fourier Transform

GENERAL INTRODUCTION

Three-phase induction motors are among the most widely used electromechanical energy-conversion devices in industrial systems because they combine structural robustness, operational reliability, affordability, and high efficiency in a broad range of applications [1–3]. Their extensive use in manufacturing, oil and gas, mining, and process industries makes their operational continuity a matter of both technical reliability and economic importance [2, 4]. When degradation is not detected at an early stage, the resulting faults may interrupt production, reduce efficiency, increase maintenance costs, and accelerate secondary mechanical and electrical damage [2, 4].

The diagnosis of induction-motor faults is closely linked to predictive maintenance. In practical environments, however, a measured current or speed anomaly is rarely caused by one isolated factor. Load level, supply imbalance, thermal drift, sensor processing, motor parameters, and the fault mechanism itself can all change the same indicators. A reliable diagnostic study therefore requires a physical model whose parameters are traceable, a validation procedure that separates numerical consistency from experimental evidence, and feature definitions that do not confuse one fault family with another.

This thesis addresses simulation-based fault diagnosis and physical modeling of a three-phase induction motor. The work uses two complementary motor contexts. A documented 500 W benchmark motor is retained to establish the power-invariant synchronous- dq formulation, reconstruct the inductances needed by the analytical model, and verify the implementation against a Simscape reference. The Siemens 1LA7096-4AA10 1.5 kW laboratory motor is then experimentally identified and used for the main 1.5 kW healthy validation and deterministic fault-simulation campaign.

Problem Statement

Fault signatures in induction motors are strongly dependent on the motor parameters and operating point. The same current asymmetry can be produced by an external supply-voltage unbalance or by an internal stator winding defect; a rotor fault sideband moves when slip changes; and a bearing-related torque disturbance can appear as both speed ripple and current modulation. If a model mixes incompatible parameters, uses an inconsistent Park transformation, or reports fault amplitudes without load context, its results can be mathematically reproducible while still being scientifically misleading.

The central problem of this thesis is therefore not only to simulate faults, but to build a consistent evidence chain: identify the available laboratory motor, validate the healthy numerical model, define reduced but explicit fault models, and interpret the resulting indicators with their assumptions and limits. The thesis does not claim physical fault experiments on the Siemens motor and does not deliver a field-ready classifier. It establishes a research-grade simulation and dataset-construction basis for later experimental acquisition and AI-based exploitation.

Objectives and Methodology

The main objective is to develop a physically interpretable simulation framework for induction-motor fault signatures, supported by experimental parameter identification on the available Siemens machine. The specific objectives are:

1. review induction-motor fault families and diagnostic methods relevant to current, torque, and speed signatures;
2. formulate a power-invariant synchronous- dq analytical model and validate it against an independent Simscape implementation;
3. document the reconstruction of the 500 W benchmark inductances so that the healthy model is internally consistent;
4. identify the Siemens 1LA7096-4AA10 1.5 kW motor from stator-resistance, no-load, blocked-rotor, load, and deceleration tests;
5. validate the Siemens 1.5 kW analytical model against Simscape, the measured 8.5 N m torque-speed operating point, and manufacturer rated data;

6. generate deterministic simulation datasets for supply-voltage unbalance, incipient inter-turn short circuit, BPFO bearing-torque disturbance, and broken-rotor-bar rotor asymmetry;
7. extract physically meaningful diagnostic indicators and evaluate their load dependence;
8. define dataset and appendix documentation suitable for later grouped train/test splitting and hardware validation.

The methodology is deliberately staged. First, the modeling convention is fixed so that power, torque, and inductance definitions are consistent. Second, the Siemens motor is identified experimentally and its moment of inertia is taken from the manufacturer datasheet because a single coast-down curve identifies only B/J . Third, the Siemens healthy model is validated through analytical, Simscape, experimental-load, and rated-data comparisons. Finally, fault cases are simulated as controlled diagnostic surrogates, and their indicators are interpreted without presenting them as physical fault tests.

Thesis Organization

The remainder of this manuscript is organized as follows. Chapter 1 reviews induction-motor operation, fault families, and diagnostic paradigms. Chapter 2 documents the Siemens experimental identification and the mathematical modeling foundations, including the 500 W benchmark reconstruction. Chapter 3 validates the Siemens 1.5 kW healthy model and discusses cross-machine transferability. Chapter 4 defines the diagnostic feature chain and signal interpretation rules. Chapter 5 presents the healthy validation and the four simulated fault studies. The manuscript closes with a conclusion, future-work perspectives, and an appendix documenting parameters, datasets, figures, and reproducibility rules.

STATE OF THE ART ON INDUCTION-MOTOR FAULT DIAGNOSIS

This chapter reviews the state of the art needed for the modeling, experimental identification, and simulation studies that follow. The thesis is not a machine-design study. Its purpose is to understand how representative induction-motor anomalies affect current, torque, speed, and frequency-domain indicators, and to document which parts of those indicators are transferable across motors and which parts depend on the identified parameter set.

1.1 State of the Art

Three-phase induction motors remain dominant industrial prime movers because they combine rugged construction, acceptable cost, high reliability, and direct compatibility with three-phase power systems [2, 3]. The current diagnostic literature treats their failures as a coupled electromechanical problem rather than as isolated signal defects. Mechanical wear can perturb the air gap and torque, electrical insulation failure can create local overheating and negative-sequence currents, rotor-cage asymmetry can modulate the stator current through slip-dependent sidebands, and environmental or thermal stress can move the healthy parameter baseline [4, 5].

Surveyed work commonly separates induction-motor anomalies into internal and external families, then refines them into mechanical, electrical, electromagnetic, and environmental mechanisms [4]. Bearing defects are repeatedly reported as the most frequent mechanical failures, often representing about 40–50% of motor failures and a still larger share in low-voltage machines [4, 6]. Stator faults are also critical because an incipient inter-turn short circuit can evolve rapidly into phase-to-phase or phase-to-ground failure [5, 7]. Rotor faults, especially broken bars and cracked end rings, are less frequent but diagnostically important because their signatures

are strongly coupled to slip and load [8].

The state of the art also shows that no single diagnostic paradigm is sufficient in isolation. Signal-based methods such as Motor Current Signature Analysis are attractive because they are non-invasive, but their spectral indicators are sensitive to load and supply quality. Model-based methods provide physical interpretability and parameter traceability, but they require a validated parameter set. Data-driven methods can classify complex patterns, but their reliability depends on physically meaningful datasets, proper case grouping, and load-aware validation [4, 9, 10]. This thesis follows that literature direction by first establishing model consistency and parameter traceability before interpreting deterministic fault-simulation datasets.

1.2 Induction-Motor Operating Principle

Operational conversion of electrical energy into mechanical torque within an induction machine relies on electromagnetic coupling between the stator winding’s rotating magnetic field and the induced currents in the rotor cage. For a supply frequency f_s and p pole pairs, the synchronous mechanical speed is

$$n_s = \frac{60f_s}{p}. \quad (1.1)$$

The rotor normally turns slightly below synchronous speed, and the relative difference is the slip

$$s = \frac{\omega_s - \omega_r}{\omega_s}. \quad (1.2)$$

Here, ω_s and ω_r must be expressed in the same reference, either both mechanical or both electrical. Slip is important because rotor-asymmetry signatures, especially broken-rotor-bar sidebands, move with operating point [1, 8, 11].

The analytical models later use the direct–quadrature reference frame to express this electromechanical behavior compactly. The objective is not to redesign the machine, but to obtain controlled simulation models whose outputs can be compared with independent references and then disturbed by explicit fault mechanisms or diagnostic surrogates.

1.3 Fault Families and Contextual Mechanisms Discussed in the Thesis

The literature reports many induction-motor faults, but the retained simulation scope is deliberately narrower. The four simulated families are supply-voltage unbalance, inter-turn short-circuit behavior, broken-rotor-bar behavior, and bearing-related mechanical disturbance. Thermal drift is kept as a contextual degradation mechanism and future extension; it is not simulated as a final fault class in this thesis.

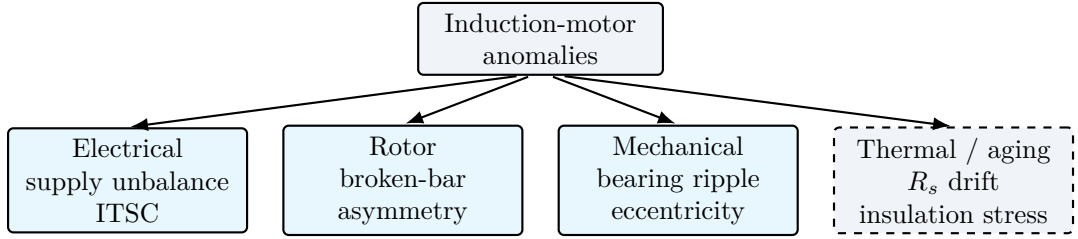


Figure 1.1: Compact taxonomy of the simulated fault families and the thermal contextual branch retained for future extension.

Family	Physical change	Useful simulated indicators
Supply unbalance	External voltage asymmetry creates negative-sequence fields and torque pulsation.	VUF, current negative-sequence factor, phase-current asymmetry, 100 Hz torque ripple.
ITSC	Local insulation failure creates a shorted-turn path and phase asymmetry.	Fault-loop current, CUF, 100 Hz torque component, speed ripple, phase-current pattern.
BRB	Rotor-cage asymmetry perturbs rotor currents and torque production.	Slip-dependent sidebands near $f_s(1 \pm 2s)$ and speed/torque modulation at the double-slip frequency $2sf_s$.
Bearing ripple	Periodic mechanical forcing modulates load torque and speed.	Geometry-derived BPFO frequency, current sidebands near $ f_s \pm f_{BPFO} $, torque and speed ripple.
Thermal drift	Heating changes stator resistance and can bias diagnostic features.	Contextual degradation mechanism and future extension; not simulated as a fault class.

Table 1.1: Fault families and contextual mechanisms discussed in the thesis.

1.4 Electrical Faults

Electrical asymmetry is central to the thesis because supply unbalance and ITSC can produce overlapping signatures. Supply unbalance is external to the machine:

the applied phase-voltage set contains a negative-sequence component. ITSC is internal: insulation degradation creates a local shorted path in a stator phase. Both mechanisms disturb the air-gap field, can increase losses, and can generate torque ripple [12, 13].

This overlap is one of the main diagnostic lessons of the thesis. A current component alone is not enough; the interpretation must also consider the voltage context, torque behavior, speed response, load level, and parameter drift. In the Siemens 1.5 kW simulations, supply unbalance and incipient ITSC are therefore treated as separate controlled cases, and their indicators are compared with load-aware caution.

1.5 Rotor and Mechanical Faults

Rotor faults such as broken bars or end-ring defects reduce the symmetry of the squirrel-cage circuit. In MCSA, they are classically associated with sidebands around the supply fundamental whose positions depend on slip [8, 14]. The thesis represents this phenomenon through a reduced rotor-asymmetry model rather than through a full spatial cage model. The resulting BRB dataset is therefore used to study the diagnostic sideband law and load dependence, not to claim detailed bar-current reconstruction.

Mechanical faults are represented through a bearing outer-race BPFO torque-disturbance surrogate. A real bearing diagnosis would require vibration measurements, contact dynamics, lubrication state, and manufacturer-specific bearing geometry. Because the manufacturer-specific internal geometry of the Siemens 6205 2ZC3 bearing was unavailable, the documented CWRU drive-end SKF 6205-2RS JEM geometry was adopted strictly as a geometric proxy [15]. The implemented simulation is therefore a geometry-derived electromechanical surrogate that shows how BPFO torque ripple propagates into current, torque, and speed.

1.6 Thermal and Environmental Effects

Temperature, humidity, dust, and lubrication degradation can accelerate insulation aging and mechanical wear. In the present thesis, this broad degradation path is reduced to the parameter most directly tied to electrical modeling: stator resistance. Since copper resistance varies with temperature, an increase in R_s can shift current and power behavior enough to affect diagnosis [16].

For this reason, stator-resistance tracking remains a useful support path for future work. It should be used as diagnostic context, especially to distinguish thermal drift

from fault-induced asymmetry, rather than as a standalone fault declaration.

1.7 Diagnostic-Method Literature Review

The detection and isolation of induction-motor anomalies have motivated extensive research over the last three decades. The available techniques are traditionally classified into three main paradigms: signal-based methods, model-based methods, and data-driven artificial intelligence methods.

1.7.1 Signal-Based Methods

Signal-based diagnosis relies on the spectral analysis of measurable machine quantities, primarily stator currents, vibration, and acoustic noise. Motor Current Signature Analysis is widely adopted because it is non-intrusive and can be implemented from electrical measurements. Rotor asymmetry and air-gap eccentricity generate predictable slip-dependent sidebands around the fundamental supply frequency [8]. The Extended Park's Vector Approach similarly translates three-phase current imbalance into a compact pattern in the dq or $\alpha\beta$ reference frames.

Signal-based methods are computationally efficient but sensitive to operating point. Fault sidebands can move, shrink, or become hard to resolve under light load. Different physical mechanisms can also produce overlapping spectral content. Both supply-voltage unbalance and ITSC disturb electrical symmetry and may generate negative-sequence current and low-frequency torque ripple [13, 17]. This ambiguity motivates the model-supported interpretation used in this thesis.

1.7.2 Model-Based Methods

Model-based diagnosis uses the mathematical equations of the machine as a reference. The healthy model can generate expected currents, torque, speed, slip, and power, while deviations are interpreted as residuals. Observers such as Extended Kalman Filters and Luenberger observers are often used to estimate unmeasurable states and detect parameter deviations [18].

Within this paradigm, Model Reference Adaptive Systems are commonly used for parameter tracking [19, 20]. In diagnostic applications, tracking stator resistance provides thermal context because R_s drift changes the electrical power balance and can bias current-based indicators [16, 21]. The present thesis keeps this path as a future support layer while concentrating the final quantitative work on validated healthy modeling and deterministic fault simulation.

1.7.3 Data-Driven and AI-Based Methods

Data-driven methods map feature vectors or time-series signals to fault classes using algorithms such as Support Vector Machines, Random Forests, Artificial Neural Networks, and deep learning architectures [9, 10, 22]. Their success depends strongly on the quality of the dataset. If windows from the same simulated run are randomly split between training and testing, the classifier can learn case identity rather than fault physics. Likewise, if load variation is not represented, a fixed threshold may appear valid in one condition and fail in another.

This literature landscape defines the positioning of the present thesis. Before an advanced classifier can be trained responsibly, the simulated data must be physically documented, load-aware, and grouped by complete cases. The thesis therefore emphasizes model consistency, parameter traceability, diagnostic feature interpretation, and dataset documentation.

1.8 Chapter Summary

The relevant background can be reduced to one idea: the same motor variables can be disturbed by different physical mechanisms. Supply unbalance and ITSC both affect electrical symmetry, BRB affects slip-dependent rotor modulation, bearing disturbance affects mechanical modulation, and thermal drift changes the parameter baseline. The following chapters build a parameter-identified simulation framework so that these mechanisms can be studied without mixing incompatible evidence levels.

EXPERIMENTAL IDENTIFICATION AND PHYSICAL MODELING

This chapter establishes the experimental and mathematical basis used by the thesis. It begins with the Siemens laboratory parameter-identification work so that the measurement procedure is documented before the simulation studies are introduced. The chapter then defines the reconstructed 500 W benchmark induction-motor model used to fix the analytical convention and Simscape comparison workflow. The Siemens parameters and the 500 W benchmark parameters are kept separate: the benchmark supports the modeling-convention validation, while the Siemens parameter set supports the 1.5 kW validation and fault-simulation campaign.

2.1 Experimental Parameter Identification of the Siemens 1.5 kW Motor

This section records the laboratory parameter-identification work before the simulation model is introduced. It is deliberately placed at the start of the modeling chapter so that the thesis evidence chain runs from experiment to model construction and then to simulation. The Siemens 1LA7096-4AA10 motor identified here is not numerically merged with the 500 W benchmark motor used to establish the modeling convention. Instead, it provides the parameter set used for the Siemens 1.5 kW validation and fault-simulation studies.

2.1.1 Role of Parameter Identification in the Thesis

Motor-current-signature-based diagnosis depends on the credibility of the underlying motor model. The electrical parameters fix the impedance, current amplitude,

torque production, and transient response of the simulated machine, while the mechanical parameters determine acceleration, speed droop, and the way load torque modulates the electrical signature. For that reason, this thesis separates the work into two linked paths:

- a reconstructed 500 W benchmark model used to validate the analytical convention and Simscape workflow; and
- a laboratory identification path carried out on the available Siemens 1.5 kW motor, used to obtain the parameter set for the main Siemens validation and fault-simulation campaign.

The parameters identified in this section therefore do not replace the 500 W benchmark parameters. They define the Siemens motor model used later for cross-machine validation and fault-feature studies, while also providing a physically grounded basis for discussing transferability and parameter sensitivity.

2.1.2 Laboratory Motor and Nameplate Data

The laboratory motor used for the experimental identification work is a Siemens 1LA7096-4AA10 three-phase squirrel-cage induction motor. The nameplate and the terminal-board plate are shown in Figures 2.1 and 2.2. At 50 Hz, the terminal information gives a 230/400 V delta/star motor. The model-specific Siemens datasheet for MLFB ordering data 1LA7096-4AA10 specifies $P_N = 1.5$ kW, $n_N = 1420$ rpm, $T_N = 10.1$ N m, $I_N = 3.45$ A at 400 V star connection, and $J = 0.0033$ kg m²; the datasheet was generated on 23 April 2021 [23]. The synchronous speed is therefore 1500 rpm, indicating a four-pole machine.



Figure 2.1: Nameplate of the Siemens 1LA7096-4AA10 laboratory induction motor.



