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Electromagnetic Signal Analysis for Electrical and Mechanical Fault Diagnosis in Synchronous Motor

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This paper presents a comprehensive approach to fault diagnosis in synchronous motors by integrating non-invasive electromagnetic signal analysis with the Finite Element Method (FEM). The study encompasses a wide range of electrical and mechanical faults, including stator and rotor winding issues, ground faults, phase short circuits, eccentricity faults, and broken damper bars. By analyzing stator current harmonics and stray magnetic flux, the proposed method significantly enhances the accuracy of fault detection. The diagnostic process is validated through simulation results, demonstrating its effectiveness in real-time monitoring and predictive maintenance. These findings contribute to the development of more reliable and cost-efficient diagnostic systems, reducing operational disruptions and extending the lifespan of electrical machinery in industrial applications.

Keywords : fault diagnosis, synchronous motor, electromagnetic signal, non-invasive method

1. Introduction

Synchronous motors are integral to power systems in both industrial and commercial applications, playing a crucial role in converting mechanical energy into electrical power [1]. The steady and reliable operation of these motors is essential for maintaining an uninterrupted power supply, making their performance and longevity a critical concern. However, these motors are susceptible to a wide range of faults, which can compromise both their efficiency and operational lifespan.

Faults in synchronous motors can be broadly categorized into electrical and mechanical types [2]. Electrical faults, such as phase-to-earth short circuits, phase-to-phase short circuits, and turn-to-turn faults in stator and rotor windings, are primarily caused by factors like insulation degradation, overheating, and electrical discharges [3]. Mechanical faults, on the other hand, include issues like eccentricity and damper winding faults. Eccentricity faults occur due to rotor misalignment, leading to uneven air gaps and increased vibration, while damper winding faults can result in overheating and subsequent mechanical damage, often stemming from mechanical wear, misalignment, or structural defects [4].

Given the diversity and complexity of these fault types, an all-encompassing diagnostic approach is required. This paper explores the implementation of electromagnetic signal analysis techniques, supported by Finite Element Method (FEM) simulations, to effectively detect both electrical and mechanical faults. The objective is to develop a robust diagnostic framework that not only identifies existing faults but also provides early warning signals, thereby enhancing the reliability, efficiency, and operational lifespan of synchronous motors. Unlike conventional studies that focus solely on either electrical or mechanical fault detection, this work integrates both stator current harmonic analysis and stray magnetic flux monitoring within a unified Finite Element Method (FEM) framework. Existing diagnostic models often rely on empirical current signatures or simplified analytical assumptions, which limit their sensitivity to coupled fault conditions. The proposed method overcomes these limitations by fusing electromagnetic signal features from both sources, enabling simultaneous detection of ground faults, turn-to-turn faults, eccentricity, and broken damper bars. Furthermore, the diagnostic algorithm is designed to differentiate fault categories through specific harmonic order patterns derived from FFT analysis, providing a

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more generalized and interpretable model. This hybrid FEM-based approach therefore bridges the gap between electrical and mechanical fault domains, improving early fault identification accuracy and robustness in real-time monitoring scenarios.

2. Fault Types in Synchronous Motors

2.1. Ground Short Circuit

Ground faults, referred to as phase-to-earth short circuits, occur when the insulation between the stator windings and the ground deteriorates, creating a conductive path that leads to fault currents. In extreme cases, these currents can reach magnitudes of up to 20 amperes [5]. Such high-amplitude currents pose a significant risk to the stator core, potentially leading to severe damage if not promptly detected and addressed. Early detection is essential, and advanced monitoring techniques, such as electromagnetic signature analysis, play a crucial role in identifying deviations from normal operation before they escalate into more serious issues.

2.2. Phase Short Circuit

Phase short circuits arise when the insulation between phases fails, resulting in direct electrical contact. These faults can be categorized into two primary types:

- Phase-to-Phase Short Circuit: This fault occurs when two phases come into direct contact due to insulation breakdown. The resulting current surge can cause significant damage to the motor if not quickly managed. Rapid intervention by protection systems is necessary to limit the extent of the damage, with real-time impedance monitoring being a commonly employed technique for swift fault detection and diagnosis.
- Three-Phase Short Circuit: A more severe type of fault, the three-phase short circuit occurs when all three phases come into direct contact simultaneously. This results in a massive surge of current, which, if not immediately controlled, could lead to catastrophic damage. Prompt activation of shutdown protocols and protection systems is vital to prevent extensive harm to the motor.

2.3. Stator Turn-to-Turn Short Circuit

A stator turn-turn short circuit occurs when the insulation between adjacent turns within the same phase of the stator windings fails, leading to a short circuit. This fault generates an asymmetrical magnetic field, causing irregular current flows that can compromise the integrity of the windings. Often this type of fault serves as an early indicator or root cause of more severe stator winding issues and can escalate into other kinds of failures if not promptly addressed.

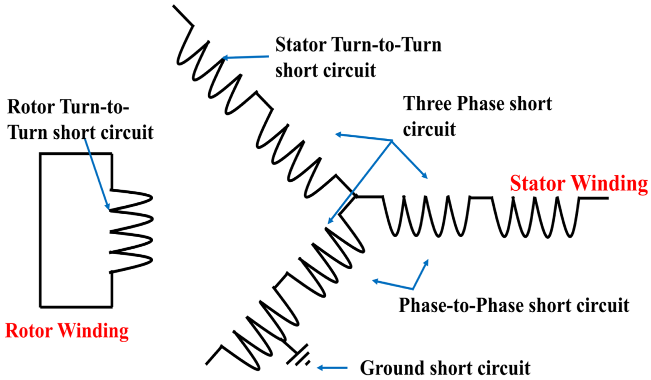


Fig. 1. (Color online) Schematic Representation of Electrical Fault Types in Synchronous Motors.

