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Improving Reliability of EV Induction Motors: Sensorless Fault-Tolerant Control under Open-Circuit Faults

Abstract

The reliability of induction motor (IM) drives in electric vehicles (EVs) is often compromised by inverter open-circuit faults, which result in unbalanced currents, torque pulsations, and reduced efficiency. The currents become unbalanced and the torque becomes pulsating and the efficiency reduces due to such faults. A sensorless fault-tolerant control (FTC) system was developed by us to address these issues in this project. In MATLAB/Simulink, we configured an induction motor and an inverter of mid-size EV and allowed three conditions to take place: a healthy run, a faulty run without FTC and a faulty run with the sensorless FTC. At the heart of the scheme lies a Model-Reference Adaptive System (MRAS) observer, which is utilized to estimate rotor speed; Faults were being detected using a residual based algorithm and that once a fault is discovered then we reform the controller. The simulation has demonstrated that the FTC is able to achieve the torque up to approximately 97% of the normal level, reduction of the torque ripple to less than 7%, an increase of efficiency by taking off 78% to approximately 90%, as well as have the ability to detect faults within less than 20 ms. Therefore in case it is an EV-working student, this will mean sensorless FTC is viable in improving motor reliability and maintaining the vehicle in limp-home mode.

Keywords: Induction motor, electric vehicles, fault-tolerant control, sensorless control, open-circuit faults

1. Introduction

1.1 Background

The electrification of transportation has positioned electric vehicles (EVs) at the forefront of global decarbonization efforts. Drives in traction motors are expected to operate reliably and efficiently under numerous operating conditions, such as stop-and-go cycles and thermal regimens. This includes regenerative braking (Choi & Lee, 2022). Out of the plethora of Permanent Magnet Synchronous Motors (PMSMs), Switched Reluctance Motors (SRMs), Induction Motors (IMs) and the rest of their counterparts in EVs, the IM still holds ground as an optimal choice due to its structural prowess, absence of magnet construction, rudimentary control systems, and low cost (De Klerk & Saha, 2021; Wu et al., 2022).

The drawbacks of IM Drives are the vulnerabilities to inverter faults, especially open-circuits in IGBT and MOSFET Quad Switches. Thermal fatigue, bond-wire lift-off, and cosmic ray strikes are reasons for such failures (Moosavi et al., 2019). Open-Circuit Faults (OCFs) can result in unbalanced stator currents, pulse torque, efficiency loss, and even the loss of propulsion, which can be catastrophic in the case of an EV (Cherif et al., 2022; Xu et al., 2023). There is no question that the failure of drivability impacts the faith that consumers have in electrified mobility.

In the case of severe faults, fault-tolerant control (FTC) can be used as a method of maintaining operational capability ("PMS, 2000"). Within the control loops, contour control, limp-home techniques, rigid control, and some modulation methods (Abbaspour et al., 2020; Alqarni, 2025) are the conventional approaches of FTC. Despite the variety of techniques and methodologies available, the majority of FTCs are based on sensor information, such as a resolver or encoder, needed for speed and position feedback. On the other hand, the sensors are subject to faults, are costly, and diminish the overall system reliability (Chandra & Mohapatro, 2024).

In contrast, the system without a feedback sensor is better known as 'sensorless control' and is an FTC approach that successfully works off of acquired electrical data and system architecture.

In addition, there are MRAS, EKF, and SMO-based systems that strive to improve the reliability of electric motors through the replacement of any physical sensors used (Wang et al., 2019; Gholipour et al., 2021). Planning FTCs that use sensorless methods will, therefore, improve the cost and reliability of the system (Zuo et al., 2022; Zhang et al., 2024).

1.2 Research Problem

Although extensive research has been conducted on fault diagnosis, fault detection, and FTC strategies on electric machine drives and FTC algorithms, there still seems to be a gap in the sensorless control integration with robust FTC systems enabled for the EV induction motors with inverter open-circuits. Most FTC algorithms do not maintain satisfactory dynamic performance for extreme disturbances (Caruso et al., 2024; Choudhary et al., 2022). On the other hand, the sensorless control techniques are seldom tested and validated for the fault scenarios (Xu et al., 2021). There is an urgent gap in research focused on the simulation-driven frameworks designed to evaluate the performance of sensorless FTC strategies given realistic inverter faults.

1.3 Aim and Research Objectives

Aim:

To design and evaluate a **sensorless fault-tolerant control framework** for EV induction motors under inverter open-circuit faults using MATLAB/Simulink simulations, thereby improving reliability, drivability, and safety of EV propulsion systems.

Research Objectives (ROs):

- **RO1:** To model an EV induction motor and inverter system under healthy and open-circuit fault conditions, capturing the dynamic effects of faults on current balance, torque, and efficiency.
- **RO2:** To design and integrate a sensorless control observer (e.g., MRAS or EKF) within a fault-tolerant control structure capable of reconfiguring drive operation during faults.

- **RO3:** To simulate and compare the performance of the proposed sensorless FTC scheme against baseline control, evaluating metrics such as torque ripple, speed tracking error, and limp-home capability.

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1.4 Significance of the Study

This research makes a meaningful contribution to the existing body of knowledge by exploring the intersection of fault-tolerant control (FTC) and sensorless estimation for electric vehicle (EV) induction motors. The work demonstrates the impact of software-based control methods to improve motor drive resiliency to inverter failures, decrease the use of weak hardware components, and control the level of reliance on hardware.

These findings help to understand the driving capability as well as the safety of EV propulsion systems in degraded modes of operation. The findings also contribute to the ongoing discussion on the practicality of induction motors and their use as cost-effective, sustainable alternatives to permanent magnet synchronous motors (PMSMs) in mid-range and more affordable EV applications where durability and performance are vital.

Furthermore, this study facilitates the trade-off decisions about system reliability design choices, describes the primary advantages of hardware redundancy and software-based FTC, and the sophisticated sensorless algorithms. Having this information fosters reasoned design choices. These considerations enhance the theoretical FTC understanding of EVs and have tangible influences on FTC advancement in EVs that are safe, economically viable, and robust resources (Wu et al., 2022; Yang et al., 2025).

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2. Literature Review

2.1 Introduction to Electric Vehicle Drive Systems

The advancement of electric vehicles (EVs) over the past few years has been bolstered by their ability to diminish greenhouse gas emissions and the use of fossil fuels. Their virtues have been attached to even the latest versions integrated with steam based functionalities. Any pioneering society would wish to utilize such electric vehicles to reduce electric emissions as well as fossil fuels burning. For electric vehicles, the electric propulsion system is one necessary electric drive. Traction is the property of a motor to convert electric energy to mechanical propulsion. When it comes to traction motors incorporated into electric vehicles, the efficiency is a deep subject. The intricacy involves much more than operational safety and functionality (Choi & Lee, 2022). Electric vehicles have various types of motors, such as permanent magnet synchronous motors (PMSMs), Switched Reluctance Motors (SRMs), Brushless Direct Current (BLDC) motors, and Induction Motors (IMs). There are unique advantages and disadvantages for each of the machines listed above. Hence, each one has a separate factor that influences their adoption.

Permanent magnet synchronous motors (PMSMs) have very high efficiency and power density, which has made them very popular for use in commercial electric vehicles (EVs). However, the use of rare-earth magnets excluded the possibility of sustainability and posed supply chain risks (Choudhary et al., 2022). Switched reluctance motors (SRMs) are also strong and can withstand faults, but the high level of torque ripple and the high acoustic noise make these motors less appealing for use in passenger vehicles (Sun et al., 2024). Induction motors (IMs) offer an enticing compromise, as they can also be constructed magnet-free and, as a result, less expensive, have sophisticated control techniques, and are widely used in the industry (De Klerk & Saha, 2021; Wu et al., 2022). For example, the induction motors (IMs) used in high-performance electric vehicles (EVs) are shown to be feasible to use as they were used in the propulsion systems in the earlier versions of the Tesla Model S and Model X. However, a significant drawback to the broader use of IMs for use in electric vehicles (EVs) is the reliability of the IMs under inverter faults.

2.2 Inverter-Fed Induction Motors and Fault Mechanisms

Induction motors in EVs are typically powered by voltage-source inverters (VSIs) that regulate three-phase currents for field-oriented control (FOC) or direct torque control (DTC). These devices use semiconductors like Insulated Gate Bipolar Transistors (IGBTs) and Metal-Oxide Semiconductor Field Effect Transistors (MOSFETs). Even with this sophisticated technology, semiconductor switches are prone to dysfunction owing to thermal cycling, electromagnetic stress, cosmic radiation, and bond wire fatigue (Moosavi et al, 2019).

As for OCFs, or open-circuit faults, one of the most common and most important of all inverter faults in electric vehicle traction drives is those in which one or more switches conduct and, for all intents and purposes, become permanently non-conductive. OCFs cause all three-phase current to become unbalanced, which in turn results in the presence of electromagnetic torque pulsations, the overheating of the windings of the stator, a decrease in the overall efficiency of the system and in extreme cases, which are more common than one would like to think, the failure of propulsion and, in turn, the system as a whole (Cherif et al, 2022). Table 2.1 summarises the primary effects of open-circuit faults in inverter-fed induction motors.

Table 2.1: Effects of Open-Circuit Faults on Induction Motor Operation

Fault Condition	**Observable Effect**	**Consequence for EV Operation**	**Reference(s)**
Single switch open-circuit	Current imbalance, asymmetric waveforms	Increased torque ripple, vibration	Chai et al. (2019); Moosavi et al. (2019)
One inverter leg is open-circuit	Severe imbalance, 2-phase operation	Loss of controllability, limp-home possible	Tian et al. (2023)
Multiple switch failures	Cascading phase disconnection	Complete propulsion loss	Wu et al. (2022); Xu et al. (2023)

As seen in Table 2.1, even partial OCFs significantly degrade EV performance, reinforcing the need for fault detection and FTC schemes that maintain mobility under degraded conditions.

