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Enhancing Engineering Education: Integrating Finite Element Method Analysis for Induction Motors Efficiency Improvement Study

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***Abstract*— This paper focuses on the educational aspect of advanced engineering practices, particularly in the incorporation of Finite Element Methods (FEM) into the engineering curriculum. It examines the transformation of a conventional three-phase induction motor (3PIM) into a more complex six-phase induction motor (6PIM) and the subsequent effects on the torque characteristics. Through the practical application of FEM in a learning environment, engineering students can quantitatively analyze and assess the torque performance of the hex-phase machine. The study's findings highlight a decrease in torque ripple and an improvement in the machine's overall efficiency. These results serve as a valuable educational tool for engineering students, enhancing their understanding and skills in applying FEM to real-world electromechanical systems.**

Keywords—Finite Element Method education; engineering student training; multiphase induction motor analysis; torque characteristics in engineering education; torque smoothness optimization; electromechanical system efficiency; hands-on FEM application.

I. Introduction

In the realm of engineering education, where practical knowledge converges with theoretical studies, there exists an opportunity to enrich the learning experience of students through hands-on application of simulation tools. This paper opens a dialogue on the educational value of incorporating Finite Element Methods (FEM) in the analysis and design of electrical machinery within an academic context, targeting the reduction of torque ripple—a crucial parameter in precision-demanding applications [1]. Students are encouraged to approach this challenge not merely as a technical obstacle but as an integral component of sustainable engineering practices, emphasizing the conservation of resources and the avoidance of rare earth materials [2]. With the aim to refine torque production, the educational exercise outlined herein involves the conversion of a standard three-phase induction motor (3PIM) into a six-phase induction motor (6PIM). This pedagogical project justifies its strategy by teaching students that an increased phase count can potentially lead to a more uniform flux distribution, which, in turn, promises a decrease in torque ripple and an improvement in the motor's performance [3][4][5].

The transition to a six-phase system enhances complexity and illustrates the integration of advanced design principles in real-world settings. Integrating Finite Element Method (FEM) in education reflects the dynamic evolution of engineering instruction, where simulation is not only a verification tool but also a platform for in-depth experimentation and understanding. This approach allows students to analyze the magnetic and torque behaviors of electrical machines within a predictive, controlled environment, supporting the industry's shift towards simulation-driven design for improved efficiency and reliability [6][7][8]. Addressing the pressing issue of sustainability, this paper underscores the importance of designing systems that are environmentally conscious and economically viable. The significance of sidestepping the use of additional rare earth elements resonates with current global narratives of environmental impact and supply chain vulnerabilities, encouraging students to consider the broader implications of their design choices [9][10].

This paper is structured to guide the reader through the educational journey as follows: • Section I: Introduces the academic premise and outlines the case study. • Section II: Details the original 3PIM design considerations and the implementation of FEM in the educational setting. • Section III: Describes the conversion process and considerations involved in transforming a 3PIM into a 6PIM. • Section IV: Discusses the results derived from the application of FEM and the subsequent analysis. • Section V: Concludes with insights gained and suggests directions for future educational research.

The narrative presented guides engineering students through an examination of how a six-phase system improves torque performance compared to a three-phase system, enhancing their theoretical and practical understanding, essential for future innovations and reliable operations.

II. INTEGRATING FINITE ELEMENT METHOD INTO ENGINEERING EDUCATION: DESIGN OF A 3-PHASE INDUCTION MOTOR

The design of a 3-phase induction motor lays the foundation for applied learning in electromechanical systems within an engineering curriculum [11]. This section elucidates the process of designing a 3.5 kW, 415 V (line-to-line), 4-pole, star-connected, 1313 rpm, 50 Hz 3-phase induction motor, reinforcing student understanding of motor operation and design principles.

Key elements of motor design, such as stator and rotor dimensions, core length, winding configuration, and material selection, are addressed [12]. The motor's geometry, as modeled in ANSYS® Maxwell RMxprt, is displayed in Figure 1, serving as the subject of study.