2.4. Rotor Turn-to-Turn Short Circuit

Rotor turn-to-turn short circuits develop when the insulation between adjacent rotor winding turns deteriorates, leading to a short circuit. Contributing factors typically include prolonged rotational vibrations, mechanical stresses, and excessive heat. Although the direct current involved in the rotor generally limits the fault's severity, persistent turn-to-turn short circuits can exacerbate rotor vibrations and temperature, further degrading the insulation and potentially leading to more significant faults [6].

2.5. Broken Damper Bars

Damper bars in synchronous motors ensure the even distribution of currents during transient operations. A failure in one of these bars—such as a break—forces the current redistribution to adjacent bars. This redistribution increases electrical losses and induces localized heating, which can exacerbate the damage to the motor. Additionally, cracks in the end rings, which serve to connect the damper bars, can further disrupt the uniform distribution of current. Such disruptions lead to additional mechanical stress and localized overheating at the connection points, compounding the risk of failure. These faults are typically challenging to diagnose through online monitoring during normal operation and are instead identified during transient conditions, such as the startup phase.

2.6. Eccentricity Fault

Eccentricity faults in synchronous motors result from mechanical misalignments, which can arise due to factors

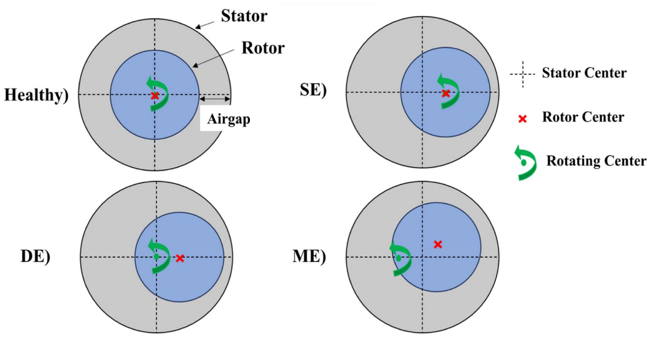


Fig. 2. (Color online) Illustration of Eccentricity Fault Types in Synchronous Motors: Healthy, SE, and DE.

such as worn bearings, loose bolts, or an elliptical stator cross-section. These faults are categorized into three distinct types:

- Static Eccentricity (SE): SE occurs when the rotor's center is offset from the stator's center while the rotor continues to rotate around a fixed axis. In this condition, the minimum air gap between the rotor and stator varies with angular position but remains consistent over time. This consistent positional offset, as depicted in Fig. 2, can lead to uneven magnetic forces, which may contribute to long-term wear and operational inefficiencies.
- Dynamic Eccentricity (DE): DE is characterized by the displacement of the rotor's center from the stator's center, coupled with the rotor's rotation around the stator's central axis. This misalignment causes the minimum air gap length to vary with both angular position and time. DE typically results from bearing wear or rotor deformation, leading to an asymmetrical air gap that fluctuates continuously as the rotor moves. The dynamic nature of this fault can induce irregular magnetic forces, further exacerbating mechanical stresses and potentially leading to more severe operational issues.

Eccentricity faults generate unbalanced magnetic forces that can create a destructive feedback loop, progressively worsening the eccentricity. This escalating condition may eventually result in physical contact between the rotor and stator, posing a significant risk of catastrophic failure. Immediate corrective action is essential to prevent such an outcome, underscoring the importance of regular monitoring and maintenance.

3. Fault Diagnosis of Synchronous Machine

By integrating stator current analysis with stray flux

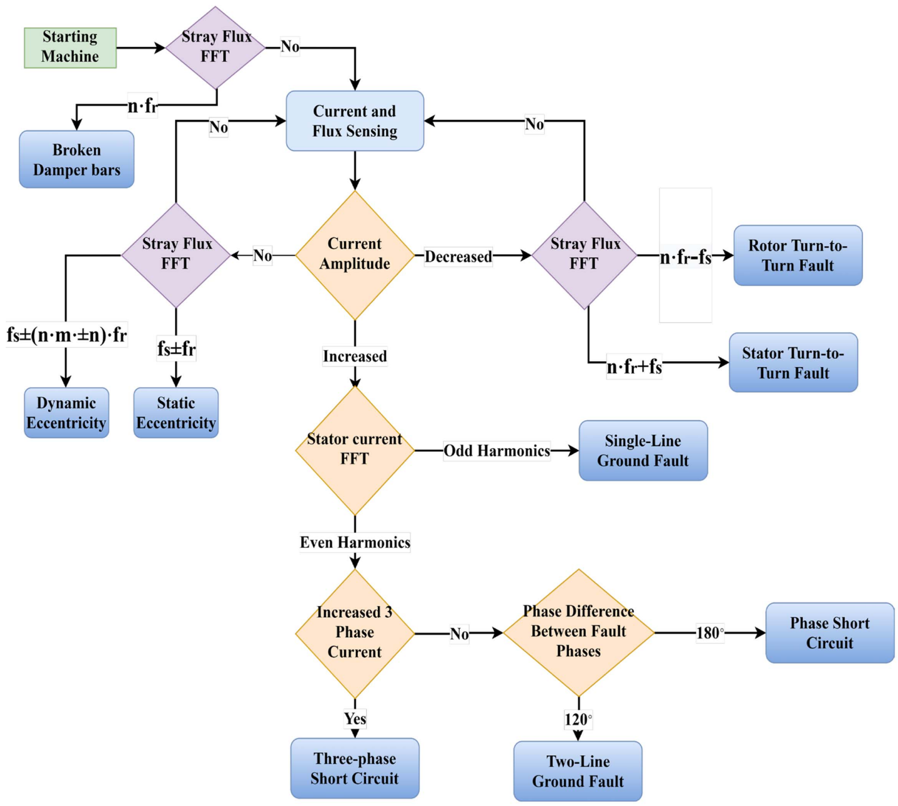


Fig. 3. (Color online) Fault Diagnosis Algorithm for Electrical and Mechanical Faults in Synchronous Motors.