Figure 2.2: Terminal-board plate of the Siemens laboratory motor showing the 230/400 V, 1.5 kW ratings.

Table 2.1: Verified 50 Hz nameplate and datasheet data of the Siemens laboratory motor.

Quantity	Value
Type	Siemens 1LA7096-4AA10
Rated output power	1.5 kW
Rated line voltage	230/400 V, delta/star
Rated frequency	50 Hz
Rated current	6.0/3.45 A
Rated speed	1420 rpm
Rated torque	10.1 N m
Manufacturer moment of inertia	0.0033 kg m ²
Power factor	0.81
Protection / frame / mounting	IP55 / 90L / IM B3
Efficiency marking	IE1, 77.2%

2.1.3 Laboratory Instruments and Measured Quantities

The identification procedure uses standard induction-machine tests: stator resistance measurement, no-load test, blocked-rotor test, load observation, and free de-

celeration. The available laboratory records identify the measured quantities and the instrument families used, but they do not provide complete accuracy classes or repeated-test statistics. For this reason, no unverified instrument resolution or uncertainty class is invented in the thesis.

Table 2.2: Laboratory instruments and retained measured quantities.

Instrument or bench unit	Main retained use	Direct or calculated	Remark
Digital multimeters	Phase-neutral stator resistance, voltage verification, and continuity checks	Direct readings	Exact accuracy class was not available in the retained records.
Three-phase power analyzer	Line voltage, line current, active power, reactive power, and power factor during no-load and blocked-rotor tests	Direct readings	Used for the electrical quantities entering the no-load and blocked-rotor calculations.
Tachometer / speed display	Shaft-speed readings during no-load, load, and coast-down tests	Direct readings	The coast-down decay ratio was obtained by fitting the retained speed decay.
Mecawatt mechanical-quantities unit	Load torque and rotational speed at the retained loaded operating point	Direct torque and speed readings; shaft power calculated	The available front-panel image is labeled “Grandeurs mecaniques” and displays torque, rotational speed, and mechanical power.

The measured values retained for the calculations are collected in Table 2.3. The load-observation active input power is not retained as a validation value because the available laboratory record was not internally consistent with the retained voltage,

current, power-factor display, and mechanical shaft-power calculation. The load comparison is therefore limited to torque, speed, and current; shaft power is calculated from measured torque and speed. The auxiliary blocked-rotor voltage display is also not used in the retained parameter calculations; the blocked-rotor resistance and leakage estimates use I_{br} , P_{br} , and Q_{br} .

Table 2.3: Laboratory measurements and retained datasheet value used for Siemens 1.5 kW motor identification.

Source	Quantity	Symbol	Retained value
Resistance	Per-phase stator resistance	R_s	5.7 Ω
No-load	Line voltage	$V_{0,LL}$	400 V
No-load	Line current	I_0	2.49 A
No-load	Input active power	P_0	210 W
No-load	Reactive power	Q_0	1689 var
No-load	Speed	n_0	1497 rpm
Blocked rotor	Line current	I_{br}	3.45 A
Blocked rotor	Input active power	P_{br}	321 W
Blocked rotor	Reactive power	Q_{br}	300 var
Load observation	Load torque from retained bench reading	T_L	8.5 N m
Load observation	Measured speed	n_L	1437 rpm
Load observation	Line current	I_L	3.34 A
Load observation	Power-factor display, auxiliary only	$\cos \varphi_L$	0.83
Deceleration	Decay ratio	λ	0.21 s ⁻¹
Datasheet	Moment of inertia	J	0.0033 kg m ²

2.1.4 Electrical Parameter Calculations

The stator resistance was measured directly between one phase terminal and the star neutral point after the motor had been switched off and returned to approximately room temperature. The retained value is therefore a cold per-phase stator resistance. No correction to a higher operating temperature was applied; the possible increase of winding resistance during loaded operation is retained as a modeling limitation.

The measured per-phase stator resistance is retained as

$$R_s = 5.7 \Omega. \quad (2.1)$$

For the no-load test at 400 V line-line RMS, the phase voltage is

$$V_{ph,0} = \frac{V_{0,LL}}{\sqrt{3}} = \frac{400}{\sqrt{3}} = 230.94 \text{ V}. \quad (2.2)$$

The no-load slip is

$$s_0 = \frac{1500 - 1497}{1500} = 0.0020. \quad (2.3)$$

Using the measured no-load reactive power, the magnetizing reactance is estimated as

$$X_m = \frac{3V_{ph,0}^2}{Q_0} = \frac{3(230.94)^2}{1689} = 94.73 \, \Omega. \quad (2.4)$$

At 50 Hz, the corresponding magnetizing inductance is

$$L_m = \frac{X_m}{2\pi f} = \frac{94.73}{2\pi \times 50} = 0.3015 \, \text{H}. \quad (2.5)$$

The no-load stator copper loss is

$$P_{\text{Cu},s0} = 3I_0^2 R_s = 3(2.49)^2(5.7) \approx 106 \, \text{W}. \quad (2.6)$$

The remaining no-load active power is therefore associated with core, friction, and windage losses:

$$P_{\text{core+mech}} = P_0 - P_{\text{Cu},s0} \approx 210 - 106 = 104 \, \text{W}. \quad (2.7)$$

For the blocked-rotor test, the equivalent per-phase resistance is obtained from

$$R_{br} = \frac{P_{br}}{3I_{br}^2} = \frac{321}{3(3.45)^2} = 8.99 \, \Omega. \quad (2.8)$$

The referred rotor resistance is then

$$R'_r = R_{br} - R_s = 8.99 - 5.7 = 3.29 \, \Omega. \quad (2.9)$$

The blocked-rotor leakage reactance is calculated from the measured reactive power:

$$X_\sigma = \frac{Q_{br}}{3I_{br}^2} = \frac{300}{3(3.45)^2} = 8.40 \, \Omega. \quad (2.10)$$

Thus,

$$L_\sigma = \frac{X_\sigma}{2\pi f} = \frac{8.40}{2\pi \times 50} = 0.02674 \, \text{H}. \quad (2.11)$$

Assuming equal stator and rotor leakage contributions gives

$$L_{ls} = L'_{lr} = \frac{L_\sigma}{2} = 0.01337 \, \text{H}. \quad (2.12)$$

These calculations use the standard approximate induction-motor equivalent-circuit assumptions: the no-load reactive power is assigned predominantly to the magnetizing branch, while the magnetizing branch is neglected during the blocked-rotor leakage calculation.

2.1.5 Load and Mechanical Parameter Calculations

At the measured load-test speed of 1437 rpm, the slip is

$$s_L = \frac{1500 - 1437}{1500} = 0.0420. \quad (2.13)$$

The shaft power calculated from the measured torque and speed is

$$P_{\text{shaft},L} = T_L \frac{2\pi n_L}{60} = 8.5 \frac{2\pi(1437)}{60} \approx 1279.10 \text{ W}. \quad (2.14)$$

This value is used only to interpret the laboratory motor operating point. The 500 W simulation results must use the slip obtained from the benchmark simulation model.

The retained load point is therefore treated as a torque-speed-current observation. No load-test input active-power value is used as a validation target in the final model because the retained laboratory record was not sufficiently consistent for power-balance validation.

Following disconnection of the electrical supply, the electromagnetic torque becomes negligible and the free mechanical deceleration is approximated by

$$J \frac{d\omega_m}{dt} = -B\omega_m. \quad (2.15)$$

Its solution is

$$\omega_m(t) = \omega_{m0} \exp\left(-\frac{B}{J}t\right). \quad (2.16)$$

Therefore,

$$\ln \omega_m(t) = \ln \omega_{m0} - \lambda t, \quad \lambda = \frac{B}{J}. \quad (2.17)$$

Linear fitting of the retained deceleration data gave

$$\lambda \approx 0.21 \text{ s}^{-1}. \quad (2.18)$$

The coast-down experiment identifies the ratio B/J , but it does not identify B and J separately under the adopted viscous-friction model. Since the motor was not available for an additional known-inertia test, the manufacturer-specified moment of inertia was retained. The Siemens 1LA7096-4AA10 datasheet gives [23]

$$J = 0.0033 \text{ kg m}^2. \quad (2.19)$$

The viscous-friction coefficient was consequently calculated as

$$B = J\lambda = 0.0033 \times 0.21 = 6.93 \times 10^{-4} \text{ N m s/rad}. \quad (2.20)$$

Thus, J is a manufacturer parameter, whereas B/J is experimentally identified and B is derived from the combination of the experimental decay rate and the datasheet inertia.

Each retained parameter represents a single laboratory-test campaign. Repeated-test standard deviations and formal uncertainty propagation were not available, so they are retained as future experimental work rather than being silently implied.

2.1.6 Final Identified Siemens Parameters

Table 2.4 summarizes the final identified parameter set for the Siemens 1.5 kW laboratory motor.

Table 2.4: Final identified Siemens 1.5 kW laboratory motor parameters.

Parameter	Symbol	Value
Stator resistance	R_s	5.7 Ω
Referred rotor resistance	R'_r	3.29 Ω
Magnetizing inductance	L_m	0.3015 H
Stator leakage inductance	L_{ls}	0.01337 H
Referred rotor leakage inductance	L'_{lr}	0.01337 H
Total stator inductance	$L_s = L_m + L_{ls}$	0.31487 H
Total referred rotor inductance	$L'_r = L_m + L'_{lr}$	0.31487 H
Leakage coefficient	σ	about 0.0831
Rotor inertia	J	0.0033 kg m ² (datasheet)
Viscous friction coefficient	B	6.93×10^{-4} N m s/rad (derived)

These values form the retained Siemens laboratory-motor parameter set. The raw laboratory tests directly provide R_s , the no-load and blocked-rotor electrical readings, the loaded torque-speed-current observation, and the coast-down decay ratio. The referred rotor resistance, magnetizing inductance, leakage inductances, total inductances, leakage coefficient, and viscous-friction coefficient are calculated from those measurements and from the datasheet inertia. They are used as the calibrated 1.5 kW motor parameters in the Siemens healthy-validation and fault-simulation chapters.

2.2 Healthy 500 W Benchmark Model in the Transformed Reference Frame

The healthy motor is modeled as a balanced, star-connected, squirrel-cage three-phase induction machine supplied by a sinusoidal 400 V line-to-line RMS source at 50 Hz. The retained model assumes sinusoidally distributed windings, linear magnetic inductances, constant parameters during one simulation, zero externally applied rotor voltage, no zero-sequence component in healthy balanced operation, and viscous mechanical friction. Magnetic saturation, hysteresis, iron-loss separation, and temperature variation are not included in the frozen healthy baseline.

The phase source is generated from

$$\theta_e(t) = \int_0^t \omega_e d\tau, \quad \omega_e = 2\pi f_s, \quad (2.21)$$

with $f_s = 50$ Hz. Since the source is star-connected,

$$V_{\text{ph,rms}} = \frac{400}{\sqrt{3}} = 230.94 \text{ V}, \quad V_m = \sqrt{2}V_{\text{ph,rms}} = 326.60 \text{ V}. \quad (2.22)$$

The phase voltages are therefore

$$v_a = V_m \cos \theta_e, \quad (2.23)$$

$$v_b = V_m \cos \left(\theta_e - \frac{2\pi}{3} \right), \quad (2.24)$$

$$v_c = V_m \cos \left(\theta_e + \frac{2\pi}{3} \right). \quad (2.25)$$

The final analytical model uses a power-invariant Park transformation with the factor $\sqrt{2/3}$ and a positive sine row. For any balanced three-phase quantity x , the retained direct transformation is

$$\begin{bmatrix} x_{ds} \\ x_{qs} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta_e & \cos \left(\theta_e - \frac{2\pi}{3} \right) & \cos \left(\theta_e + \frac{2\pi}{3} \right) \\ \sin \theta_e & \sin \left(\theta_e - \frac{2\pi}{3} \right) & \sin \left(\theta_e + \frac{2\pi}{3} \right) \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}. \quad (2.26)$$

The same transformation convention is used for voltages, currents, and flux-related

quantities. The matching inverse used to reconstruct phase currents is

$$i_a = \sqrt{\frac{2}{3}} (\cos \theta_e i_{ds} + \sin \theta_e i_{qs}), \quad (2.27)$$

$$i_b = \sqrt{\frac{2}{3}} \left[\cos \left(\theta_e - \frac{2\pi}{3} \right) i_{ds} + \sin \left(\theta_e - \frac{2\pi}{3} \right) i_{qs} \right], \quad (2.28)$$

$$i_c = \sqrt{\frac{2}{3}} \left[\cos \left(\theta_e + \frac{2\pi}{3} \right) i_{ds} + \sin \left(\theta_e + \frac{2\pi}{3} \right) i_{qs} \right]. \quad (2.29)$$

This convention is important because it fixes the power and torque scaling used later. Under the retained power-invariant transformation,

$$P_s = v_{ds} i_{ds} + v_{qs} i_{qs}, \quad (2.30)$$

so no external 3/2 multiplier is introduced in the power expression. The torque expression is written consistently with the same convention in Section 2.3. Mixing this convention with an amplitude-invariant Park transformation would produce incorrect power, torque, and parameter interpretations.

Assumption	Status	Meaning in this thesis
Balanced sinusoidal source	Retained	Healthy reference supply before fault extensions.
Star-connected stator	Retained	400 V line-line RMS is converted to 230.94 V phase RMS.
Squirrel-cage rotor	Retained	Rotor voltages are zero in the healthy model.
Power-invariant Park frame	Retained	Uses $\sqrt{2/3}$ scaling and the torque/power equations stated here.
Linear inductances	Retained	No saturation or hysteresis is modeled in the frozen baseline.
Zero-sequence component	Neglected	Healthy balanced operation satisfies $v_a + v_b + v_c = 0$.
Viscous friction	Retained	Mechanical losses are represented by $B\omega_m$.

Table 2.5: Healthy-model assumptions retained after the model reconstruction.

2.3 State Representation and Simulation Architecture of the 500 W Benchmark

The retained analytical model uses five dynamic states:

$$\mathbf{x} = \begin{bmatrix} i_{ds} & i_{qs} & \lambda_{dr} & \lambda_{qr} & \omega_r \end{bmatrix}^T. \quad (2.31)$$

Here ω_r is the electrical rotor angular speed. The mechanical speed is

$$\omega_m = \frac{\omega_r}{p}. \quad (2.32)$$

The leakage coefficient and slip angular speed are

$$\sigma = 1 - \frac{L_m^2}{L_s L_r}, \quad \omega_{sl} = \omega_e - \omega_r. \quad (2.33)$$

The following five-state formulation follows the standard synchronously rotating dq induction-machine equations reported by Krause et al. and the exact five-state representation presented by Kerboua in Chapter I, Section I.1.1, Eqs. (I.1)–(I.2) [11, 24]. The notation is adapted here by writing the mutual inductance as L_m , the rotor fluxes as λ_{dr} and λ_{qr} , the viscous-friction coefficient as B , and the load torque as T_L ; the mathematical structure and sign convention are retained.

With the retained convention, the stator-current dynamics are

$$\frac{di_{ds}}{dt} = -\frac{1}{\sigma L_s} \left(R_s + R_r \frac{L_m^2}{L_r^2} \right) i_{ds} + \omega_e i_{qs} + \frac{L_m R_r}{\sigma L_s L_r^2} \lambda_{dr} + \frac{L_m}{\sigma L_s L_r} \omega_r \lambda_{qr} + \frac{1}{\sigma L_s} v_{ds}, \quad (2.34)$$

$$\frac{di_{qs}}{dt} = -\omega_e i_{ds} - \frac{1}{\sigma L_s} \left(R_s + R_r \frac{L_m^2}{L_r^2} \right) i_{qs} - \frac{L_m}{\sigma L_s L_r} \omega_r \lambda_{dr} + \frac{L_m R_r}{\sigma L_s L_r^2} \lambda_{qr} + \frac{1}{\sigma L_s} v_{qs}. \quad (2.35)$$

The rotor-flux dynamics are

$$\frac{d\lambda_{dr}}{dt} = \frac{L_m R_r}{L_r} i_{ds} - \frac{R_r}{L_r} \lambda_{dr} + \omega_{sl} \lambda_{qr}, \quad (2.36)$$

$$\frac{d\lambda_{qr}}{dt} = \frac{L_m R_r}{L_r} i_{qs} - \omega_{sl} \lambda_{dr} - \frac{R_r}{L_r} \lambda_{qr}. \quad (2.37)$$

The electromagnetic torque is

$$T_e = p \frac{L_m}{L_r} (\lambda_{dr} i_{qs} - \lambda_{qr} i_{ds}), \quad (2.38)$$

and the electrical rotor-speed equation is

$$\frac{d\omega_r}{dt} = \frac{p}{J} (T_e - T_L) - \frac{B}{J} \omega_r. \quad (2.39)$$

The outputs used for interpretation are the mechanical speed, rotor speed in rpm, and slip:

$$n = \omega_m \frac{60}{2\pi}, \quad s = \frac{\omega_e - \omega_r}{\omega_e}. \quad (2.40)$$

Figure 2.3 gives the compact architecture of the retained healthy analytical model. The same idea is implemented in Simulink through the detailed block diagram shown in Figure 2.4.

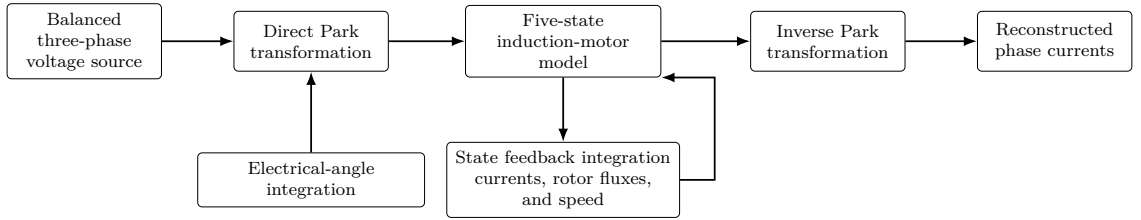


Figure 2.3: Retained healthy 500 W benchmark analytical-model architecture: balanced phase source, direct Park transformation, five-state motor block, feedback integration, and inverse Park reconstruction.

