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TEPES
TURKISH JOURNAL OF
ELECTRICAL POWER
AND ENERGY SYSTEMS

TEPES, Vol. 4, Issue. 3, 118-126, 2024 **DOI:** 10.5152/tepes.2024.24020

RESEARCH ARTICLE

ANSYS-Based Broken Magnet, Demagnetization and Short Circuit Fault Evaluation for a BLDC Motor Designed for Light Electric Vehicle

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Cite this article as: M. Abaci and D. Bayram Kara, "ANSYS-based broken magnet, demagnetization and short circuit fault evaluation for a BLDC motor designed for light electric vehicle," *Turk J Electr Power Energy Syst.*, 2024; 4(3), 118-126.

ABSTRACT

With the growing adoption of light electric vehicles (LEVs), it is becoming increasingly important to optimize their propulsion systems. Brushless DC (BLDC) motors are widely utilized for their high efficiency, precise control, and strong performance. Nevertheless, their reliability faces challenges from various operational failures that can greatly affect the functionality of the vehicle. This study employs Finite Element Method (FEM) analysis to investigate and quantify the effects of specific faults in BLDC motors, with a focus on magnet and stator insulation issues. Two primary types of magnet faults—broken magnets and demagnetization—are explored. Our findings indicate that the severity of these faults correlates directly with adverse effects on motor performance, including changes in current levels, torque, and magnetic flux density. A simulated reduction in magnet coercivity by 30% showcases critical consequences such as increased current draw and failure to generate net torque, highlighting potential performance degradation under high-temperature conditions or other stressors. Additionally, the study examines the impacts of unbalanced single-phase short circuits, which increase harmonic content and torque oscillations, further degrading motor performance. By demonstrating the significant influence of these faults through detailed FEM analysis, this research underlines the necessity for robust motor design and proactive maintenance to enhance the reliability and efficiency of LEVs. This work contributes valuable insights into the fault dynamics of BLDC motors, providing a valuable reference for engineers and researchers in the field of electric vehicle propulsion systems.

Index Terms—BLDC, failure, finite element method, light electric vehicle

I. INTRODUCTION

The efficiency of electrical motors has become vital for industry within the context of the expanding global economy. Compared to other electrical machines, Brushless Direct Current (BLDC) motors have become a preferred option across various sectors, including defense and space, medical devices, and automotive, owing to their low maintenance needs, high performance, and efficiency [1-3]. Beyond these applications, BLDC motors are also used in light electric vehicles (LEVs), such as large-scale scooters and special project vehicles, because of their high power density [2].

BLDC motors are classified as synchronous motors because the rotor speed matches the speed of the revolving magnetic field in the air gap generated by the stator current [4]. A key characteristic of the BLDC machine is the use of magnets instead of windings on the rotor. This design choice enhances the machine's power density by eliminating the brushes and collector structure, which reduces losses, weight, and volume. There are various types of BLDC motors used in different applications, depending on the design and position of the rotor and stator, the layout of the magnets in the rotor, and the motion pattern. However, BLDC motors have two main drawbacks: high cost and complex speed control.

Diagnosing faults in BLDC motors is crucial, especially in high-stakes application areas [5]. These motors, like other electrical machines, can fail due to a variety of reasons including the end of their expected lifespan, excessive or unbalanced loads, and various forms of stress such as mechanical, dynamic, thermal, or electrical [6]. Due to their unique structure, BLDC motors can experience different types of faults compared to typical electrical machines. These faults are generally categorized into electrical and mechanical types. Electrical faults, which are widely discussed in the literature, are

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Received: July 30, 2024
Revision Requested: August 26, 2024
Last Revision Received: September 6, 2024
Accepted: September 17, 2024
Publication Date: October 21, 2024

mainly divided into stator winding faults (short circuit faults) [7] and magnet faults [8, 9]. On the other hand, mechanical faults commonly include bearing faults and eccentricity issues [6].