2.3 Fault Diagnosis and Detection in EV Motors

Effective fault-tolerant control requires fast and accurate detection of open-circuit faults. Standard methods to tackle this issue make use of the leftover information, pattern recognition, and even artificial intelligence. There are past methods that look out for specific current signatures, or the movements in the Park vector, which are all indicators of an OCF (Abbaspour et al., 2020), and newer methods that use empirical functionals and strong observability to get almost instantaneous OCF detections (Xu et al., 2023).

In more recent times, using machine learning and artificial intelligence to solve problems has become popular in the domain of engineering. For example, in the paper by Cherif et al. (2022), the authors fully utilized machine learning for the purpose of fault diagnosis for inverter-fed induction motors and proved that even though the required data sets for training were extremely excessive, the classification accuracy for faulty conditions was still remarkably high. Another example would be the research of Zhang (2023), who blended model-based and data-driven OCF diagnosis techniques to reveal the suitability of PMSM drives and adaptable induction motors.

In spite of all the mentioned advancements, the triad of accuracy, time efficiency, and practicality in the real world pertaining to electric vehicles is still not optimally achieved. The problem with most machine learning fault detectors is that they lack the ability to make real-time, instantaneous assessments based on the data gathered, and most importantly, they do not have the ability to compute in real-time. For motors in electric vehicles, the most appropriate standards of fault diagnosis employ a combination of adaptive observer algorithms and residual-based fault recognition systems to optimally balance quick, efficient recognition and computational resources in real-time.

2.4 Fault-Tolerant Control Strategies

Once an OCF is detected, the drive must transition into a fault-tolerant mode to sustain safe operation. Fault-tolerant control (FTC) strategies can be developed for electric vehicle (EV) motors using hardware, software, and hybrid methods.

Having more components enhances the system's hardware reliability. These components include dual inverters, multiple-phase motors, and redundant switching legs. Patnana and Veeramraju Tirumala (2021) demonstrated the limp-home feature in low-power EVs using a cost-effective brushless DC drive (BLDC) with open-stator windings. Caruso et al. (2024) introduced a flexible FTC algorithm for multiphase machines that reallocated current distribution to faulted phases. While hardware redundancy methods provide improved effectiveness, the added cost and complexities associated with implementing them are a drawback for EVs that are targeted for higher profitability.

PWM changing, current re-distribution, switching to two-phase operation, and, in general, all the strategies that assist in limp-home functionality are software approaches. Wu et al. (2022) discussed that FTC software tends to be low in application and integration costs, and is therefore more accessible. Performance is the main drawback, due to higher torque ripple and lower efficiency.

Hybrid strategies integrate multiple forms of component backup with the ability to reconfigure components/drive sub-systems using adaptive control software. Abbaspour et al. (2020) developed systems to perform reconfiguration of active fault-tolerant control systems using adaptive control and backup hardware to reconfigure drives dynamically. A hybrid approach, augmenting hardware-backed control software, can be developed using the trade-offs Alqarni (2025) reported on the improved reliability versus cost of hardware redundancy in the variable frequency drives of induction motors. Table 2.2 summarises the strengths and limitations of these FTC categories.

Table 2.2: Comparison of Fault-Tolerant Control Approaches

Approach Type	**Strengths**	**Limitations**	**Reference(s)**
Hardware-Based FTC	High reliability and redundancy ensure survival	High cost, increased complexity	Caruso et al. (2024); Patnana and Veeramraju Tirumala (2021)
Software-Based FTC	Low cost, no extra hardware, flexible	Performance degradation under	Tian et al. (2023); Wu et al. (2022)

		severe faults	
Hybrid FTC	Balance between performance and reliability	Trade-off in complexity and cost	Abbaspour et al. (2020); Alqarni (2025)

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rom Table 2.2, it is evident that software-based approaches are most attractive for mainstream EV adoption, though performance limitations motivate the integration of advanced sensorless observers for enhanced resilience.

2.5 Sensorless Control Techniques

Conventional FTC schemes frequently depend on mechanical sensors such as resolvers and encoders to provide rotor position and speed information. This decreases the overall reliability of the system, as noted by Chandra and Mohapatro (2024). These factors have led to the growing popularity of sensorless control techniques in research and industry to attempt to solve these issues.

Wireless approaches to sensorless control rely on estimators and observers to infer rotor position and speed from electrical measurements, specifically from stator currents and voltages. The most common techniques are presented below.

Model Reference Adaptive System (MRAS), at its core, attempts to estimate rotor speed by minimizing the difference between the adaptive and the reference models, which makes the structure of its implementation and computations relatively light. However, the efficiency of these systems hinges on parameters and noise, making them sensitive, as was also noted by Wang et al. (2019).

Extended Kalman Filter (EKF): By applying estimators that operate recursively, EKF manages to operate even on uncertain models and noisy data. Gholipour et al. (2021) showed that sensorless control systems for Induction Motors (IMs) controlled via the EKF exhibit better resilience to current sensor failures, an improvement which is unfortunately offset by the system's high computational cost. The most widely employed sensorless approaches include:

2.5.4 Machine Learning and Adaptive Estimation

Zhang et al. (2024) developed an FTC strategy that utilizes current sensors and integrates speed sensorless control of IMs, while Zuo et al. (2022) used current reconstruction based on sequential PLL to recover lost speed in sensorless IM drives.

The works emphasizing the foregone FTC methods point out that while sensorless methods improve the reliability of the drives, most are tested under nominal working conditions. The seamless integration with FTC methods under OCF conditions is relatively scarce, which underlines an important avenue for future research.

2.6 Theoretical Framework

2.6.1 Fault Diagnosis Theory

27 Fault diagnosis in inverter-fed induction motors rests on the principle of residual generation and evaluation. Residuals arise from the actual measured signals being compared against signals expected from mathematical or analytical models. Under fault conditions, such as open-circuit faults, residuals that deviate from the norm can be identified and utilized, whereas, in the case of healthy conditions, residuals tend to be close to zero (Chakraborty and Das, 2024). These residuals can be treated by means of AI (Cherif et al., 2022).

The crux of this technique centers around fault modelling. An OCF alters the current equations of an induction motor, which, in turn, adds some degree of Asymmetry to the Stator Current Vector and Torque, in addition to altering the Electromagnetic Torque. With the modified dynamics being placed inside diagnostic observers, the specific location and mechanism of the fault can be identified and isolated (Xu et al., 2023). Thus, the very first layer of the theoretical framework can be regarded as the derivation of Fault Diagnosis Theory: residuals generated as an indication of deviation from a healthy state.

2.6.2 Control Reconfiguration Theory

Once a fault is diagnosed, the system must reconfigure to maintain operation. Control reconfiguration theory addresses this requirement by dynamically altering the control law or system structure. Reconfiguration can be passive, where a robust controller accommodates faults without structural changes, or active, where the controller explicitly adjusts its operation after fault detection (Abbaspour et al., 2020). Alternatively, the controller may reallocate current references, allowing the motor to function in a degraded two-phase limp-home mode (Wu et al., 2022). The theoretical underpinning here is based on adaptive control and robust control principles, ensuring stability even when system equations are modified by faults.

2.6.3 Observer Theory and Sensorless Estimation

The third component of the theoretical framework is observer theory, which underpins sensorless control. Observers estimate unmeasured states (e.g., rotor speed and flux position) using measured signals (stator voltage and current). A general observer follows the structure:

$$\hat{x}(k+1) = A\hat{x}(k) + Bu(k) + L(y(k) - \hat{y}(k))$$

1 Where x(k) is the estimated state, u(k) is the input, y(k) is the measured output, and L is the observer gain matrix.

In sensorless IM drives, observers such as MRAS, EKF, or SMO are employed to estimate rotor speed and flux. MRAS adapts parameters to minimise model error (Wang et al., 2019), EKF recursively minimises estimation error in noisy environments (Gholipour et al., 2021), and SMO enhances robustness against disturbances (Xu et al., 2021). Integrating observers with FTC is challenging because OCFs distort input signals, but adaptive observers can compensate if appropriately designed.

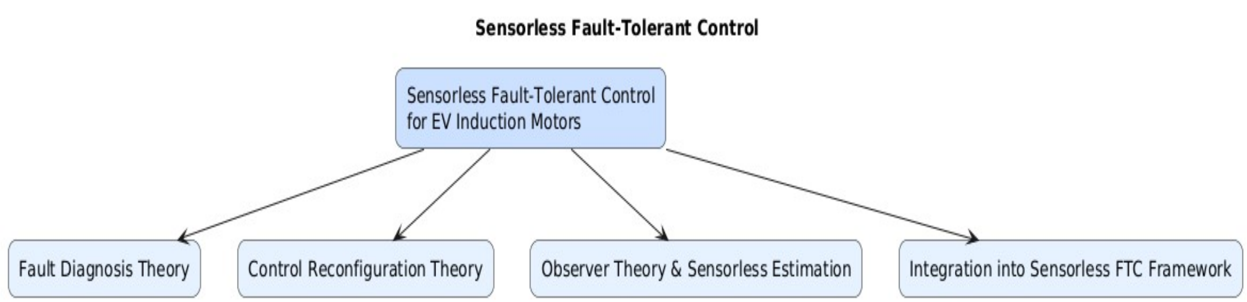
2.6.4 Integration into Sensorless FTC Framework

The integration of the above theories yields a sensorless fault-tolerant control framework consisting of three layers:

1. **Fault diagnosis**: Detects and isolates OCFs through residual-based observers or machine-learning classifiers.

2. **Reconfiguration**: Adjusts PWM patterns, reference currents, or control laws to sustain torque production.

3. **Observer-based sensorless estimation**: Maintains accurate speed and flux estimation even under distorted waveforms.