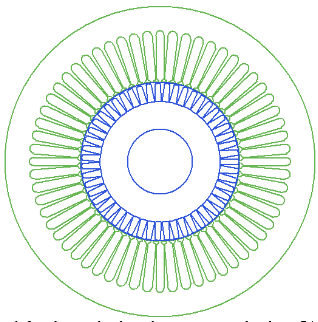
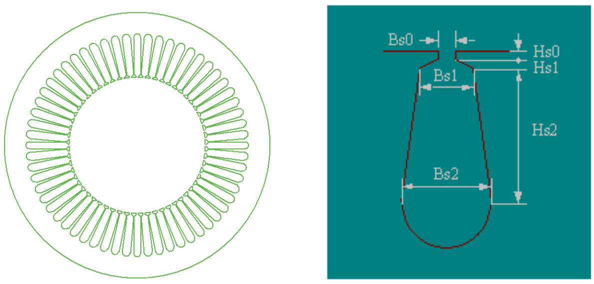


Fig. 1. Conventional 3-phase induction motor design [13]

Figure 1 details the template of the base motor. A 60-slot stator (depicted in green) and a 51-slot rotor with its shaft (highlighted in blue) are visible, demonstrating the fundamental components of the motor's architecture.

A. Stator and slot geometry

The stator's design, along with its slot geometry, is presented in Figure 2, with additional parameters detailed in Table I.



a) b)

Fig. 2. a) Stator geometry; b) slots geometry [13]

TABLE I. GEOMETRICAL CHARACTERISTICS OF THE STATOR

Parameter	***Values***
External diameter	165.00 mm
Inner diameter	85.00 mm
Length	194.00 mm
Nº Slots	60
Material used	Steel_1008
Hs0	0.50 mm
Hs1	1.00 mm
Hs2	22.90 mm
Bs0	1.30 mm
Bs1	4.20 mm
Bs2	5.10 mm

The stator features 60 slots, and Figure 2 along with Table I reveal the specifics of the slot shapes and dimensions.

B. Stator winding configuration

The configuration of the stator's windings is illustrated in Figure 3, demonstrating the implementation of winding theory in practice.

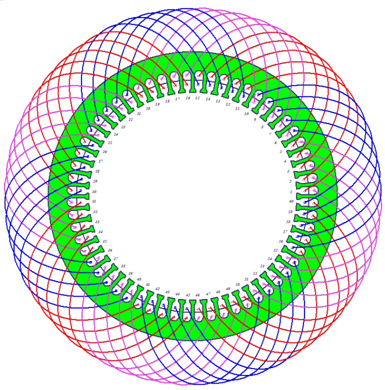


Fig. 3. Stator's winding configuration [13]

As depicted in Figure 3, the stator slots accommodate a double-layer winding pattern with alternating sequences for each phase, colored in red (Phase A), blue (Phase B), and violet (Phase C). This configuration utilizes a 10º coil pitch and employs a full-coil winding scheme. The design finalizes with each slot containing 66 conductors composed of 10 filaments each. Through calculations, a conductor diameter of 2.743 mm was chosen, resulting in a resistance of 34.166 mΩ and an inductance of 2.425 mH per phase.

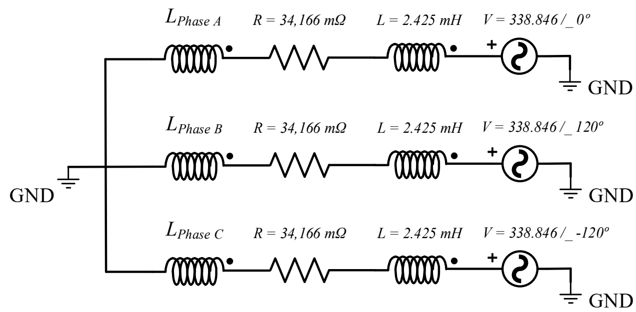
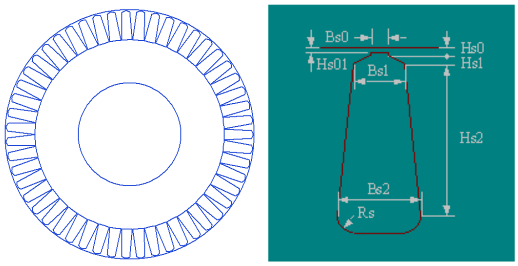