monitoring, a more efficient and comprehensive fault diagnosis process can be achieved in synchronous motors. Stator current analysis involves monitoring the currents flowing through the stator windings, where variations in amplitude or phase can serve as indicators of electrical faults. Stray flux monitoring complements this technique by detecting changes in the magnetic field surrounding the motor, allowing for the identification of faults that may not be detectable through current analysis alone. This combined approach is particularly effective in diagnosing turn-to-turn faults in both the stator and rotor windings, as well as mechanical issues, thereby offering a thorough assessment of the motor's overall condition. they are required.

3.1. Fault Diagnosis Algorithm

The fault diagnosis algorithm, depicted in Fig. 3, integrates stator current and stray flux sensing to systematically identify both electrical and mechanical faults in synchronous motors. The diagnostic process begins during the motor's startup phase, where stray flux is analyzed using the Fast Fourier Transform (FFT). An increase in harmonic content during startup is typically indicative of broken damper bars.

Following the startup phase, the algorithm continuously monitors the current amplitude and stray flux. If the current amplitude remains stable—usually indicative of a healthy operating state—the algorithm subsequently analyzes the stray flux for signs of eccentricity faults. Stray flux FFT analysis can detect spatial or temporal variations characteristic of static or dynamic eccentricity, respectively.

In cases where a significant decrease in current amplitude is observed, the algorithm proceeds to analyze the 5th harmonics of the stray magnetic flux. A reduction in these harmonics suggests a rotor turn-to-turn fault, while an increase indicates a stator turn-to-turn fault.

Conversely, if an increase in current amplitude is detected, the algorithm conducts an FFT analysis of the stator current to identify specific harmonic patterns. The presence of odd harmonics generally indicates a single-line-to-ground fault. If even harmonics are detected, further analysis is warranted. The algorithm then checks whether the increase in current is consistent across all three phases. A uniform increase across all phases typically signals a three-phase short circuit. If the increase is not uniform, the algorithm proceeds to phase shift analysis. A 120-degree phase shift between the faulted phases indicates a two-line-to-ground fault, while a 180-degree phase shift confirms a phase-to-phase short circuit.

3.2. FFT Analysis

The Fast Fourier Transform (FFT) is a highly effective tool for analyzing the frequency components of stator current and stray magnetic flux in synchronous motors. By transforming time-domain signals into their frequency-domain equivalents, FFT makes it easier to identify specific harmonics that signal various electrical faults. The mathematical expression of the Fourier series for a periodic function $f(t)$ is represented as:

$$f(x) = a_0 + \sum_{n=1}^{N} (a_n \cos nx + b_n \sin(n)) \tag{1}$$

In equation (1), a_0 represents the DC component of the function over one period, while a_n and b_n are the Fourier coefficients for each harmonic n, and T is the period of the function.

In the context of fault diagnosis, the presence and magnitude of specific harmonics provide critical insights into the nature of potential faults. For example, an increase in odd harmonics typically suggests a single-line-to-ground fault, whereas an increase in even harmonics warrants further analysis to diagnose the underlying issue

Table 1. Frequency Variation Patterns of Fault Types.

Signal	Fault Type	Frequency Variation Pattern
Stator Current Signal	Stator Single-Line Ground Fault	$f_{ground} = k_{odd} \cdot f_s$
	Stator Two-Line Ground Fault	$f_{ground} = k_{even} \cdot f_s$
	Phase-to-Phase Short Circuit	$f_{phase} = k_{even} \cdot f_s$
	Three-Phase Short Circuit	$f_{3-phase} = k_{even} \cdot f_s$
Stray Magnetic Flux Signal	Stator Turn-to-Turn Short Circuit	$f_{stator\ turn} = \mathrm{n} \cdot f_r + f_s$
	Rotor Turn-to-Turn Short Circuit	$f_{rotor\ turn} = \mathrm{n} \cdot f_r - f_s$
	Broken Damper bars	$f_{damper} = \mathrm{n} \cdot f_r$
	Static Eccentricity	$f_{SE} = f_s \pm f_r$
	Dynamic Eccentricity	$f_{DE} = f_s \pm (\mathrm{n} \cdot \mathrm{m} \cdot \pm \mathrm{n}) \cdot f_r$

precisely.

Table 1 illustrates the frequency variation patterns associated with different fault types in synchronous motors [7, 8]. This table is a reference for identifying the fault types based on the observed harmonic content in the stator current and stray flux signals. In this table, f_s represents the power supply frequency in hertz, f_r denotes the rotation frequency of the rotor in hertz, m is the number of pole pairs in the machine, k_{even} refers to an even integer, k_{odd} refers to an odd integer, and n represents an integer value.

3.3. Decision Threshold Criteria

To enable automatic fault identification, quantitative decision thresholds were established for both current amplitude and harmonic content variations. The thresholds were determined from baseline measurements of a healthy motor obtained through FEM simulation.

For each monitored signal $S_i(t)$ (stator current or stray flux), its root mean square (RMS) and harmonic amplitudes were continuously evaluated. The normalized deviation of a measured quantity from its baseline reference $S_{i,ref}$ is expressed as:

$$\Delta Si = \frac{|Si - Si,ref|}{Si,ref} \times 100\% \quad (2)$$

A fault is detected when the deviation exceeds a predefined limit:

$$\Delta S_i > \delta_i \quad (3)$$

where δ_i is the decision threshold.