A common fault in the industry is broken magnet (BM) failure, leading to decreased back EMF, electromagnetic torque, mechanical speed, and magnetic flux, while causing increased phase currents and vibrations [8, 10, 11]. These faults typically stem from the mechanical or magnetic deterioration of the magnets. Various methods, such as Current Signature Analysis (CSA) [8], experimental analysis [6], mathematical model analysis [8], and Finite Element Method (FEM) [9], have been used to compare BLDC motors with broken permanent magnets to healthy ones. Among these, FEM is the most prevalent for motor fault analysis [8, 12]. In FEM, BMs are usually modeled in three ways: (1) by reducing the magnetic coercivity value, (2) by removing sections from the magnet model, and (3) by replacing the magnet material with a non-magnetic one [8]. FEM studies confirm that BLDC motors with damaged magnets exhibit lower back EMF, higher stator current, and increased torque ripple [8]. Another experiment found that some harmonic amplitudes in BLDC motors with magnet damage are approximately 9.1 times greater than in healthy motors [13]. Furthermore, research examining the orientation of magnetic crack defects created horizontal, vertical, and zigzag-type cracks, applying FEM to analyze them. The results showed an increase in all sidebands of fundamental and low-order harmonics, findings that were also validated experimentally. This study concluded that the most critical parameter in magnetic defects is the overall volume of the crack [14, 15].

On the other hand, the most prevalent of these issues is the loss of magnetic properties due to magnet saturation. Factors leading to the demagnetization of a magnet include high operating temperatures, cooling system failures, aging of magnets, corrosion, mechanical wear, and improper stator currents.

Reference [16] compares FEM analysis of partially demagnetized (with 20% and 50% demagnetization) BLDC motors with a healthy system. The impact of demagnetization is hazardous to the machine. It leads to a stark reduction in electromotive force, dramatic drops in stator current and voltages, air gap flux density, and generated torque. Moreover, magnet faults are a primary cause of increased vibration and acoustic noise in the machine. The reduction in torque results in an increase in the current flowing through the windings, which, in turn, leads to further faults in the windings [17].

This integrated description elucidates the severity of permanent magnet faults in BLDC motors and underscores the importance of addressing these issues to ensure optimal motor performance and longevity.

As for the stator winding faults, it is obvious that the primary cause is the damage to the insulation material due to various factors [18]. This deterioration can be attributed to machine overloading, high operating temperatures, cooling system failure, manufacturing defects, transient high voltages, and vibrations that cause friction. Initially, these faults appear as turn-to-turn faults. If monitoring and maintenance are neglected, these faults can escalate into more severe issues, such as phase-to-ground, coil-to-coil, or phase-to-phase faults.

In reference [16], a three-conductor short circuit in one winding of a motor was compared with healthy operation using FEM. This comparison revealed variations in magnetic flux density in the air gap of the motors, indicating that such faults can grow into more significant errors. Another research noted that when comparing a motor with turn-to-turn faults to a healthy motor, the faulty motor exhibited a lower average magnetic flux density. This reduction leads to distortions in the back EMF waveform [19]. These types of faults can also result from eccentricity errors or bearing failures, which cause vibrations, damaging the insulation material. With the occurrence of short circuits in the coils, an opposing magnetic field is generated due to the rotary magnetic field, inevitably leading to the demagnetization of the magnets [20]. Furthermore, when short circuits occur in the internal windings of BLDC, excessive heating of the coils ensues [11].

Motivation of the study: The increasing importance of sustainable transportation solutions underscores the need for advanced research in electric vehicle propulsion systems. Specifically, BLDC motors have become essential in the design of LEVs due to their efficiency and dependability. However, the complexity of these systems and their vulnerability to malfunctions necessitate a deeper understanding of potential failure modes and their extensive impacts. This research aims to improve the reliability and performance of BLDC motors, thereby supporting the wider adoption of LEVs as a sustainable transportation option.

In this study, we conduct a failure analysis based on the FEM for a BLDC motor that has been designed for use in LEVs. A reference model representing the healthy state of the motor is initially established to serve as a baseline. Subsequently, the research examines magnet and stator insulation faults of varying severities through a detailed FEM analysis. This approach not only facilitates comprehensive modeling and understanding of the faults but also explores the impact of BMs and demagnetization processes on motor performance. Furthermore, the study encompasses an investigation of the effects of unbalanced single-phase short circuits and their

Main Points

- Fault analysis using FEM can provide significant insights into understanding BLDC motor faults.
- Magnet faults, such as demagnetization and broken magnets, can lead to increased current draw and reduced motor efficiency due to the fixed load condition.
- Single-phase short circuits result in increased harmonic content and torque oscillations, negatively affecting motor performance.
- The study underscores the necessity for robust motor design and proactive maintenance to enhance the reliability and efficiency of LEVs.
- This research provides valuable insights into BLDC motor faults, emphasizing the need for ongoing development to optimize motor performance in LEVs.

