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Advanced control techniques for performance improvement of axial flux machines

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ABSTRACT

The topological advancements in twin rotor axial flux induction motors (TRAxFIMs) have spurred the interest in performance optimization and control strategies for electric vehicle (EV) applications in particular. This paper investigates for the enhanced performance of multi-level inverters (MLIs) fed TRAxFIMs with different advanced control techniques. The performance evaluation is done under variable speed conditions at constant torque and vice versa. The TRAxFIMs offer unique advantages like high power density, high efficiency and most suitable for EV applications. The performance analysis of MLIs fed TRAxFIM has been carried out with proportional-integral (PI), fuzzy controllers, and artificial neural network (ANN) controllers. The PI controller provides a conventional control approach, while the fuzzy and ANN controllers serve as advanced control strategies. The integration of MLIs and advanced control techniques with TRAxFIMs aims to enhance dynamic response, stability and efficiency. The proposed control strategies are evaluated through extensive MATLAB simulations and the potential of MLIs fed TRAxFIMs is emphasized for EV applications.

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1. INTRODUCTION

The rapid advancement of electric vehicle (EV) technology has spurred significant interest in optimizing electric motor designs to meet the demands of modern transportation. In this context, the choice between radial flux induction motors (RFIMs) and axial flux induction motors (AFIMs) has emerged as a crucial consideration for EV propulsion systems. While RFIMs have traditionally been favored for their simplicity and widespread use, the emergence of axial flux designs presents a compelling alternative due to their potential for higher power density and efficiency. One notable variant of axial flux induction motors is the TRAFIM, which offers unique advantages in terms of compactness and performance. The comparison between RFIMs and AFIMs underscores the importance of understanding their respective characteristics and performance attributes. RFIMs typically feature a radial arrangement of stator and rotor components, facilitating simpler construction and maintenance. In contrast, AFIMs adopt a configuration where the magnetic flux flows parallel to the axis of rotation, resulting in a more compact design and potentially higher power density. TRAFIM, a specialized variant of AFIMs, stands out for its twin rotor configuration, which further enhances its power output and efficiency.

Central to the development and optimization of TRAFIMs is the process of modeling, which involves accurately capturing the motor's dynamic behavior and performance characteristics. By employing sophisticated modeling techniques, researchers can gain insights into the complex interactions between electromagnetic fields, mechanical components, and control strategies within the TRAFIM system. This modeling process serves as a foundation for design optimization, control algorithm development, and performance evaluation, ultimately paving the way for the advancement of TRAFIM technology in the context of EV propulsion. Dual rotor systems represent a remarkable advancement in engineering, offering innovative solutions to a variety of challenges across diverse industries [1], [2]. At their core, dual rotor systems feature two rotating components designed to work synergistically in achieving specific tasks or functions. These rotating components, commonly referred to as rotors, can take various forms depending on the application, ranging from blades attached to a central hub in aviation to turbines in fluid dynamics systems and beyond. This dual-rotor configuration harnesses the power of coordinated motion to enhance performance, efficiency, and versatility in numerous applications [3], [4].

One prominent domain where dual rotor systems find extensive application is in the realm of aviation. Helicopters equipped with tandem or coaxial rotors exemplify the utilization of dual rotor configurations [5], [6]. By leveraging two rotors instead of one, these aircraft can achieve enhanced lifting capacity, stability, and maneuverability, offering advantages over traditional single-rotor designs [7], [8]. The twin rotor axial flux machines having larger diameters offer an attractive alternative for wind energy conversion system [9]. Furthermore, unmanned aerial vehicles (UAVs) and drones frequently employ dual rotor setups to improve control, agility, and payload capacity, demonstrating the adaptability and effectiveness of this configuration across various aerospace applications. Moreover, dual rotor systems play a significant role in renewable energy and industrial machinery sectors. In the renewable energy sector, wind turbines featuring dual rotors have gained prominence due to their ability to capture more wind energy and increase efficiency compared to single-rotor designs [10], [11]. Additionally, in industrial machinery applications such as mixers, blenders, and agitators, dual rotor configurations ensure thorough mixing and blending of materials, enhancing productivity and quality in sectors such as chemical processing, food production, and pharmaceutical manufacturing. The versatility and performance benefits offered by dual rotor systems underscore their importance in shaping the landscape of modern engineering and innovation across multiple industries [12], [13].

The quest for enhancing the performance and control of electric motors has been a driving force behind technological advancements in various industries [14], [15]. One such area of focus is the optimization of twin rotor axial flux induction motors (TRAxFIMs), which have garnered increasing interest due to their unique characteristics and potential applications. TRAxFIMs, with their compact design, high power density, and efficiency, offer promising solutions for diverse industrial tasks. However, achieving optimal performance and precise control in TRAxFIMs presents challenges owing to their complex dynamics and nonlinear characteristics [16], [17]. To address these challenges and unlock the full potential of TRAxFIMs, researchers and engineers have turned to innovative strategies and technologies. Multi-level inverters (MLIs) emerge as a promising solution to enhance motor control precision and efficiency. MLIs enable the synthesis of output voltage waveforms with multiple voltage levels, leading to smoother operation, reduced harmonic distortion, and improved efficiency. By leveraging MLIs, it becomes possible to achieve finer control over motor speed, torque, and overall performance, thereby maximizing the capabilities of TRAxFIMs in various industrial applications [18], [19]. The integration of advanced control techniques offers a pathway to further enhance the performance and versatility of TRAxFIMs [20].

In wind turbine systems (WTSs), direct power control (DPC) is employed to control the doubly-fed induction generators (DFIG's) energy [21]. In order to examine the nonlinear behavior of a dual-rotor bearing-casing framework, this research proposes an altered version of the HB-AFT approach [22]. With 284 levels of freedom, the equations for motion of a dual-rotor bearing-casing structure exposed to the unequal stimulation of the two rotors are developed. In an aero engine dual-rotor structure, inter-shaft rub-impact, or the rub-impact among two rotors, could transpire. This research is the initial effort to study the inter-shaft rub-impact nonlinear dynamics of a dual-rotor systems [23]. By taking into account the inter-shaft friction actions, the dynamic models of a complicated dual-rotor system is constructed utilizing the three-dimensional (3D) finite material component approach. The work that is being given assesses and enhances the efficiency of dual-rotor turbines that are mounted inside of designed ducts [24]. Comparing dual-rotor wind turbine (DRWT) and single-rotor wind turbine (SRWT), the impact of various operating circumstances on the recovered energy was contrasted. These conditions of operation, which were assessed using the multiple-variate statistical approach based on response surfaces, involve the kind of DRWT set up in the duct's throat portion, the separation among a turbine's two rotors, and the overall flow speed within the duct throat. This work investigates a dual-rotor bearing-coupling misaligned systems with blade-casing friction using computational modelling and measurements from experiments to unveil the nonlinear vibration features of a real dual-rotor aero turbine with this friction [25].