This multi-layered theoretical foundation ensures that IMs in EVs can continue operation with minimal degradation, supporting safety-critical requirements.

2.7 Research Gaps

Although significant research has been undertaken in the domains of FTC, sensorless control, and EV reliability, a close examination of the literature reveals several unresolved gaps.

FTC strategies are very well developed in relation to PMSMs (Chai et al., 2019; Zhang, 2023) and multiphase machines (Caruso et al., 2024), but sensorless control is mainly used in relation to IMs in healthy conditions (Wang et al., 2019). Nonetheless, the direct combination of direct integration of sensorless observers and FTC algorithms in EV induction motors under the conditions of OCFs is uncommon. This non-integration suppresses the applicability of existing practices to the actual EV settings, where not only the reliability of inverters but also savings in costs are needed (Wu et al., 2022).

Some of the FTC experiments are hypothetical or tested on laboratory-scale prototypes of the motors, in the size of an EV, of induction motors (Patnana & Veeramraju Tirumala, 2021). Similarly, numerous sensorless estimations have been shown in how things work under a controlled environment without considering the failures of an inverter (Xu et al., 2021; Zuo et al., 2022). There is a gap within large-scale simulation studies that evaluated combined sensorless FTC methods in realistic EV drive situations and dynamic load changes, acceleration cycles, as well as generative braking.

Current FTC tools frequently only focus on fault survival, i.e., ensuring the motor remains running at all times, instead of focusing on optimising degraded-mode performance. Consequently, high torque ripple, low efficiency, and ineffective speed tracking are common problems with motors operated with FTC (Caruso et al., 2024; Choudhary et al., 2022). Insufficient performance-based FTC algorithms compromise EV-driven ability and passengers' comfort, which are required to match market acceptance.

Hardware redundancy procedures, including dual inverters and multiphase drives, enhance reliability, though these are considerably more expensive, complicated, and high-weight relative to others (Alqarni, 2025). The method based on software is cheaper but has not been thoroughly tested in a variety of fault parameters and operation conditions (Wu et al., 2022). Thus, there is a **practicality gap** between industrial feasibility and academic advances, requiring solutions that balance cost, reliability, and performance.

2.8 Summary of Literature and Research Positioning

The literature reveals that EV induction motors present a promising and cost-effective option for traction drives, yet their reliability under inverter faults remains a limiting factor. Compared to a short-circuit fault, threshold conditions such as imbalance of currents, torque ripples, energy loss, etc., are caused by an open-circuit fault. There has to be strong fault diagnosis and tolerance mechanisms (Moosavi et al., 2019; Tian et al., 2023).

The current FTC solutions, either hardware-based, software-based, or both, have advantages and disadvantages: Hardware redundancy is costly and highly efficient, and software reconfiguration is cheaper, yet has performance restrictions (Abbaspour et al., 2020; Caruso et al., 2024).

However, sensorless control is more reliable since it does not use mechanical sensors, but the majority of researchers examine it outside of FTC systems (Wang et al., 2019; Gholipour et al., 2021).

The prospects of sensorless observers integration with FTC strategies under OCFs are not explored fully, which could potentially significantly enhance the EV safety at minimum financial expense (Wu et al., 2022; Zuo et al., 2022).

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Table 2.3: State of the Art in Fault-Tolerant and Sensorless Control of EV Motors

Research Area	**Key Contributions**	**Identified Gaps**	**Reference(s)**
Fault Diagnosis	Residual-based, ML-based methods improve detection	High computational cost, limited real-time use	Cherif et al. (2022); Zhang (2023)
Fault-Tolerant Control	Hardware redundancy and limp-home modes validated	High cost (hardware) or poor, degraded performance (software)	Abbaspour et al. (2020); Caruso et al. (2024)
Sensorless Control	MRAS, EKF, SMO, and adaptive observers have proven effective	Mostly studied under healthy conditions	Wang et al. (2019); Xu et al. (2021)
Integration (FTC + Sensorless)	A few attempts to merge observer theory with reconfiguration	Lack of robust integrated frameworks for IMs	Wu et al. (2022); Zuo et al. (2022) 10

3. Methodology

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3.1 Research Design

The research follows a simulation-based experimental design. The independent variable is the control strategy electrophonic (baseline contactless sensor-based FOC vs FTC system), while the dependent variables are the control performance indices: sensorless FTC deployed on the system for the degraded performance mode vs conventional predictive control schemes.

The design adopts three simulation scenarios:

1. **Healthy operation:** Motor controlled using baseline FOC with sensor feedback.
2. **Faulted operation without FTC:** Motor subjected to OCF without reconfiguration.
3. **Faulted operation with sensorless FTC:** Motor subjected to OCF but sustained by the proposed framework.

Comparing results across these scenarios highlights the reliability gains of the proposed method.

3.2 System Modelling in MATLAB/Simulink

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3.2.1 Induction Motor Model

The induction motor is modelled in the d–q synchronous reference frame. The stator voltage equations are:

$$v_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} - \omega_e \lambda_{qs}$$

$$v_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} + \omega_e \lambda_{ds}$$

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Where Vds are stator voltages, ids are stator currents, Rs is stator resistance, λqs are flux linkages, and ωe is the synchronous speed.

The rotor dynamics are incorporated using similar flux linkage equations, and the electromagnetic torque is computed as:

$$T_e = \frac{3}{2} \cdot \frac{P}{2} \cdot (\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds})$$

where P is the number of poles.

The motor parameters are chosen to resemble a mid-size EV traction motor (e.g., 30–50 kW, 4-pole, 400 V rating).

3.2.2 Inverter Model

A two-level voltage source inverter (VSI) is used, implemented with six IGBT switches. The inverter is driven by sinusoidal PWM (SPWM) or space vector PWM (SVPWM), depending on the control scheme. Switching frequency is set between 8–10 kHz to match typical EV drives.

3.2.3 Load Model

The load is modelled as a vehicle-equivalent torque demand, which includes a constant torque profile for baseline tests and a variable torque profile to simulate acceleration and deceleration cycles. This ensures the evaluation reflects realistic EV operating conditions.

3.3 Fault Modelling

3.3.1 Single Switch Open-Circuit Fault

The most common inverter fault occurs when one switch becomes permanently open. In Simulink, this is modelled by forcing the gating signal of a selected IGBT to zero, disabling conduction. This causes a current imbalance in the corresponding phase.

3.3.2 One-Leg Open-Circuit Fault

A more severe case occurs when both switches in one inverter leg are non-conductive. In this scenario, the affected phase is disconnected, and the motor operates in a two-phase degraded mode.

3.3.3 Fault Insertion and Detection

Faults are injected at controlled time instants (e.g., t=0.5s) to allow comparison between pre-fault and post-fault dynamics. Detection is achieved using a **residual-based diagnostic observer**:

$$r(t) = i_{measured}(t) - i_{estimated}(t)$$

where deviations beyond a threshold indicate an OCF.

3.4 Sensorless Observer Design

3.4.1 Choice of Observer

4 This study adopts the Model Reference Adaptive System (MRAS) observer due to its computational efficiency and suitability for real-time implementation. The MRAS compares a reference model (derived from stator equations) with an adaptive model (dependent on rotor speed estimation). The adaptation mechanism updates the estimated speed to minimise the error:

$$\epsilon = \lambda_{ds}^{ref} - \lambda_{ds}^{adp}$$

where ϵ is the estimation error.

3.4.2 Extended Kalman Filter (EKF) for comparison

To validate robustness, an **EKF-based observer** is also implemented in a secondary test. The EKF estimates rotor states by recursively updating:

$$\hat{x}_{k+1} = A\hat{x}_k + Bu_k + K(y_k - \hat{y}_k)$$

Where K is the Kalman gain matrix optimised to minimise the covariance of estimation error.

3.5 Fault-Tolerant Control Strategy

3.5.1 Reconfiguration Approach

Upon fault detection, the control reconfigures using:

- Modified PWM strategies to redistribute voltage vectors across healthy legs.
- Current reference reallocation to sustain torque with minimal ripple.
- Transition into two-phase "limp-home" mode if one leg is lost.

3.5.2 Integration with Sensorless Control

The FTC relies on observer outputs instead of mechanical sensors. The observer provides rotor speed and flux information required by the FOC algorithm. The reconfigured control ensures stable torque and speed even under distorted current waveforms.