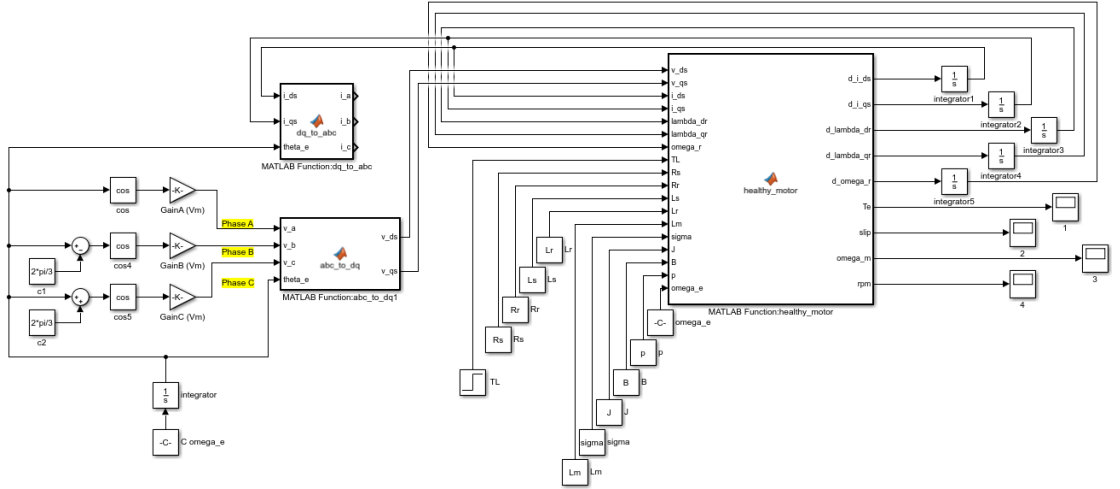


Figure 2.4: Detailed Simulink implementation of the retained healthy 500 W benchmark analytical model.

The parameter values are taken from the identification material of Bellakhdar and Elasri and then reconstructed to match the inductance definitions required by the five-state model [25]. The source reports $R_s = 11.73 \, \Omega$, $R_r = 11.08 \, \Omega$, $J = 0.0030 \, \text{kg m}^2$, $B = 0.00092 \, \text{N m s/rad}$, a no-load inductive value of $0.7354 \, \text{H}$, and a total leakage inductance of $0.08 \, \text{H}$. Its final parameter table also lists $L_s = L_r = 0.7354 \, \text{H}$ and $M_{SR} = 0.360 \, \text{H}$. Those final table entries are not sufficient,

by themselves, to define the T-equivalent inductances required by the adopted dq model.

The parameter identification tests performed by Bellakhdar and Elasri yielded two experimentally useful inductive quantities: $L_{\text{no-load}} = 0.7354$ H from the no-load test and $L_{\sigma,\text{total}} = 0.08$ H from the blocked-rotor test. Since the source summary does not explicitly decompose leakage into stator and rotor parts, the present thesis reconstructs the T-equivalent set by using the no-load inductive value as the magnetizing branch and by splitting the total leakage equally between stator and rotor.

Those inductive entries are not copied directly into the retained implementation, because the adopted dq state equations require separate magnetizing, stator-leakage, and rotor-leakage terms satisfying

$$L_s = L_m + L_{ls}, \quad L_r = L_m + L_{lr}, \quad \sigma = 1 - \frac{L_m^2}{L_s L_r}. \quad (2.41)$$

The no-load inductive result is therefore used as an adopted approximation of the dominant magnetizing inductance, $L_m = 0.7354$ H, while the blocked-rotor result is retained as the total leakage inductance. Since separate stator and rotor leakage values are not reported, an equal-leakage split is assumed:

$$L_{ls} = L_{lr} = 0.04 \text{ H}, \quad L_s = L_r = 0.7354 + 0.04 = 0.7754 \text{ H}. \quad (2.42)$$

Using Eq. (2.41), the leakage coefficient used by the present dq model is $\sigma = 0.10051$. This parameter set is a model-consistent reconstruction from the reported identification tests, not a direct experimental isolation of each individual inductance.

The retained reconstruction is one model-consistent T-equivalent parameterization compatible with the published no-load and blocked-rotor results. It is not claimed to be the unique decomposition of the original machine inductances.

Quantity	Symbol	Value	Origin or interpretation
Stator resistance	R_s	11.73 Ω	Directly retained from source test.
Rotor resistance referred to stator	R_r	11.08 Ω	Directly retained from source test.
Magnetizing inductance	L_m	0.7354 H	Interpreted from no-load inductive result.
Stator leakage inductance	L_{ls}	0.0400 H	Equal split of reported total leakage.
Rotor leakage inductance	L_{lr}	0.0400 H	Equal split of reported total leakage.
Total stator inductance	L_s	0.7754 H	$L_s = L_m + L_{ls}$.
Total rotor inductance	L_r	0.7754 H	$L_r = L_m + L_{lr}$.
Leakage coefficient	σ	0.10051	$1 - L_m^2/(L_s L_r)$.
Moment of inertia	J	0.0030 kg m ²	Directly retained from source test.
Viscous friction	B	0.00092 N m s/rad	Directly retained from source test.
Pole pairs	p	1	Nameplate/source interpretation.
Nominal load torque	T_L	1.6 N m	500 W benchmark load point.

Table 2.6: Final reconstructed 500 W benchmark parameters used in the analytical and Simscape implementations.

The final analytical simulations use a variable-step stiff solver such as `ode23tb` or `ode15s`, a maximum step size of 1×10^{-4} s, and a relative tolerance of 10^{-6} . This solver constraint is part of the model definition because coarse solver steps did not resolve the 50 Hz phase currents reliably.

The independent Simscape model is shown in Figure 2.5. It uses the same physical parameter set, a three-phase source at 400 V line-line RMS and 50 Hz, a squirrel-cage asynchronous machine block, continuous `powergui`, and the same mechanical load step. A high-value three-phase shunt of 1 M Ω per phase is used as numerical regularization; it is not interpreted as a physical motor load.

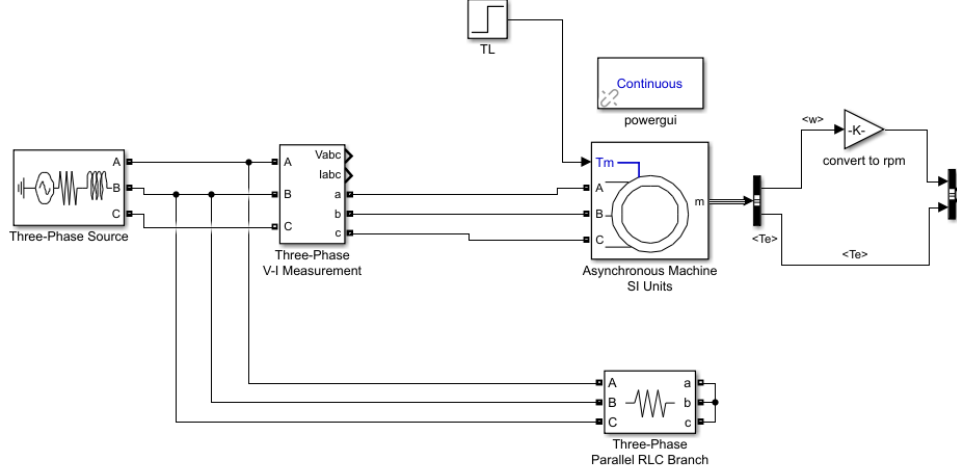


Figure 2.5: Independent Simscape Electrical implementation used for numerical cross-validation of the healthy 500 W benchmark model.

2.4 Numerical Validation of the 500 W Benchmark Model

The retained validation has three levels. First, the Park transformation is checked by transforming the balanced phase voltages to dq and reconstructing them back to abc . Figure 2.6 shows that the original and reconstructed phase voltages overlap, while the reconstruction error remains on the order of 10^{-13} V. This is numerical roundoff and validates the direct/inverse transformation pair.

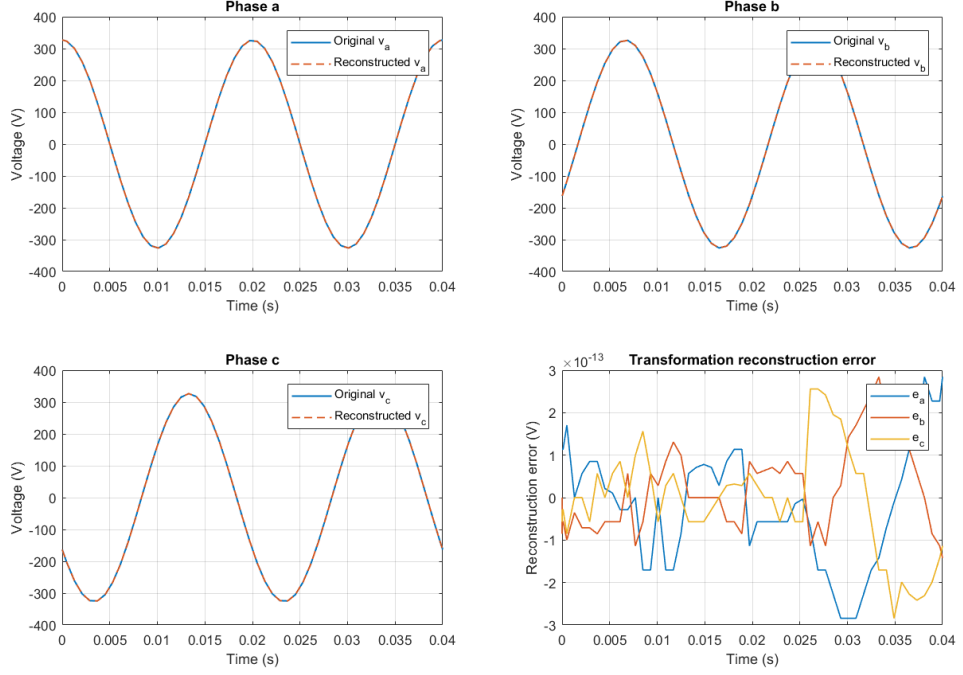


Figure 2.6: Direct/inverse Park reconstruction test for the retained power-invariant convention.

Second, the analytical model is tested at no load. Figure 2.7 shows a physically coherent startup: a transient current peak, acceleration toward the 3000 rpm synchronous speed, slip reduction, and torque settling to the viscous-friction demand. At steady state, the electromagnetic torque satisfies

$$T_e \approx B\omega_m, \quad (2.43)$$

with a numerical torque-balance error of approximately -2.6×10^{-14} N m.

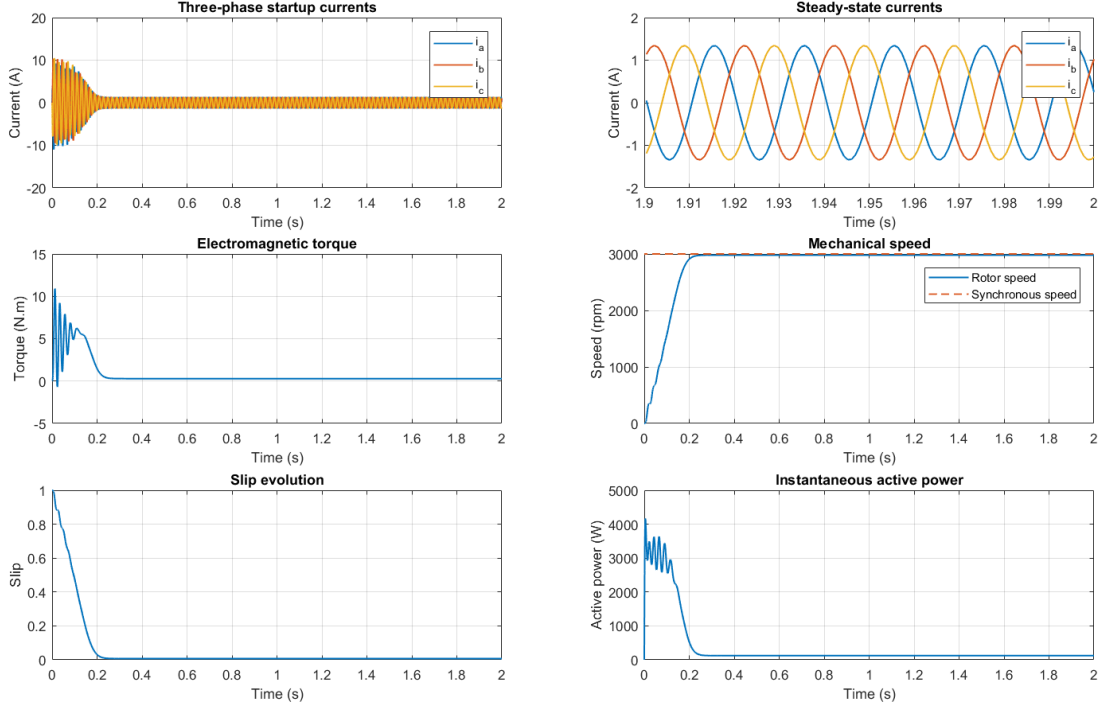


Figure 2.7: Final no-load startup response of the retained healthy analytical model.

Third, a load torque step of 1.6 N m is applied at $t = 1$ s. Figure 2.8 shows the expected increase in phase current and electromagnetic torque, together with the expected speed decrease and slip increase. At the final loaded steady state,

$$T_e = T_L + B\omega_m. \quad (2.44)$$

Using the simulated speed 2848.52 rpm gives $\omega_m = 298.29$ rad/s and therefore $T_L + B\omega_m = 1.8744$ N m, which matches the simulated mean electromagnetic torque to numerical precision.

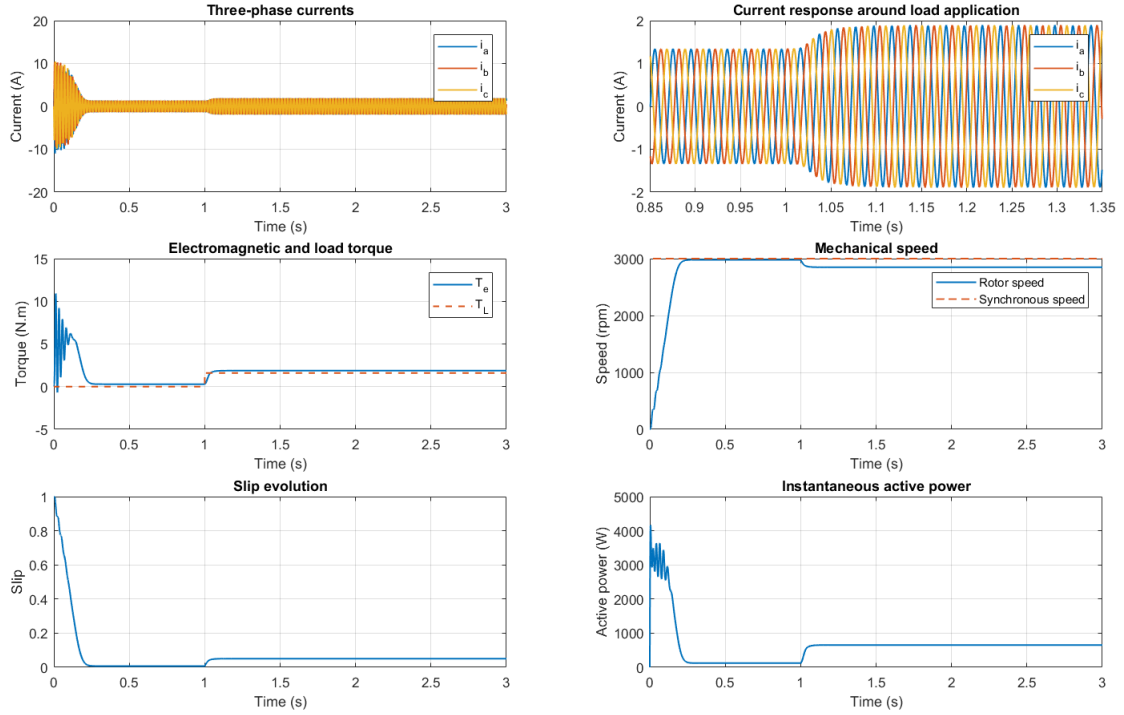


Figure 2.8: Loaded response of the retained healthy analytical model with a 1.6 N m load step at $t = 1$ s.

Case	T_L (N m)	Speed (rpm)	Slip (%)	I_{rms} (A)	T_e (N m)	P_{in} (W)	Torque error (N m)
No load	0.0	2978.84	0.70526	0.95176	0.28699	122.04	-2.58×10^{-14}
Load 1.6 N m	1.6	2848.52	5.0495	1.3422	1.8744	652.26	-1.69×10^{-14}

Table 2.7: Steady-state quantitative results of the retained 500 W benchmark analytical healthy model.

Finally, the analytical model is compared with the independent Simscape implementation. The comparison uses RMS current, mean torque, mean speed, and slip rather than point-by-point phase-current error, because the two implementations have a phase-reference offset in the plotted phase currents. This is a reference-angle issue, not a steady-state electromechanical disagreement.