Fig. 4. 3-phase system with the star connection scheme [13]

Figure 4 elucidates the star connection of the phases, with a clear depiction of the phase-to-neutral voltage relationship and the placement of measurement instruments for circuit analysis.

C. Rotor design

Figure 5 and Table II outline the rotor's geometry, exhibiting the design and the bar configuration.



a) b)

Fig. 5. a) Rotor geometry; b) Bar geometry [13]

TABLE II. ROTOR GEOMETRICAL CHARACTERISTICS

Parameter	***Values***
External diameter	84.50 mm
Inner diameter	35.00 mm
Length	194.00 mm
Nº Slots	51
Material used	Steel_1008
Hs0	0.50 mm
Hs01	0.50 mm
Hs1	9.29 mm
Bs0	0.91 mm
Bs1	2.78 mm
Bs2	3.75 mm
Bars and conductors	Aluminum

The rotor, as shown in Figure 5 and Table II, is designed with 51 bars, and the details of its bar shape and configuration are described, demonstrating practical aspects of motor design.

The finalized design of the induction motor within the ANSYS® Maxwell 2D environment is showcased in Figure 6.

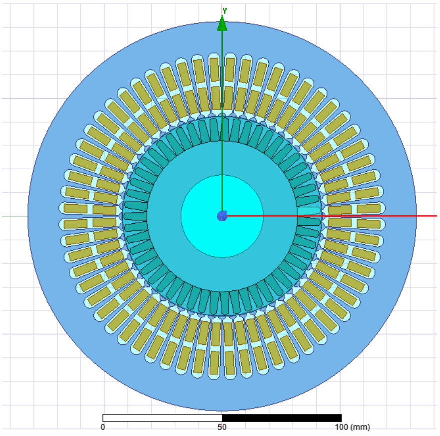


Fig. 6. 3-phase induction machine in ANSYS® Maxwell 2D [13]

Figure 6 depicts the motor that forms the foundation for the applied learning in this paper.

D. Finite Element Method Implementation

To analyze the machine proposed through finite element methods (FEM), without compromising financial investment in a new machine, software ANSYS® Maxwell 2D was used for this study.

To facilitate an educational simulation of the proposed machine, ANSYS® Maxwell 2D software was utilized, allowing students to explore the electromagnetic principles without the financial burden of constructing a physical prototype.

The magnetostatic transient solver in ANSYS® Maxwell provides the means to simulate time-varying magnetic fields and transient phenomena accurately. Students are introduced to mesh generation, material modeling, and setting boundary conditions, foundational skills for electromagnetic analysis.

The mesh plot in ANSYS® Maxwell 2D is a visual tool for understanding node distribution, crucial for optimizing simulations and understanding field behavior, as depicted in Figure 7.