Based on the simulation results, suitable thresholds were empirically determined as follows:

- Current amplitude threshold: δ_i = 8% for detecting abnormal current rise or drop.
- Harmonic amplitude threshold: δ_H = 5% variation in dominant harmonic order (e.g., 5th or 7th) relative to the healthy state.

The algorithm uses these limits to classify faults:

- If $\Delta I > \delta_I \rightarrow$ electrical fault suspected.
- If $\Delta H_5 > \delta_H$ and $\Delta I > \delta_I \rightarrow$ turn-to-turn or mechanical fault suspected.

These thresholds ensure consistent fault detection performance across simulation scenarios and provide a foundation for future experimental tuning.

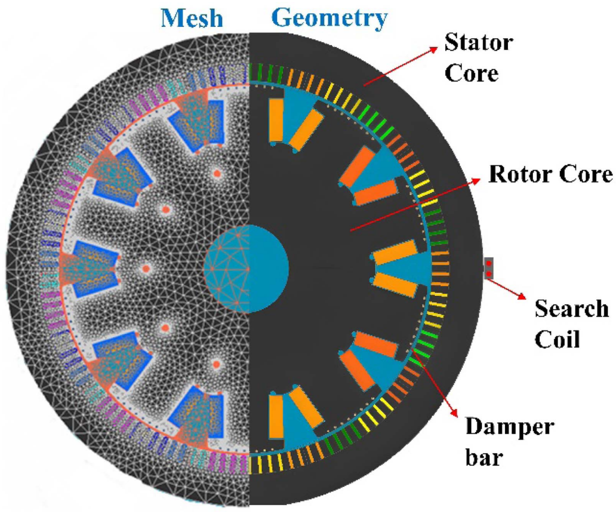


Fig. 4. (Color online) Geometric Structure and Mesh Configuration of the Synchronous Motor Used in Simulation.

4. Simulation Results

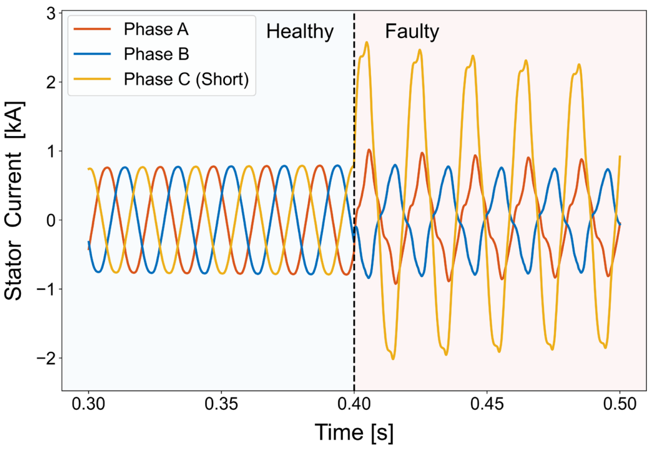
The simulation of the synchronous motor was conducted using Altair's Flux 2D software. The key parameters of the motor are provided in Table 2. The design of the motor, as shown in Fig. 4.

4.1. Ground Short Circuit

During the simulation of ground faults in synchronous motors, significant changes in the electrical characteristics were observed. For a single-phase ground fault, the FFT analysis revealed a noticeable increase in odd harmonics. This fault condition resulted in a marked rise in the current of the affected phase, simplifying fault localization. The simulation results, which include the stator current

Table 2. Key Parameters of The Motor.

Parameter	Value	Parameter	Value
Rated Power [kVA]	6400	Radial Air-gap Length [mm]	20
Pole Pairs	5	Stator outer diameter [mm]	2700
Stator Slots	120	Stator inner diameter [mm]	2120
Rated Voltage [V]	4600	Rotor core outer diameter [mm]	2080
Load [Ohms]	7	Rotor core inner diameter [mm]	500
Rated Rotor Current [A]	230	Stack length [mm]	800



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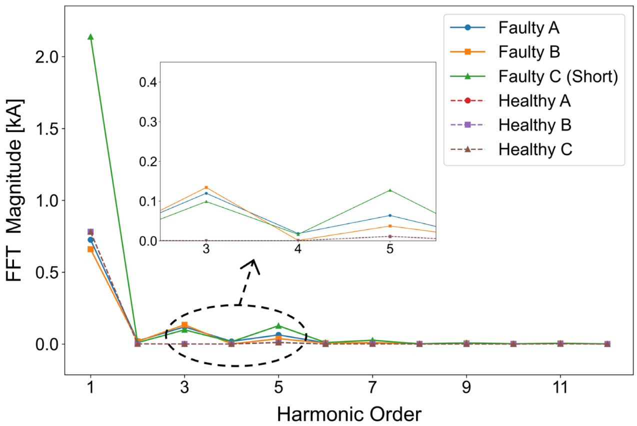

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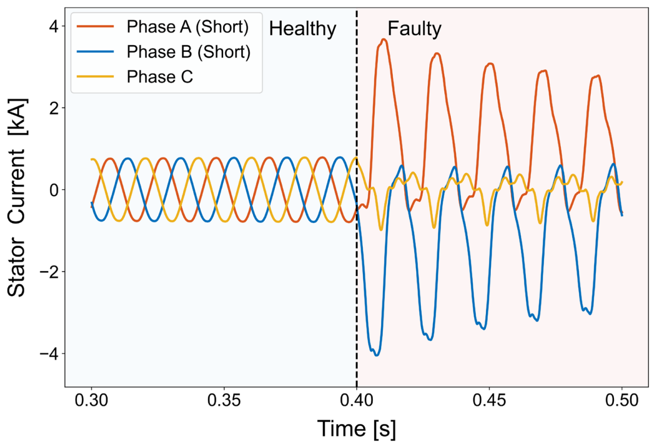
Fig. 5. (Color online) Simulation results of single-phase ground fault (a) Stator currents (b) FFT of stator currents.