Case	Quantity	Unit	Analytical	Simscape	Error (%)
No load	Mean phase current RMS	A	0.95176	0.93206	2.1131
No load	Steady-state speed	rpm	2978.8	2977.9	0.0316
No load	Slip	%	0.70526	0.73666	4.2629
No load	Mean electromagnetic torque	N m	0.28699	0.28692	0.0220
Load 1.6 N m	Mean phase current RMS	A	1.3422	1.3468	0.3457
Load 1.6 N m	Steady-state speed	rpm	2848.5	2839.6	0.3141
Load 1.6 N m	Slip	%	5.0495	5.3468	5.5602
Load 1.6 N m	Mean electromagnetic torque	N m	1.8744	1.8736	0.0459

Table 2.8: Analytical 500 W benchmark model versus Simscape steady-state validation.

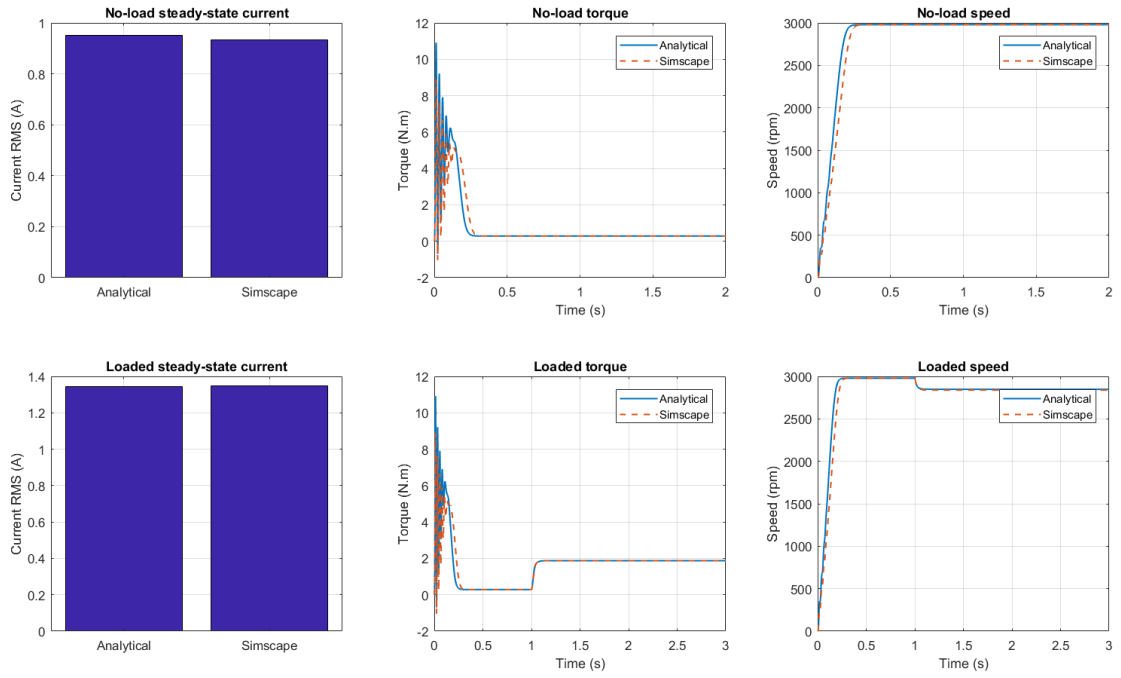


Figure 2.9: Analytical and Simscape comparison using RMS current and electromechanical response indicators.

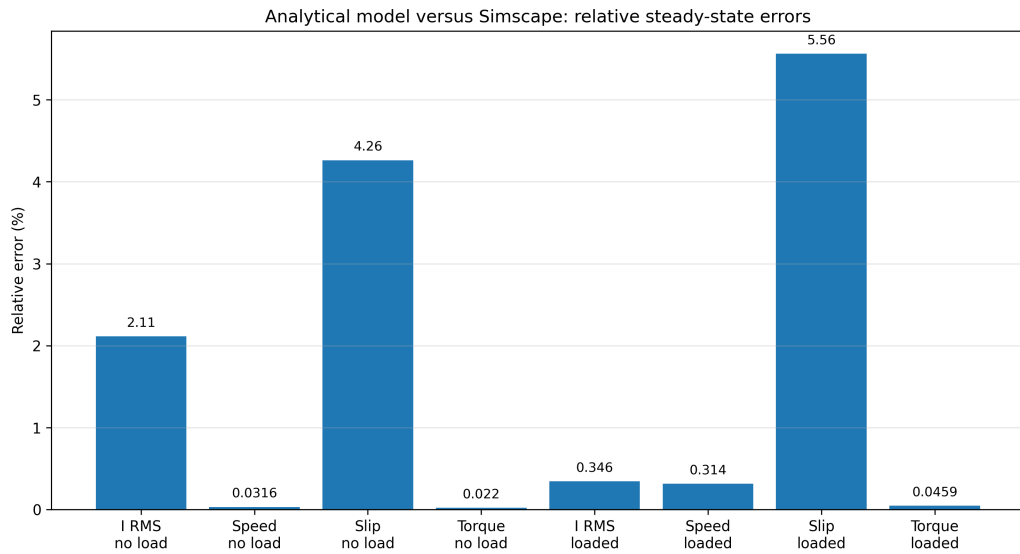


Figure 2.10: Relative steady-state differences between analytical and Simscape implementations.

The current, speed, and torque differences remain small for the retained thesis scope. The larger relative slip error is expected because slip is calculated from the small difference between synchronous speed and rotor speed. This validation is therefore described as analytical verification and numerical cross-validation. It is not presented as experimental validation on the real motor.

2.5 Stator and Supply-Related Fault Modeling

The Siemens 1.5 kW fault studies use two electrical-asymmetry mechanisms. Supply-voltage unbalance is imposed externally by adding a controlled negative-sequence voltage component to the otherwise balanced three-phase supply. Its severity is measured by the voltage-unbalance factor,

$$VUF = 100 \frac{|V_2|}{|V_1|}, \quad (2.45)$$

where V_1 and V_2 are the positive- and negative-sequence voltage phasors.

In the implemented supply-unbalance block, the positive-sequence phase-to-neutral peak voltage remains equal to the rated value $V_m = 326.60$ V. The negative-sequence magnitude is imposed as

$$V_2 = k_2 V_1, \quad k_2 = H_u(t) \frac{VUF}{100}, \quad H_u(t) = \begin{cases} 0, & t < t_u, \\ 1, & t \geq t_u, \end{cases} \quad (2.46)$$

with activation time $t_u = 1.5$ s. For a negative-sequence orientation φ_2 , the three phase voltages are

$$v_a(t) = V_m \cos \theta_e + k_2 V_m \cos(\theta_e + \varphi_2), \quad (2.47)$$

$$v_b(t) = V_m \cos \left(\theta_e - \frac{2\pi}{3} \right) + k_2 V_m \cos \left(\theta_e + \frac{2\pi}{3} + \varphi_2 \right), \quad (2.48)$$

$$v_c(t) = V_m \cos \left(\theta_e + \frac{2\pi}{3} \right) + k_2 V_m \cos \left(\theta_e - \frac{2\pi}{3} + \varphi_2 \right). \quad (2.49)$$

The retained dataset uses $VUF = 0, 1, 2, 3, 4$, and 5% , with $\varphi_2 = 0^\circ, 120^\circ$, and 240° for nonzero unbalance. The healthy case is recovered exactly when $H_u = 0$ or $VUF = 0$.

The inter-turn short-circuit case is represented as an incipient shorted-turn diagnostic surrogate. Its severity is the shorted-turn fraction μ , and the retained quantitative range is limited to $\mu \leq 2\%$ with $R_f = 5 \Omega$. The value $R_f = 5 \Omega$ is a retained regularizing fault-loop resistance used to bound the incipient injected current; it was not experimentally measured on the Siemens motor. The implemented MATLAB Function block keeps the validated healthy dq dynamics and adds a published stationary $\alpha\beta$ fault-loop injection model [12]. The effective shorted-turn fraction is

$$\mu_e = H_f(t) \max(\mu, 0), \quad H_f(t) = \begin{cases} 0, & t < t_f, \\ 1, & t \geq t_f, \end{cases} \quad t_f = 1.5 \text{ s}. \quad (2.50)$$

The selected faulted phase is represented by the physical fault-axis angle

$$\theta_f = \begin{cases} 0, & \text{phase A,} \\ -2\pi/3, & \text{phase B,} \\ 2\pi/3, & \text{phase C.} \end{cases} \quad (2.51)$$

After converting the healthy stator and rotor currents to stationary $\alpha\beta$ coordinates, the currents projected on the fault axis are

$$i_{sf}^h = \cos \theta_f i_{\alpha s}^h + \sin \theta_f i_{\beta s}^h, \quad (2.52)$$

$$i_{rf} = \cos \theta_f i_{\alpha r} + \sin \theta_f i_{\beta r}, \quad (2.53)$$

$$i_{r\perp} = -\sin \theta_f i_{\alpha r} + \cos \theta_f i_{\beta r}. \quad (2.54)$$

For $\mu_e > 0$, the fault-loop flux state ψ_f and loop current i_f are related by

$$i_f = \frac{\psi_f - \mu_e L_s i_{sf}^h - \mu_e L_m i_{rf}}{\frac{2}{3}\mu_e^2 L_s - \frac{2}{3}\mu_e^2 L_m - \mu_e L_{ls}}, \quad (2.55)$$

and the fault-loop state equation is

$$\frac{d\psi_f}{dt} = \left(R_f + \mu_e R_s - \frac{2}{3}\mu_e^2 R_s \right) i_f - \mu_e R_s i_{sf}^h. \quad (2.56)$$

The loop current then modifies the terminal-current reconstruction through a compensation current along the selected phase axis:

$$i_{\alpha s} = i_{\alpha s}^h + \frac{2}{3}\mu_e i_f \cos \theta_f, \quad (2.57)$$

$$i_{\beta s} = i_{\beta s}^h + \frac{2}{3}\mu_e i_f \sin \theta_f. \quad (2.58)$$

The phase currents are reconstructed as

$$i_a = i_{\alpha s}, \quad (2.59)$$

$$i_b = -\frac{1}{2}i_{\alpha s} - \frac{\sqrt{3}}{2}i_{\beta s}, \quad (2.60)$$

$$i_c = -\frac{1}{2}i_{\alpha s} + \frac{\sqrt{3}}{2}i_{\beta s}. \quad (2.61)$$

The electromagnetic torque used in the ITSC model is

$$T_e = \frac{3}{2}pL_m (i_{\alpha r} i_{\beta s} - i_{\alpha s} i_{\beta r}) - \mu_e pL_m i_f i_{r\perp}. \quad (2.62)$$

When $\mu = 0$ or $H_f = 0$, the implementation sets $i_f = 0$ and $d\psi_f/dt = 0$, the compensation terms vanish, and the terminal currents and torque reduce to the validated healthy model. It is not presented as a complete turn-resolved winding model.

For both mechanisms, the interpretation is intentionally load-aware. Current asymmetry, current negative-sequence factor, torque ripple at 100 Hz, and speed ripple are compared against the healthy case at the same load. A simulated electrical-asymmetry result is not described as an experimental fault measurement unless the fault is physically imposed on the laboratory motor.

2.6 Rotor and Bearing Extensions

The rotor and bearing studies are implemented as reduced electromechanical fault models on the identified Siemens motor. For broken-rotor-bar behavior, the diagnostic sideband law

$$f_{brb} = f_s(1 \pm 2ks), \quad k = 1, 2, 3, \dots, \quad (2.63)$$

where the slip s is obtained from the simulated operating point, is a diagnostic consequence of the implemented rotor asymmetry. The model equation itself is a rotor-fixed anisotropic resistance represented in the synchronous dq frame. The damaged-axis and healthy-axis rotor resistances are

$$R_{rd} = R'_r(1 + \alpha), \quad R_{rq} = R'_r, \quad (2.64)$$

where α is the retained electrical rotor-asymmetry coefficient. The initial asymmetry angle is $\theta_0 = 0^\circ, 120^\circ$, or 240° for nonzero asymmetry cases. With θ_{sl} the rotor-asymmetry orientation relative to the synchronous frame,

$$\frac{d\theta_{sl}}{dt} = \omega_e - \omega_r, \quad \theta_{sl}(0) = \theta_0, \quad (2.65)$$

the rotor-resistance matrix applied to the rotor currents is

$$\mathbf{R}_r(\theta_{sl}) = \begin{bmatrix} R_{av} + R_\Delta \cos 2\theta_{sl} & R_\Delta \sin 2\theta_{sl} \\ R_\Delta \sin 2\theta_{sl} & R_{av} - R_\Delta \cos 2\theta_{sl} \end{bmatrix}, \quad (2.66)$$

with $R_{av} = (R_{rd} + R_{rq})/2$ and $R_{\Delta} = (R_{rd} - R_{rq})/2$. The rotor-flux equations are therefore modified to

$$\frac{d\lambda_{dr}}{dt} = -(R_{dd}i_{dr} + R_{dq}i_{qr}) + (\omega_e - \omega_r)\lambda_{qr}, \quad (2.67)$$

$$\frac{d\lambda_{qr}}{dt} = -(R_{dq}i_{dr} + R_{qq}i_{qr}) - (\omega_e - \omega_r)\lambda_{dr}. \quad (2.68)$$

When $\alpha = 0$, $R_{rd} = R_{rq} = R'_r$, $R_{\Delta} = 0$, and Eqs. (2.66)–(2.68) reduce to the healthy rotor-flux model. The retained BRB implementation is used to study sideband location, sideband amplitude, and torque/speed modulation, not to reconstruct individual rotor-bar currents. The coefficient α represents rotor-resistance anisotropy; it is not a direct measurement of one broken bar, a percentage of bars broken, or a crack size.

For the bearing case, the Siemens datasheet identifies the drive-end bearing as 6205 2ZC3. Because the manufacturer-specific internal geometry of the Siemens 6205 2ZC3 bearing was unavailable, the documented CWRU drive-end SKF 6205-2RS JEM geometry was adopted strictly as a geometric proxy [15]. The generic modulation relation

$$f_b = |f_s \pm k f_v|, \quad k = 1, 2, 3, \dots \quad (2.69)$$

is then evaluated with $f_v = f_{BPFO}$. The implemented model imposes a periodic load-torque disturbance:

$$T_{L,\text{total}}(t) = T_L + H_b(t)\gamma_b T_N \sin \theta_b(t), \quad H_b(t) = \begin{cases} 0, & t < t_b, \\ 1, & t \geq t_b, \end{cases} \quad (2.70)$$

where $t_b = 1.5$ s, $T_N = 10.1$ N m, and γ_b is the retained BPFO torque-disturbance amplitude expressed as a fraction of rated torque. The bearing angle satisfies

$$\frac{d\theta_b}{dt} = 2\pi f_{BPFO}(t), \quad f_{BPFO}(t) = 3.58477554 \frac{n(t)}{60}. \quad (2.71)$$

In steady operation this is equivalent to a sinusoidal term at f_{BPFO} with initial phase φ_b . The dataset uses $\gamma_b = 0, 1, 3$, and 5% of rated torque, with $\varphi_b = 0^\circ, 120^\circ$, and 240° for nonzero cases. These percentages are imposed torque-disturbance levels, not percentages of physical outer-race damage. It is therefore a geometry-derived BPFO electromechanical surrogate, not a full contact, vibration, or thermal bearing model.

2.7 Chapter Summary

This chapter first documented the Siemens 1.5 kW laboratory identification path, including the verified nameplate data and the retained electrical and mechanical parameters. It then defined the 500 W benchmark model used to establish the power-invariant dq convention and the analytical-versus-Simscape validation workflow. Finally, it stated the reduced fault-model interfaces used later on the Siemens motor: imposed supply unbalance, incipient ITSC, BPFO bearing torque disturbance, and BRB rotor asymmetry.

CALIBRATION OF THE SIEMENS MODEL AND CROSS-MACHINE TRANSFERABILITY

The Siemens laboratory motor identified in Section 2.1 is the main calibrated motor used for the 1.5 kW validation and fault-simulation campaign. This chapter explains how the identified parameters are inserted into the analytical and Simscape models, how the resulting healthy response is validated, and which diagnostic conclusions can be transferred from one motor to another.

3.1 Cross-Rating Transferability with the 500 W Benchmark Motor

The 500 W benchmark motor and the Siemens 1.5 kW motor serve different scientific roles. The benchmark motor documents the modeling convention and inductance-reconstruction logic; the Siemens motor provides the experimentally identified parameter set used for the main 1.5 kW simulations. Their numerical parameters must not be mixed.

Table 3.1: Benchmark and Siemens motor domains used in the thesis.

Quantity	500 W benchmark motor	Siemens 1.5 kW motor	Interpretation
Rated power	500 W	1.5 kW	Different power scale.
Pole pairs	$p = 1$	$p = 2$	Different synchronous speeds.
Synchronous speed at 50 Hz	3000 rpm	1500 rpm	Speed plots are not directly comparable.
Rated or representative torque	about 1.6 N m	10.1 N m	Torque indicators must be normalized or recalibrated.
Parameter origin	Published tests and reconstruction	Laboratory tests and datasheet J	Separate calibration domains.
R_s	11.73 Ω	5.70 Ω	Motor-specific resistance.
R_r or R'_r	11.08 Ω	3.29 Ω	Referred rotor value and convention dependent.
L_m	0.7354 H	0.3015 H	Motor-specific magnetizing branch.
L_{ls} and L_{lr}	0.0400 H	0.01337 H	Different ratings and test results.
L_s and L_r	0.7754 H	0.31487 H	Total inductances for each model.
σ	0.10051	0.08312	Same concept, different motor.
J	0.0030 kg m ²	0.0033 kg m ²	Benchmark value versus Siemens datasheet value.
B	0.00092 N m s/rad	6.93×10^{-4} N m s/rad	Siemens value derived from measured B/J and datasheet J .

