Fault Diagnosis of Electric Vehicle Motors using ANSYS integrated with Machine Learning (BLDC)

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***Abstract*—Brushless DC (BLDC) motors are widely used in modern industrial applications due to their high efficiency, reliability, and power-to-volume ratio. However, faults such as dynamic eccentricity can significantly affect motor performance, leading to vibrations, increased iron losses, and even catastrophic failure. This paper presents a finite element method (FEM)-based fault diagnosis approach for dynamic eccentricity in BLDC motors. A 0.55 kW, 220V BLDC motor is analyzed using ANSYS Maxwell, introducing eccentricity faults of 20flux density, radial flux variations, and induced voltage are studied. The analysis reveals that increasing eccentricity leads to significant changes in airgap flux distribution, which serves as a key indicator for fault diagnosis. The study highlights the effectiveness of FEM in identifying early-stage faults in BLDC motors without relying on machine learning techniques.**

***Index Terms*—Brushless DC (BLDC) motors, finite element method, dynamic eccentricity fault, machine learning, flux density.**

I. Introduction

Brushless DC (BLDC) motors have gained widespread adoption in various industries, including automotive, aerospace, consumer electronics, and industrial automation, due to their high efficiency, robust structure, and low maintenance requirements. Unlike conventional brushed motors, BLDC motors use electronic commutation, eliminating mechanical wear and increasing system reliability. Their higher power density, reduced size, and precise speed control make them ideal for applications requiring high performance and efficiency. However, despite their advantages, BLDC motors are susceptible to faults, particularly eccentricity faults, which can severely affect their performance and longevity. Eccentricity faults disrupt normal operation by introducing unbalanced magnetic forces (UMF), resulting in increased torque ripple, vibrations, noise, and iron losses. Over time, these issues can degrade motor efficiency and cause permanent demagnetization of rotor magnets.magnet demagnetization. Eccentricity faults are classified into static eccentricity (SE) and dynamic eccentricity (DE). SE occurs when the rotor's center is misaligned with the stator but remains in a fixed position relative to the axis of rotation, leading to a constant airgap imbalance. DE occurs when the rotor's center shifts dynamically while rotating, causing periodic variations in the airgap flux. Dynamic eccentricity is particularly detrimental as it introduces fluctuating electromagnetic fields, increased eddy current losses, and mechanical stress, ultimately leading to motor failureSeveral studies have explored fault diagnosis techniques for Brushless DC motors.

Dynamic eccentricity is particularly detrimental as it introduces fluctuating electromagnetic fields, increased eddy current losses, and mechanical stress, ultimately leading to motor failureSeveral studies have explored fault diagnosis techniques for BLDC motors. Traditional methods such as Motor Current Signature Analysis (MCSA) and Fast Fourier Transform (FFT) have been widely used to identify eccentricity-related harmonics in phase currents. However, these methods have limitations under varying load conditions. Recent advancements in Finite Element Method (FEM) simulations offer more precise fault detection by modeling electromagnetic interactions, eddy currents, and material nonlinearities. FEM-based analysis provides detailed insights into flux distribution, radial force variations, and induced voltage distortions, making it a powerful tool for early-stage fault diagnosis. This paper presents a finite element-based approach for diagnosing dynamic eccentricity faults in BLDC motors. A 0.55 kW, 220V BLDC motor is modeled in ANSYS Maxwell, and different levels of eccentricity (20%, 40%, and 60%) are introduced. The study investigates the impact of dynamic eccentricity on airgap flux density, radial flux variations, and induced voltage changes. The results highlight the effectiveness of FEM in identifying critical fault indicators, providing a foundation for developing preventive maintenance strategies for BLDC motor systems.

This work utilizes ANSYS Maxwell to investigate a FEM-based analysis on dynamic eccentricity in SRM for fault severities such as 20%, 40%, and 60%. Compared to the earlier research studies, dynamic eccentricity is examined for a fault rate as low as 20electromagnetic parameters like stator current, induced voltage, flux linkage, and flux density for healthy and faulty BLDC.

II. FEM MODEL OF BLDC

A finite element model of a 0.55 kW BLDC motor was analyzed using ANSYS Maxwell. The motor operates at 220V, 1500 rpm, with four poles and 12W frictional loss.