TABLE I.
FUNDAMENTAL PARAMETERS OF THE BRUSHLESS DIRECT CURRENT MOTOR

Symbol	Parameters	Value
V	Rated voltage	50 VDC
P	Number of poles	24
N	Reference speed	300 rpm
P_O	Output power	1000 W
NdFeB	Magnet type	Surface Mounted
b_T	Magnet thickness	0.4 cm

implications on harmonic content and torque oscillations. Given that the motor was designed for realistic operational conditions and that the simulation results align with existing literature, the findings from these analyses are intended to provide in-depth insight into the failure mechanisms of BLDC motors used in LEVs. Furthermore, they are designed to highlight the critical areas for future research and development in electric vehicle propulsion systems.

II. ANSYS-BASED BLDC MODEL FOR LEV

To achieve more accurate fault analysis results, a BLDC motor specifically designed for LEVs and manufactured by BINGEZ Automotive Ind. Ltd. Co. was selected. Table I provides a summary of the motor's electrical and geometrical parameters.

For the finite element (FE) analysis, ANSYS software was utilized. Initially, the motor's analytical model was constructed using the RMxprt module in ANSYS. This model was then transferred to MAXWELL 2D to conduct the FE analysis. The analysis was conducted with a total time of 40 ms and a step-time of 0.2 ms. The 2D model and the resultant magnetic flux density distribution of the motor are illustrated in Fig. 1.

III. ANSYS-BASED FAULT EVALUATION FOR BLDC

In this section, the faults related to BMs and demagnetization of varying severities have been investigated using the FEM. This detailed simulation approach provides a comprehensive analysis of how different levels of these faults impact the motor's functionality.

To simulate a BM fault, a piece of about 5% of the surface area of the magnet is removed initially. This amount is later increased to 40%. Each scenario is analyzed separately and compared to the reference motor.

When examining the analysis results, critical changes are observed in the current, average torque, and magnetic flux density of the motor.

A. Broken Magnet Fault

As the magnet's contribution to torque induction decreases, the current increases to balance the load. For the reference motor, the maximum current value is around 79 amperes. In contrast, the maximum current value increases to 82 amperes and 92 amperes for magnet breakage rates of 5% and 40%, respectively. Additionally, to understand the current drawn more analytically, Fast Fourier Transforms (FFTs) of current signals are calculated, as seen in Fig. 2. The harmonic components of motors with BM failure increase compared to the reference motor. Moreover, the number of harmonic components increases as the failure percentage rises. The FFTs performed refer to a transformation applied by ANSYS based on the time step specified by the user. In the context of this study, ANSYS establishes a minimum Δf range of 25 Hz, which is quite large for signal processing purposes. Despite this limitation, the calculated FFTs provide important outputs that contribute to the interpretation of FE results.

The torque calculated for the reference motor has significant torque ripples, which led to the decision to conduct all fault analyses solely under nominal load and speed conditions. The reason for this is that FEM does not take into account the mechanical damping factors to calculate the torque; it only considers the current waveform to deduce it. Moreover, the optimization of cogging torque is achieved by adjusting the slot-to-magnet ratio. This modification effectively minimizes the torque ripple, which is critical for enhancing the operational smoothness and efficiency of BLDC motors. For this motor, the cogging torque ratio is anticipated due to the design prioritizing commercial concerns over performance expectations.

Compared to the torque produced in a healthy state, the average torque of the motor with a slight BM fault was found to be

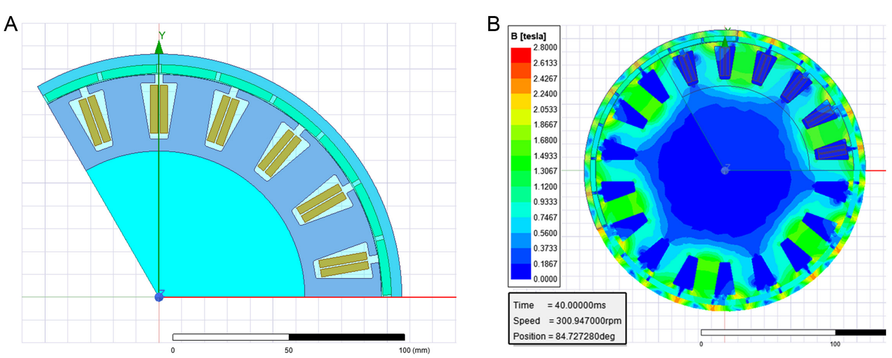

Fig. 1. (A) 2D design and (B) magnetic flux density map of the reference motor.