The transferable part is the modeling and identification workflow: resistance measurement, no-load magnetizing estimation, blocked-rotor leakage estimation, load verification, and deceleration-based mechanical estimation. Fault-frequency laws can also be transferred after the target motor slip is known, but amplitudes, thresholds, transient damping, and classifier features remain motor-specific.

3.2 Healthy 1.5 kW Siemens Model

The Siemens analytical model uses the same power-invariant dq convention as Chapter 2, but with the identified Siemens parameters:

$$\begin{aligned} R_s &= 5.70 \, \Omega, \quad R'_r = 3.29 \, \Omega, \quad L_m = 0.3015 \, \text{H}, \\ L_{ls} &= L'_{lr} = 0.01337 \, \text{H}, \quad L_s = L'_r = 0.31487 \, \text{H}, \quad \sigma = 0.083121, \\ J &= 0.0033 \, \text{kg m}^2, \quad B = 6.93 \times 10^{-4} \, \text{N m s/rad}, \quad p = 2. \end{aligned} \quad (3.1)$$

Four operating points are retained, all supplied at 400 V line-line RMS and 50 Hz. The load torque is applied after the no-load acceleration stage so that the response contains both startup and loaded settling.

Table 3.2: Siemens 1.5 kW healthy operating cases.

Case	T_L (N m)	Load (pu)	Use in the validation
No load	0	0	Healthy reference for magnetizing current and friction torque.
Half load	5.05	0.5	Intermediate load-dependence case.
Experimental load	8.5	0.8416	Main comparison with the measured laboratory torque-speed point.
Rated load	10.1	1.0	Comparison with manufacturer rated current, speed, and shaft power.

3.3 Analytical Healthy Results

The analytical model produces the expected load dependence: current and slip increase with load, speed decreases with load, and the electromagnetic torque satisfies the mechanical balance

$$T_e = T_L + B\omega_m. \quad (3.2)$$

The steady-state quantities are computed from the final time interval using time-weighted numerical integration, which is required because the solver uses variable step sizes.

Table 3.3: Analytical steady-state results for the identified Siemens 1.5 kW model. The efficiency column is the reduced-model electromechanical efficiency.

Case	I_{rms} (A)	n (rpm)	s (%)	T_e (N m)	P_{in} (W)	P_{shaft} (W)	η_{red} (%)	Balance error (N m)
No load	2.3295	1499.42	0.0385	0.1088	109.89	0.00	–	1.30×10^{-7}
Half load	2.6151	1470.89	1.9410	5.1568	926.96	777.86	83.92	8.49×10^{-6}
8.5 N m	3.1525	1448.98	3.4014	8.6051	1521.63	1289.76	84.76	-1.02×10^{-5}
Rated load	3.4732	1437.96	4.1359	10.2044	1809.17	1520.89	84.07	-5.60×10^{-7}

The measured no-load current is 2.49 A, or about 72.2% of the rated current. The analytical model gives 2.3295 A and the Simscape model gives 2.2120 A, so the high no-load current is not a simulation anomaly; it is also present in the real motor. No-load active power is different. The measured value, 210 W, contains stator copper, core, mechanical, and windage losses, whereas the reduced analytical model contains stator copper and viscous friction but no explicit core-loss branch, stray-load loss, hysteresis, or nonlinear windage. For that reason, no-load input power is not used as a direct validation criterion. The efficiency values in Table 3.3 are reduced-model electromechanical efficiencies and must not be interpreted as manufacturer-efficiency predictions.

3.4 Analytical–Simscape Cross-Validation

An independent Simscape Electrical model is configured with the same Siemens parameter set. The two implementations are not expected to produce identical startup peaks because source phase conventions, internal block initialization, and flux initial conditions differ. The validation therefore focuses on steady-state current, speed, torque, and slip.

The nominal parameter vector of the Asynchronous Machine SI Units block was set to [2390, 400, 50], where 2390 VA is the rated three-phase apparent power calculated from

$$S_N = \sqrt{3}V_{LL}I_N = \sqrt{3}(400)(3.45) \approx 2390.2 \text{ VA.} \quad (3.3)$$

This value must be distinguished from the manufacturer-rated mechanical output power of 1.5 kW. The correction fixes the block parameter definition and documentation; a sensitivity check using 1500 and 2390 VA produced negligible differences in the physical SI outputs because the stator and rotor parameters, mutual inductance, inertia, friction, supply voltage, and load torque were entered explicitly in SI units. This interpretation is consistent with the Simscape asynchronous-machine block definition and per-unit base-quantity documentation [26, 27].

Table 3.4: Analytical and Simscape comparison for the Siemens healthy model.

Case	Mean I_{rms} anal. (A)	Mean I_{rms} Sim. (A)	Current error (%)	n anal. (rpm)	n Sim. (rpm)	Speed error (%)	Torque error (%)
No load	2.3295	2.2120	5.311	1499.42	1499.36	0.004	0.0037
Half load	2.6151	2.5470	2.672	1470.89	1467.23	0.249	0.0053
8.5 Nm	3.1525	3.1721	0.619	1448.98	1441.46	0.521	0.0062
Rated load	3.4732	3.5479	2.107	1437.96	1427.92	0.703	0.0071

The maximum speed difference between analytical and Simscape results is 0.703%, and the torque difference remains below 0.008% in all four cases. The current dif-

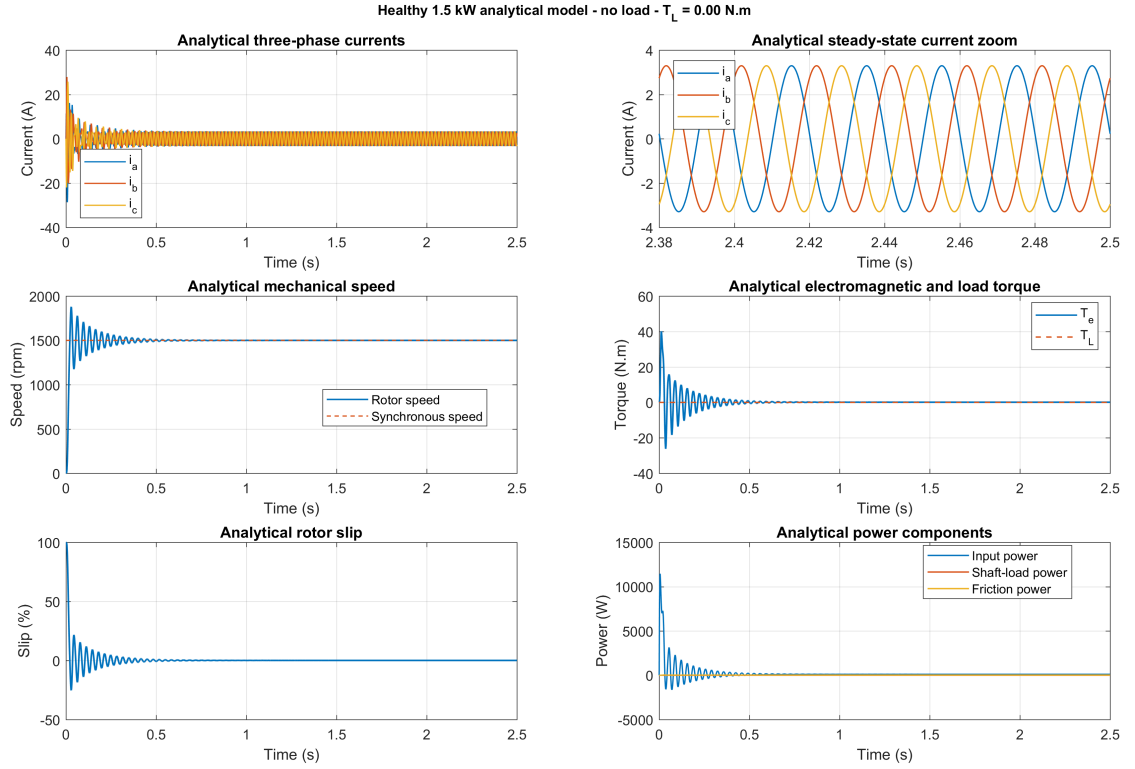


Figure 3.1: Analytical no-load response of the identified Siemens 1.5 kW model.

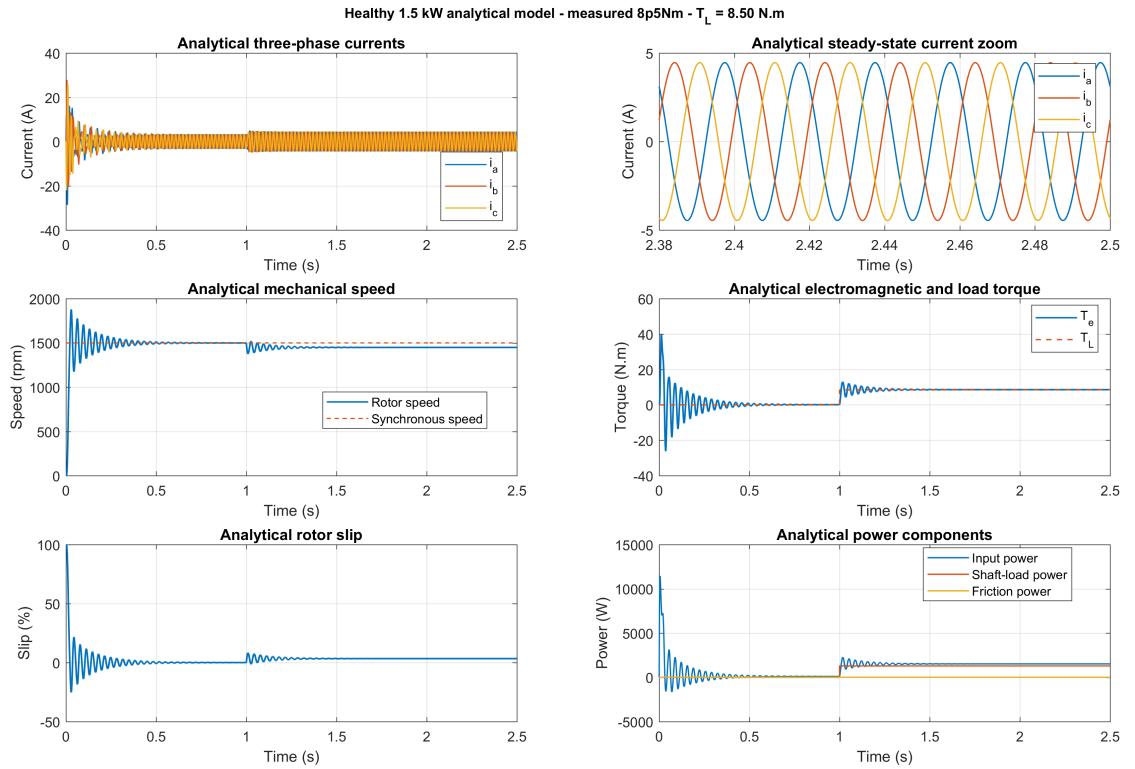


Figure 3.2: Analytical response at the 8.5 N m experimental operating point.

ference is highest at no load, where the magnetizing branch dominates and small implementation differences have a larger relative effect. Under loaded operation the current error remains below 2.68%.

Slip errors should be read in absolute percentage points rather than only as relative percentages, because slip is a small difference between synchronous speed and rotor speed. The absolute slip differences remain about 0.0042, 0.2437, 0.5010, and 0.6695 percentage points from no load to rated load.

3.5 Validation Against Laboratory and Manufacturer Data

The available load observation gives a measured speed of 1437 rpm at approximately 8.5 N m, with a retained line-current reading of 3.34 A. The load-test input active power is not used because the available record was not internally consistent with the retained voltage, current, and power-factor display. At the same load torque, the analytical model predicts 1448.98 rpm, corresponding to a 0.834% speed error, while the Simscape model predicts 1441.46 rpm, corresponding to a 0.311% speed error. At the same operating point, the measured line current was 3.34 A. The analytical model predicts 3.1525 A, corresponding to a difference of approximately 5.61%, while the Simscape model predicts 3.1721 A, corresponding to a difference of approximately 5.03%. The shaft power calculated from the measured torque and speed is approximately 1279.10 W:

$$P_{\text{shaft}} = T_L \frac{2\pi n}{60} = 8.5 \frac{2\pi(1437)}{60} \approx 1279.10 \text{ W}. \quad (3.4)$$

The analytical value is 1289.76 W and the Simscape value is 1283.07 W.

The rated-load simulation is also compared with the Siemens datasheet values $I_N = 3.45$ A, $n_N = 1420$ rpm, and $P_N = 1500$ W [23]. The analytical rated values differ by 0.672% in current, 1.265% in speed, and 1.393% in shaft power. The Simscape rated values differ by 2.839% in current, 0.558% in speed, and 0.684% in shaft power. These differences are acceptable for the reduced model scope because core-loss separation, saturation, stray-load losses, nonlinear windage, and temperature-dependent parameters are not modeled explicitly.

3.6 Transient Interpretation

The visible oscillations in the Siemens startup and load-step figures are damped electromechanical transients. They are expected when the simulation starts from zero speed and zero flux under direct connection to a 50 Hz supply, and when the load is applied suddenly after the acceleration stage. The Siemens motor has

$$\frac{B}{J} = \frac{6.93 \times 10^{-4}}{0.0033} \approx 0.21 \text{ s}^{-1}, \quad \tau_r = \frac{L'_r}{R'_r} = \frac{0.31487}{3.29} \approx 0.0957 \text{ s}. \quad (3.5)$$

These values explain why the 1.5 kW response has a visible electromechanical settling interval. The transient is not filtered out because it is part of the physical response of the reduced model. Steady-state diagnostic features, however, are extracted from retained post-transient windows.

3.7 Chapter Summary

This chapter established the Siemens 1.5 kW identified motor as the main calibrated simulation platform of the thesis. The analytical and Simscape healthy models agree closely in torque and speed, and both remain consistent with the measured 8.5 N m torque-speed point and manufacturer rated data. The chapter also clarified the transferability rule used later: frequency laws can be recalculated for another motor once slip and geometry are known, but amplitudes, thresholds, damping, and fault indicators must be calibrated on the target motor.

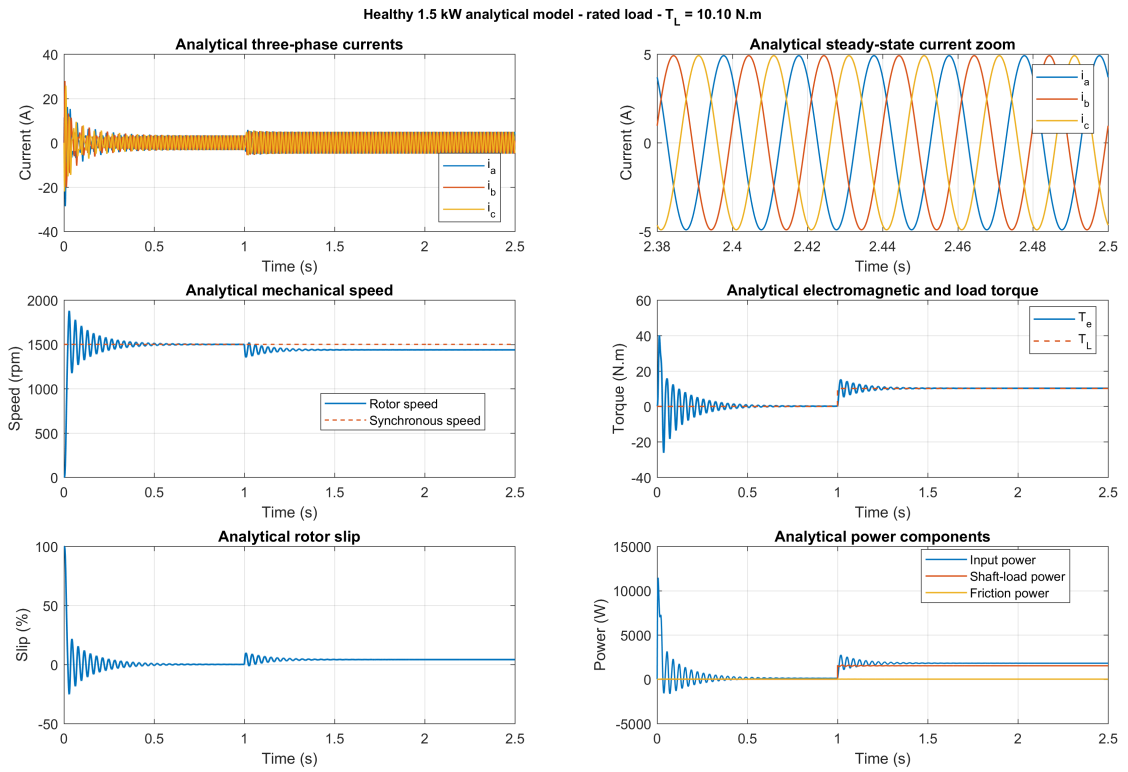


Figure 3.3: Analytical response at the 10.1 N m rated-load operating point.

DIAGNOSTIC METHODS AND TECHNIQUES

Chapter 2 defined the modeling convention and the Siemens parameter identification, while Chapter 3 validated the Siemens healthy model. The role of the present chapter is to define how the simulated signals are converted into diagnostic indicators. The thesis uses a model-supported signal approach: current, voltage, torque, and speed are interpreted with the physical fault mechanism, the load point, and the known model assumptions.

4.1 Retained Diagnostic Paradigms

Induction-motor diagnosis is commonly grouped into signal-based, model-based, and data-driven approaches [9, 10, 22]. The present work combines the first two. Signal-based features are extracted from phase currents, voltages, torque, and speed. Model-based interpretation is used to avoid assigning a fault label from one spectral component alone. Data-driven classification is left for later work after grouped datasets are consolidated.