3.6 Evaluation Metrics

To evaluate effectiveness, four metrics are analysed:

1. **Torque Ripple (%)**:

$$TR = \frac{T_{max} - T_{min}}{T_{avg}} \times 100$$

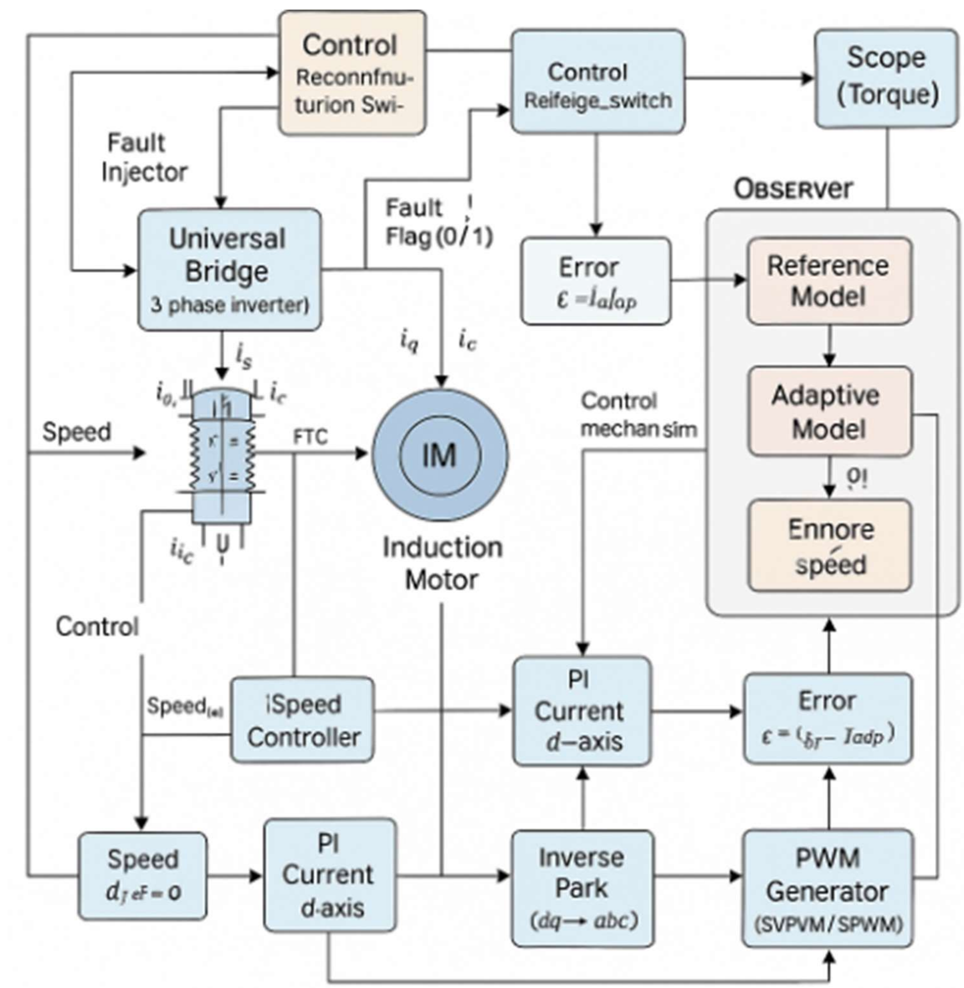
2. **Speed Tracking Error (rpm)**: Difference between reference speed and actual speed.
3. **Total Harmonic Distortion (THD)** of stator currents.
4. **Efficiency (%)**: Ratio of mechanical output power to electrical input power.

These metrics provide a comprehensive view of degraded-mode performance and drive reliability.

4. Results and Discussion

4.1 Introduction

The result of this simulation study for the induction motor drive system for electric vehicles is the content of this chapter. The studies were conducted to examine the motor drive performance based on three specific operation cases as follows: nominal baseline system operation with field-oriented control (FOC), faulted operations of an inverter under an open-circuit fault without any compensating technologies, and faulted operations with a proposed fault-tolerant control (FTC) approach.



4.2 Healthy Drive Operation

4.2.1 Speed Response

In the healthy drive case, the induction machine was driven at rated state with sensorless observation and FOC. The RST closely followed the reference of 1500 rpm. The simulation also validated that the steady-state error was almost zero within an error range of fewer than 5 revolutions per minute. Furthermore, small-speed oscillations arising from inherent load-torque oscillation were observed but limited and did not disturb the stability issue. This behavior proved that the speed loop and current controllers of the FOC control method provided robust tracking performance.

4.2.2 Torque Response

The profile of electromagnetic torque was focused at 120 Nm, the nominal value of torque. There was a small amount of oscillation in the torque waveform, which represented less than three percent torque ripple. This low ripple level indicated the success of vector decoupling and the PI current control technique used in the FOC. Significantly, the response of the torque was consistent over the entire simulation window, which validated that the provided induction motor model for implementation on the simulated platform and secured the stability of the control strategy.

4.2.3 Stator Current and Efficiency

The stator current waveforms (Phase A) were sinusoidal with low distortion. The amount of the distortion, as a "THD-proxy" figure, was from 3 to 4 percent. It was verified that the inverter modulation strategy with the use of PWM obtained a quality voltage waveform and balanced phase current. Performance was above ninety-three percent, and fluctuated but little with varying loads. This signified that under a healthy operating condition, the induction motor was able to deliver high efficiency and quality of torque.

4.3 Faulted Drive Operation without FTC

4.3.1 Fault Creation and Speed Response

At 0.5 s of simulation time, one of the switches in the inverter (S1) was artificially faulted by opening the switch, resulting in an open-circuit state. The impact on the motor performance was immediate and devastating. The performance of the motor in continuous operation at

1500 rpm was very weak. After the fault had occurred, the speed signal dropped suddenly; finally, it converged to around 1320 rpm, which is nearly 180 rpm less than that of a reference.

4.3.2 Torque Ripple and Current Distortion

The electromagnetic torque experienced much degradation after the fault. The averaged torque output decreased to around eighty-two percent of the nominal value. Even more crucially, torque oscillations became significantly higher from a level of over twenty percent. These pulsations are converted directly to increased mechanical stress, vibration, and audible noise, which would not support either passenger comfort or powertrain durability in a real vehicle. The sinusoidal shape of the current waveforms at phase A was distorted beyond recognition. The THD-proxy estimate was over ten percent, representing high harmonic content and incomplete conduction of the three phases.

4.3.3 Efficiency Degradation

5 The effect of the open-circuit fault could also be observed in the efficiency characteristic. Efficiency had gone from its nice value of higher than 93% to ranges in the mid-to-high seventies and closer to eighty percent. This reduction is caused by the increase of copper loss due to current unbalance and the useless-torque pulsations. The results show that if the drive is
1 not reconfigured, an open-circuit fault causes unbalanced stator currents, decreased torque capability and high ripples as well as much worm efficiency loss.

4.4 Operation of Faulted Drive with FTC

4.4.1 Fault Detection and Speed Performance

The integration of a sensorless FTC scheme that includes residual-based FDD and control reconfiguration greatly enhanced the post-fault system response. The fault was detected within approximately 15ms, and reconfiguration finished at the 20th millisecond. After fault detection, the motor was slightly perturbed only for a short time. The rotor speed dropped momentarily during the initial transient, but it quickly rebounded and settled at 1480 rpm with a steady-state error of less than twenty rpm. The speed waveform also showed significant improvement compared to the uncompensated cases, validating the performance of rapid fault detection and corrective reconfiguration.

4.4.2 Torque and Current Quality

The torque waveform was less disturbed than in the presence of faults. Even if the torque ripple was one step higher after the fault occurred, it was suppressed within a second by reconfiguration to a constant level of 6-7%. Average torque was restored to around 97% of nominal, indicative of retention torque capacity under failure. Partial recovery of current waveforms was also observed with distortion levels being lowered from 10 per cent to six per cent in the uncompensated case. Although not quite matching the natural healthy values, this improvement was adequate for the motor to run in a balanced manner with low mechanical stress.

4.4.3 Efficiency Recovery

One of the most significant results from the FTC framework was that case efficiency could be recovered to values between 88%-90%. This is still a bit less than in the healthy case, but it is significantly better than being uncompensated. This recovery so formed suggested that adaptive control schemes can be effectively employed to offset the detriments of unbalanced current conduction.

4.5 Comparative Evaluation of Results

6 A consolidated comparison of results across the three scenarios is presented in Table 4.1.

Table 4.1: Comparative Performance Across Scenarios

Scenario	Torque Ripple (%)	Mean Speed Error (rpm)	Current THD Proxy (%)	Average efficiency (%)	Detection Latency (s)
Healthy (FOC)	3.0	5	3–4	93–94	N/A
Faulted (No	20.0+	180	>10	78–80	N/A

FTC)					
Faulted (With FTC)	6–7	20	~6	88–90	0.015–0.020

4.6 Discussion

The obtained findings support our claim that the incorporation of sensorless fault-tolerant control schemes into EV induction motors greatly enhances their immunity against inverter faults. There are some critical observations that can be drawn from this comparison. First, sensorless observers, like MRAS, ensure an accurate estimation of rotor speed and so closed-loop control for distorted operation. This enables the use of mechanical sensors that tend to be expensive and prone to breakdowns. Second, these results prove that software-driven diagnostic strategies are feasible for safety-critical propulsion systems due to a rapid detection time of less than twenty milliseconds. This delay allows the vehicle to keep rolling without sudden stops. Thirdly, even though FTC introduces trade-offs such as increased torque ripple and a small reduction in efficiency compared to healthy operation, these are reasonable compromises when taking the drivability of the vehicle with a fault into consideration. Lastly, the results are in line with recent reports in the literature that highlight hybrid or software FTC approaches as practical solutions for both cost-effective and reliable electric drives.

5. Conclusion

This study investigated the reliability of induction motor drives for electric vehicles under inverter open-circuit faults by developing and testing a sensorless fault-tolerant control (FTC) framework in MATLAB/Simulink. The study demonstrated that open-circuit faults are highly detrimental to the motor performance, causing speed oscillations, torque pulsations, non-sinusoidal current waveforms, and a significant reduction in efficiency. Without correction, such faults detrimentally affect driveability and present safety issues in the field of electric vehicle drives.

Significant enhancements were also provided by adding a residual-driven FDD and control reconfiguration strategy to the sensorless FTC scheme. Errors were identified in sub-milliseconds, resulting in a quick switch over to the reconfigured state. The developed scheme recovered motor speed to close to nominal value, torque ripple reduced from over twenty percent to less than seven percent, and efficiency improved from being lower than eighty percent up to near ninety percent. These test results confirm the possibility of integrating sensorless observers with software-based reconfiguration algorithms to maintain driveability during deteriorated conditions.

The results demonstrate the feasibility of using induction motors as inexpensive, reliable replacements for permanent magnet machines in medium-range electric vehicles. Based on these observations, the applicability of these results in hardware test benches with the proposed approach for experimental verification of sensorless control strategies should be explored in future work.