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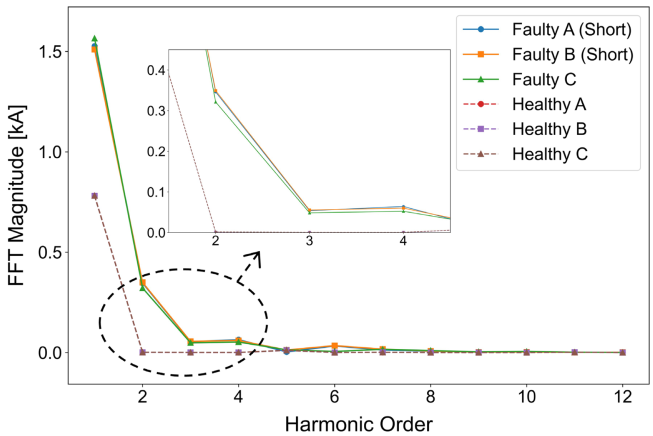


(b)

Fig. 6. (Color online) Simulation results of two-phase ground fault (a) Stator currents (b) FFT of stator currents.

waveforms and corresponding FFT analysis, are presented in Fig. 5.

In the case of two-phase ground faults, a substantial increase in the currents of the faulted phases was observed, along with a phase shift of approximately 120 degrees between them. The FFT analysis indicated a distinct rise in even harmonics, as illustrated in Fig. 6.

4.2. Phase Short Circuit

In the phase-to-phase short circuit scenario, the magnitude of the stator current significantly increased following the occurrence of the fault.

A 180-degree phase difference between the two faulted phases was observed, attributed to the currents in these phases flowing in opposite directions. While there was a minor increase in odd harmonics, the even harmonics became notably more pronounced, as shown in Fig. 7.

A similar trend was observed in three-phase short circuits, where the faulted phases displayed an increase in current levels. The FFT analysis further confirmed the rise in even harmonics, as depicted in Fig. 8.

4.3. Stator Turn-to-Turn Short Circuit

Fig. 9 illustrates the scenario of a stator turn-to-turn fault, where the line current in the affected stator coil decreases by 11.4%, corresponding to the reduction in the number of active turns. The severity of the fault directly influences the extent of this current reduction—more severe faults lead to greater decreases. However, despite these reductions, FFT analysis did not reveal significant changes in the harmonic content. The reduction in stator current could result from temporary reductions due to the activation of protective functions or insulation degradation, complicating the diagnosis of a stator turn-to-turn fault based solely on current measurements. This is where the analysis of stray flux becomes critical. By evaluating

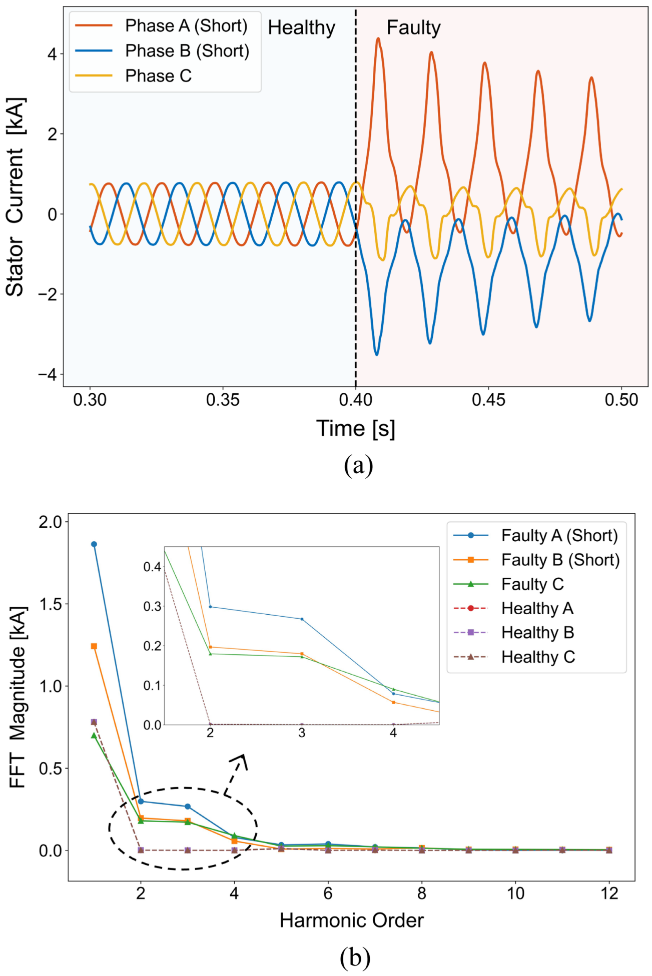


Fig. 7. (Color online) Simulation results of phase-to-phase short circuit (a) Stator currents (b) FFT of stator currents.