The key contributions of the article is,

- Performance evaluation through MATLAB simulations under variable speed conditions while maintaining constant torque and vice versa, providing insights into the dynamic behavior of TRAxFIMs.
- Addressing challenges in optimizing TRAxFIMs' performance and control due to their complex dynamics and nonlinear characteristics.
- Investigation of three advanced control strategies proportional-integral (PI), fuzzy, and artificial neural network (ANN) controllers for improved dynamic response and robustness.
- Integration of MLIs and advanced control techniques aiming to enhance efficiency, stability, and response speed of TRAxFIMs.

The paper is organized as follows: problem statement is presented in section 2 and section 3. Section 4 and 5 gives the methodology and results and discussion. Section 6 concludes the article.

2. PROBLEM STATEMENT

The existing methods for optimizing performance and control strategies of TRAxFIMs in EV applications face limitations due to the complex dynamics and nonlinear characteristics of these motors. While TRAxFIMs offer high power density and efficiency, achieving optimal performance and control remains challenging. Therefore, this study aims to address these limitations by investigating enhanced performance and control strategies utilizing MLIs and advanced control techniques. The proposed approach integrates MLIs to enhance motor control precision and efficiency, while also exploring the effectiveness of three advanced control strategies PI, fuzzy, and ANN controllers. Unlike conventional methods, these advanced control strategies offer improved dynamic response and robustness, allowing for more efficient and reliable electric motor systems. Through extensive MATLAB simulations under variable speed conditions, the effectiveness of the proposed strategies is evaluated; aiming to demonstrate improved motor control precision, reduced energy consumption, and enhanced dynamic response. Thus, by addressing the limitations of existing methods and leveraging advanced control techniques, this study seeks to pave the way for optimizing the performance of TRAxFIMs in EV applications, leading to more efficient and reliable electric motor systems [26].

3. PROPOSED CONTROL STRATEGIES FOR TRAxFIMs UTILIZING MLIs

The methodology encompasses a comprehensive exploration of various electric motor configurations and control techniques to optimize the performance of TRAxFIMs in EV applications. It includes the investigation of single stator induction motors, both axial and radial type, as well as the specialized dual rotor single stator IM configuration, aiming to understand their operational principles and performance characteristics. Additionally, the study delves into the utilization of MLIs to enhance motor control precision and efficiency. Furthermore, advanced control strategies such as PI, fuzzy, and ANN controllers are explored to improve dynamic response and robustness. By integrating these methodologies, the research aims to develop comprehensive insights into the optimization of TRAxFIM performance, paving the way for more efficient and reliable electric motor systems in EV applications.

3.1. Twin rotor axial flux IM

The TRAxFIM is a specialized configuration designed to enhance motor performance and efficiency by utilizing two rotors within a single stator assembly. In this unique design, a common stator is shared by two separate rotor assemblies, each positioned on opposite sides of the stator. When alternating current is supplied to the stator windings, it creates a rotating magnetic field within the motor, as in conventional single-rotor induction motors. However, in TRAxFIMs, the presence of two rotors introduces additional complexities to the motor operation. Both rotors are subject to the rotating magnetic field produced by the stator, leading to the induction of currents in their respective conductors. As a result, each rotor experiences electromagnetic forces that produce torque, causing them to rotate in opposite directions. The combined rotational motion of the two rotors provides enhanced torque output and mechanical power compared to single-rotor induction motors.

The utilization of dual rotors in a single stator configuration allows for increased power density, improved efficiency, and enhanced performance in TRAxFIMs. By distributing the torque production between two rotors, DRIMs can achieve higher torque-to-weight ratios and smoother operation, making them suitable for applications requiring high torque output and precise control. Additionally, the dual-rotor design offers redundancy and fault tolerance, as the motor can continue to operate even if one rotor experiences failure.

3.2. Multi-level inverter

MLIs play a crucial role in enhancing motor control by providing a more refined and precise voltage modulation compared to traditional inverters. By synthesizing output voltage waveforms with multiple levels, MLIs enable smoother transitions between voltage states, resulting in reduced harmonic distortion and improved power quality. This finer control over voltage modulation allows for optimized energy utilization, enhanced dynamic response, and increased efficiency in motor operation. Additionally, MLIs offer greater flexibility in adjusting motor speed and torque across various operating conditions, making them invaluable for achieving superior performance and responsiveness in industrial applications. MLIs stand as a promising solution to augment motor control precision and efficiency in the context of TRAxFIMs. MLIs offer a significant advancement over traditional inverters by synthesizing output voltage waveforms with multiple voltage levels, leading to smoother operation and reduced harmonic distortion. In the realm of TRAxFIMs, where precise control of motor speed and torque is paramount, the integration of MLIs opens up new avenues for enhancing performance and responsiveness. Table 1 shows the switching table for MLI.

Table 1. Switching table for MLI

S.NO	O/P voltage level	Current direction	1	2	3	4	5	6	7
1	5Vdc	Ln-S3-Vdc3-Vdc1-S4-C-S7-Lp	0	0	1	1	0	0	1
2	4Vdc	Ln-S3-Vdc3-Vdc1-S4-S6-Lp	0	0	1	1	0	1	0
3	3Vdc	Ln-S2-Vdc1-S4-C-S7-Lp	0	1	0	1	0	0	1
4	2Vdc	Ln-S2-Vdc1-S4-S6-Lp	0	1	0	1	0	1	0
5	Vdc	Ln-S1-S4-C-S7-Lp	1	0	0	1	0	0	1
6	0	Ln-S1-S4-S6-Lp	1	0	0	1	0	1	0
7	-Vdc	Ln-S3-S5-C-S6-Lp	0	0	1	0	1	1	0
8	-2Vdc	Ln-S2-Vdc3-S5-S7-Lp	0	1	0	0	1	0	1
9	-3Vdc	Ln-S2-Vdc3-S5-C-S6-Lp	0	1	0	0	1	1	0
10	-4Vdc	Ln-S1-Vdc1-Vdc3-S5-S7-Lp	1	0	0	0	1	0	1
11	-5Vdc	Ln-S1-Vdc1-Vdc3-S5-C-S6-Lp	1	0	0	0	1	1	0

The utilization of MLIs in TRAxFIMs enables finer control over motor operation, allowing for optimized energy utilization and improved dynamic response. By generating output voltage waveforms with multiple levels, MLIs facilitate smoother transitions between voltage states, minimizing voltage distortion and reducing electromagnetic interference. The inverter circuit is depicted in Figure 1. Figure 2 shows a triggering circuit in an inverter provides gate pulses to power electronic switches at appropriate intervals. It ensures correct switching sequence and timing for converting DC to AC output with desired waveform and frequency.