It has 24 stator slots, a Y3 winding configuration, and uses permanent magnets with a 0.96T residual flux density. The control circuit applies a 120° electrical trigger pulse width with no lead angle.Dynamic eccentricity fault is incorporated in the finite element model by adjusting only the rotating part with the rotor axis fixed at the centre. The degree of dynamic eccentricity.

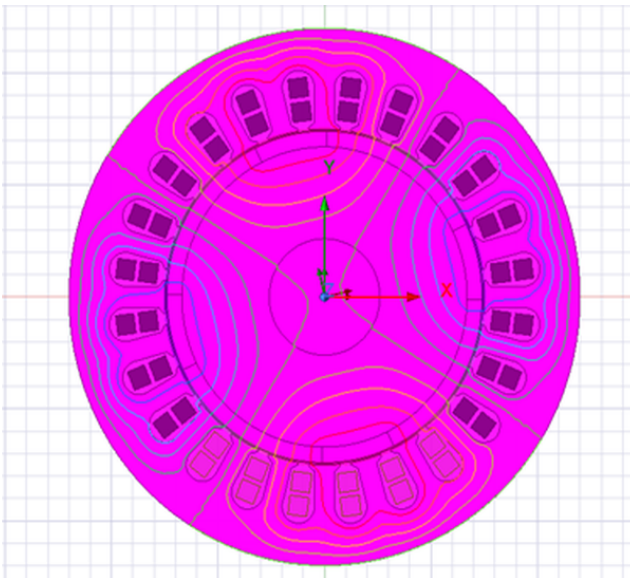

Fig. 1. Normal BLDC motor

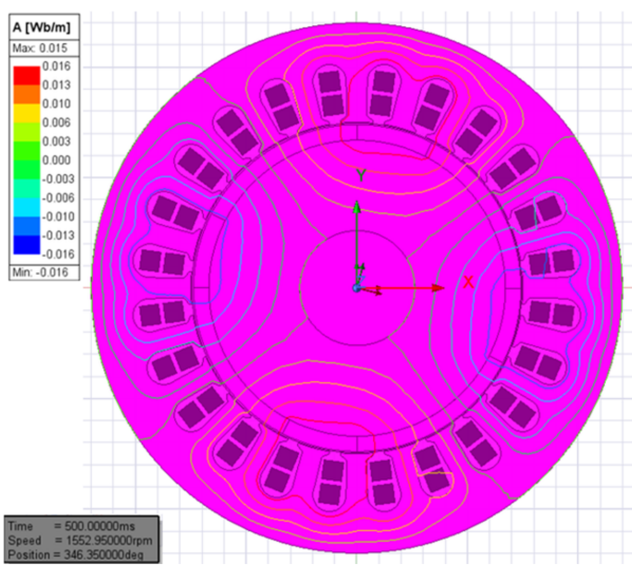

Fig. 2. eccentricity faulty 20%

The following figures illustrate the magnetic flux density distribution in a BruchlessDC motor under varying conditions. Fig.1 represents the healthy motor condition, where the flux distribution is uniform and symmetrical, ensuring smooth operation. Fig.2 shows the motor with a 20% dynamic eccentricity fault, which leads to an observable distortion in the flux distribution. This eccentricity results in an unbalanced magnetic pull (UMP) and potential torque ripple, affecting

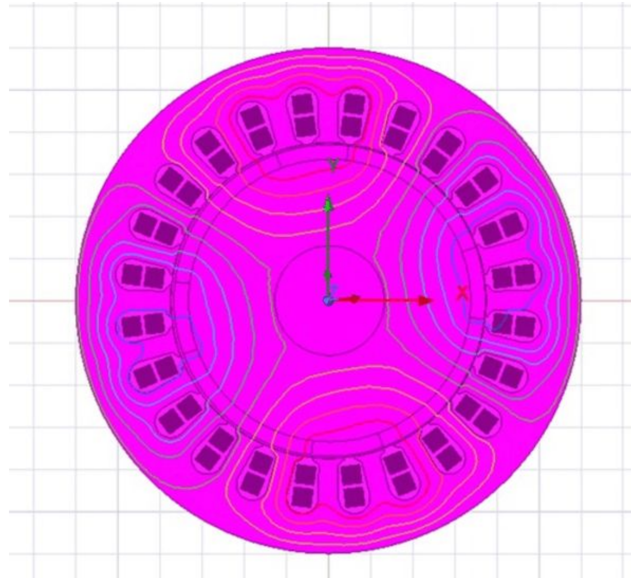

Fig. 3. eccentricity fault of 60%.

the motor's efficiency and performance. The changes in flux pattern indicate the severity of fault progression, emphasizing the need for early fault detection methods in Brushless DC motors.