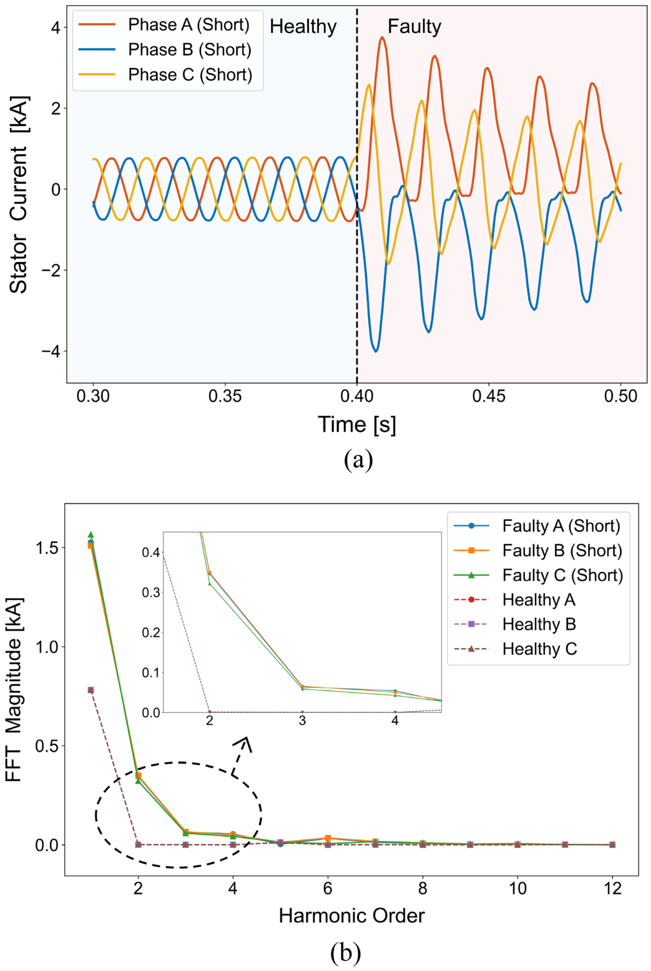


Fig. 8. (Color online) Simulation results of three-phase short circuit (a) Stator currents (b) FFT of stator currents.

harmonic orders using the rotational frequency as the fundamental frequency, it is possible to diagnose turn-to-turn short circuit faults. Notably, changes in the fifth harmonic, influenced by both the supply frequency and the rotational frequency, are particularly useful in identifying these faults.

4.4. Rotor Turn-to-Turn Short Circuit

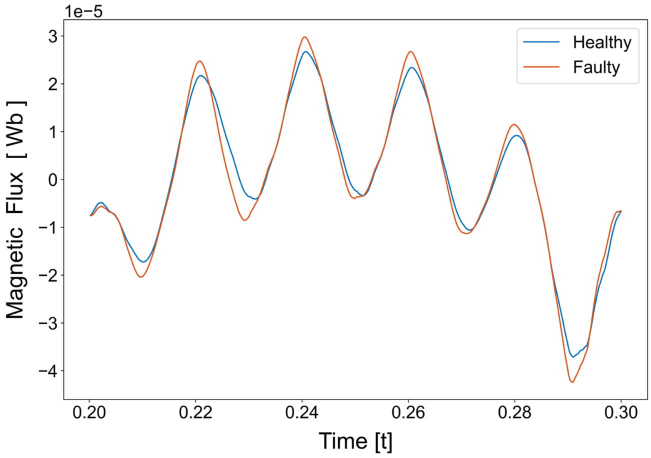
Fig. 10 presents the simulation results for rotor turn-to-turn faults with a 10% fault severity. The reduction in the number of turns in the rotor coils led to a proportional decrease in stator currents across all phases. FFT analysis did not show any significant changes under this fault condition. As fault severity increased, the stator current correspondingly decreased. Stray flux analysis detected distortions as the faulty rotor poles approached the sensors, with variations observed across different harmonic orders, particularly a decrease in the previously dominant fifth harmonic.

4.5. Broken Damper Bars

Unlike other types of faults, broken damper bars or end ring cracks do not cause significant changes in the stator current or stray flux during normal steady-state operation. This is because the primary role of damper bars is to manage transient conditions, such as when there are rapid changes in the motor's speed or load. Damper bars help to stabilize the rotor by dampening oscillations and minimizing torque pulsations, ensuring smooth operation. When the motor is running under steady conditions, the damper bars are not heavily engaged, so their absence does not significantly impact the system's electrical characteristics.

However, broken damper bars can be detected during the motor's startup phase as the field current gradually increases. During this process, stray flux exhibits a

(a)



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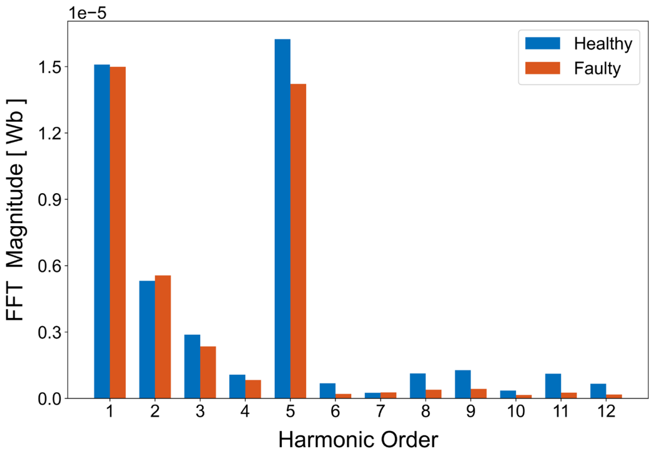
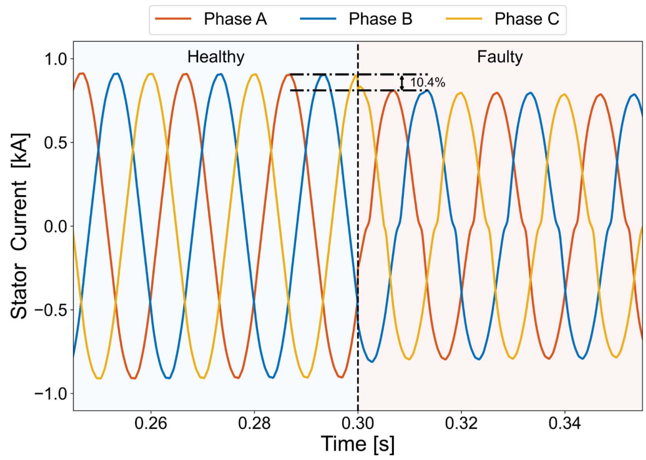