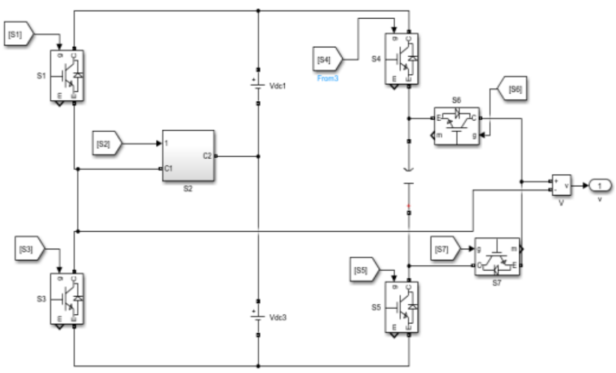

Figure 1. Inverter circuit

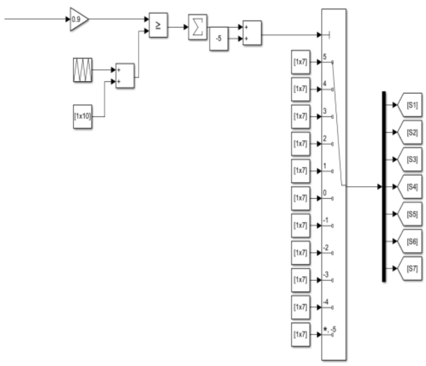

Figure 2. Triggering circuit

3.3. Controllers

3.3.1. Proportional-integral controller

The PI controller serves as a fundamental component in motor control systems, playing a pivotal role in regulating motor speed, torque, and position. By comparing the desired reference signal with the actual output, the PI controller generates a control signal that adjusts the motor's operation proportionally to the error signal and its integral over time. This dual-action approach ensures stable and precise control, minimizing steady-state error and oscillations while enabling rapid response to changes in operating conditions. The simplicity, robustness, and effectiveness of the PI controller make it a cornerstone in motor control applications, providing reliable and efficient performance across a wide range of EV systems.

In the initial layout method, a traditional PI controller is added to regulate the speed of an implicit field-oriented IM order. Additionally, the beginning condition is examined. A phase-locked loop technique that coordinates with the utilities voltage regulation converter formulas are included in the suggested control framework, as shown in Figure 3. The phase winds (i_a, i_b, and i_c) are transformed into a d–q frames from a–b–c dimensions. Several transformations may be used to characterize the elements of d–q.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} sin\,(\omega t) & sin\left(\omega t - \frac{2\pi}{3}\right) & sin\left(\omega t + \frac{2\pi}{3}\right) \\ cos\,(\omega t) & cos\left(\omega t - \frac{2\pi}{3}\right) & cos\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix} * \begin{bmatrix} i_{ra} \\ i_{rb} \\ i_{rc} \end{bmatrix} \quad (1)$$

Normal and oscillatory elements are now included in the computation of active and reactive power. To get the average elements of the active power and reactive power outputs, nevertheless, two external PI - circuits are employed. According to the subsequent conversions, this PI generates active current references (i_d^*) and reactive current references (i_q^*).

$$i_d^* = k_p(P_{ref} \text{ -} P) + k_i \int (P_{ref} - P)\, dt \quad (2)$$

$$i_q^* = k_p(Q_{ref} \text{ -} Q) + k_i \int (Q_{ref} - Q)\, dt \quad (3)$$

When, for the PI controllers in use, ki is the fundamental variable and k_p is the inverse proportional variable. The electrical power benchmark is called Pref, and the reactive energy needed by the electrical supply is referred to as Q_{ref}.

The inner present loop and the outside voltage loop are integrated to provide the control. The electrical reference, which is employed to regulate the inner loop, is produced through the comparison of the reference voltage of the current with the real voltage in the outer loop. As a result, by contrasting the values of the line currents acquired from the park transformation, the inside PI loops are produced.

$$\begin{bmatrix} d_d \\ d_q \end{bmatrix} = \frac{1}{V_{dc}} \begin{bmatrix} e_d + v_d + 3\omega H * i_q \\ e_q + v_q - 3\omega H * i_d \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} D_a \\ D_b \\ D_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} sin\,(\omega t) & cs(\omega t)o \\ sin\left(\omega t - \frac{2\pi}{3}\right) & cos\left(\omega t - \frac{2\pi}{3}\right) \\ sin\left(\omega t + \frac{2\pi}{3}\right) & cos\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix} * \begin{bmatrix} d_d \\ d_q \end{bmatrix} \quad (5)$$

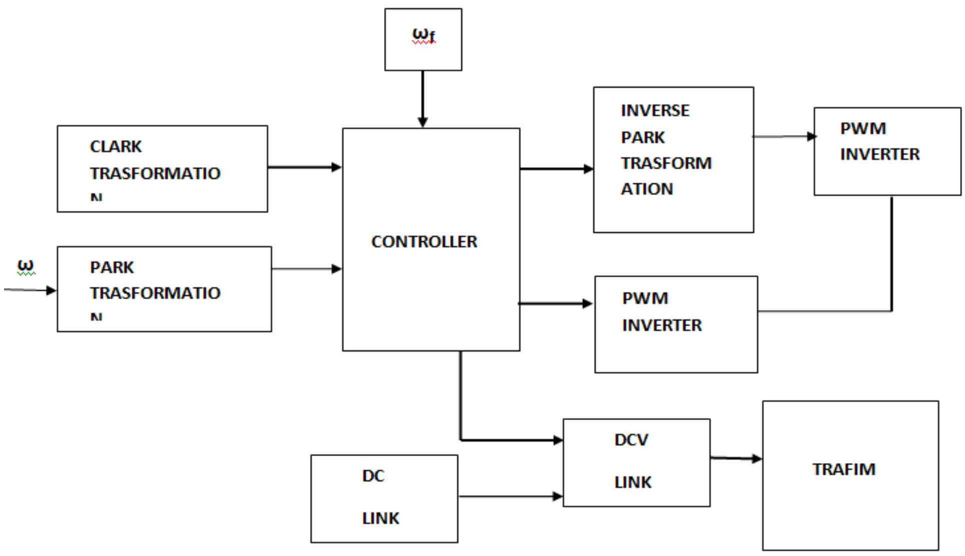

Figure 3. PI controller circuit

3.3.2. Fuzzy controller

In the pursuit of enhancing the performance and control strategies for TRAxFIMs using MLIs and advanced control techniques, the fuzzy controller emerges as a significant player. Fuzzy logic controller (FLC) offers a unique approach to motor control by incorporating human-like reasoning and linguistic variables to handle complex and uncertain systems. Within the framework of the proposed study, the fuzzy controller is employed to optimize the dynamic response and efficiency of TRAxFIMs under variable speed conditions while ensuring constant torque output.