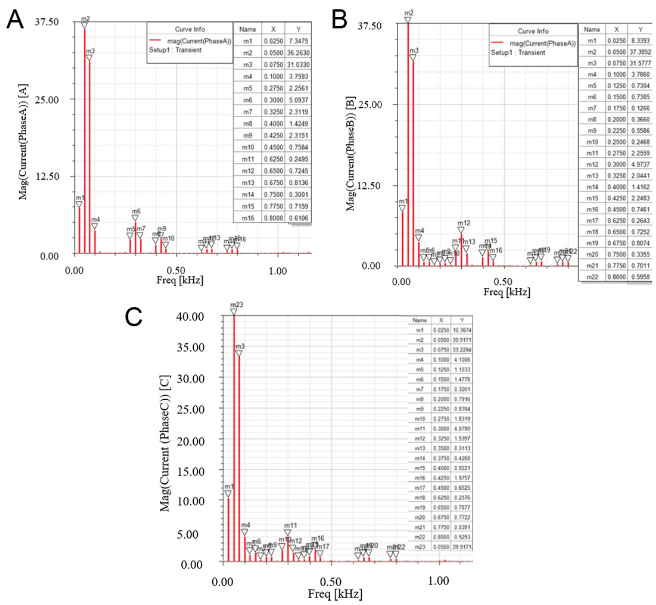

Fig. 2. Fast fourier transform of currents for (A) reference motor (B) motor with 5% broken magnet fault, (C) motor with 40% broken magnet fault.

slightly higher than that of the healthy condition, accompanied by an increase in the oscillation interval. These average torque values were calculated in ANSYS, taking into account the transient phases. Such unexpected results are understandable, given the variability in transient oscillations, particularly when using FE analysis that hasn't been finely calibrated.

At 5% fault, the oscillation range increased, while at 40% fault, the average torque value decreased despite the transient oscillations, and the oscillation range expanded significantly. To eliminate the confusing effects of transient phases, we focused solely on steady-state operation. The recalculated average values for each condition are provided in Table II. The average steady-state torque for the motor with a 5% BM fault is very close to that of the healthy condition. This outcome is not uncommon, especially when using a FE analysis that has not been precisely tuned due to computational limitations. However, as the severity of the BM fault increases, the average steady-state torque decreases noticeably, while both the fluctuation intervals and the time required to achieve steady-state torque increase.

As a final evaluation criterion, magnetic flux density plots are analyzed. In the magnetic flux density map of the reference motor, minimal saturation appears around the rotor yoke, while the distribution is mostly balanced.

In the graph of the motor with 5% BM in Fig. 3A, the magnetic flux density disappears at the location of the BM, as highlighted by the red circle, creating an unbalanced distribution. This imbalance is clearly visible in the map of the motor with 40% BM, around the BM and associated teeth, as shown in Fig. 3B.

This observation can be considered a justification for the exaggerated oscillations in torque and the increased cogging effect seen in Fig. 4C, resulting naturally from this magnetic flux density distribution.

B. Demagnetization Fault

To model the demagnetization fault, manipulations have been made to the material properties of the magnets. The analysis has been conducted by reducing the coercivity value by 30% for a motor magnet, which is a derivative of Neodymium Iron Boron (NdFeB35).

When comparing the current graphs to those of a healthy motor, significant changes are clearly observable. The maximum and minimum values of the current have increased by approximately 20–30%, as seen in Fig. 5.

Examination of the torque graph reveals a significant drop in torque. As can be seen in Fig. 6, the demagnetization of all magnets has resulted in the motor's inability to produce a net rotational torque different from zero. This situation leads to a torque drop that is large enough to prevent the motor from rotating. The primary reason behind the low torque is the choice of a cost-oriented motor design. In such designs, less expensive magnets are used that are not resistant to demagnetization. Consequently, the motor loses its ability to produce torque over time and fails to deliver the desired performance.