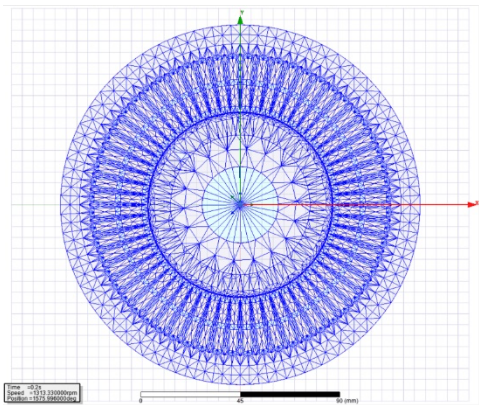


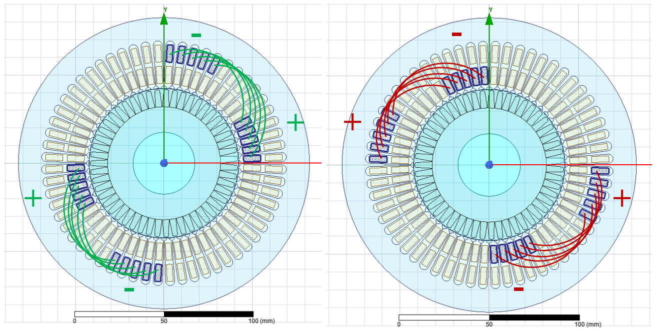
Fig. 7. Mesh of 3-phase induction machine in ANSYS® Maxwell 2D [13]

In this educational model, a mesh comprising 9044 elements, as shown in Figure 7, is adequate for capturing the expected waveforms, which will be further demonstrated in the following sections.

III. EDUCATIONAL EXPANSION TO HEX-PHASE INDUCTION MOTOR DESIGN

The evolution from a three-phase to a six-phase induction motor offers a practical case study in the application of advanced electromechanical concepts for engineering students. This section covers the design modifications implemented to expand a conventional three-phase induction motor into a hex-phase machine, fostering an understanding of the effects of phase multiplication on motor performance.

The process entailed integrating three new phases, designated as A2, B2, and C2, while the original phases were rebranded as A1, B1, and C1, to distinguish between the sets. Figure 8 illustrates the modified winding arrangement for two of the six phases, A1 and A2, with the "+" and "−" symbols denoting the positive and negative terminals, respectively.



a) b)

Fig. 8. Winding arregement of phases a) A1 and b) A2 [13]

In this configuration, used as the foundation for investigating the stabilization of torque development, the additional phases follow a mirrored pattern, maintaining symmetry in design.

The transition to a hex-phase structure required the division of each original phase into two, resulting in a proportional decrease in both resistance and inductance to maintain electrical balance. The resistance was adjusted to 17.0832 mΩ and the inductance to 1.2125 mH, as depicted in Figure 9. Figure 10 presents the vector diagram for the six-phase system, illustrating the spatial relationship between the phases.

Figure 9 demonstrates the dual-star configuration unique to the six-phase system. The left circuit retains the original star connection shown in Figure 4, whereas the right circuit exhibits an identical configuration with reversed polarity. This reversal establishes the 60º electrical phase shift necessary for the six-phase operation, which is graphically represented in Figure 10.

Through this module, students explore the intricacies of induction motor design beyond the traditional scope, examining the potential for increased efficiency and stability in torque output that a six-phase system may offer. The learning outcome is a deeper understanding of the theoretical and practical aspects of polyphase motor design, crucial for modern engineering challenges.

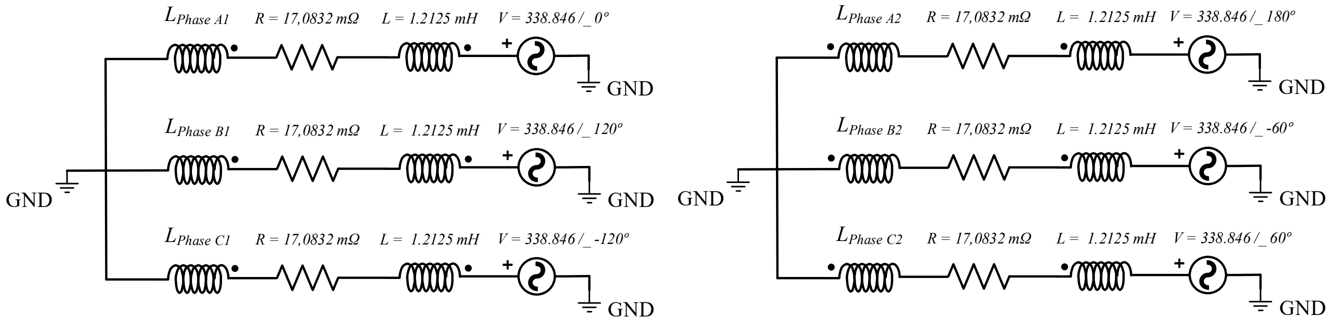


Fig. 9. 6-phase system with the double star connection scheme [13]