The utilization of the fuzzy controller within the context of TRAxFIMs presents several distinct advantages. Firstly, FLC offers inherent robustness to uncertainties and disturbances, making it well-suited for real-world applications where system dynamics may vary or be poorly understood. Moreover, by integrating the fuzzy controller with MLIs, as proposed in the study, the overall performance and efficiency of TRAxFIMs can be further enhanced. Through rigorous simulation studies and experimental validation, the efficacy of the fuzzy controller in optimizing TRAxFIM performance can be thoroughly evaluated, paving the way for its practical implementation in EV propulsion systems and other EV applications. The fuzzy circuit is depicted in Figure 4.

Within this framework, FLCs effectively handle the complex dynamics inherent in DRAFIM systems, enabling smooth and accurate regulation of motor speed, torque, and other operational parameters. By leveraging linguistic variables and fuzzy logic rules, FLCs adaptively adjust control actions based on real-time feedback from sensors and system states. This adaptive capability is particularly advantageous in dynamic operating conditions, where conventional control strategies may struggle to maintain optimal performance. Furthermore, FLCs excel in handling imprecise or incomplete information, making them well-suited for DRAFIM systems where uncertainties in load conditions or environmental factors are prevalent. In conjunction with MLIs and neural network controllers, FLCs contribute to the overall sophistication and effectiveness of the control system. MLIs provide high-quality voltage waveforms and reduced harmonic distortion, enhancing the robustness and efficiency of the motor drive system. Meanwhile, neural network controllers offer learning capabilities and adaptability to changing system dynamics, further refining control strategies and improving overall performance. Through the synergistic integration of FLCs, MLIs, and neural network controllers, advanced control strategies for DRAFIM systems achieve superior levels of precision, efficiency, and reliability. This comprehensive approach not only optimizes motor performance but also facilitates seamless integration into diverse industrial and automotive applications, where stringent performance requirements and dynamic operating conditions are commonplace.

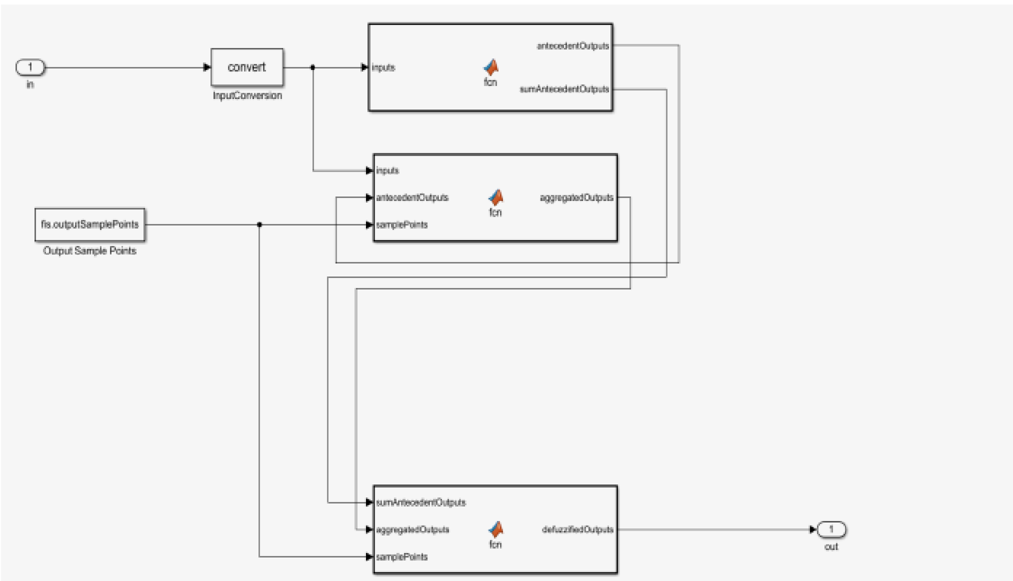

Figure 4. Fuzzy controller circuit

3.3.3. Artificial neural network controller

The ANN controller serves as a sophisticated control strategy within the framework of enhanced performance and control strategies for TRAxFIMs using MLIs and advanced control techniques. In this context, the ANN controller operates by emulating the structure and function of biological neural networks to learn and adapt to complex motor dynamics. The ANN controller can effectively model the nonlinear relationships between motor inputs and outputs, enabling precise and adaptive control of TRAxFIMs under varying operating conditions. This advanced control strategy offers several advantages, including the ability to handle uncertainties and nonlinearities inherent in TRAxFIM systems, thereby enhancing motor performance, efficiency, and stability.

In the proposed framework, the ANN controller plays a pivotal role in optimizing the performance of TRAxFIMs by dynamically adjusting control parameters based on real-time motor responses. Through extensive training on historical data and iterative learning processes, the ANN controller can refine its control policies to achieve desired motor performance objectives, such as minimizing speed variations, reducing settling time, and enhancing energy efficiency. Additionally, the ANN controller offers the flexibility to adapt to changing operating conditions and system uncertainties, ensuring robust and reliable motor control in diverse industrial applications. By integrating the ANN controller with MLIs and other advanced control techniques, the proposed framework aims to unlock the full potential of TRAxFIMs, paving the way for more efficient and responsive electric motor systems in various industrial sectors. Figure 5 shows the ANN circuit.