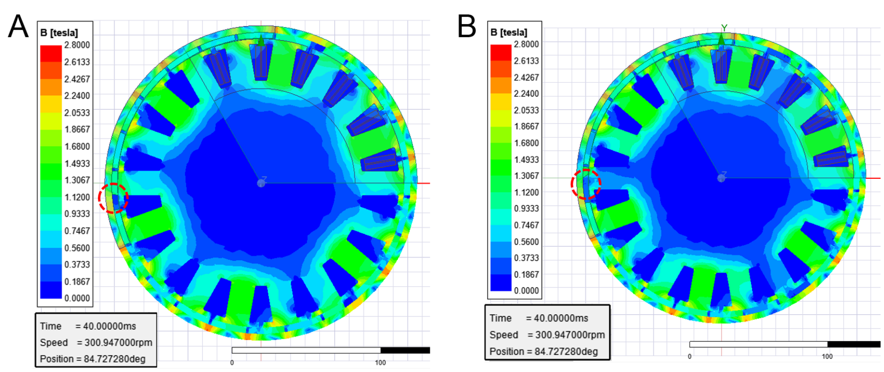

Fig. 3. Magnetic flux density maps for motors with (A) 5% (B) 40% broken magnet fault.

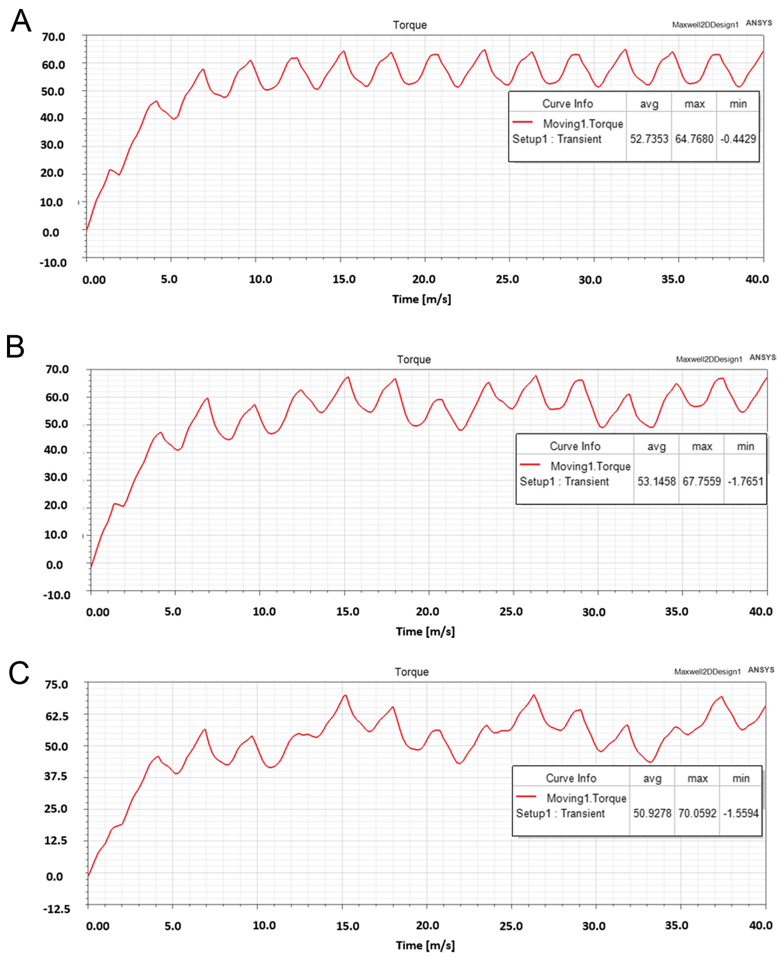

Fig. 4. Torque graph of (A) reference motor, (B) motor with 5% broken magnet fault, (C) motor with 40% broken magnet fault.