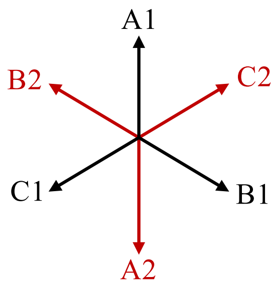


Fig. 10. Vector diagram of the 6-phase system [13]

IV. ANALYSIS OF ELECTROMECHANICAL PERFORMANCE IN HEX-PHASE INDUCTION MOTOR DESIGN

This section delivers a comparative analysis between a standard three-phase induction motor and a reconfigured six-phase model. Simulations for both setups were conducted in a no-load torque condition at the rated speed of 1313 rpm using the 2D ANSYS® Maxwell Electronics suite. This approach is aimed at imparting a deeper understanding of motor performance to engineering students through visual and quantitative analyses.

A. Currents and Voltages

Figure 11 illustrates the current flow in the original 3-phase and the modified 6-phase induction motors. In the standard system, currents progress in a balanced manner with a 120º phase difference, with an RMS value of 9.7 A. The 6-phase system presents a similar pattern but with 60º phase shifts, and each phase's RMS current is approximately halved to 5.0 A.

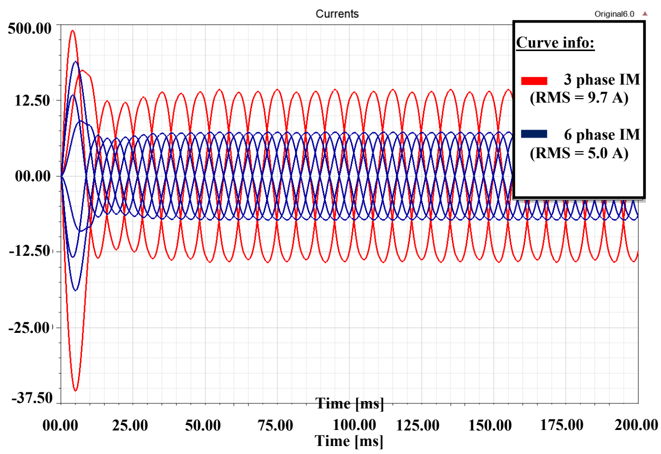


Fig. 11. *Electrical currents: 3-phase IM (red) vs 6-phase IM (blue)* [13]

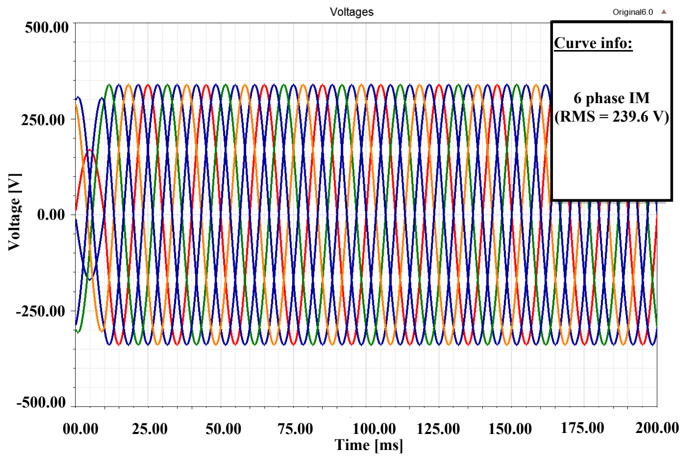


Fig. 12. *Voltage in the 6-phase IM* [13]

In Figure 12, we observe the voltage behavior in the 6-phase induction motor, which maintains an RMS value of 239.6 V, consistent with the 3-phase system. This visual representation aids in the comprehension of the electrical dynamics inherent in the modified motor structure.