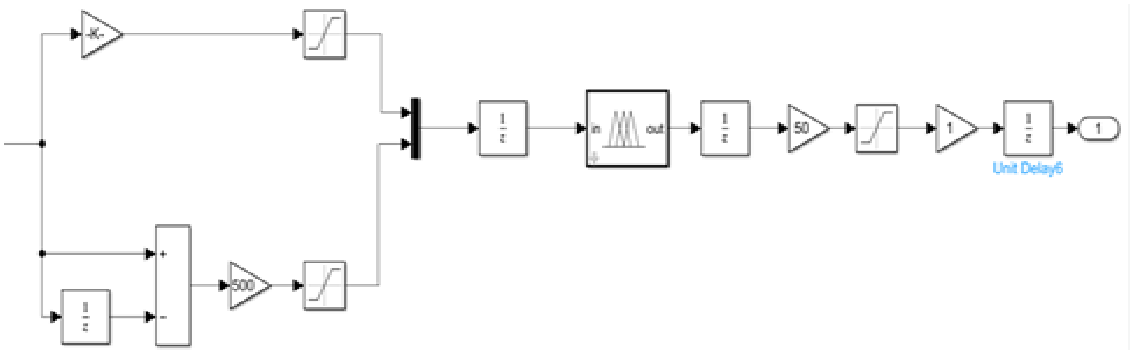

Figure 5. ANN controller circuit

Tables 2 to 4 outlines the parameters for an ANN employed in a motor control system. These parameters include electrical, mechanical, and control characteristics of the system, such as winding inductances, resistances, rotor dimensions, and time constants. They are essential for accurately modeling and simulating the motor's behavior, facilitating precise control and optimization strategies. The table provides key values necessary for the ANN to effectively predict and regulate the motor's performance, ensuring efficient and reliable operation across various operating conditions.

Table 2. MOTOR parameters

Parameters	f	P	Ls	Lr1	Lr2	Lm1	Lm2	rs	rr1	rr2	H	F
Values	50	6/2	0.73e-3	1.1e-3	1.2e-3	56.63e-3	58.74e-3	0.345	0.347	0.404	0.25	0.01

Table 3. Derived MOTOR parameter equations

Parameters	$Lmrp$	$dLmrp$	sr	Srh	dsr	$dSrh$
Values	(1/2)*((Lm1^2/Lr1) +(Lm2^2/Lr2))	(1/2)*((Lm2^2/Lr2)-(Lm1^2/Lr1))	(1/2)*((rr1/Lr1) +(rr2/Lr2))	(1/2)*((rr1/Lr1) +(rr2/Lr2));	(1/2)*((rr2/Lr2)-(rr1/Lr1));	(1/2)*((rr2/Lr2)-(rr1/Lr1))

Table 4. Time constants and additional MOTOR characteristics

Parameters	$Trmc$	Ts	$Tr1$	$Sr1$	$Tr2$	$Sr2$	L	Ir	dr	r	K
Values	1e-3;	50e-6;	Lr1/rr1	1/Tr1	Lr2/rr2	1/Tr2	2.285	0.347	0.835	1.35	0.395

4. RESULTS AND DISCUSSION

The results obtained from the study are implemented in MATLAB to facilitate the evaluation of performance metrics. Through MATLAB simulations, the effectiveness and efficiency of the proposed methodologies, including the integration of MLIs and advanced control techniques such as PI, fuzzy and

ANN controllers are assessed. This rigorous evaluation process enables a thorough analysis of the performance enhancements achieved by the implemented strategies in optimizing TRAxFIMs for industrial applications.

4.1. Outputs of PI controller

4.1.1. Rotor speed

The rotor speed graph in Figures 6 and 7, with time depicted on the x-axis and rotor speed levels plotted on the y-axis, offers a detailed insight into the performance of a PI controller in regulating the speed of the second rotor in a dual-rotor system over time. This graph provides crucial information regarding the dynamic behavior and stability of the speed control process, showcasing how the PI controller adjusts the rotor speed to track the desired reference speed setpoint. Fluctuations, trends, or deviations in rotor speed over time indicate the controller's effectiveness in maintaining stable and accurate speed control, while overshoot or settling time can reveal aspects of controller responsiveness and tuning. By analyzing the rotor speed graph, engineers can evaluate the performance of the PI controller, identify potential issues such as oscillations or steady-state error, and fine-tune controller parameters to optimize speed regulation and ensure smooth and reliable operation of the dual-rotor system.

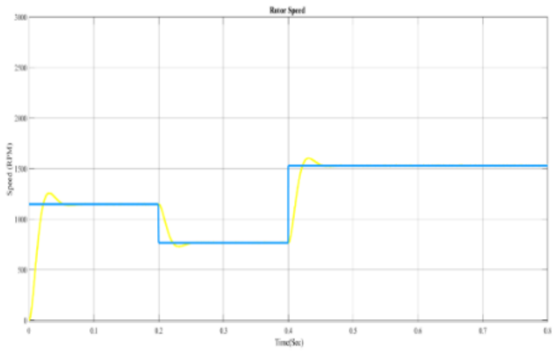

Figure 6. Rotor 1 speed

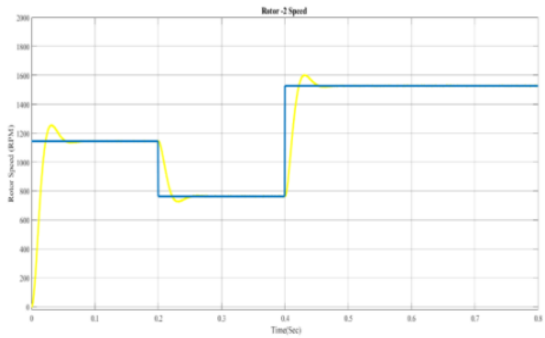

Figure 7. Rotor 2 speed

4.1.2. Torque

The torque graph in Figure 8, with time depicted on the x-axis and torque levels plotted on the y-axis, offers a detailed representation of the dynamic response and performance of a system controlled by a PI controller over time. This graph provides critical insights into how the PI controller regulates torque output to maintain desired levels, reflecting the system's ability to generate the necessary mechanical force while adhering to control objectives. Fluctuations, trends, or deviations in torque over time reveal the controller's responsiveness, stability, and effectiveness in achieving and maintaining the target torque setpoint. By analyzing the torque graph, engineers can evaluate the performance of the PI controller, identify potential issues such as overshoot, settling time, or steady-state error, and fine-tune controller parameters to optimize torque regulation and ensure efficient and reliable operation of the system for various industrial applications.