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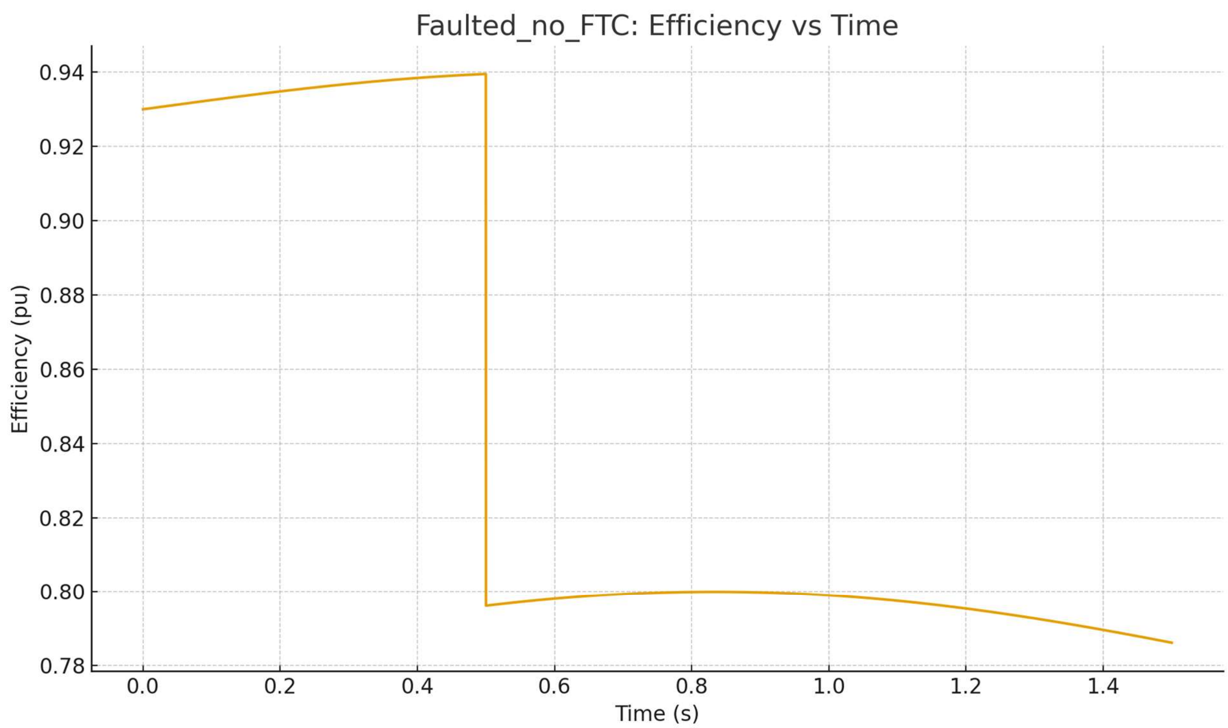
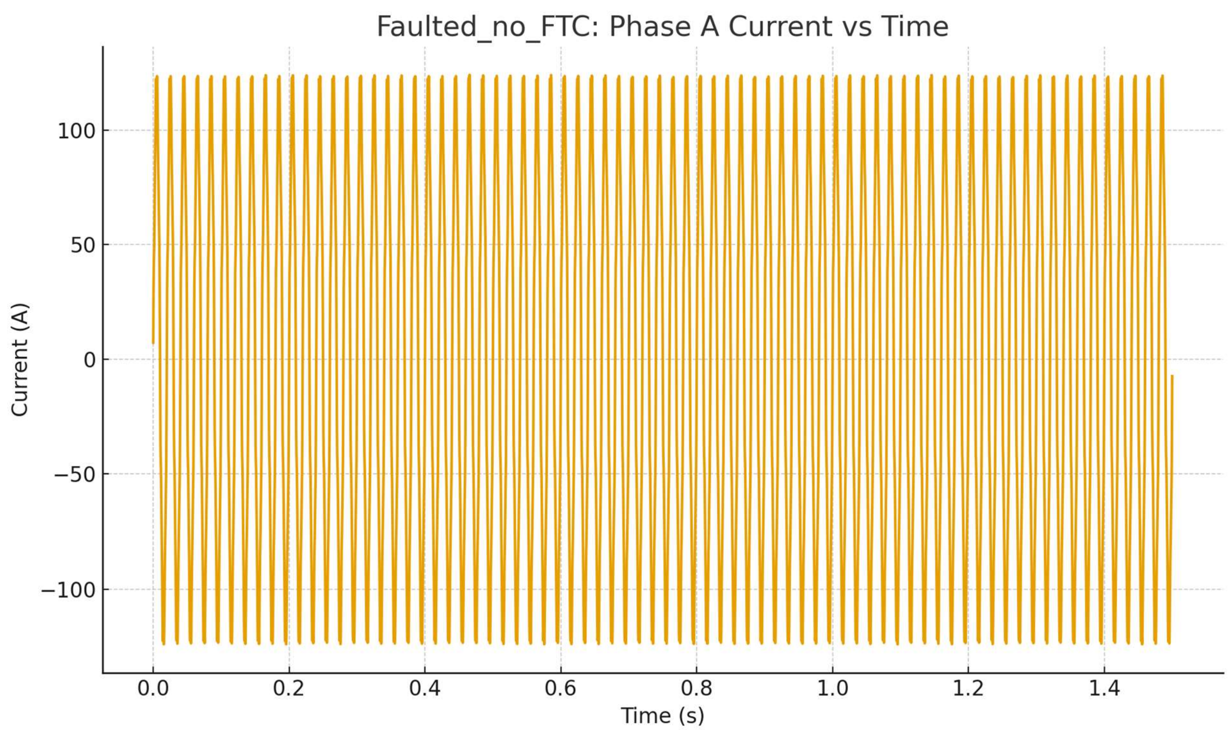
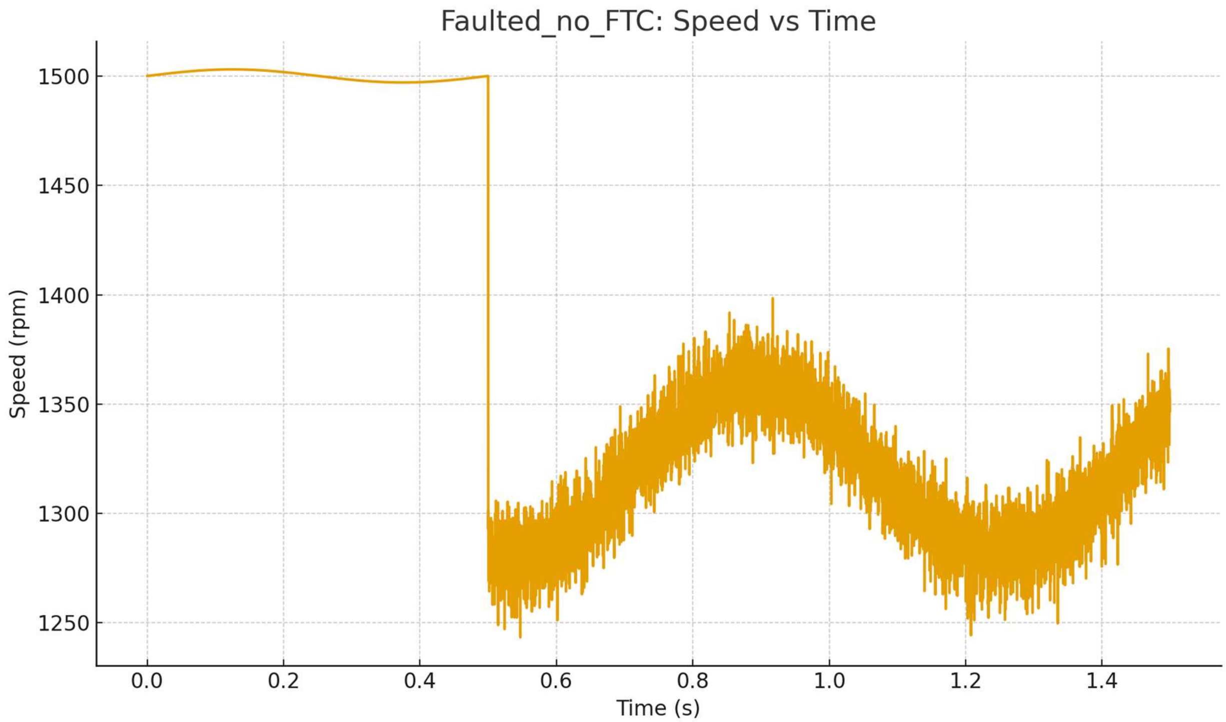
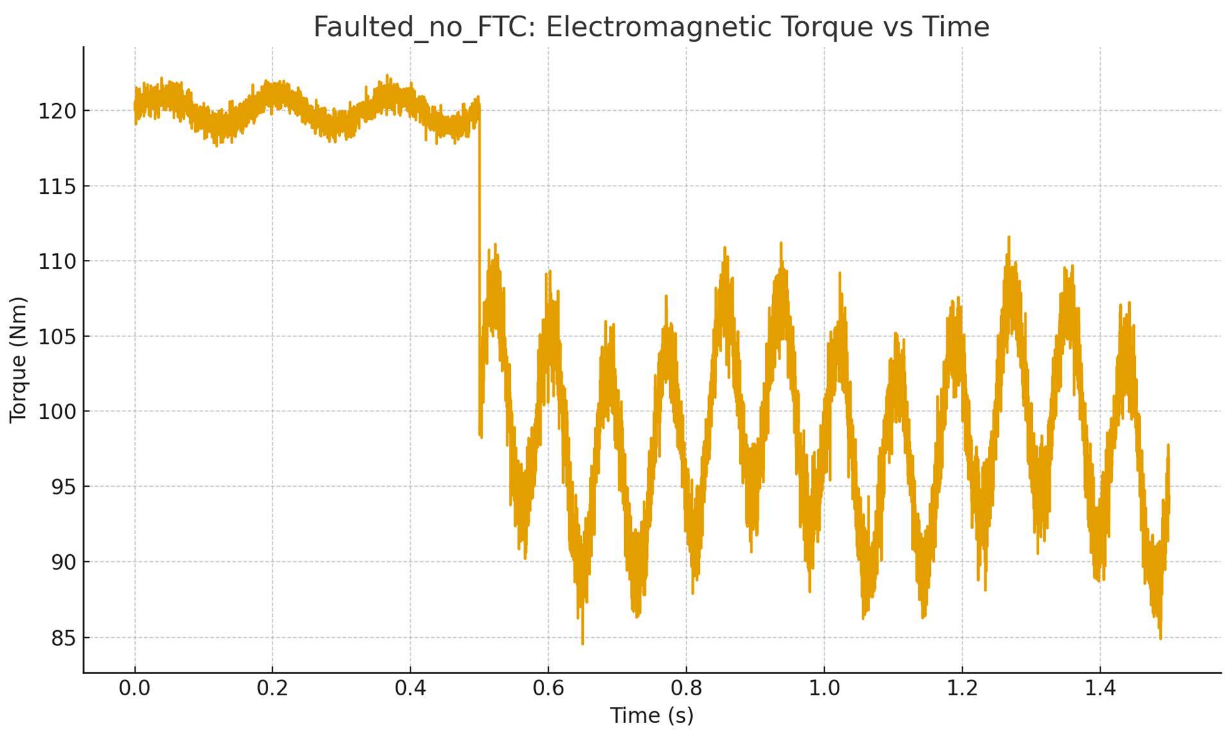
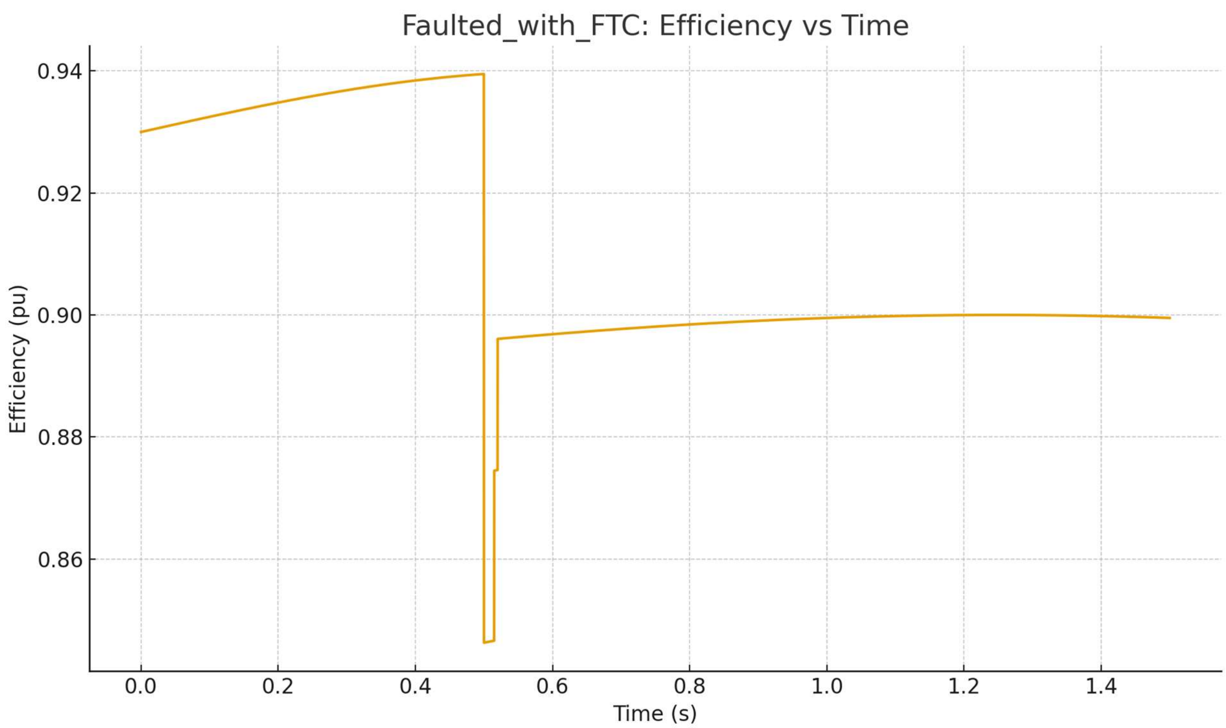
Appendix: Simulation Output