(c)

Fig. 9. (Color online) Simulation results of stator turn-to-turn fault (a) Stator currents (b) Stray flux (c) FFT of stray flux.

noticeable increase due to the intensification of magnetic coupling between the rotor and stator as the field current ramps up. Normally, intact damper bars help dampen oscillations and evenly distribute magnetic forces. When damper bars are broken, they fail to provide this damping effect, leading to an uneven distribution of magnetic forces, which is reflected in increased stray flux.

Furthermore, FFT analysis of the stray flux during the startup phase reveals increased harmonic content across all orders. This increase indicates that broken damper bars disrupt the uniformity of the rotor's magnetic field, creating irregularities that manifest as harmonic distortions in the stray flux. As shown in Fig. 9, this abnormal rise in stray flux and its harmonic components during startup serves as a key diagnostic indicator, signaling the presence of broken damper bars.



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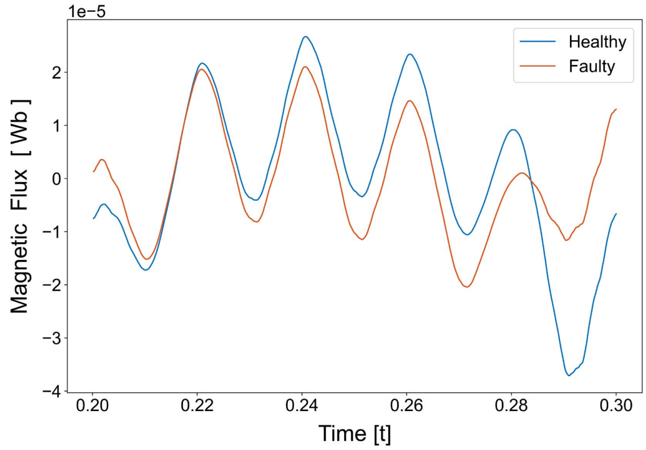

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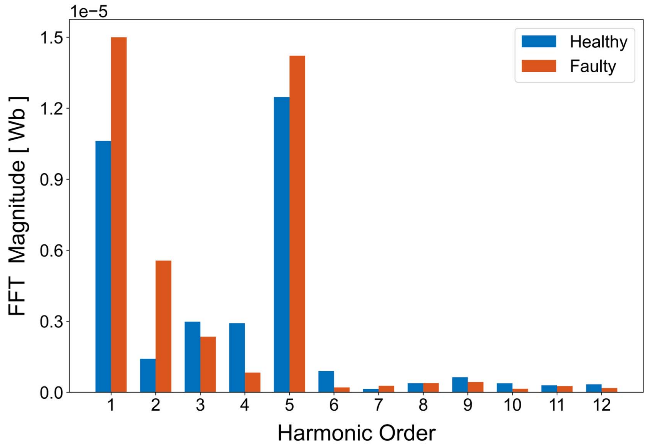

(c)

Fig. 10. (Color online) Simulation results of rotor turn-to-turn fault (a) Stator currents (b) Stray flux (c) FFT of stray flux.

4.6. Eccentricity Fault

Eccentricity faults in synchronous motors, whether SE or DE, induce distinct changes in the magnetic field. SE is characterized by consistent spatial variations in the

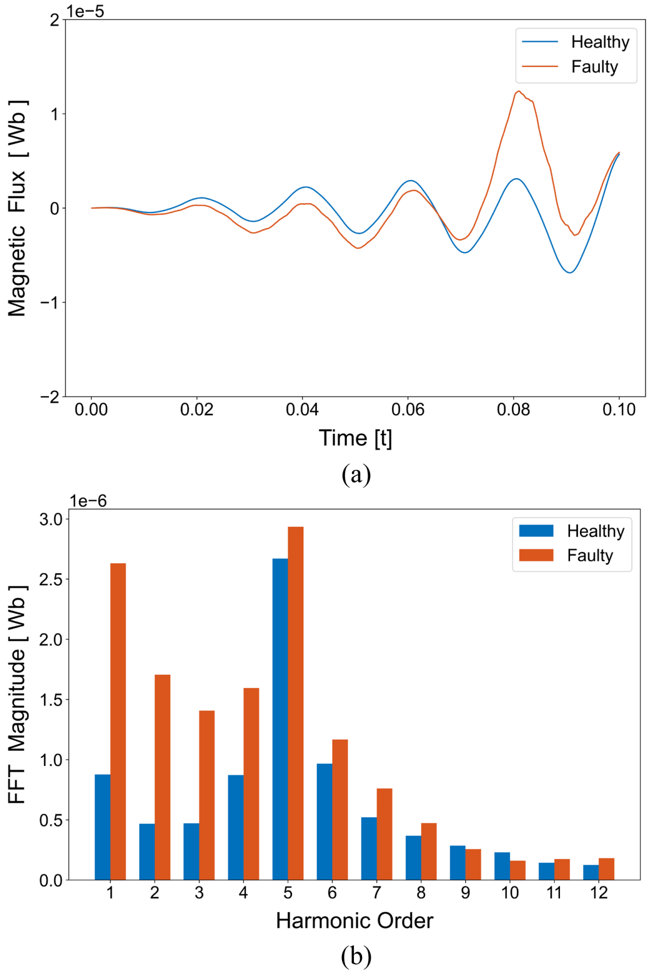

Fig. 11. (Color online) Simulation results of broken damper bar fault (a) Stray flux (b) FFT of stray flux.