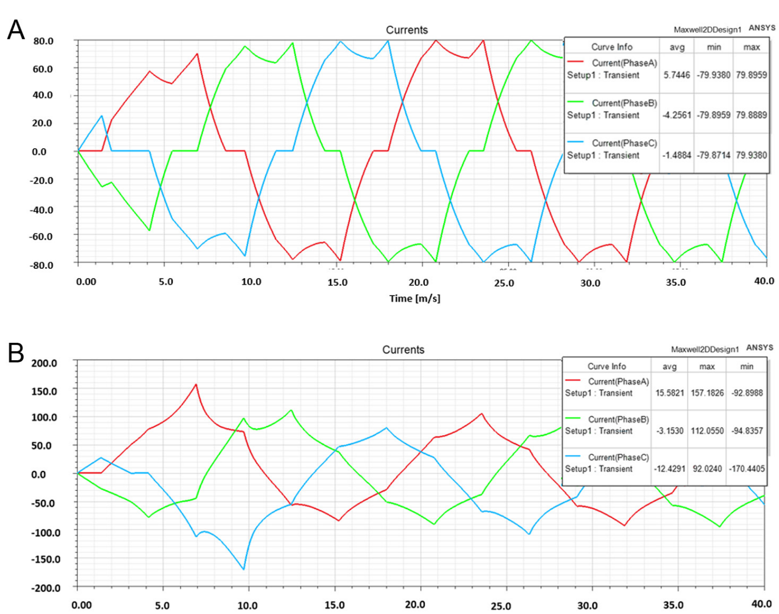

Fig. 5. Current for (A) reference motor, (B) motor with 30% demagnetization fault.

TABLE II.
TORQUE PERFORMANCES FOR HEALTHY AND BROKEN MAGNET-BRUSHLESS DIRECT CURRENTS

	Ref. Motor	Motor With 5% Broken Magnet Fault	Motor With 40% Broken Magnet Fault
Resulted average torque (Nm)	52.73	53.14	50.92
Resulted average steady-state torque (Nm)	58.36	58.78	56.91
Torque fluctuation intervals (Nm)	13.21	19.70	27.20
Required time to average torque (ms)	10	12	18

Finally, the magnetic flux density is examined. Fig. 6 illustrates the magnetic flux density of the motor. The reduced magnetic field due to demagnetization of the magnets has also diminished the amount of generated magnetic flux.

C. Short-Circuit Fault

Currently, the short-circuit fault is one of the most common faults and significantly affects the current and torque of the motor. Modifications were made to the resistance values in the equivalent circuit to model this fault in the ANSYS program. In this context, the fault is better described as a turn fault since it simulates a localized short circuit within a coil by reducing the resistance of one of the rotor windings.

Similar to the BM fault, this type of fault is also implemented for two separate severity levels, 30% and 50% while their currents can be

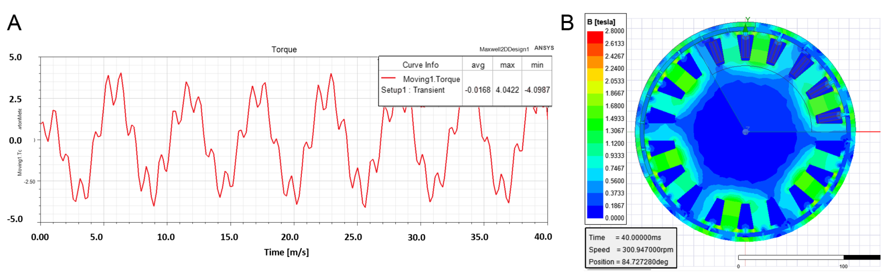

Fig. 6. (A) Torque and (B) Flux density map of Brusless Direct Current motor with 30% demagnetization fault.

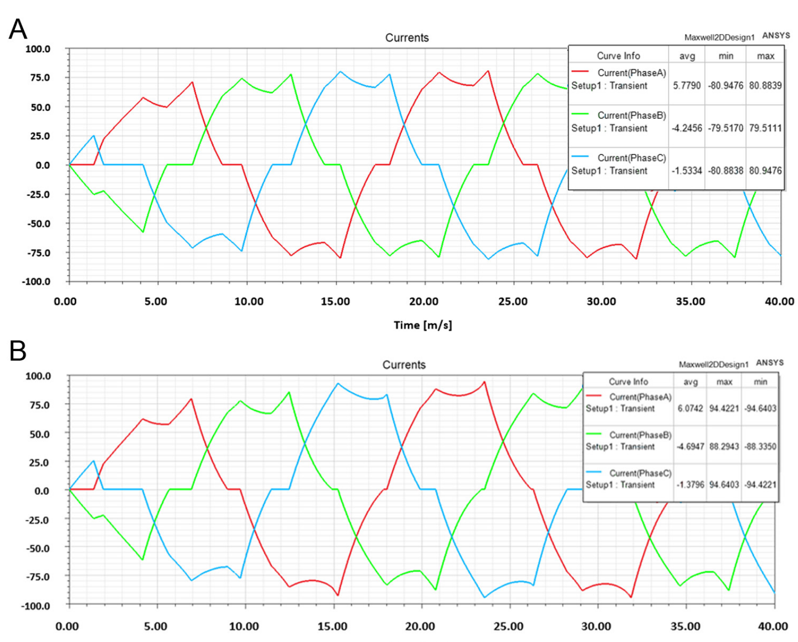

Fig. 7. Current of (A) motor with 30% short-circuit fault, (B) motor with 50% short-circuit fault.