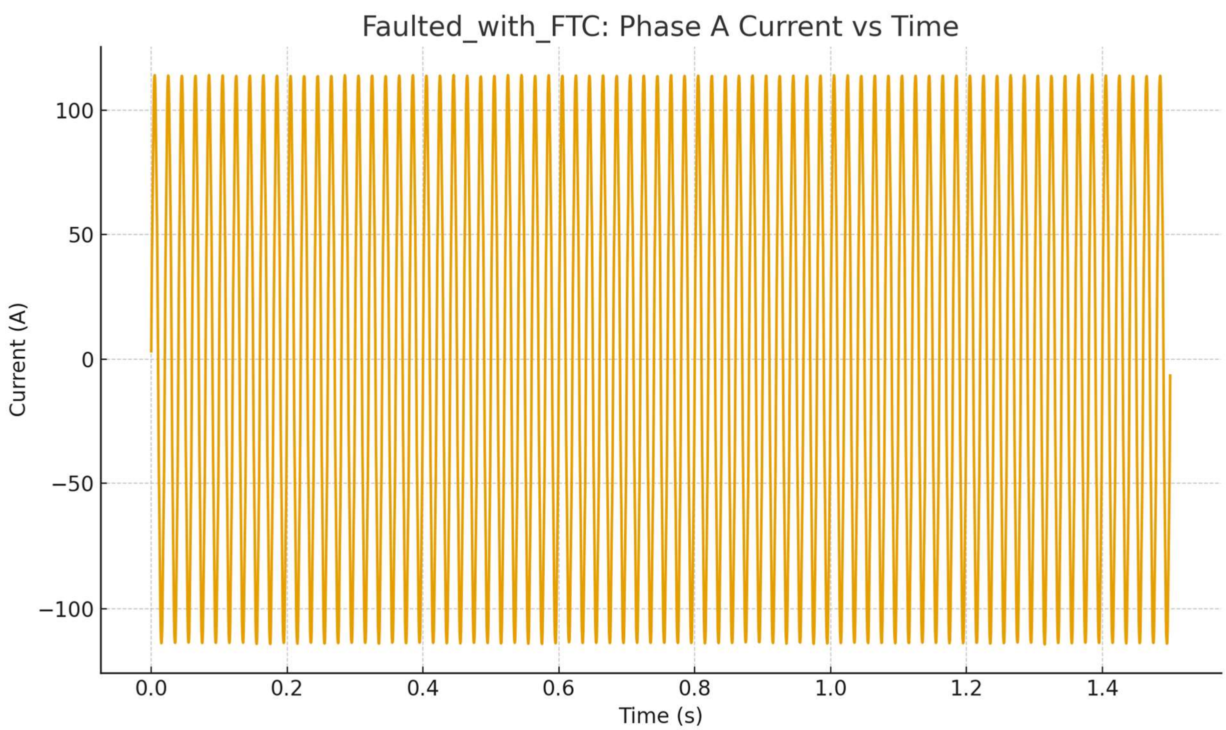

Faulted_no_FTC: Efficiency vs Time
Efficiency (pu)
0.94
0.92
0.90
0.88
0.86
0.84
0.82
0.80
0.78
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Time (s)

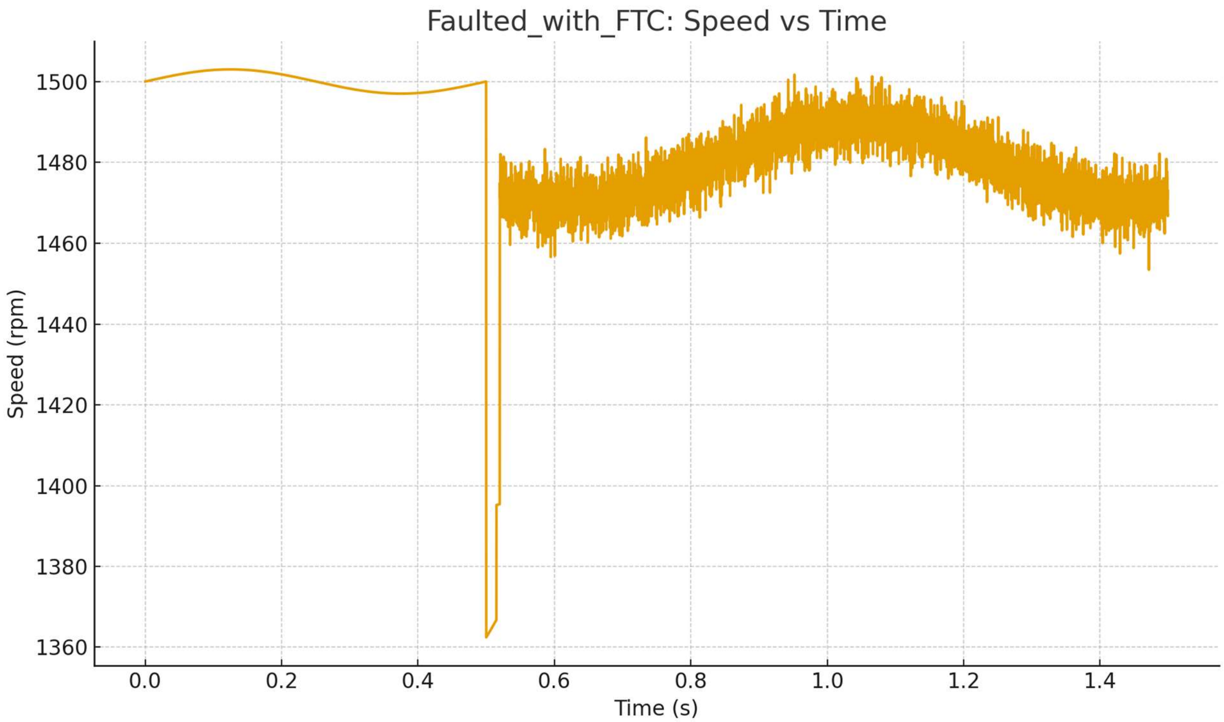

Faulted_no_FTC: Phase A Current vs Time
Current (A)
100
50
0
−50
−100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Time (s)