B. Electrical and Mechanical Powers

The power profiles for the original and modified induction motors are shown in Figures 13 and 14. The 3-phase motor, shown in Figure 13, achieves a mechanical output of 3.5 kW against an electrical input of 4.1 kW. In contrast, the 6-phase configuration, depicted in Figure 14, generates 3.6 kW mechanically from a 4.2 kW electrical input, suggesting a slightly enhanced performance.

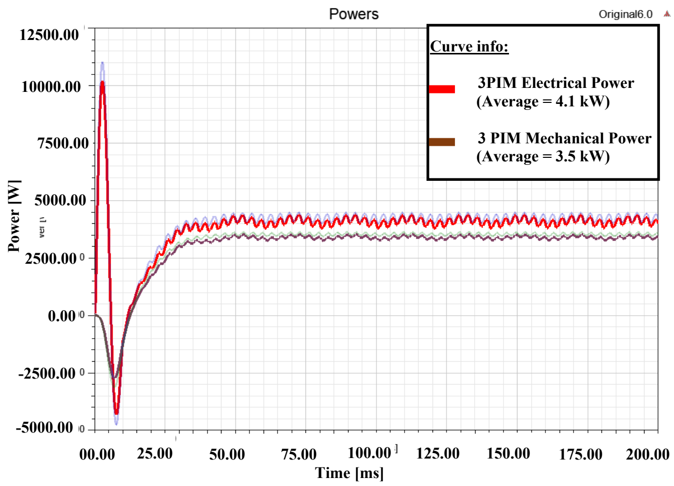


Fig. 13. Electrical currents: 3-phase IM (red) vs 6-phase IM (blue) [13]

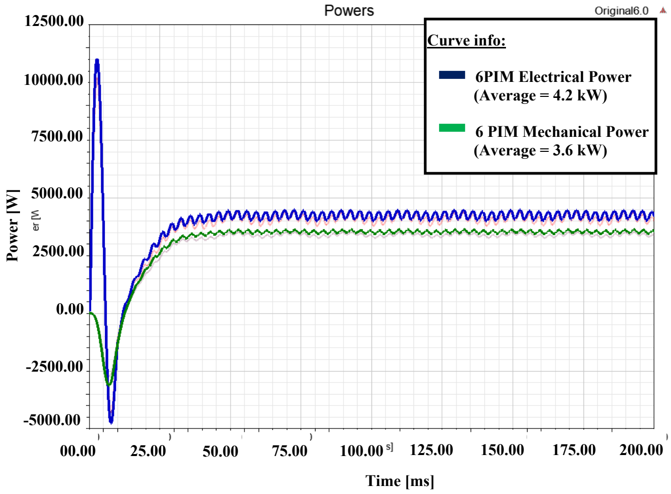


Fig. 14. 6-phase IM: Electrical power (blue) vs Mechanical power (green) [13]

C. Effiencency

Efficiency calculations indicate that the 3-phase motor operates at an 85.36% efficiency rate, while the 6-phase counterpart exhibits a slightly improved efficiency of 85.71%. Figure 15 graphically captures this efficiency gain, presenting a side-by-side comparison where the 6-phase system's improvement is visibly discernible.

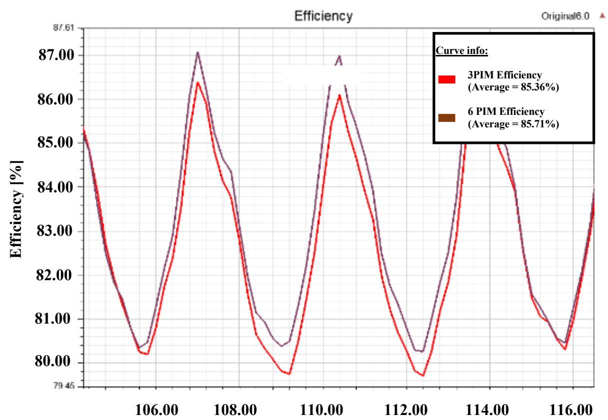


Fig. 15. Efficiency: 3-phase IM (red) vs 6-phase IM (brown) [13]

Figure 15 serves as a graphical testament to the empirical efficiency gains realized by adopting a hex-phase configuration. The visualization reinforces the numerical data, confirming the enhanced energy performance of the 6-phase motor.