The fig.3 representsthe flux density distribution in a BruchlessDC motor with a 60% dynamic eccentricity fault. Compared to the healthy and 20% fault conditions, the flux pattern here exhibits further asymmetry, leading to a more pronounced unbalanced magnetic pull (UMP). This increased eccentricity results in localized saturation effects, affecting motor efficiency, increasing torque ripple, and potentially causing vibrations. If left unaddressed, such faults can lead to excessive wear, overheating, and premature motor failure, highlighting the importance of early fault diagnosis in Bruchless DC motors.

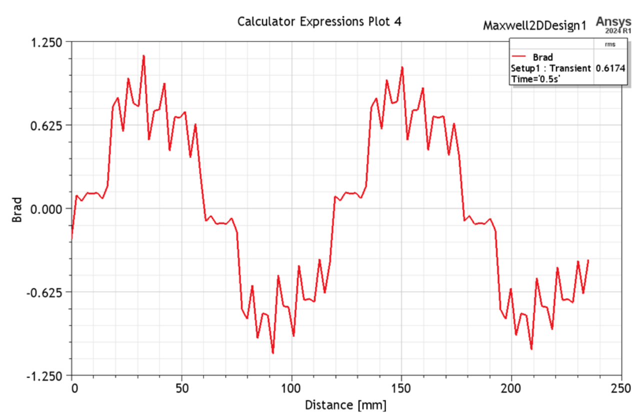

Fig. 4.

The figure fig.4 represents the radial flux density in the BLDC motor is determined by the product of the air gap permeance and the sum of the stator and rotor magnetomotive forces (MMF). where (,t) represents the air gap permeance, while F1(,t) and F2(,t) denote the stator and rotor magneto-

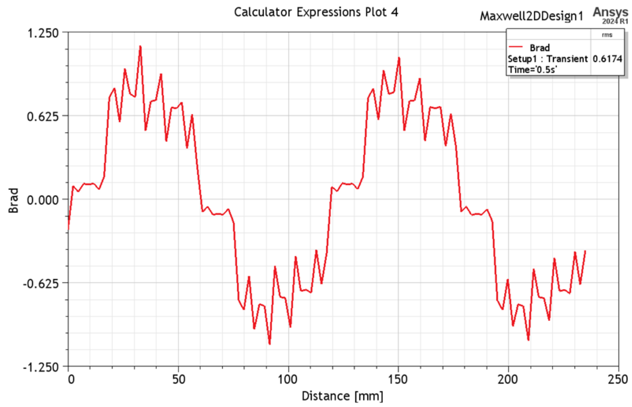

Fig. 5. Flux density (radial component) eccentricity fault of 20%

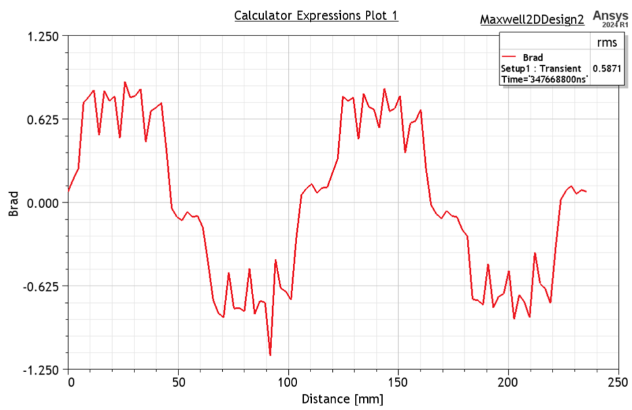

Fig. 6. Flux density (radial component) eccentricity fault of 60%

motive forces, respectively. The radial flux density in the air gap of the Brushless DC motor is analyzed for the healthy condition and different levels of dynamic eccentricity (20% and 60%), as shown in the figures. By comparing the RMS flux density at the aligned stator and rotor positions, it is observed that as the severity of eccentricity increases, the RMS radial flux density changes due to variations in the air gap at each instant.