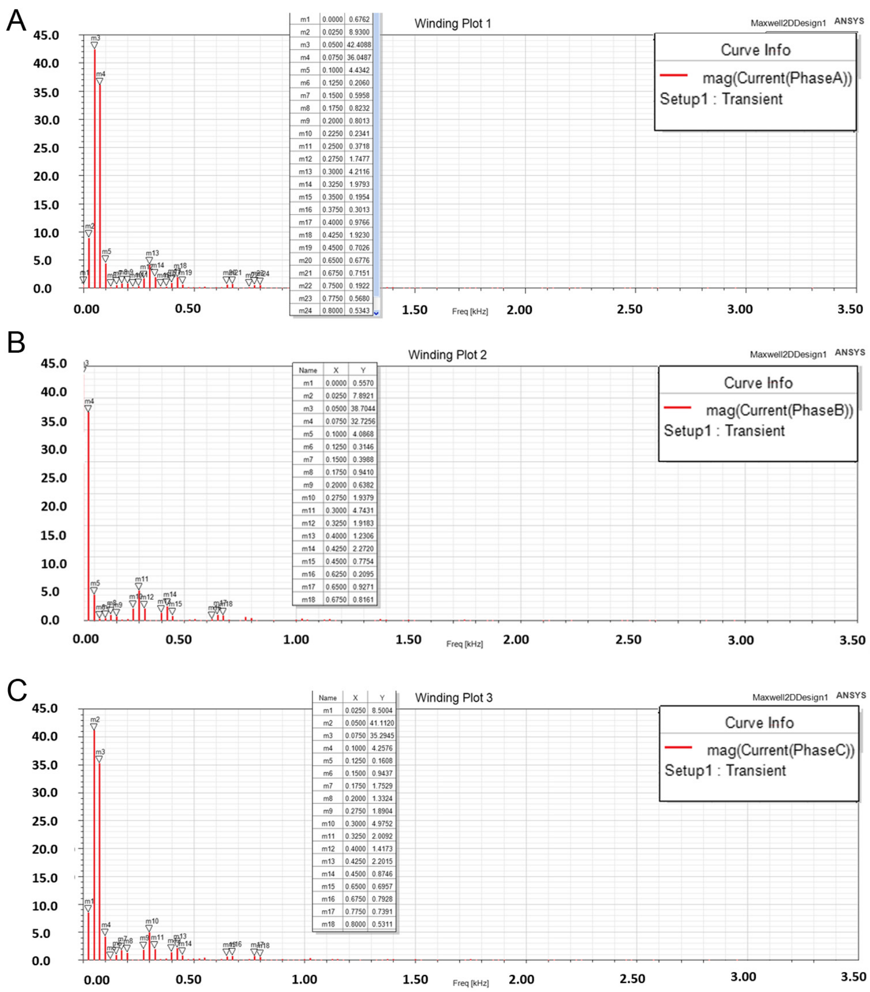

Fig. 8. Current fast fourier transforms for brushless direct current with a 50% short-circuit fault (A) Phase A (B) Phase B (C) Phase C.

seen in Fig. 7. The unbalanced increase in currents is also clearly evident in the FFT graphs. In Fig. 8, the FFTs for phase currents A, B, and C are shown, respectively. Upon examining the figure, it has been determined that phase A, where the turn short-circuit occurred, exhibits more harmonics compared to the other phases.

As for torque values of motors with short-circuit faults, it is observed that the fluctuations in torque increase as the severity of the short-circuit increases, as seen in Fig. 9A.

Finally, changes in magnetic flux density are examined. As shown in Fig. 9B, it is clearly evident that the magnetic flux density of the motor with the short-circuit fault increases in certain regions compared to the healthy motor. Additionally, when examining the stator yoke of the motor with the short-circuit fault, accumulated flux densities caused by the short-circuit are clearly observed.

IV. CONCLUSION

As LEVs become more prevalent in our daily lives, the selection of propulsion systems assumes great importance for optimizing performance and sustainability. Among the various options, BLDC motors are particularly well-suited for LEV propulsion, offering robustness, efficiency, and a high degree of control. These advantages, when considered alongside the growing prevalence of LEVs, highlight the necessity of investigating operational failures, which have emerged as a prominent area of examination in the field of research.