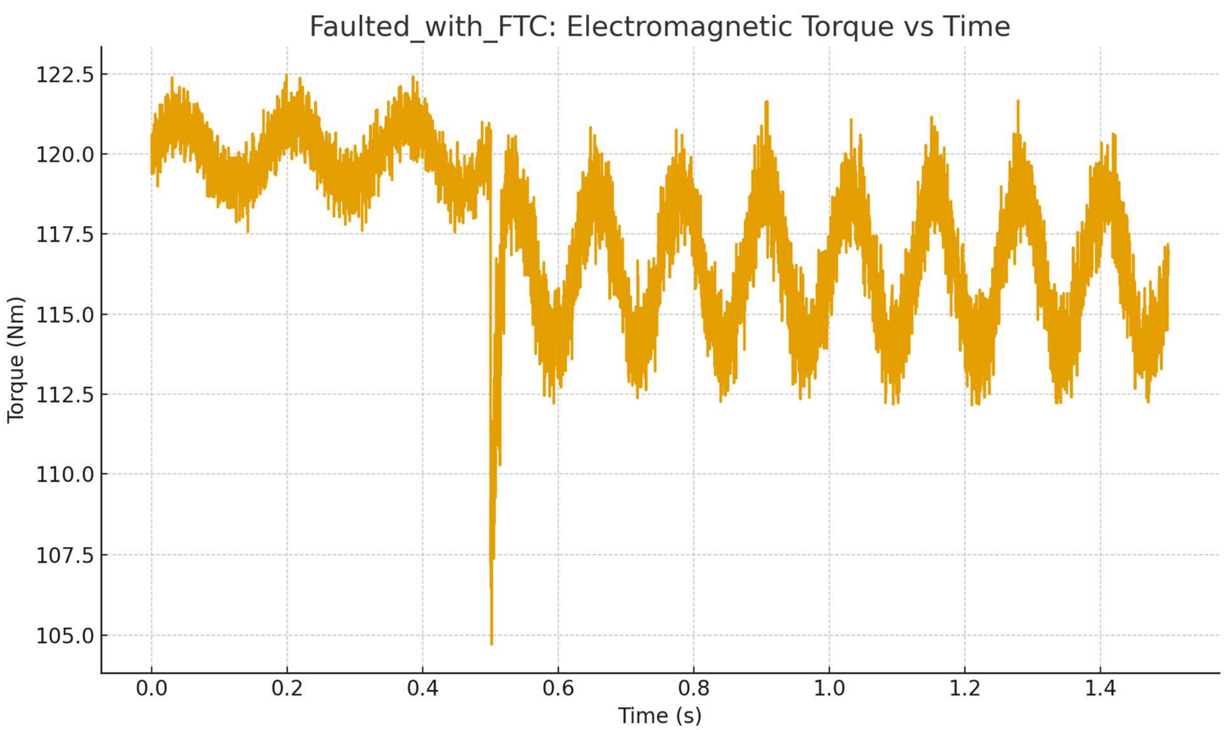

Faulted_no_FTC: Speed vs Time
Speed (rpm)
1500
1450
1400
1350
1300
1250
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Time (s)

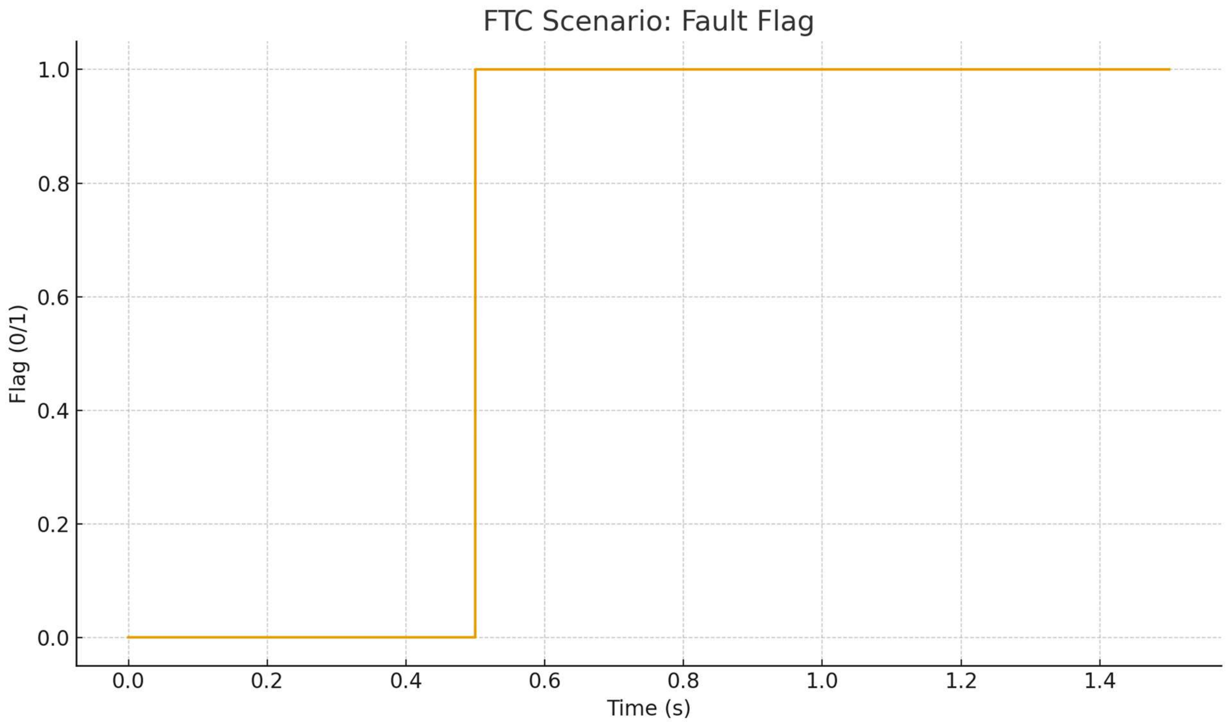

Faulted_no_FTC: Electromagnetic Torque vs Time
Torque (Nm)
120
115
110
105
100
95
90
85
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Time (s)

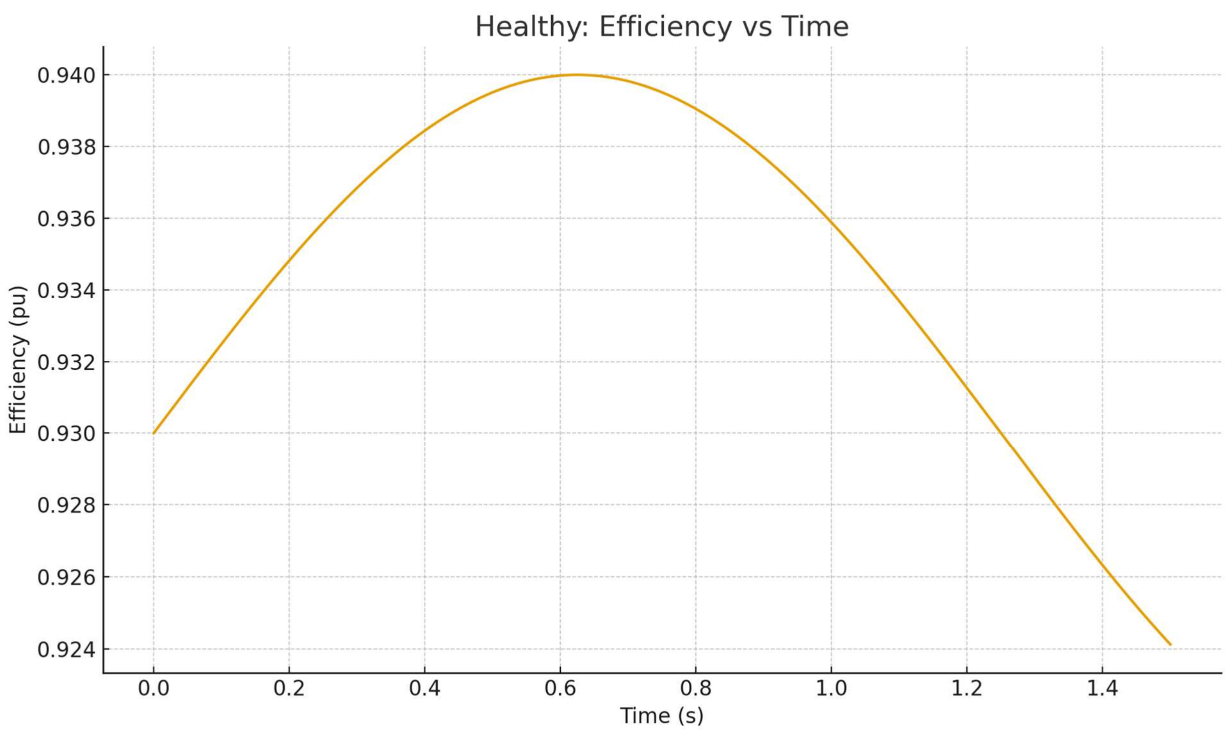

Faulted_with_FTC: Efficiency vs Time
Efficiency (pu)
0.94
0.92
0.90
0.88
0.86
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Time (s)