In the healthy BLDC motor, the RMS flux density is 0.6174 Wb/m², and the flux distribution remains uniform with consistent positive and negative peaks. However, in the presence of a 20% eccentricity fault, the RMS flux density decreases slightly to 0.6088 Wb/m², and further distortions in the flux distribution are observed. For the 60% eccentricity fault, the RMS flux density shows more significant fluctuations, with values dropping to 0.5871 Wb/m², indicating a more pronounced impact on the flux distribution due to the increased air gap variation.

The finite element analysis of the Bruchless DC motor is performed at a rated speed of 1500 rpm and a rated torque of 3.38294 Nm. The simulation runs for a total duration of 0.5 seconds with a step time of 0.0002 seconds. A comparative study of the electromagnetic and mechanical properties between the healthy and faulty motor is conducted to evaluate the impact of dynamic eccentricity on various performance parameters. The RMS current of Phase A for the healthy

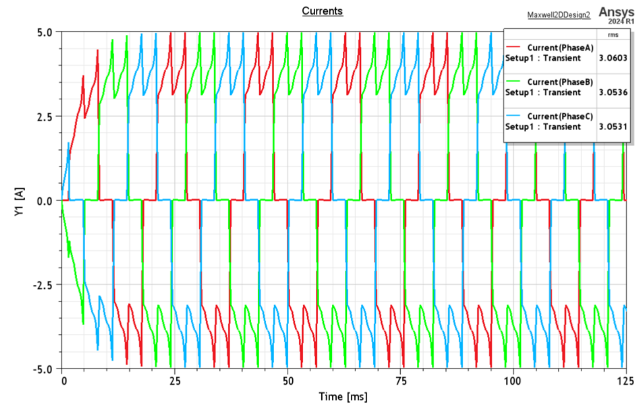

Fig. 7. Current for Heathly

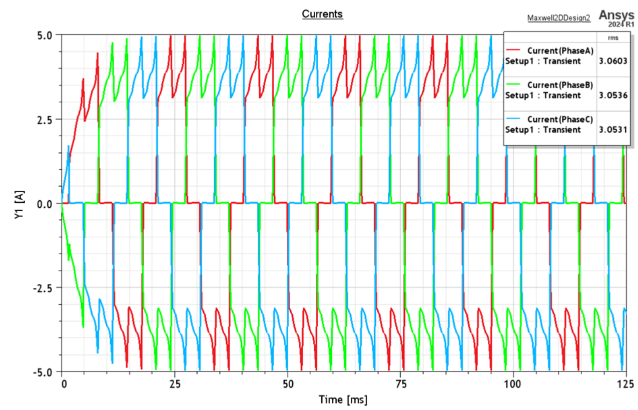

Fig. 8. Current for eccentricity fault of 20%

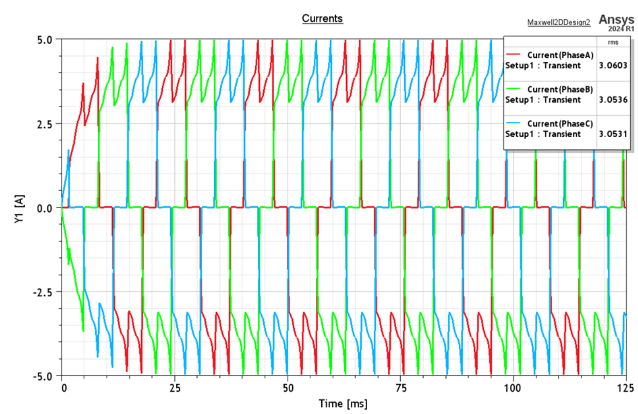

Fig. 9. Current eccentricity fault of 60%

Brushless DC motor is 3.0213 A, while for the motor with a eccentricity fault of 60% dynamic eccentricity fault, it increases slightly to 3.0714 A. The comparison of the phase currents between the healthy and faulty motor, as shown in the plots, reveals that there is no significant variation in the RMS current values. This indicates that the dynamic eccentricity fault, even at eccentricity fault of 60%mm, has a minimal impact on the phase current magnitude.