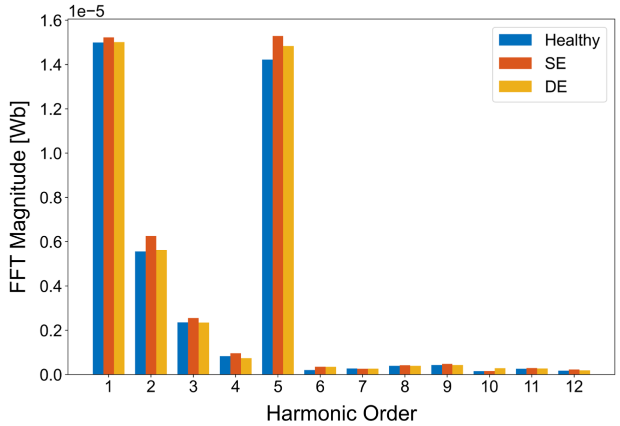

Fig. 12. (Color online) Simulation result of Eccentricity fault.

magnetic field due to a fixed offset between the rotor and stator centers. This results in a difference between the maximum and minimum air gap lengths that remains constant over time. In contrast, DE involves a continuously changing offset as the rotor rotates, leading to temporal fluctuations in magnetic field strength as the air gap dynamically changes.

These variations are reflected in the FFT analysis of the stray flux. For SE faults, there is an increase in harmonic content across all orders, indicating the constant spatial distortion of the magnetic field caused by the uneven air gap. Conversely, DE faults lead to a selective increase in the 5th and 10th harmonics, owing to the temporal variations in the air gap that primarily influence these specific harmonic orders.

These diagnostic patterns are essential for accurately identifying the type of eccentricity fault. The overall rise in harmonics for SE and the specific increases in the 5th and 10th harmonics for DE serve as clear indicators, enabling precise fault diagnosis and facilitating the implementation of effective corrective actions.

4.7. Comparative Harmonic Signature Summary

To consolidate the observations from all simulated fault

Table 3. Comparative Harmonic Signature Summary.

Fault Type	Primary Signal Used	Dominant Harmonic Change	Diagnostic Observation
Single-Phase Ground Fault	Stator current	↑ Odd harmonics (3rd, 5th, 7th)	Sharp rise in current amplitude of affected phase
Two-Phase Ground Fault	Stator current	↑ Even harmonics	Phase shift ≈ 120° between faulted phases
Phase-to-Phase Short Circuit	Stator current	↑ Even + minor odd harmonics	180° phase opposition; simultaneous rise in both faulted phases
Three-Phase Short Circuit	Stator current	↑ Even harmonics across all phases	Uniform current surge; no phase imbalance
Stator Turn-to-Turn Fault	Stray flux	↑ 5th harmonic	Reduced current amplitude; flux distortion visible
Rotor Turn-to-Turn Fault	Stray flux	↑ 5th harmonic	Symmetrical current decrease; harmonic attenuation
Broken Damper Bars	Stray flux	↑ All harmonic orders during startup	Abnormal flux surge due to uneven magnetic coupling
Static Eccentricity	Stray flux	↑ All harmonic orders during startup	Steady spatial air-gap distortion
Dynamic Eccentricity	Stray flux	↑ 5th and 10th harmonics	Time-varying air-gap variation with rotation

conditions, Table 3 summarizes the dominant harmonic variations for each fault type. The comparison highlights distinctive frequency-domain behaviors that enable accurate fault classification. For electrical faults such as ground and phase short circuits, the increase in odd and even harmonics of the stator current is prominent, whereas for mechanical or mixed faults (turn-to-turn, damper bar, eccentricity), the variations appear mainly in the stray flux spectrum. The table serves as a diagnostic reference for distinguishing fault categories using FFT-based harmonic analysis.

5. Conclusion

This study highlights the effectiveness of data fusion techniques involving stator current and stray flux analysis for comprehensive fault diagnosis in synchronous motors. By addressing both electrical and mechanical faults, including stator and rotor winding faults, ground faults, phase short circuits, eccentricity faults, and broken damper bars, this approach provides a robust framework for early detection and accurate diagnosis. The use of stator current harmonics and stray flux analysis allows for the identification of specific fault types through distinctive harmonic patterns, thereby enhancing the reliability of condition monitoring systems.

From a practical implementation standpoint, the diagnostic algorithm requires a minimum sampling frequency of at least 10 kHz, corresponding to more than 200 samples per electrical cycle (50 Hz supply). This rate ensures adequate spectral resolution for identifying low-order harmonics such as the 3rd, 5th, and 7th components in both current and stray-flux signals. In real-time operation, the FFT and deviation analysis can be executed over a 100 ms observation window, yielding a fault detection latency of approximately 0.1 s. Such latency is sufficiently low for early fault interception in industrial synchronous motor drives.

The simulation results validate the proposed diagnostic algorithm's capability to detect faults in real-time, offering valuable insights for predictive maintenance. This methodology not only minimizes operational disruptions but also extends the lifespan of electrical machinery, making it a valuable tool for industrial applications. Future work will focus on refining the diagnostic process and expanding its application to other types of rotating machinery, further improving the efficiency and accuracy of fault detection in power systems.

Acknowledgements

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