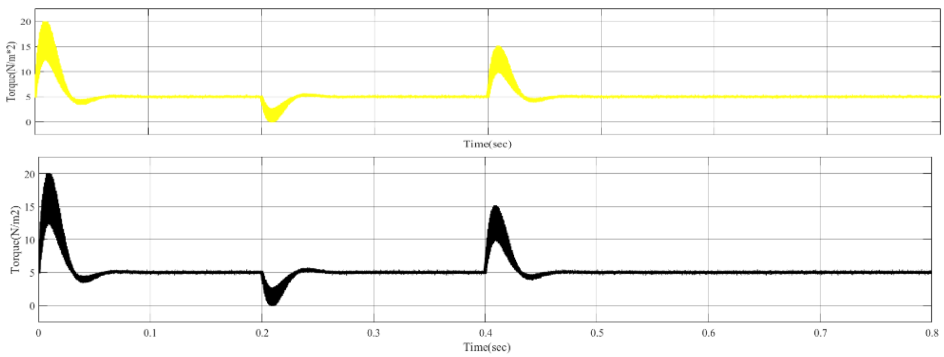

Figure 8. Torque

4.2. Output of fuzzy controller

4.2.1. Rotor speed

The rotor speed graph, controlled by the fuzzy controller, presents a visual representation of the motor's rotational behavior under the influence of the controller's input signals. Figures 9 and 10 serves as a critical tool for evaluating the effectiveness of the fuzzy controller in regulating rotor speed over time. By analyzing the trajectory of the speed curve, engineers can assess the controller's ability to maintain stable operation, minimize deviations from the desired speed setpoint, and respond promptly to changes in load or environmental conditions. Any deviations or oscillations observed in the speed curve may indicate areas for further refinement or adjustment of the fuzzy controller parameters to optimize its performance and ensure precise control of rotor speed.

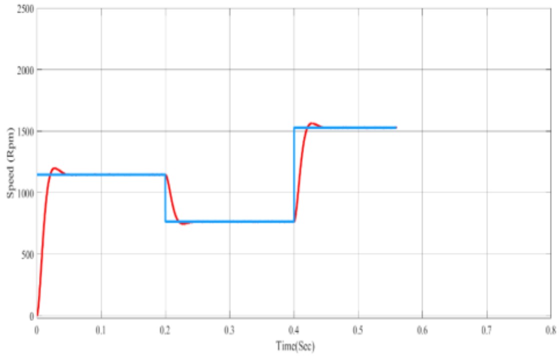

Figure 9. Rotor 1 speed

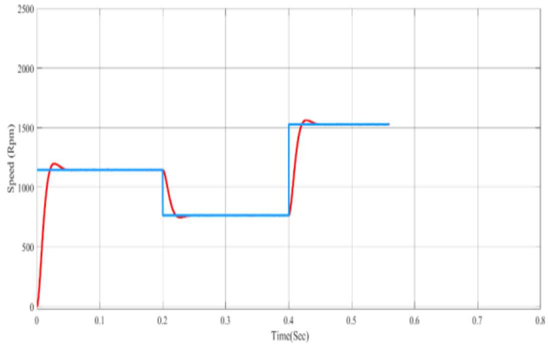

Figure 10. Rotor 2 speed

4.2.2. Torque

The torque graph in Figure 11, governed by the fuzzy controller, provides critical insights into the motor's torque output influenced by the controller's input signals. This graph serves as a fundamental indicator of the fuzzy controller's effectiveness in regulating torque production over time. Analyzing the torque curve allows engineers to assess the controller's ability to maintain consistent torque levels, minimize deviations from the desired torque setpoint, and swiftly adapt to changes in operational conditions or load demands. Any irregularities or fluctuations observed in the torque curve may indicate areas for further optimization or adjustment of the fuzzy controller parameters to enhance its performance and ensure precise control of motor torque.

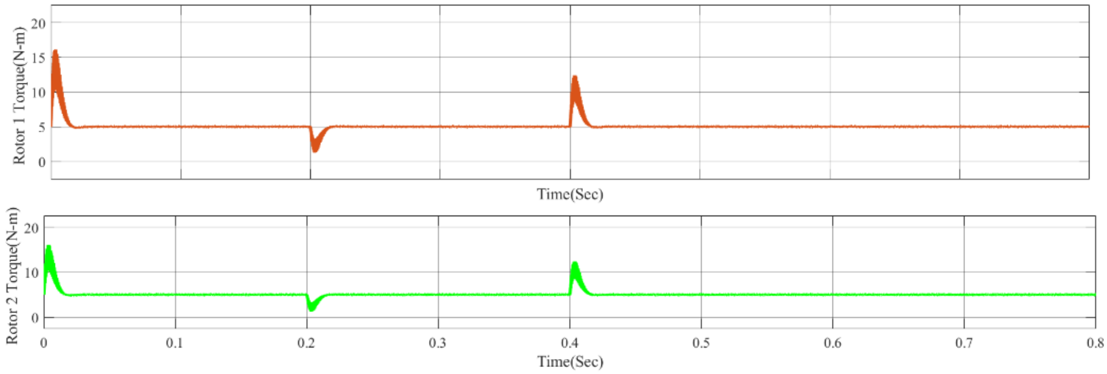

Figure 11. Torque

4.3. Output of ANN controller

4.3.1. Rotor speed

The rotor speed graph generated by the ANN controller depicts the dynamic response of the motor under the influence of the controller's input signals. Figures 12 and 13 provides valuable insights into the effectiveness of the ANN controller in regulating rotor speed over time. By analyzing the trajectory of the speed curve, engineers can assess the controller's ability to maintain stable operation, minimize deviations from the desired speed setpoint, and respond promptly to changes in load or operating conditions. Moreover, deviations or oscillations in the speed curve may indicate areas for further optimization or fine-tuning of the ANN controller parameters to enhance its performance and ensure optimal motor operation.

4.3.2. Torque

The torque graph in Figure 14, governed by the ANN controller, offers valuable insights into the motor's torque output as influenced by the controller's input signals. This graph serves as a critical indicator of the ANN controller's effectiveness in regulating torque production over time. Analyzing the torque curve's behavior allows engineers to assess the controller's ability to maintain consistent torque levels, minimize deviations from the desired torque set-point, and swiftly adapt to changes in operating conditions or load demands. Any deviations or fluctuations observed in the torque curve may indicate areas for further optimization or fine-tuning of the ANN controller parameters to enhance its performance and ensure precise control of motor torque.