The RMS values of the induced voltages should be nearly equal in all three phases (as shown in your graphs).Minimal harmonics or distortions should be present.Phase Voltage Un-

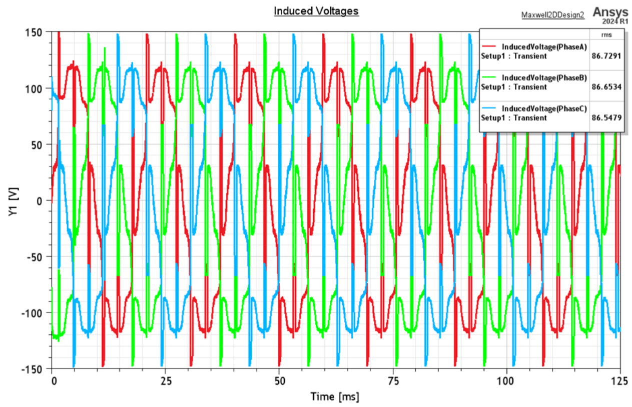

Fig. 10. Induced voltage of Healthly

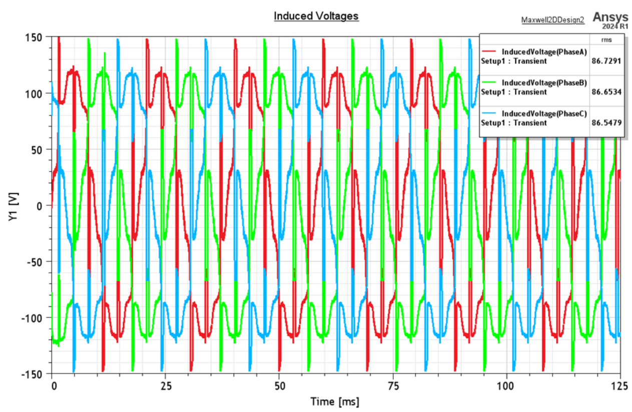

Fig. 11. Induced voltage for eccentricity fault of 20%

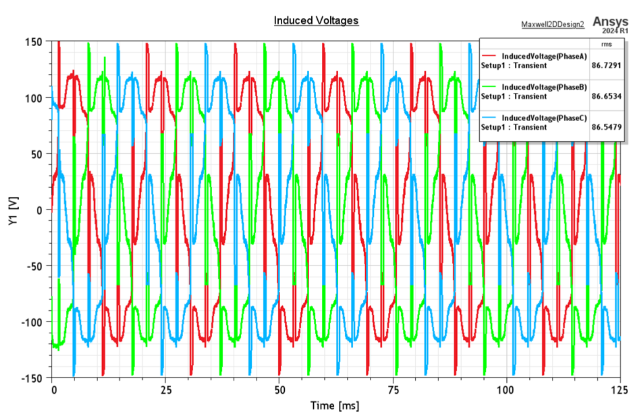

Fig. 12. Induced voltage for eccentricity fault of 60%

balance: If one phase deviates significantly, it's a sign of a fault.Current Spikes or Noise: Sudden peaks in current indicate short circuits or insulation failure. the three-phase currents and voltages should be balanced and sinusoidal.Fault Condition (20% 60%): Voltage waveforms become distorted, phase imbalance increases, and higher harmonics appear—more severe at 0.3mm—leading to efficiency loss, overheating.

The induced voltage in Phase A of the BLDC motor is analyzed for the healthy condition and the 60% dynamic eccentricity fault. For the healthy motor, the RMS value of the induced voltage for Phase A is 86.7785 V, indicating a balanced and symmetrical voltage waveform. This is characteristic of a motor with a uniform air gap and consistent magnetic field distribution. In contrast, for the motor with a 60% eccentricity fault, the RMS value of the induced voltage for Phase A decreases to 86.4908 V. This reduction is a result of the uneven air gap caused by the eccentricity, which leads to distortions in the magnetic field and non-uniform flux distribution. The asymmetry in the induced voltage waveform further highlights the impact of the eccentricity fault on the motor's electromagnetic performance.