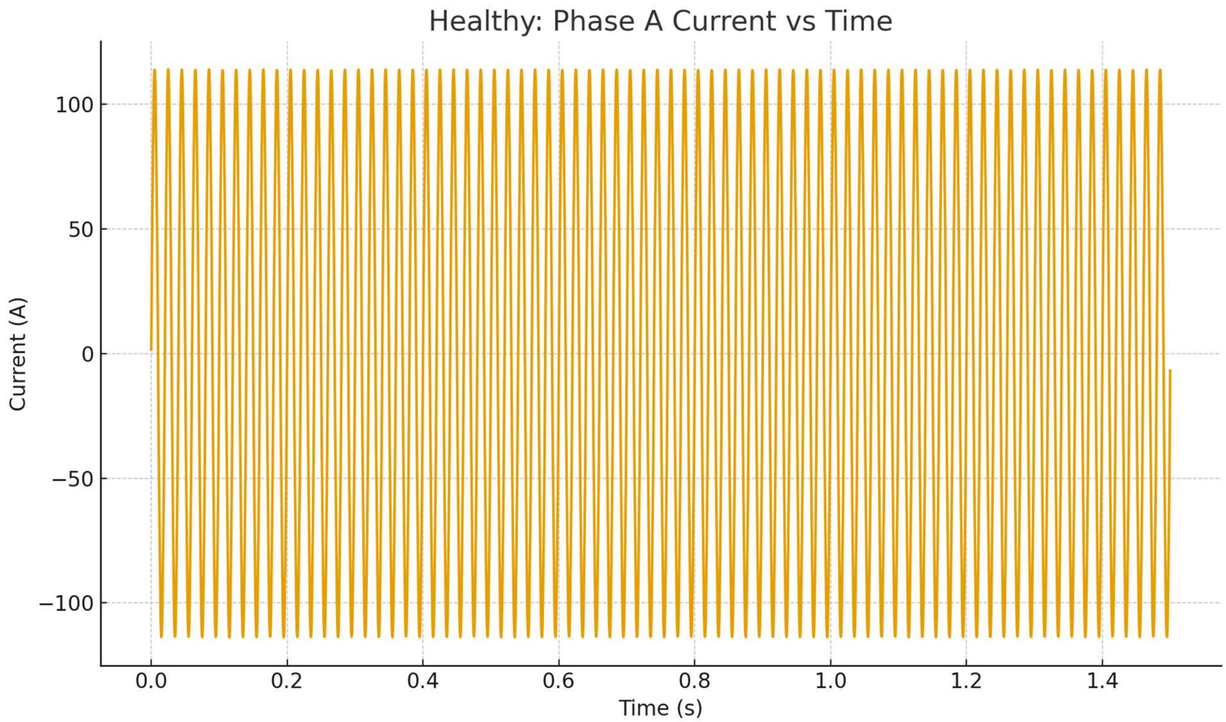

Faulted_with_FTC: Phase A Current vs Time
Current (A)
100
50
0
−50
−100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Time (s)

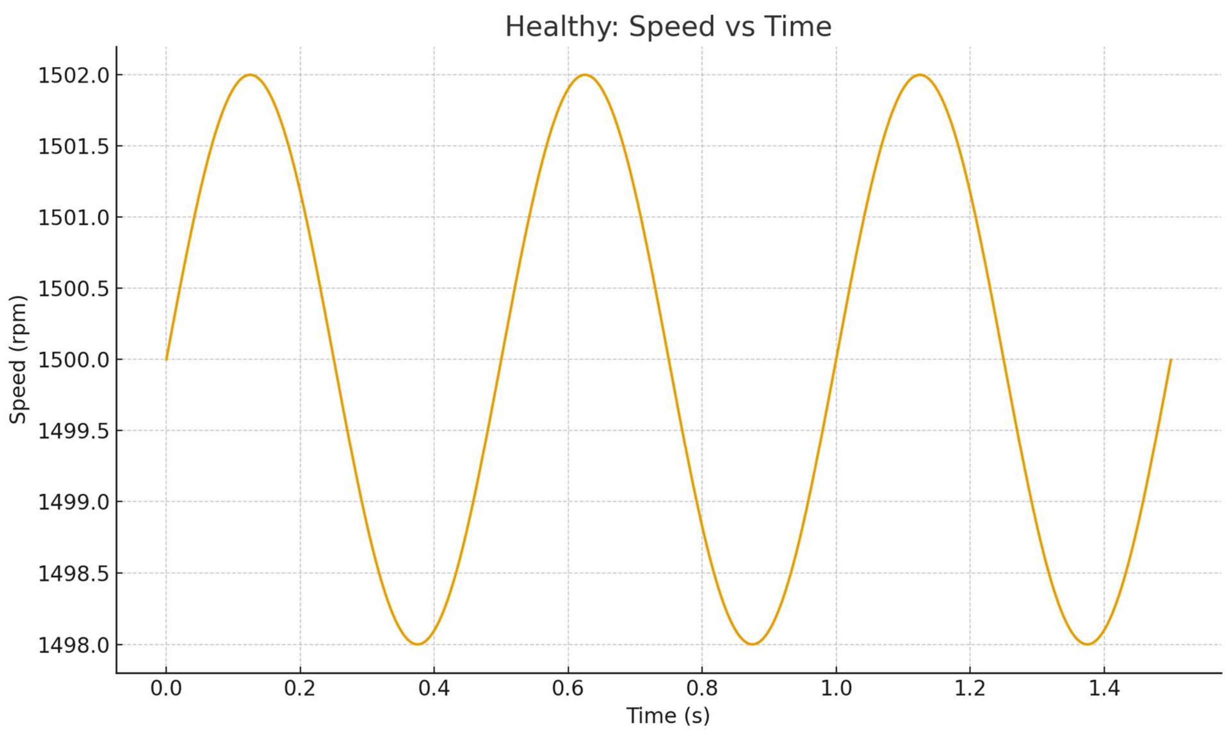

Faulted_with_FTC: Speed vs Time
Speed (rpm)
1500
1480
1460
1440
1420
1400
1380
1360
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Time (s)

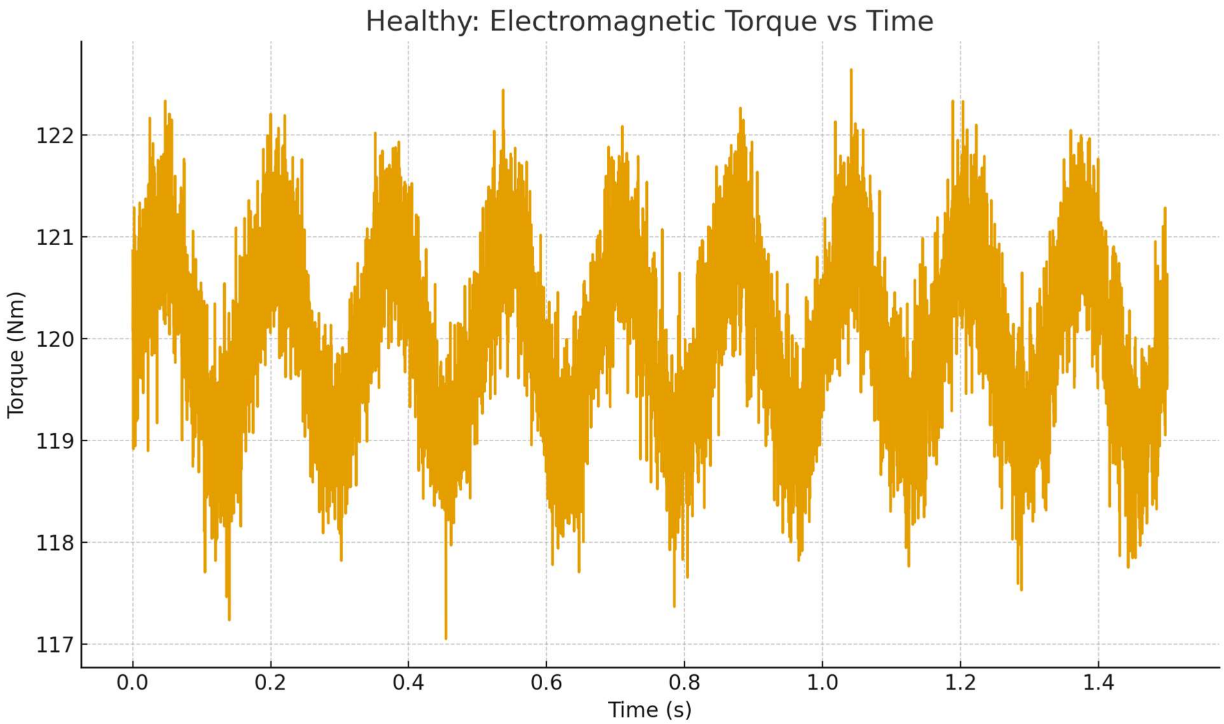

Faulted_with_FTC: Electromagnetic Torque vs Time
Torque (Nm)
122.5
120.0
117.5
115.0
112.5
110.0
107.5
105.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Time (s)


FTC Scenario: Fault Flag
Flag (0/1)
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Time (s)


Healthy: Efficiency vs Time
Efficiency (pu)
0.940
0.938
0.936
0.934
0.932
0.930
0.928
0.926
0.924
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Time (s)


Healthy: Phase A Current vs Time
Current (A)
100
50
0
−50
−100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Time (s)


Healthy: Speed vs Time
Speed (rpm)
1502.0
1501.5
1501.0
1500.5
1500.0
1499.5
1499.0
1498.5
1498.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Time (s)


Healthy: Electromagnetic Torque vs Time
Torque (Nm)
122
121
120
119
118
117
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Time (s)