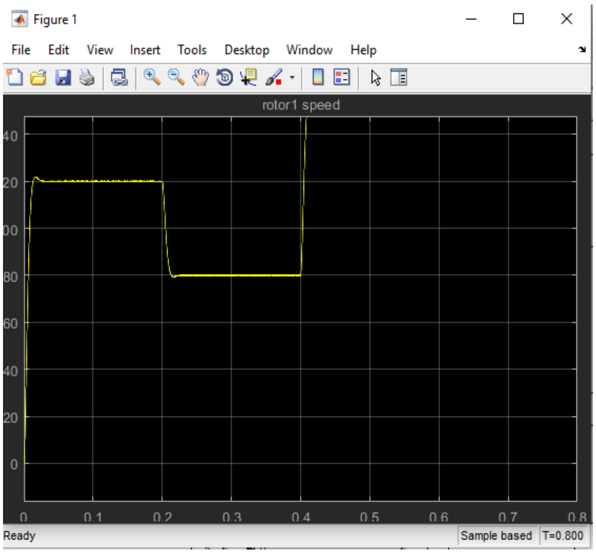

Figure 12. Rotor 1 speed

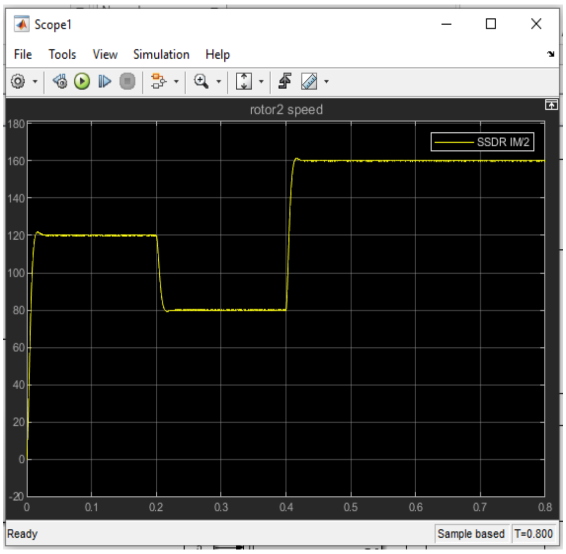

Figure 13. Rotor 2 speed

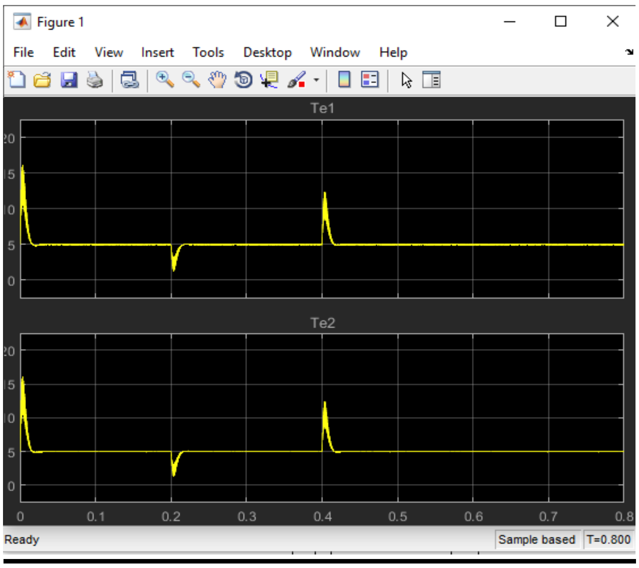

Figure 14. Torque

4.4. Discussion

The simulations have unequivocally validated the effectiveness of our proposed methodology in augmenting the performance of TRAxFIMs. Through the strategic integration of MLIs alongside advanced control strategies like PI, fuzzy, and ANN controllers, substantial enhancements have been discerned in various facets of motor operation. Noteworthy improvements in motor control precision, energy efficiency, and dynamic response have been observed, underscoring the efficacy of the approach. Leveraging MLIs has afforded finer control over motor parameters, culminating in smoother operation and mitigated energy losses. These outcomes collectively emphasize the promising prospect of amalgamating advanced control methodologies with MLIs, thus rendering TRAxFIMs better equipped to meet the demands of a diverse array of EV applications.

The comparison between conventional control methods such as the PI controller and advanced techniques like fuzzy logic and ANN controllers reveals distinct performance characteristics in terms of speed variation and settling time. In particular, the settling time observed with the PI controller is found to be greater compared to that of the fuzzy controller. This discrepancy suggests that the fuzzy controller exhibits faster response dynamics, potentially attributed to its ability to adapt to changing system conditions and uncertainties more effectively. Conversely, while the ANN controller showcases faster settling times than the fuzzy controller, it still demonstrates a longer settling time compared to the PI controller. This observation underscores the trade-offs inherent in selecting control strategies, highlighting the need for a balanced consideration of speed variation and settling time when designing control systems for dynamic applications.

5. CONCLUSION AND FUTURE WORKS

In conclusion, this study has successfully investigated for enhanced performance and control strategies for TRAxFIMs utilizing MLIs and advanced control techniques. Through MATLAB simulations conducted under variable speed conditions while maintaining constant torque, we have demonstrated the effectiveness of these strategies in optimizing TRAxFIM performance for EV applications. By employing MLIs to enhance motor control precision and efficiency, and investigating advanced control strategies including PI, fuzzy, and ANN controllers, the challenges associated with proposed system are addressed. Future research could explore further refinements and optimizations of the proposed strategies to achieve even greater performance enhancements in TRAxFIMs. This may involve fine-tuning control parameters, exploring alternative control algorithms, or investigating new motor configurations. Additionally, experimental validation of the proposed strategies using real-world hardware setups would provide valuable insights and validation of the simulation results. Overall, the findings of this study underscore the potential of employing MLIs and advanced control techniques for EV applications and beyond.

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AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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Ramesh Babu Veligatla	✓	✓	✓			✓		✓	✓	✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

Not applicable. This study did not involve human participants.

ETHICAL APPROVAL

Not applicable. This study did not involve human or animal subjects.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

REFERENCES

[1] V. Kumar and S. Kumar, "A novel multilevel inverter fed open-end winding coupled-induction motor drive for sugar industry," *IEEE Transactions on Energy Conversion*, vol. 38, no. 4, pp. 2706–2716, Dec. 2023, doi: 10.1109/TEC.2023.3294301.

[2] B. P. Reddy, M. Meraj, A. Iqbal, S. Keerthipati, and M. S. Bhaskar, "A hybrid multilevel inverter scheme for nine-phase PPMIM drive by using three-phase five-leg inverters," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 3, pp. 1895–1904, Mar. 2021, doi: 10.1109/TIE.2020.2975460.

[3] H. Benbouhenni, I. Colak, N. Bizon, A. G. Mazare, and P. Thounthong, "Direct vector control using feedback PI controllers of a DPAG supplied by a two-level PWM inverter for a multi-rotor wind turbine system," *Arabian Journal for Science and Engineering*, vol. 48, no. 11, pp. 15177–15193, 2023, doi: 10.1007/s13369-023-08035-w.

[4] Y.-F. Jia *et al.*, "Control strategy for an open-end winding induction motor drive system for dual-power electric vehicles," *IEEE Access*, vol. 8, pp. 8844–8860, 2020, doi: 10.1109/ACCESS.2020.2964105.

[5] T. Porselvi*et al.*, "Combined harmonic reduction and DC voltage regulation of a single DC source five-level multilevel inverter for wind electric system," *Electronics (Switzerland)*, vol. 9, no. 6, pp. 1–19, 2020, doi: 10.3390/electronics9060979.