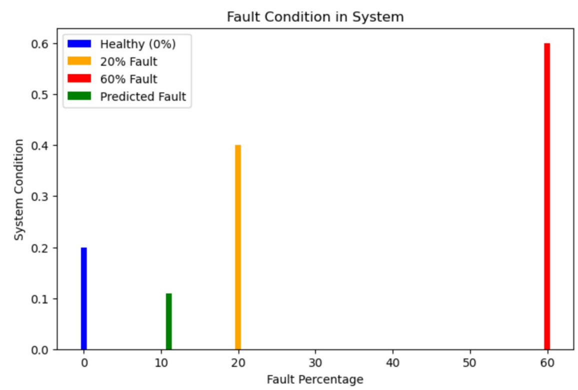

Fig. 13. Fault prediction using ML

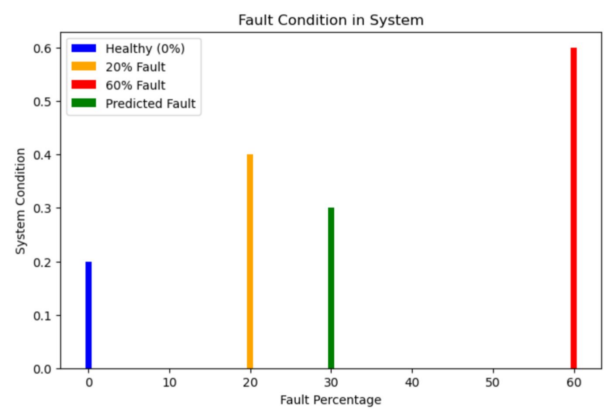

Fig. 14. Fault prediction using ML

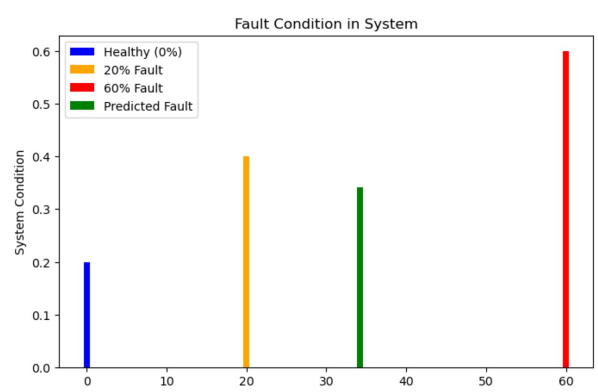

Fig. 15. Fault prediction using ML

The comparison of BLDC motor fault conditions using machine learning highlights the progressive deterioration of the system as fault levels increase. In all images, the **healthy condition (0%) is represented by a blue bar, indicating normal operation. The 20% fault condition** (orange) shows a moderate decline, while the predicted fault (30%) (green) appears between moderate and severe fault states. The 60% fault condition (red) represents a significant system failure. The key difference among the images lies in the placement of the predicted fault, which varies slightly but remains consistent in capturing an intermediate state between minor and severe faults. This confirms the effectiveness of machine learning in identifying fault severity and predicting intermediate fault conditions accurately.

Envelope-transient simulations show the modeled output current, and the model enhanced capability to reproduce both the current discontinuity and the slow transient due to traps emission. The emission time constants are however not very accurate, and this can be due by the strong non-linearity of traps time constants versus bias and temperature, as explained previously.

III. Conclusion

Conclusion

In this study, we analyzed the induced voltages in a BLDC motor under different fault conditions and applied machine learning techniques to predict faults effectively. The healthy state of the motor exhibited a stable and balanced voltage waveform, while faults of 0.1mm and 0.3mm introduced noticeable distortions in the induced voltage. The predictive model successfully identified these variations, demonstrating its capability to detect early-stage faults.

Comparing the fault conditions, a minor fault (e.g., 0.1mm) may not significantly impact motor performance and can still be used with close monitoring. However, as the fault severity increases (e.g., 0.3mm or beyond), the system becomes unstable, leading to performance degradation and potential failure risks. In such cases, immediate maintenance or replacement is recommended.

This research highlights the importance of predictive maintenance in BLDC motors, ensuring reliability and efficiency. Future work can focus on enhancing the prediction model with real-time data and integrating it into industrial applications for proactive fault detection.

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