Family	Useful information	Role in this thesis
Signal-based	RMS current, sequence components, FFT peaks, sidebands, torque and speed ripple.	Main feature-extraction layer for the simulated datasets.
Model-based	Healthy dq model, Simscape comparison, torque balance, slip, and parameter origin.	Physical interpretation and validation of fault-feature plausibility.
Data-driven	Windowed feature tables and future classifiers such as SVM, trees, CNN, or recurrent models.	Future exploitation path; no trained classifier is claimed.

Table 4.1: Diagnostic paradigms retained at thesis level.

4.2 Feature Chain Used in the Thesis

The feature chain starts from simulated electrical and mechanical signals. For deployable diagnosis, the most realistic input signals are phase voltages, phase currents, and speed. Electromagnetic torque, slip, fault-loop current, and imposed severity variables are retained as validation and labeling variables because they are available inside the simulation but not necessarily on a field drive.

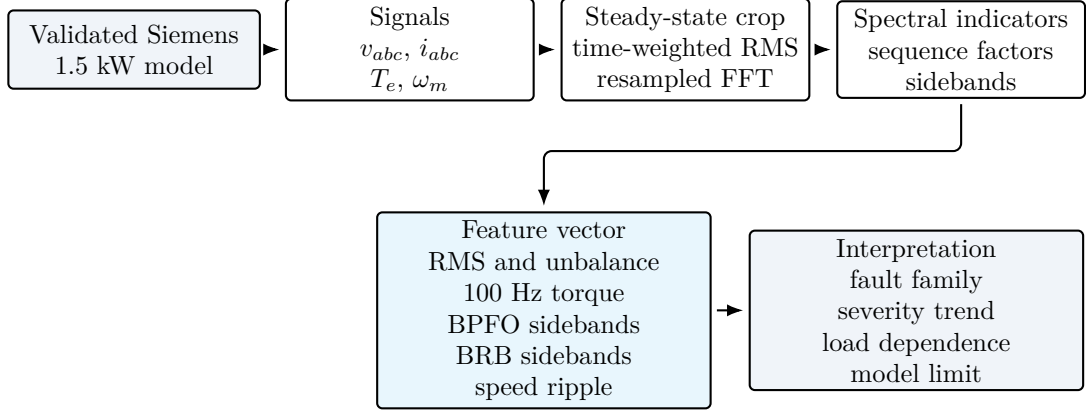


Figure 4.1: Signal-feature chain used for the Siemens fault-simulation datasets.

4.3 Sequence Components for Electrical Asymmetry

Supply unbalance and ITSC are both electrical-asymmetry cases. For a phasor set X_a , X_b , X_c , the symmetrical components are

$$\begin{bmatrix} X_0 \\ X_1 \\ X_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix}, \quad a = e^{j2\pi/3}. \quad (4.1)$$

The voltage-unbalance factor and current negative-sequence factor are then

$$VUF = 100 \frac{|V_2|}{|V_1|}, \quad CUF = 100 \frac{|I_2|}{|I_1|}. \quad (4.2)$$

In the supply-unbalance dataset, VUF is imposed externally and the current negative-sequence response is measured. In the ITSC dataset, the supply remains balanced and the current asymmetry comes from the simulated shorted-turn loop.

Electrical asymmetry also produces a double-frequency torque component. At 50 Hz supply, the retained scalar feature is the 100 Hz torque peak extracted from the post-transient torque spectrum. This feature is useful but not unique: both

supply unbalance and ITSC can increase it, so it must be read together with voltage-sequence information and fault-model context.

4.4 Spectral Estimators Retained for the Final Results

The retained frequency-domain quantities use peak amplitudes, not RMS amplitudes. For a single expected frequency f_0 , the mean is first removed and the one-sided peak amplitude is estimated by complex projection,

$$A(f_0) = \frac{2}{t_2 - t_1} \left| \int_{t_1}^{t_2} (x(t) - \bar{x}) e^{-j2\pi f_0 t} dt \right|. \quad (4.3)$$

No additional FFT window is applied to these deterministic projection features; the retained post-transient interval defines the record.

For BRB and the final bearing-current sideband index, the close frequencies around the 50 Hz fundamental are fitted simultaneously by least squares:

$$x(t) = c_0 + \sum_{k=1}^{N_f} [a_k \cos(2\pi f_k \tau) + b_k \sin(2\pi f_k \tau)], \quad A_k = \sqrt{a_k^2 + b_k^2}, \quad (4.4)$$

where $\tau = t - t_1$. The retained current sideband index is

$$\text{Sideband Index} = 100 \frac{A_{\text{lower}} + A_{\text{upper}}}{2A_{50}}. \quad (4.5)$$

For BRB, the fitted frequencies are $f_s(1 - 2s)$, f_s , $f_s(1 + 2s)$, $2f_s$, and $3f_s$ over the 2.0–5.0 s retained interval. For the bearing-current sideband index, the fitted frequencies are $|50 - f_{BPFO}|$, 50, $50 + f_{BPFO}$, 100, and 150 Hz over the 2.3–3.0 s retained interval, with f_{BPFO} recalculated from the load-dependent mean speed. The 100 Hz torque peaks in the supply-unbalance and ITSC studies use Eq. (4.3) after mean removal over 2.3–3.0 s. The BPFO torque and speed peaks use the same direct projection at the expected BPFO frequency. No FFT-bin search tolerance is used in the reported scalar features; the expected frequencies are supplied by the imposed fault law or by the simulated slip.

4.5 Rotor and Bearing Spectral Indicators

For rotor asymmetry, the main MCSA target is the slip-dependent sideband family

$$f_{brb} = f_s(1 \pm 2ks), \quad k = 1, 2, 3, \dots, \quad (4.6)$$

where f_s is the supply frequency and s is the slip [8, 28]. The first-order lower and upper sidebands are close to the fundamental when slip is small, so a sufficiently long analysis window is required. This is why the BRB dataset excludes no-load cases and why the consolidated dataset should preserve case-level windows instead of relying on short random crops.

For bearing-related mechanical forcing, the generic current-modulation relation is

$$f_{sb} = |f_s \pm m f_v|, \quad m = 1, 2, 3, \dots, \quad (4.7)$$

where f_v is the imposed or geometry-derived mechanical disturbance frequency [29]. In the retained bearing study, the disturbance frequency is the outer-race ball-pass frequency,

$$f_{BPFO} = 3.58477554 f_r, \quad (4.8)$$

where f_r is the shaft rotational frequency. Because the manufacturer-specific internal geometry of the Siemens 6205 2ZC3 bearing was unavailable, the documented CWRU drive-end SKF 6205-2RS JEM geometry was adopted strictly as a geometric proxy [15]. The simulation remains an electromechanical torque-disturbance surrogate and is not a complete bearing-contact or vibration model.

4.6 Model-Supported Interpretation

The thesis avoids declaring faults from a single spectral peak. Instead, each feature is read together with the model context:

- supply unbalance requires voltage-sequence information because current asymmetry alone may resemble ITSC;
- ITSC interpretation uses fault-loop current and phase pattern in addition to CUF and 100 Hz torque;
- BRB interpretation uses the simulated slip because the sidebands move with operating point;
- bearing interpretation uses the geometry-derived BPFO order and the retained current-sideband index;

- R_s tracking is a support feature for thermal context, not an isolated fault class in this thesis.

A generic residual can be written as

$$\Delta \mathbf{z} = \mathbf{z}_{fault} - \mathbf{z}_0, \quad (4.9)$$

where $\mathbf{z}_0$ is the healthy feature vector and $\mathbf{z}_{fault}$ is the feature vector obtained under the simulated disturbance. The residual is interpreted with load context because the healthy current, slip, and torque all change with load.

4.7 Dataset Rules for Later Classification

The final classification stage is not implemented in this thesis, but the simulation records are prepared so that future machine-learning work can be done without data leakage. The following rules are retained:

- use phase voltages, phase currents, and speed as deployable input signals;
- keep torque, slip, fault-loop current, and imposed severity as validation or labeling variables;
- sample or resample records consistently before FFT feature extraction;
- use windows long enough to resolve BRB sidebands near the fundamental;
- split data by complete CaseID or GroupID, never by randomly mixing windows from the same run across training and test sets.

4.8 Chapter Summary

This chapter defined the diagnostic feature chain used to read the Siemens simulation datasets. Sequence components support supply-unbalance and ITSC interpretation, BPFO and BRB sidebands define the main spectral indicators for mechanical and rotor-asymmetry cases, and all features are interpreted with load and model context. These rules are used in Chapter 5 to report the retained simulation results.

SIMULATION, VALIDATION, AND RESULTS

This chapter presents the final retained results. The healthy Siemens 1.5 kW model is first summarized as the validated baseline. Four simulated fault families are then reported: supply-voltage unbalance, incipient inter-turn short circuit, bearing outer-race BPFO torque disturbance, and broken-rotor-bar rotor asymmetry. The faulted cases are simulation studies, not physical fault experiments on the laboratory motor.

5.1 Simulation Environment and Retained Operating Cases

The Siemens model uses the identified parameter set of Chapter 2 and the validation logic of Chapter 3. The analytical model and the Simscape model are both supplied at 400 V line-line RMS and 50 Hz. Fault studies are derived from the validated Siemens healthy model so that load, speed, slip, current, torque, and diagnostic features are all evaluated within one motor parameter domain.

Table 5.1: Retained Siemens simulation studies and dataset sizes.

Study	Runs	Loads	Purpose
Healthy Siemens model	4	0, 0.5, 0.8416, 1.0 pu	Validate the identified 1.5 kW model.
Supply-voltage unbalance	64	0, 0.5, 0.8416, 1.0 pu	Study VUF severity, orientation, and load dependence.
Incipient ITSC	28	0, 0.5, 0.8416, 1.0 pu	Study shorted-turn indicators up to $\mu = 2\%$ with $R_f = 5 \Omega$.
Bearing BPFO surrogate	40	0, 0.5, 0.8416, 1.0 pu	Study geometry-derived BPFO torque-disturbance amplitudes.
BRB rotor asymmetry	30	0.5, 0.8416, 1.0 pu	Study slip-dependent rotor-resistance anisotropy sidebands.

The 0.8416 pu load corresponds to the measured 8.5 Nm laboratory operating

point. The BRB dataset excludes no-load operation because the first-order sidebands become too close to the 50 Hz fundamental for reliable short-record separation at very low slip.

5.2 Healthy 1.5 kW Baseline

The healthy Siemens baseline was validated in Chapter 3. The most important result is that the analytical and Simscape models agree closely in torque and speed across the retained load range, and both remain consistent with available laboratory and manufacturer data. At the 8.5 N m torque-speed point, the analytical speed error relative to the measured 1437 rpm point is about 0.834%, while the Simscape speed error is about 0.311%. At rated load, the analytical current differs from the datasheet current by 0.672%, and the Simscape rated speed differs from the datasheet speed by 0.558%.

This healthy baseline is used as the reference for all fault indicators. In each fault dataset, the healthy run at the same load is therefore the comparison case; fault severity is not interpreted without the corresponding load-matched healthy value.

5.3 Supply-Voltage Unbalance Results

The supply-unbalance study imposes a controlled negative-sequence voltage component. The dataset contains four load levels, one healthy case per load, and five VUF severities with three negative-sequence orientations. This gives

$$4(1 + 5 \times 3) = 64 \tag{5.1}$$

accepted simulations.

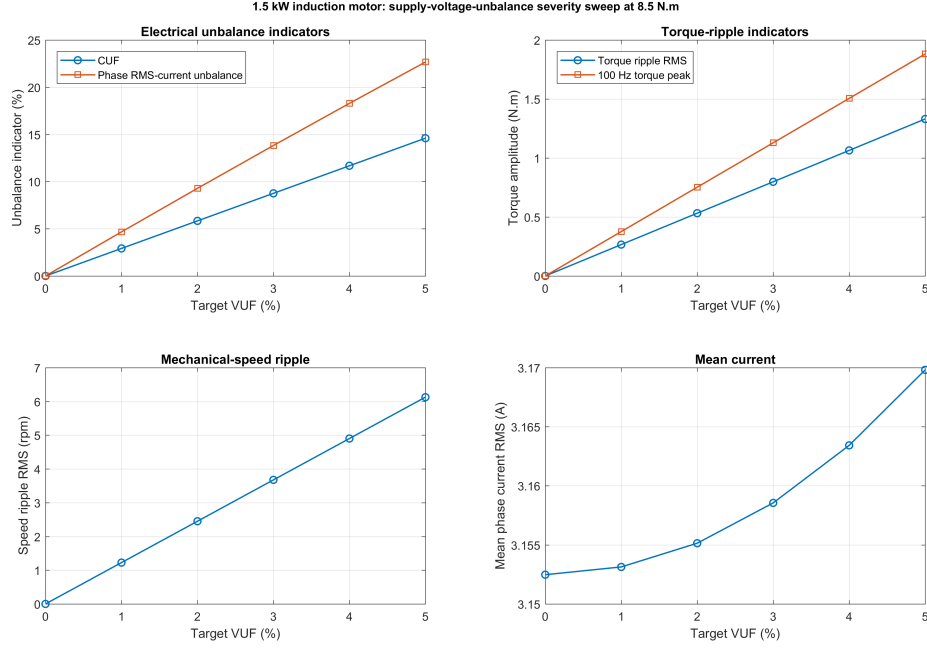


Figure 5.1: Supply-unbalance severity trends at the 8.5 N m operating point.

At the 8.5 N m load, increasing VUF from 1% to 5% increases the current negative-sequence factor from about 2.92% to 14.60%, and the 100 Hz torque peak from about 0.376 N m to 1.882 N m. The response is nearly linear over the retained severity range.

Table 5.2: Load dependence of the supply-unbalance indicators for orientation $\phi_2 = 0^\circ$.

Load	CUF at 1% VUF (%)	CUF at 5% VUF (%)	T_{100} at 1% VUF (N m)	T_{100} at 5% VUF (N m)
0 pu	3.976	19.873	0.3964	1.9819
0.5 pu	3.528	17.644	0.3851	1.9255
0.8416 pu	2.919	14.597	0.3763	1.8816
1.0 pu	2.646	13.231	0.3719	1.8596

Table 5.2 shows that fixed current-unbalance thresholds cannot be transferred blindly across load. For the same imposed VUF, the current negative-sequence factor decreases as load increases because the positive-sequence current grows with torque demand. The 100 Hz torque peak is less sensitive to load but still changes measurably.

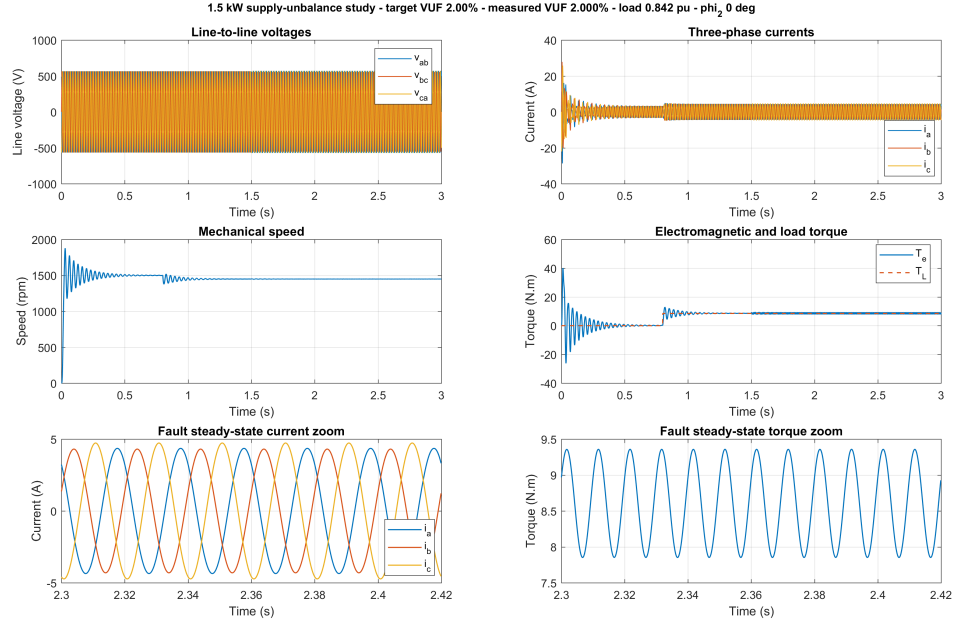


Figure 5.2: Time-domain validation example for 2% VUF at the 8.5 N m operating point.

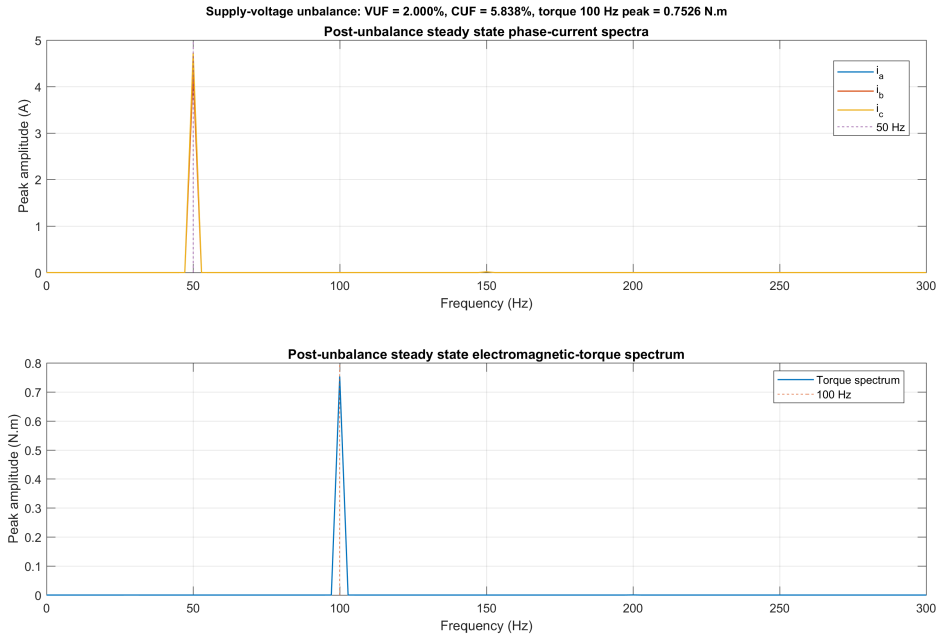


Figure 5.3: Frequency-domain validation example for 2% VUF at the 8.5 N m operating point.