D. Torque

Figure 16 contrasts the torque profiles of the conventional 3-phase motor and the 6-phase motor. The 3-phase motor exhibits noticeable torque ripple, indicative of fluctuations. In contrast, the 6-phase motor demonstrates a smoother torque curve, indicative of reduced ripple.

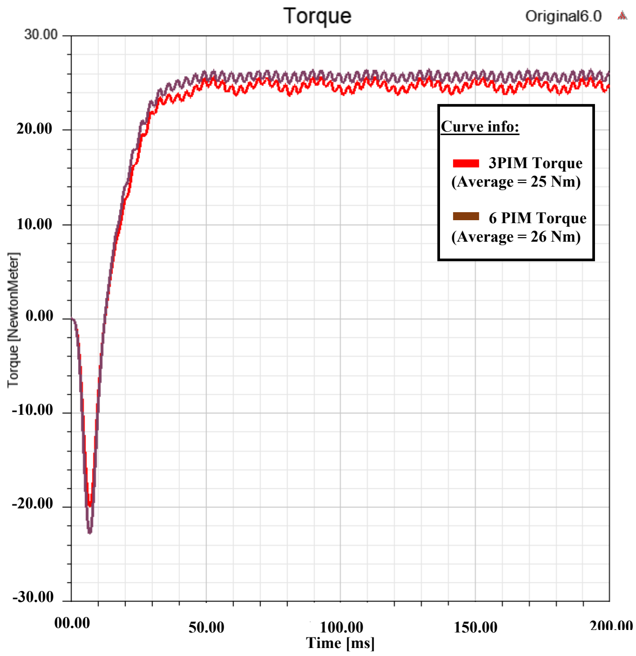


Fig. 16. Torque: 3-phase IM (red) vs 6-phase IM (brown) [13]

A closer inspection of the torque curves is provided in Figure 17, which zooms in for a detailed examination. This finer view underscores the hex-phase motor's advantage in delivering a more consistent torque output.

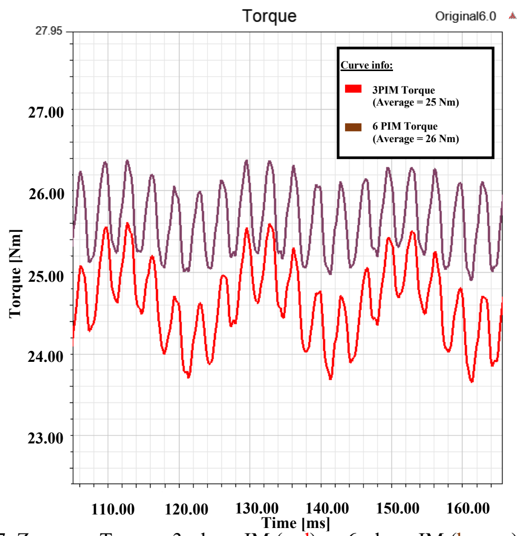


Fig. 17. Zoom on Torque: 3-phase IM (red) vs 6-phase IM (brown) [13]

The observed reduction in torque ripple in the hex-phase induction motor is attributable to a more balanced magnetic force interaction. The FEM-generated magnetic flux density maps in Figures 18 and 19 offer insights into the physical phenomena underlying the motors' performance.

Comparing Figures 18 and 19, it is clear that the 6-phase motor, lacking the pronounced blue hues seen in the 3-phase motor, suggests a more uniform magnetic flux distribution. Moreover, the hex-phase motor achieves a slightly higher maximum flux density of approximately 2.4757 T, compared to the 3-phase motor's 2.4631 T.