Considering their extensive usage, understanding the possible effects of such failures is essential. This research utilizes the FEM as a non-intrusive approach to assess the potential impacts of faults in BLDC motors, specifically focusing on two key components: magnets and stator insulation.

This study examines the effects of magnet errors, with a particular focus on BMs and demagnetization. In the case of BMs, the study has demonstrated that the severity of the fault directly influences the increase in current values and the decrease in both the average torque and torque ripples. Moreover, the demagnetization process, which was simulated by intentionally lowering the coercivity values of magnets, revealed critical impacts at a 30% reduction. These included a reduction in flux density, an increase in current,

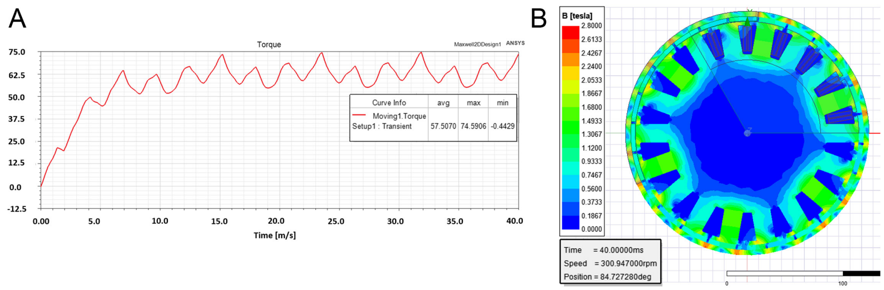

Fig. 9. Torque (A) and (B) magnetic flux density for BLDC with a 50% short-circuit fault.

and an inability to generate a net moment. Such conditions have the potential to arise due to elevated temperatures and other contributing factors, which could significantly impact the performance of the LEV.

Furthermore, an investigation was conducted into the effects of a single-phase unbalanced short circuit condition. It was observed that the affected phase exhibited a notable increase in the harmonic content of the current, which subsequently resulted in torque oscillations. This performance degradation has a predictable preliminary effect due to the magnetic material not being as homogeneously utilizable as it is in a healthy state.

The results of these FEM analyses effectively demonstrate the considerable performance deterioration in BLDC motors under fault conditions. This study not only contributes to our comprehension of the ways in which LEVs can be affected by motor faults but also underscores the necessity for robust design and maintenance strategies to mitigate these issues. By investigating these specific faults through FEM, this research offers distinctive and valuable insights into the challenges and solutions for optimizing motor performance in LEVs in a manner that is beneficial to both academic and industrial contexts.

In summary, engineers should consider the following key recommendations:

- Magnet Design: Enhance magnet design by improving coercivity and structural integrity to reduce the risks of faults, such as BMs and demagnetization, particularly under high temperatures.
- Insulation Techniques: Use advanced insulation materials and methods to lower the chances of short-circuit faults, thereby minimizing harmonic distortion and torque fluctuations.
- Maintenance Protocols: Develop proactive maintenance routines that focus on early fault detection and repair, especially in critical components like magnets and stator windings.
- Simulation and Testing: Integrate comprehensive FEM analysis during design and testing to identify potential faults early, allowing for timely design improvements and performance optimization.
- These strategies are aimed at developing more reliable and efficient BLDC motors for LEVs, ensuring better performance and longevity.

Availability of Data and Materials: The data that support the findings of this study are available on request from the corresponding author.

Peer-review: Externally peer-reviewed.

Acknowledgments: The authors would like to thank BINGEZ Automotive Ind. Ltd. Co., for generously sharing their BLDC design parameters and permission to publish it. A preliminary version of this study was presented at ELECO 2023, which was held in Bursa, Turkey. The authors acknowledge the feedback and insights received during the conference, which have significantly contributed to the refinement and expansion of this research.

Author Contributions: Concept – D.B.K.; Design – M.A.; Supervision – D.B.K.; Resources – D.B.K., M.A.; Data Collection and/or Processing – M.A.; Analysis and/or Interpretation – D.B., M.A.; Literature Search – M.A.; Writing – D.B.K.; Critical Review – D.B.K.

Declaration of Interests: Duygu Bayram Kara is a member of Advisory Board of Turkish Journal of Electrical Power and Energy Systems, however, her involvement in the peer review process was solely as an author. Mahmut Abaci has no conflicts of interest to declare.

Funding: This study received no funding.

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