The three negative-sequence orientations mainly rotate which phase carries the largest RMS current. They do not significantly change aggregate indicators such as CUF or the 100 Hz torque component. At rated load and 5% VUF, the CUF remains about 13.23% and the 100 Hz torque peak about 1.86 N m for all orientations.

5.4 Incipient ITSC Results

The ITSC model is used as an incipient diagnostic surrogate with an exact healthy limit. The retained dataset uses severity levels $\mu = 0, 1\%$, and 2% , a fault-loop resistance $R_f = 5 \Omega$, three possible faulted phases, and four load levels. The resistance R_f is a modeling parameter used to bound the incipient loop current; it was not experimentally measured on the Siemens motor. The dataset contains

$$4(1 + 2 \times 3) = 28 \quad (5.2)$$

accepted simulations. Quantitative interpretation is restricted to $\mu \leq 2\%$ because the simplified fault injection is not a full winding-level energy model at higher severities. A practical power-accounting check showed that the reduced injection remained close to the healthy energy balance at $\mu = 2\%$ with about -0.51% closure error, whereas the residual increased appreciably at $\mu = 5\%$ to about -3.16% . Consequently, the retained quantitative dataset was limited to the incipient range $\mu \leq 2\%$.

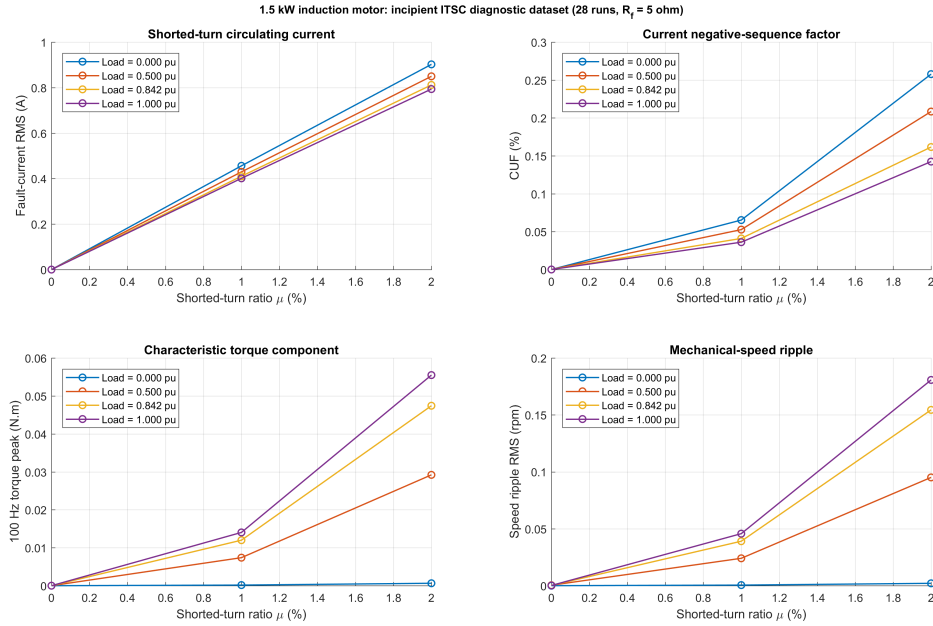


Figure 5.4: Incipient ITSC dataset trends for $\mu = 0, 1\%$, and 2% .

Table 5.3: ITSC indicators for phase-A faults at the 8.5 N m operating point.

Case	$I_{f,rms}$ (A)	CUF (%)	T_{100} (N m)	Speed ripple RMS (rpm)	Mean current (A)
Healthy	0.0000	0.000126	4.53×10^{-7}	0.000318	3.1525
$\mu = 1\%$	0.4104	0.0417	0.0120	0.0391	3.1513
$\mu = 2\%$	0.8117	0.1621	0.0474	0.1544	3.1480

The shorted-turn effect is clear in fault-loop current, CUF, 100 Hz torque, and

speed ripple. Mean RMS current is a weak feature by itself: at 8.5 N m it changes from 3.1525 A healthy to 3.1480 A at $\mu = 2\%$. This confirms that incipient ITSC should not be detected from average current alone.

Table 5.4: Load dependence of phase-A ITSC indicators at $\mu = 2\%$.

Load	$I_{f,rms}$ (A)	CUF (%)	T_{100} (N m)	Speed ripple RMS (rpm)
0 pu	0.9022	0.2580	0.00064	0.00208
0.5 pu	0.8496	0.2090	0.02920	0.09510
0.8416 pu	0.8117	0.1621	0.04742	0.15441
1.0 pu	0.7936	0.1431	0.05549	0.18071

The fault-loop current decreases slightly with load, while the torque and speed ripple increase. This opposite trend is important: a classifier trained only on one load could misread the severity-load interaction.

5.5 Bearing BPFO Surrogate Results

The Siemens datasheet identifies the drive-end bearing as a 6205 2ZC3 bearing. Because the manufacturer-specific internal geometry of the Siemens 6205 2ZC3 bearing was unavailable, the documented CWRU drive-end SKF 6205-2RS JEM geometry was adopted strictly as a geometric proxy [15]. With nine rolling elements, ball diameter 7.94004 mm, pitch diameter 39.03980 mm, and zero contact angle, the retained order is

$$BPFO = 3.58477554 f_r. \quad (5.3)$$

The fault model imposes a periodic load-torque disturbance at BPFO. It is therefore a geometry-derived electromechanical diagnostic surrogate, not a detailed contact, vibration, or thermal bearing model.

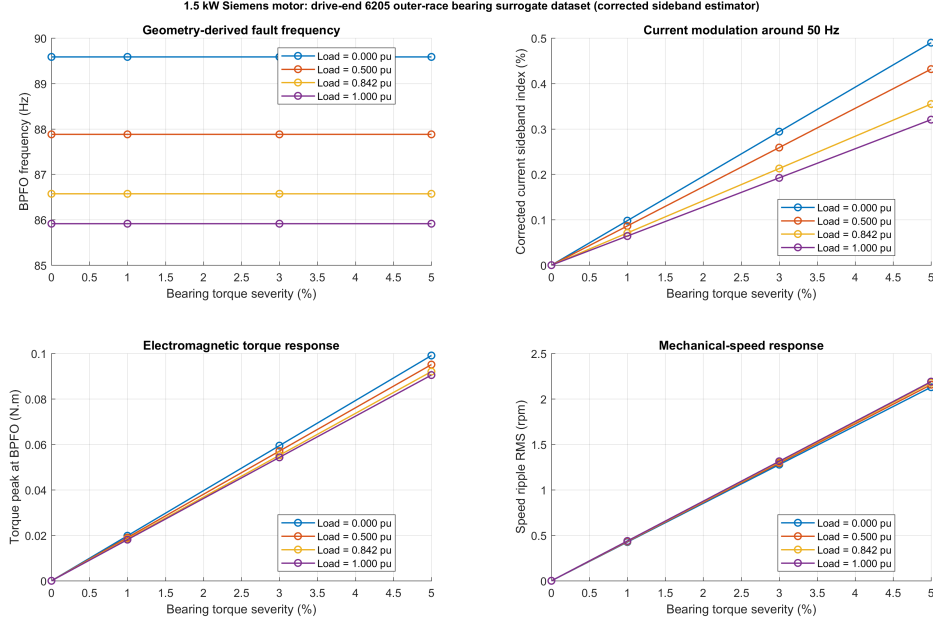


Figure 5.5: Bearing BPFO surrogate trends using the retained current-sideband index.

Table 5.5: BPFO surrogate indicators at the 8.5 N m operating point.

Disturbance amplitude	f_{BPFO} (Hz)	Current sideband index (%)	Torque at BPFO (N m)	Speed ripple RMS (rpm)	Torque ripple RMS (N m)
0%	86.5710	3.47×10^{-6}	5.38×10^{-7}	0.00032	2.02×10^{-5}
1%	86.5710	0.07094	0.01838	0.4360	0.01301
3%	86.5709	0.21281	0.05515	1.3079	0.03902
5%	86.5708	0.35468	0.09191	2.1799	0.06503

The current sideband index and the torque component at BPFO increase monotonically with the imposed torque-disturbance amplitude. Only the retained sideband estimator is used in the thesis results. BPFO frequency decreases with load because it is proportional to shaft rotational speed, moving from about 89.585 Hz at no load to about 85.912 Hz at rated load.

5.6 Broken-Rotor-Bar Rotor-Asymmetry Results

The BRB study uses a reduced rotor-asymmetry representation to reproduce the main electromechanical consequences of a broken rotor bar. The diagnostic target is the slip-dependent sideband family

$$f_{brb} = f_s(1 \pm 2s), \quad (5.4)$$

and the associated torque and speed modulation at $2sf_s$. The dataset contains three loads, one healthy case per load, and three severities with three asymmetry orientations:

$$3(1 + 3 \times 3) = 30. \quad (5.5)$$

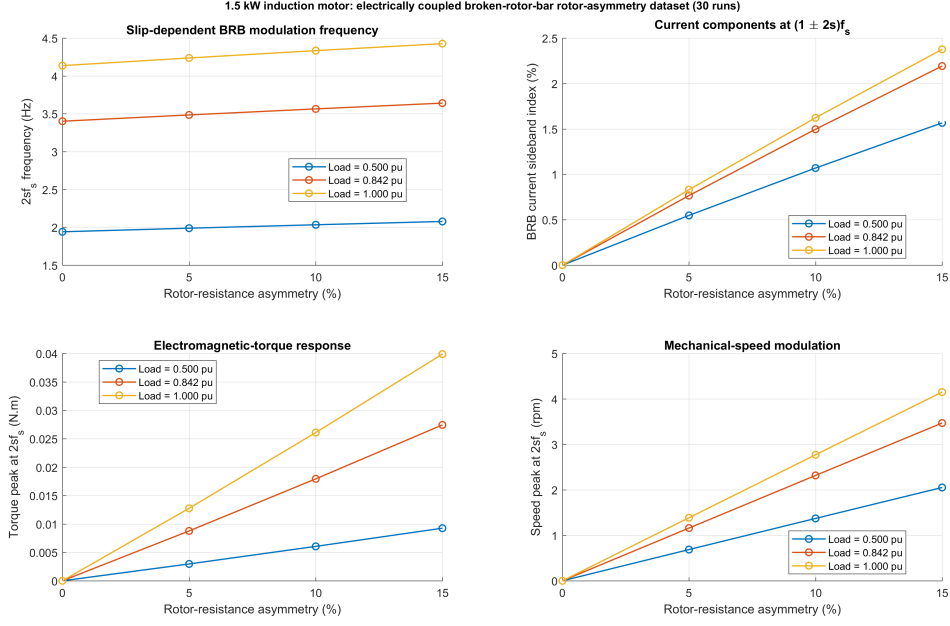


Figure 5.6: BRB rotor-asymmetry dataset trends.

Table 5.6: BRB indicators at the 8.5 N m operating point for the 0° asymmetry orientation.

Asymmetry coefficient	Slip (%)	$2sf_s$ (Hz)	Current sideband index (%)	Torque at $2sf_s$ (N m)	Speed at $2sf_s$ (rpm)
0%	3.4015	3.4015	1.48×10^{-5}	2.86×10^{-6}	1.01×10^{-5}
5%	3.4832	3.4832	0.7659	0.00877	1.1599
10%	3.5664	3.5664	1.4968	0.01793	2.3171
15%	3.6417	3.6417	2.1922	0.02743	3.4688

At $\alpha = 10\%$ and 8.5 N m, the simulated slip is 3.5664%, giving sidebands at 46.4336 Hz and 53.5664 Hz. The lower and upper sideband amplitudes are nearly symmetric, and the current sideband index rises from essentially zero in the healthy case to about 1.497%. The power-closure error remains below 0.004% for this validation case.

Table 5.7: BRB current sideband index by load and rotor-asymmetry coefficient for the 0° orientation.

Load	Healthy (%)	$\alpha = 5\%$ (%)	$\alpha = 10\%$ (%)	$\alpha = 15\%$ (%)	
0.5 pu	1.81×10^{-5}	0.548	1.069	1.568	
0.8416 pu	1.48×10^{-5}	0.766	1.497	2.192	
1.0 pu	6.13×10^{-6}	0.830	1.622	2.375	

The sideband index increases with both rotor-resistance anisotropy and load in the retained BRB range. This differs from the ITSC CUF trend and shows why fault-family-specific load behavior matters.

5.7 Synthesis of Diagnostic Significance

Table 5.8: Main diagnostic indicators retained from the Siemens simulation campaign.

Fault family	Strong indicators	Key interpretation limit
Supply unbalance	VUF, CUF, phase-current unbalance, 100 Hz torque.	Current unbalance decreases with load for the same imposed VUF.
Incipient ITSC	Fault-loop current, CUF, 100 Hz torque, speed ripple, phase pattern.	Mean RMS current alone is weak; results limited to $\mu \leq 2\%$.
Bearing BPFO surrogate	BPFO torque component, retained current sideband index, speed ripple.	Torque-disturbance surrogate, not a full bearing-contact model.
BRB rotor asymmetry	$f_s(1 \pm 2s)$ sidebands, $2sf_s$ torque and speed modulation.	Requires slip and adequate window length; no no-load BRB dataset retained.

The central result is that the same signal family cannot be interpreted without context. Electrical asymmetry indicators overlap between supply unbalance and ITSC. Spectral sidebands shift with load through slip or bearing frequency. Torque and speed ripple may be strong validation indicators inside simulation, but a future deployable system must rely primarily on measurable voltages, currents, and speed.

5.8 Chapter Summary

This chapter consolidated the retained Siemens 1.5 kW simulation results. The healthy model was validated against Simscape, the measured 8.5 N m torque-speed point, and rated manufacturer data. Four simulated fault datasets were then reported with explicit assumptions: supply-voltage unbalance, incipient ITSC, BPFO bearing-torque surrogate, and BRB rotor asymmetry. Across the datasets, the dominant lesson is load-aware diagnosis: thresholds and amplitudes must be calibrated for the target motor and operating condition before being used in an experimental or AI-based diagnostic system.

CONCLUSION AND FUTURE WORK

Conclusion

This thesis developed a physically consistent modeling and simulation framework for induction-motor diagnosis, supported by experimental parameter identification on a Siemens 1LA7096-4AA10 1.5 kW laboratory motor. The final work separates evidence levels clearly: the laboratory tests identify the Siemens parameters, the healthy Siemens model is validated numerically and against available operating data, and the fault cases are deterministic simulations or diagnostic surrogates rather than physical fault experiments.

The main contributions are:

1. a documented power-invariant synchronous- dq modeling convention, including a model-consistent reconstruction of the 500 W benchmark inductances;
2. experimental identification of the Siemens 1.5 kW motor from a phase-to-neutral stator-resistance measurement, no-load, blocked-rotor, load, and coast-down tests, with J retained from the Siemens datasheet and B derived from the measured B/J ratio;
3. validation of the Siemens 1.5 kW healthy analytical model against Simscape, the measured 8.5 N m torque-speed point, and rated manufacturer values;
4. deterministic simulation datasets for supply-voltage unbalance, incipient ITSC, BPFO bearing-torque disturbance, and BRB rotor asymmetry;
5. a diagnostic interpretation showing that negative-sequence current, 100 Hz torque ripple, bearing sidebands, BRB sidebands, and speed ripple must be read with load and model context.

Across the Siemens healthy operating cases, the analytical and Simscape models agree closely in speed and torque, while current differences remain within the ex-

pected range for two different simulation implementations. At the measured 8.5 N m torque-speed point, the analytical speed differs from the measured speed by about 0.834%, and the Simscape speed by about 0.311%. At rated load, both implementations remain close to the manufacturer current, speed, and shaft-power values. These comparisons support the use of the identified Siemens model as the main simulation platform of the thesis.

The fault studies confirm the importance of load-aware interpretation. In supply unbalance, current negative-sequence factor and 100 Hz torque components increase with VUF, but their amplitudes change with load. In the incipient ITSC study, fault-loop current, CUF, torque ripple, and speed ripple reveal the shorted-turn effect, while mean RMS current alone remains weak. The BPFO bearing surrogate shows geometry-derived frequency placement and monotonic sideband growth, but it remains a torque-disturbance model rather than a full bearing-contact model. The BRB rotor-asymmetry study produces the expected slip-dependent sidebands and electromechanical modulation, with no-load operation excluded because the short-record sidebands would not be reliably resolved.

Future Work

Future research should extend this work in five directions:

1. acquire real healthy and faulted current, voltage, speed, torque, vibration, and temperature data from the laboratory bench;
2. repeat the simulation datasets with common windowing rules and grouped case-level train/test splits before training classifiers;
3. improve the ITSC and bearing models using winding-level energy consistency and manufacturer-specific bearing geometry where available;
4. include combined faults, especially ITSC under supply-voltage unbalance, to evaluate feature overlap under realistic operating conditions;
5. implement and retune stator-resistance tracking as a support feature for thermal context rather than as an isolated fault detector.