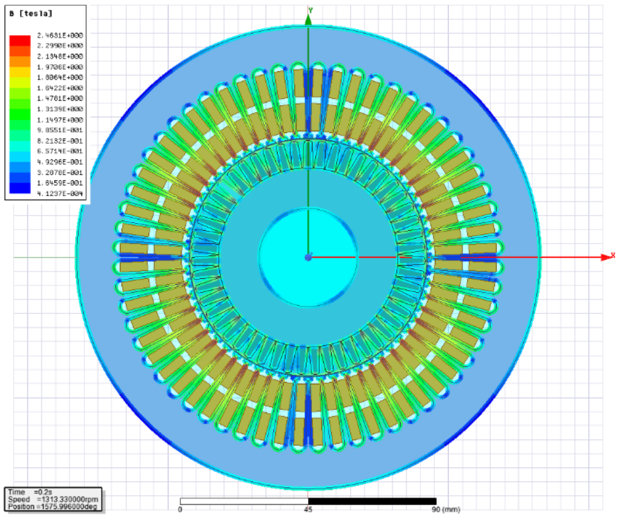


Fig. 18. Magnetic flux density in the 3-phase IM [13]

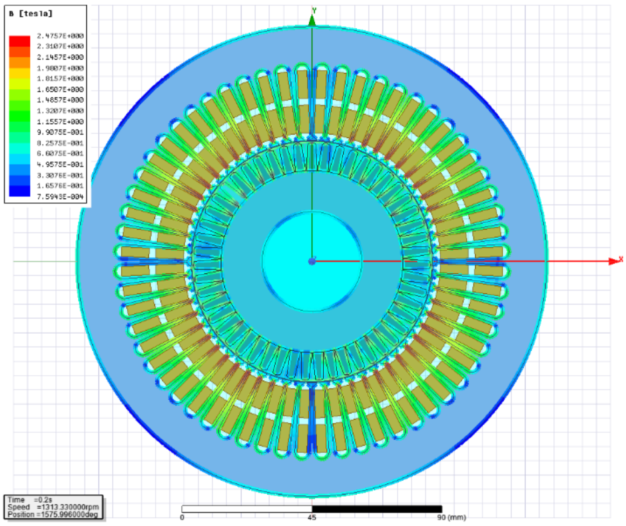


Fig. 19. Magnetic flux density in the 6-phase IM [13]

These results show students how motor design affects performance and the advantages of multi-phase systems in electrical machines.

V. CONCLUSIONS AND EDUCATIONAL IMPLICATIONS

This study has successfully demonstrated the benefits of incorporating a six-phase induction motor into the engineering curriculum, highlighting the educational value of such an innovative approach. The adaptation of a standard three-phase induction motor to a six-phase system has revealed distinct advantages, especially in the areas of torque ripple reduction, motor efficiency enhancement, and a more uniform magnetic flux density distribution.

The educational implementation of Finite Element Method (FEM) simulations has proven to be an indispensable pedagogical tool, allowing students to visualize and comprehend the effects of design changes on motor performance. The use of FEM has facilitated a deeper understanding of the principles of electromechanical systems in a hands-on learning environment, showcasing the method's potency in refining and optimizing electrical machine characteristics without the need for physical alterations.

Looking forward, the pedagogical journey should extend to examining the dynamic behavior of the six-phase induction motor (6PIM) under varying load conditions. Comparative studies on different phase configurations and winding arrangements could further enhance the educational experience, offering students insights into the optimization of motor design. Additionally, investigations into fault tolerance, longevity, and the economic aspects of the 6PIM are necessary to evaluate its practicality and overall viability as a component of sustainable engineering practices.

In synthesizing these findings, the conclusion is clear: the inclusion of a six-phase induction motor study not only benefits the engineering students' knowledge and skills but also aligns with global sustainability goals by reducing reliance on scarce resources. The adoption of such systems could potentially set a new standard in the design and operation of future electrical machines.

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