[6] P. T. Giang, V. T. Ha, and V. H. Phuong, "Drive control of a permanent magnet synchronous motor fed by a multi-level inverter for electric vehicle application," *Engineering, Technology & Applied Science Research*, vol. 12, no. 3, pp. 8658–8666, Jun. 2022, doi: 10.48084/etasr.4935.

[7] H. Hatas and M. N. Almali, "Design and control of a novel topology for multilevel inverters using high frequency link," *Electric Power Systems Research*, vol. 221, p. 109458, 2023, doi: 10.1016/j.epsr.2023.109458.

[8] H. Benbouhenni, N. Bizon, P. Thounthong, I. Colak, and P. Mungporn, "A new integral-synergetic controller for direct reactive and active powers control of a dual-rotor wind system," *Measurement and Control*, vol. 57, no. 2, pp. 208-224, 2024, doi: 10.1177/00202940231195117.

[9] A. Kalpana, V.R. Babu, "Novel axial flux machine topology assessment and their feasible applications," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 13, no. 1, March 2022, pp. 84-92, doi: 10.11591/ijpeds.v13.i1.pp84-92.

[10] X. Wang *et al.*, "Fault-tolerant control of common electrical faults in dual three-phase PMSM drives fed by T-Type three-level inverters," *IEEE Transactions on Industry Applications*, vol. 57, no. 1, pp. 481–491, Jan. 2021, doi: 10.1109/TIA.2020.3026987.

[11] K. V. Praveen Kumar andT. Vinay Kumar, "Predictive torque control of open-end winding induction motor drive fed with multilevel inversion using two two-level inverters," *IET Electric Power Applications*, vol. 12, no. 1, pp. 54-62, 2018, doi: 10.1049/iet-epa.2017.0209.

[12] R. Kumar, P. Kant, and B. Singh, "Harmonic suppression scheme for multipulse converter fed multilevel inverter-based IM drive," *IEEE Transactions on Industry Applications*, vol. 57, no. 6, pp. 6058–6068, Nov. 2021, doi: 10.1109/TIA.2021.3110832.

[13] H. Benbouhenni, I. Colak, N. Bizon, and E. Abdelkarim, "Fractional-order neural control of a DFIG supplied by a two-level PWM inverter for dual-rotor wind turbine system," *Measurement and Control (United Kingdom)*, vol. 57, no. 3, pp. 301–318, 2024, doi: 10.1177/00202940231201375.

[14] P. Dharmendra Kumar, T. Ramesh, and P. Ramakrishna, "Performance analysis of multi-level inverter-fed position sensorless PMSM drive using modified MPTC," *IETE Journal of Research*, vol. 69, no. 9, pp. 6537–6556, Sep. 2023, doi: 10.1080/03772063.2021.1999863.

[15] S. Foti, A. Testa, S. D. Caro, L. D. Tornello, G. Scelba, and M. Cacciato, "Multi-level multi-input converter for hybrid renewable energy generators," *Energies*, vol. 14, no. 6, Art. no. 6, Jan. 2021, doi: 10.3390/en14061764.

[16] B. N. Ch.V. Chakravarthi, P. Naveen, S. Pragaspathy, and V. S. N. N. Raju, "Performance of induction motor with hybrid multi level inverter for electric vehicles," in 2021 *International Conference on Artificial Intelligence and Smart Systems (ICAIS)*, Mar. 2021, pp. 1474–1478, doi: 10.1109/ICAIS50930.2021.9395885.

[17] V. Rathore, D. Kumar and K. B. Yadav, "A 5-level T-type inverter fed six-phase induction motor drive for industrial applications. *International Journal of Electronics*, vol. 111, no. 2, 259-279, 2024, doi: 10.1080/00207217.2022.2164068.

[18] H. Benbouhenni *et al.*, "Simplified super twisting sliding mode approaches of the double-powered induction generator-based multi-rotor wind turbine system," *Sustainability*, vol. 14, no. 9, Art. no. 9, Jan. 2022.

[19] H. Benbouhenni, Z. Boudjema, N. Bizon, P. Thounthong, and N. Takorabet, "Direct power control based on modified sliding mode controller for a variable-speed multi-rotor wind turbine system using PWM strategy," *Energies*, vol. 15, no. 10, p. 3689, 2022.

[20] L. Yin and L. Chen, "High-dimensional multiple fractional-order controllers for doubly-fed induction generator-based wind turbines," *Journal of Control, Automation and Electrical Systems*, vol. 33, no. 3, pp. 822–837, Jun. 2022, doi: 10.1007/s40313-021-00884-w.

[21] H. Benbouhenni, N. Bizon, M. I. Mosaad, I. Colak, A. B. Djilali, and H. Gasmi, "Enhancement of the power quality of DFIG-based dual-rotor wind turbine systems using fractional order fuzzy controller," *Expert Systems with Applications*, vol. 238, p. 121695, Mar. 2024, doi: 10.1016/j.eswa.2023.121695.

[22] Y. Chen *et al.*, "Nonlinear dynamics analysis of a dual-rotor-bearing-casing system based on a modified HB-AFT method," *Mechanical Systems and Signal Processing*, vol. 185, p. 109805, Feb. 2023, doi: 10.1016/j.ymssp.2022.109805.

[23] P. Yu, C. Wang, L. Hou, and G. Chen, "Dynamic characteristics of an aeroengine dual-rotor system with inter-shaft rub-impact," *Mechanical Systems and Signal Processing*, vol. 166, p. 108475, Mar. 2022, doi: 10.1016/j.ymssp.2021.108475.
[24] J. Taghinezhad, R. Alimardani, M. Masdari, and E. Mahmoodi, "Performance optimization of a dual-rotor ducted wind turbine by using response surface method," *Energy Conversion and Management: X*, vol. 12, p. 100120, Dec. 2021.
[25] Y. Jin, Z. Liu, Y. Yang, F. Li, and Y. Chen, "Nonlinear vibrations of a dual-rotor-bearing-coupling misalignment system with blade-casing rubbing," *Journal of Sound and Vibration*, vol. 497, p. 115948, Apr. 2021, doi: 10.1016/j.jsv.2021.115948.
[26] A. Oukassi and S. Elbourhichi, "Sensorless indirect control of induction motor fed by a multi-level inverter with consideration of variation in rotor and stator resistances," in 2020 7th *International Conference on Electrical and Electronics Engineering (ICEEE)*, Apr. 2020, pp. 142–149, doi: 10.1109/ICEEE49618.2020.9102534.

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