REPRODUCIBILITY AND DATASET DOCUMENTATION

This appendix records the parameter sets, numerical post-processing rules, dataset-file aliases, and figure sources needed to reproduce the retained thesis results. It is written as documentation for the final manuscript rather than as a work log.

A.1 Benchmark 500 W Simulation Parameters

Parameter	Value	Use in the thesis
R_s	11.73 Ω	Stator resistance retained from the source identification test.
R_r	11.08 Ω	Rotor resistance referred to the stator.
L_m	0.7354 H	Magnetizing inductance reconstructed from the no-load inductive result.
L_{ls}, L_{lr}	0.0400 H	Equal split of the reported total leakage inductance 0.08 H.
L_s, L_r	0.7754 H	Total stator and rotor inductances used by the five-state dq model.
σ	0.10051	Leakage coefficient calculated from $1 - L_m^2/(L_s L_r)$.
J	0.0030 kg m ²	Mechanical inertia of the benchmark model.
B	0.00092 N m s/rad	Viscous friction coefficient.
p and f_s	1, 50 Hz	One pole pair and 50 Hz supply.

Table A.1: Reconstructed 500 W benchmark parameters used for the modeling-convention validation.

The source identification material reports a no-load inductive value of 0.7354 H and a total leakage inductance of 0.08 H. The thesis therefore reconstructs a T-equivalent parameter set with $L_m = 0.7354$ H and $L_{ls} = L_{lr} = 0.0400$ H. This avoids mixing the reported summary-table entries with the inductance definitions required by the retained dq state equations.

A.2 Siemens 1LA7096-4AA10 Parameter Set

The Siemens 1.5 kW motor is the calibrated motor used for the main validation and fault-simulation campaign. The laboratory tests provide the electrical parameters and the coast-down ratio B/J . The manufacturer datasheet provides the inertia J [23], allowing B to be calculated from the measured ratio.

For the bearing surrogate, the Siemens datasheet identifies the drive-end bearing designation as 6205 2ZC3. Because its manufacturer-specific internal geometry was not available, the documented CWRU drive-end SKF 6205-2RS JEM geometry was adopted strictly as a geometric proxy for the BPFO-order calculation [15].

Table A.2: Retained Siemens 1.5 kW parameter set.

Parameter	Value	Origin
R_s	5.70 Ω	Cold phase-to-neutral resistance measurement at approximately room temperature.
R'_r	3.29 Ω	Blocked-rotor active-power calculation.
L_m	0.3015 H	No-load reactive-power calculation.
$L_{ls} = L'_{lr}$	0.01337 H	Equal split of blocked-rotor leakage.
$L_s = L'_r$	0.31487 H	$L_m + L_l$.
σ	0.083121	$1 - L_m^2/(L_s L'_r)$.
J	0.0033 kg m ²	Siemens model-specific datasheet.
B	6.93 $\times 10^{-4}$ N m s/rad	$B = J\lambda$ with $\lambda = 0.21$ s ⁻¹ .
p	2	Four-pole motor at 50 Hz.

A.3 Numerical Post-Processing Rules

For variable-step simulations, RMS and mean values are computed with time-weighted integration rather than by assuming uniform samples. For a signal $i(t)$ over a retained interval $[t_1, t_2]$,

$$I_{\text{RMS}} = \sqrt{\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} i^2(t) dt}. \quad (\text{A.1})$$

In MATLAB post-processing, this is implemented with trapezoidal numerical integration over the retained time vector. Frequency-domain features are extracted only after a post-transient interval is selected and, when required, the signal is represented on a uniform sampling grid.

The reported sideband index is defined from one-sided peak amplitudes as

$$\text{Sideband Index} = 100 \frac{A_{\text{lower}} + A_{\text{upper}}}{2A_{50}}, \quad (\text{A.2})$$

where A_{50} is the fitted 50 Hz current fundamental peak. BRB sidebands are obtained from a simultaneous least-squares fit at the lower sideband, 50 Hz, the upper sideband, 100 Hz, and 150 Hz. The final bearing current sideband estimator uses the same simultaneous multitone method at $|50 - f_{BPFO}|$, 50, $50 + f_{BPFO}$, 100, and 150 Hz. Supply-unbalance and ITSC 100 Hz torque peaks are obtained by direct complex projection after subtracting the mean torque. No extra FFT window or bin-search tolerance is used for the scalar metrics reported in the thesis tables.

A.4 Dataset Inventory

Table A.3: Signal properties and manuscript aliases for the primary retained datasets.

Study	Rows	Sampling	Retained interval	Samples/run	Raw signals	Manuscript alias
Healthy Siemens analytical model	4	Variable-step summary	Final steady-state windows	Summary	i_{abc} , speed, torque, power	MATLAB/Healthy/healthy_1p5kW_analytical_summary.csv
Analytical-Simscape comparison	4	Variable-step summary	Final steady-state windows	Summary	Mean phase current, speed, torque	MATLAB/Healthy/healthy_1p5kW_analytical_vs_simscape.csv
Supply unbalance	64	2000 Hz re-sampled from variable-step output	2.3-3.0 s signals and metrics	1401	v_{abc} , i_{abc} , i_{dq} , speed, slip, torque, power	MATLAB/SupplyUnbalance/M1500_supply_unbalance_dataset_summary.csv
Incipient ITSC	28	2000 Hz standardized	2.2-3.0 s signals; 2.3-3.0 s metrics	1601	v_{abc} , i_{abc} , i_f , ψ_f , torque, speed, slip, fault power	MATLAB/ITSC/M1500_ITSC_incipient_dataset_summary.csv
Bearing BPFO surrogate	40	2000 Hz standardized	2.2-3.0 s signals; 2.3-3.0 s metrics	1601	v_{abc} , i_{abc} , torque, speed, T_b , $T_{L,total}$, f_{BPFO}	MATLAB/BearingBPFO/M1500_bearing_BPFO_dataset_summary.csv
BRB rotor asymmetry	30	2000 Hz standardized	2.0-5.0 s, final endpoint excluded	6000	v_{abc} , i_{abc} , torque, speed, slip, load torque	MATLAB/BRB/M1500_BRB_rotor_asymmetry_dataset_summary.csv

The aliases above are used for clean manuscript documentation. They identify the retained datasets by study family and file role; the raw MATLAB export folders remain unchanged in the project workspace. The supply-unbalance simulations are solved from variable-step model outputs and represented on the retained 2000 Hz grid before dataset-level signal documentation. The BRB sample count is 6000 because the implemented retained window is treated as $[2.0, 5.0)$ s at 2000 Hz, with the final endpoint deliberately excluded. The thesis does not concatenate the four fault-family raw-signal datasets into one classifier table; it reports and interprets them as separate, traceable simulation families.

A.5 Manuscript Figure Inventory

The figures used in the main manuscript are copied to stable thesis paths while the original MATLAB result folders are kept unchanged. The retained manuscript figures are:

- `images/ch2/motor_nameplate.jpg`
- `images/ch2/motor_upper.jpg`
- `images/ch2/healthy_model_simulink_detail.png`
- `images/ch2/healthy_simscape_model_2026.png`
- `images/ch2/park_transform_validation_2026.png`
- `images/ch2/healthy_no_load_test_2026.png`
- `images/ch2/healthy_load_test_2026.png`
- `images/ch2/compare_analytical_simscape_rms_2026.png`
- `images/ch2/analytical_simscape_relative_errors_2026.png`
- `images/ch3/siemens_1p5kw_no_load_response.png`
- `images/ch3/siemens_1p5kw_8p5nm_response.png`
- `images/ch3/siemens_1p5kw Rated_response.png`
- `images/ch5/supply_unbalance_severity_trends.png`
- `images/ch5/supply_unbalance_vuf02_time.png`
- `images/ch5/supply_unbalance_vuf02_fft.png`
- `images/ch5/itsc_incipient_trends.png`
- `images/ch5/bearing_bpfo_trends.png`
- `images/ch5/brb_rotor_asymmetry_trends.png`

A.6 Dataset Consolidation Rules

The final diagnostic classes retained by the simulation work are:

1. healthy motor;
2. supply-voltage unbalance;
3. incipient ITSC;

4. BPFO bearing-torque surrogate;
5. BRB rotor asymmetry.

Future classifier construction should avoid duplicate healthy cases by retaining one canonical healthy record per load. The preferred sampling rate for any later raw-signal consolidation is 2000 samples/s, and the supply-unbalance records have been documented after resampling to that rate. Nevertheless, raw-signal concatenation is not performed in this thesis. For features that depend on close spectral spacing, especially BRB sidebands near the 50 Hz fundamental, a 1.0 s window is preferable to a 0.2 s window. A 50% overlap may be used for window generation, but train/test splitting must be performed by complete CaseID or GroupID. Windows from the same simulation run must not be divided between training and testing.

Deployable input channels should be limited to measured quantities such as v_a , v_b , v_c , i_a , i_b , i_c , and speed. Internal quantities such as electromagnetic torque, slip, imposed disturbance amplitude, asymmetry coefficient, and fault-loop current are valuable for validation and labeling, but should not be assumed available in a field diagnostic system unless the future test bench measures or estimates them explicitly.

A.7 Model Scope

The Siemens healthy model is calibrated and validated for the reduced modeling assumptions stated in Chapters 2 and 3. The faulted cases are deterministic simulation studies. Supply unbalance is an imposed voltage condition, ITSC is an incipient shorted-turn diagnostic surrogate with $\mu \leq 2\%$ and $R_f = 5 \Omega$, bearing BPFO is an imposed torque disturbance at a geometry-derived frequency, and BRB is a reduced rotor-asymmetry model. These limitations are part of the result definition and should be preserved in any later use of the datasets.

BIBLIOGRAPHY

- [1] S. J. Chapman, *Electric Machinery Fundamentals*, 5th ed. New York: McGraw-Hill, 2012.
- [2] Ademola Abdulkareem, Tochukwu Anyim, Olawale Popoola, John Abubakar, and Agbetuyi Ayoade, “Prediction of induction motor faults using machine learning,” *Heliyon*, vol. 11, no. 1, p. e41493, Jan. 2025.
- [3] Shoaib Shaikh, Dileep Kumar, Abdul Hakeem, and Arsalan Muhammad Soomar, “Protection System Design of Induction Motor for Industries,” *Modelling and Simulation in Engineering*, vol. 2022, pp. 1–13, Aug. 2022.
- [4] Bahgat Hafez Bahgat, Enas A. Elhay, Tole Sutikno, and Mahmoud M. Elkholy, “Revolutionizing motor maintenance: A comprehensive survey of state-of-the-art fault detection in three-phase induction motors,” *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 15, no. 3, p. 1968, Sep. 2024.
- [5] Sarvarbek Ruzimov, Jianzhong Zhang, Xu Huang, and Muhammad Shahzad Aziz, “Detection of Inter-Turn Short-Circuit Faults for Inverter-Fed Induction Motors Based on Negative-Sequence Current Analysis,” *Sensors*, vol. 25, no. 15, p. 4844, Aug. 2025.
- [6] Tomas Garcia-Calva, Daniel Morinigo-Sotelo, Vanessa Fernandez-Cavero, and Rene Romero-Troncoso, “Early Detection of Faults in Induction Motors—A Review,” *Energies*, vol. 15, no. 21, p. 7855, Oct. 2022.
- [7] An Zhao, Giovanni Zanuso, and Luca Peretti, “Transient thermal models of induction machines under Inter-turn short-circuit fault conditions,” *IET Electric Power Applications*, vol. 17, no. 10, pp. 1304–1320, Oct. 2023.

- [8] Sudip Halder, Sunil Bhat, Daria Zychma, and Pawel Sowa, “Broken Rotor Bar Fault Diagnosis Techniques Based on Motor Current Signature Analysis for Induction Motor—A Review,” *Energies*, vol. 15, no. 22, p. 8569, Nov. 2022.
- [9] S.X. Ding, “Data-Driven Design of Model-based Fault Diagnosis Systems,” *IFAC Proceedings Volumes*, vol. 45, no. 15, pp. 840–847, 2012.
- [10] Usha Sengamalai, Geetha Anbazhagan, T. M. Thamizh Thentral, Pradeep Vishnuram, Tahir Khurshaid, and Salah Kamel, “Three Phase Induction Motor Drive: A Systematic Review on Dynamic Modeling, Parameter Estimation, and Control Schemes,” *Energies*, vol. 15, no. 21, p. 8260, Nov. 2022.
- [11] P. C. Krause, O. Wasynczuk, S. D. Sudhoff, and S. D. Pekarek, *Analysis of Electric Machinery and Drive Systems*, 3rd ed. Hoboken, NJ: IEEE Press/Wiley, 2013.
- [12] Seong-Hwan Im and Bon-Gwan Gu, “Study of Induction Motor Inter-Turn Fault Part I: Development of Fault Models with Distorted Flux Representation,” *Energies*, vol. 15, no. 3, p. 894, Jan. 2022.
- [13] F. Babaa, A. Khezzar, and M. E. K. Oumaamar, “Experimental investigation and comparative study of inter-turn short-circuits and unbalanced voltage supply in induction machines,” *Frontiers in Energy*, vol. 7, no. 3, pp. 271–278, 2013.
- [14] Francesca Muzio, Lorenzo Mantione, Tomas Garcia-Calva, Lucia Frosini, and Daniel Morinigo-Sotelo, “Detection of broken bars in induction motors operating with closed-loop speed control,” *Machines*, vol. 12, no. 9, p. 662, Sep. 2024.
- [15] Case Western Reserve University Bearing Data Center, “Bearing information,” <https://engineering.case.edu/bearingdatacenter/bearing-information>, 2026, drive-end SKF 6205-2RS JEM bearing geometry and defect-frequency orders, accessed Jun. 16, 2026.
- [16] Yu Luo, Liguang Wang, Denis Sidorov, Aliona Dreglea, and Elena Chistyakova, “An Approach to Estimate the Temperature of an Induction Motor under Non-linear Parameter Perturbations Using a Data-Driven Digital Twin Technique,” *Energies*, vol. 17, no. 19, p. 4996, Oct. 2024.
- [17] P. Gnaciński, M. Pepliński, A. Muc, and D. Hallmann, “Induction motors under voltage unbalance combined with voltage subharmonics,” *Energies*, vol. 17, no. 24, p. 6324, Dec. 2024.

- [18] Ines Miloud, Sebastien Cauet, Erik Etien, Jack P. Salameh, and Alexandre Ungerer, “Real-Time Speed Estimation for an Induction Motor: An Automated Tuning of an Extended Kalman Filter Using Voltage–Current Sensors,” *Sensors*, vol. 24, no. 6, p. 1744, Mar. 2024.
- [19] Szymon Antoni Bednarz and Mateusz Dybkowski, “Estimation of the induction motor stator and rotor resistance using active and reactive power based model reference adaptive system estimator,” *Applied Sciences*, vol. 9, no. 23, p. 5145, Nov. 2019.
- [20] Saptarshi Basak, A. V. Ravi Teja, Chandan Chakraborty, and Yoichi Hori, “A new model reference adaptive formulation to estimate stator resistance in field oriented induction motor drive,” in *Proceedings, IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society*. Vienna, Austria: IEEE, 2013, pp. 8470–8475.
- [21] Hossein Madadi Kojabadi, Mostafa Abarzadeh, and Said Aghaei Farouji, “Robust stator resistance identification of an IM drive using model reference adaptive system,” *Energy Conversion and Management*, vol. 65, pp. 507–517, Jan. 2013.
- [22] Abderrahim Boushaba, Sebastien Cauet, Afzal Chamroo, Erik Etien, and Laurent Rambault, “Comparative Study between Physics-Informed CNN and PCA in Induction Motor Broken Bars MCSA Detection,” *Sensors*, vol. 22, no. 23, p. 9494, Dec. 2022.
- [23] Siemens AG, *Data Sheet for Three-Phase Squirrel-Cage Motors—MLFB Ordering Data: 1LA7096-4AA10*, Siemens AG, 2021, manufacturer product datasheet, generated Apr. 23, 2021, accessed Jun. 14, 2026.
- [24] A. Kerboua, “Commandes et observateurs par mode de glissement: application a une machine asynchrone alimentee en tension,” These de Magister en Electrotechnique, Ecole Nationale Polytechnique, Alger, Algerie, 1999, chap. I, Sec. I.1.1, Eqs. (I.1)–(I.2), p. 4.
- [25] F. Bellakhdar and M. Elasri, “Etude de structure de commande pour le moteur asynchrone et validation experimentale sur le systeme dspace ds1104,” Master thesis, Universite Aboubakr Belkaid de Tlemcen, 2022, appendix A identification data used for the 500 W benchmark reconstruction.
- [26] The MathWorks, Inc., *Asynchronous Machine Block Documentation*, MathWorks, 2026, Simscape Electrical / Specialized Power Systems

- documentation, accessed Jun. 16, 2026. [Online]. Available: <https://www.mathworks.com/help/sps/powersys/ref/asynchronousmachine.html>
- [27] —, *Per-Unit System of Units*, MathWorks, 2026, MATLAB and Simulink documentation, accessed Jun. 16, 2026. [Online]. Available: <https://ww2.mathworks.cn/help/sps/ug/per-unit-system-of-units.html>
- [28] Haiyang Li, Zuolu Wang, Dong Zhen, Fengshou Gu, and Andrew Ball, “Modulation Sideband Separation Using the Teager–Kaiser Energy Operator for Rotor Fault Diagnostics of Induction Motors,” *Energies*, vol. 12, no. 23, p. 4437, Nov. 2019.
- [29] Liangyuan Huang, Niaoqing Hu, Yi Yang, Ling Chen, Jihong Wen, and Guoji Shen, “Study on Electromagnetic-Dynamic Coupled Modeling Method—Detection by Stator Current of the Induction Motors with Bearing Faults,” *Machines*, vol. 10, no. 8, p. 682, Aug. 2022.