AI Control Based Matrix Converter Fed Induction Motor Drives in Cement Industries

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Abstract: The cement industry plays a crucial role in infrastructure development and construction activities. There is a need to enhance the efficiency and performance of cement industries to meet the growing demand for cement while reducing energy consumption and environmental impact. One potential solution for enhancing efficiency and performance in cement industries is the use of matrix converter-fed induction motor drives with fuzzy logic control. By implementing this technology, the cement industry can benefit from improved energy conversion, utilization, higher motor efficiency, reduced power losses and enhanced control capabilities. This can result in significant energy savings, reduced operating costs, and a more sustainable cement manufacturing process. The use of matrix converter-fed induction motor drives with fuzzy logic control allows for better control of motor speed and torque, ensuring optimal performance and productivity in cement production. The application of fuzzy logic control enables the system to adapt to changing operating conditions and variations in load demand, leading to more precise and efficient motor operation. Overall, the integration of matrix converter-fed induction motor drives with fuzzy logic control holds great potential for enhancing efficiency and performance in cement industries. This paper provides a comprehensive review of the matrix converter fed induction motor drive in cement industries.

1 INTRODUCTION

In today's rapidly evolving industrial landscape, the quest to enhance the cement industry's efficiency and performance has become more pressing than ever. As the demand for cement continues to rise alongside the need for sustainable and environmentally conscious production processes, it is evident that implementing advanced technologies is imperative for the sector's growth and success. Among these technologies, matrix converter-fed induction motor drives with fuzzy logic control have emerged as a promising solution with the potential to revolutionise the efficiency and productivity of cement manufacturing (Bento et al., 2021).

This review aims to interpret the groundbreaking potential of matrix converter-fed induction motor drives with fuzzy logic control in revolutionizing the cement industry (Swami et al., 2022). By exploration into the complexity of this innovative technology and its implications for the industry. Through this exploration, to reveal the integration of these advanced systems can lead to substantial improvements in energy efficiency, cost savings, and overall sustainability within the cement manufacturing sector (Ninduwezuor-Ehiobu et al., 2023).

1.1 Overview of Cement Industries and Drive Systems

The cement industry serves as a cornerstone of infrastructure and construction, supplying the essential building material for various developmental projects. With the global demand for cement on the rise, cement manufacturing processes have increasingly come under scrutiny for their energy consumption and environmental impact (Ninduwezuor-Ehiobu et al., 2023). As a response to these challenges, the integration of advanced drive systems in cement manufacturing has garnered significant attention.

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Drive systems in the cement industry play a vital role in the operation of machinery and equipment involved in the production process, such as crushers, mills, and kilns. These systems are tasked with providing the necessary power, control, and efficiency for the smooth functioning of the equipment. Traditional drive systems often encounter limitations in energy conversion and control, leading to in efficiencies and higher operating costs (Peng et al., 2021). This has prompted the exploration of innovative solutions to enhance drive system performance, thereby optimizing energy usage and overall productivity in cement manufacturing.

1.2 Overview of Cement Industries and Drive Systems

Efficiency and performance are critical factors in cement manufacturing, influencing both the operational costs and the environmental footprint of the industry. By improving efficiency and performance, cement manufacturers can reduce energy consumption, minimize emissions, and enhance overall sustainability (Vaghela & Bhesaniya, 2024). It increased efficiency and performance directly impact the bottom line by reducing operating costs and increasing production output.

The efficiency and performance in cement manufacturing aligns with the broader global efforts to promote sustainable industrial practices. It is imperative for the cement industry to embrace technologies and methodologies that prioritize resource efficiency and environmental responsibility, ensuring its long-term viability and contribution to sustainable development (Vaghela & Bhesaniya, 2024).

1.3 Introduction to Matrix Converter-Fed Induction Motor Drives

Matrix converter-fed induction motor drives represent a technological advancement in the fields of motor drives for industrial applications (Barbhuiya et al., 2024). Unlike conventional drives, which depend on intermediate energy conversion stages, matrix converters facilitate direct energy conversion from the supply to the motor, eliminating the need for bulky and inefficient conversion components.

This direct energy conversion capability diffuse matrix converter-fed induction motor drives with superior energy efficiency, reduced power losses, and enhanced control precision. Such attributes make them particularly well-suited for the demanding operational requirements of the cement industry, where consistent and precise motor control is essential for optimizing performance and efficiency.

1.4 Role of Fuzzy Logic Control in Enhancing Drive Performance

Fuzzy logic control has emerged as for enhancing the performance of drive systems within industrial settings. Its adaptive and robust control capabilities allow for the effective regulation of motor speed, torque, and operational parameters in response to varying load conditions and process dynamics. Within the context of cement manufacturing, the integration of fuzzy logic control in matrix converter-fed induction motor drives holds the potential to fine-tune motor operation, ensuring optimal efficiency and performance in the face of dynamic and unpredictable operating conditions.

The collective combination of matrix converter-fed induction motor drives with fuzzy logic control represents a fundamental change in drive system optimization, promising to revolutionize the efficiency and performance of the cement industry. Through their collaborative impact, these technologies offer the means to achieve unusual levels of energy efficiency, operational flexibility, and performance reliability in the production of cement (Abunike et al., 2023).

2 MATRIX CONVERTER TECHNOLOGY

The implementation of matrix converter technology in various industrial applications, including cement manufacturing, has collected significant attention due to its potential to revolutionize energy efficiency, control precision, and overall system performance (Omrany et al., 2023).

2.1 Principles of Matrix Converters

Matrix converters represent a novel approach to power conversion, enabling direct energy conversion from the input to the output without the need for intermediate energy storage or conversion stages. Unlike traditional converters that rely on components such as rectifiers and inverters. Matrix converters facilitate seamless energy transfer thereby minimizing power losses and enhancing overall efficiency. The principle of matrix converters involves the use of semiconductor switches to dynamically control the energy flow between the input and output, allowing for precise and efficient operation within industrial motor drive systems (Gerami et al., 2021).

In the specific context of the cement industry, the principles of matrix converters are particularly compelling due to their ability to provide direct and efficient energy conversion, ultimately contributing to enhanced motor performance and energy efficiency in critical cement manufacturing processes.

Matrix converters are single-stage alternating current (AC/AC) power converters mainly based on power transistors with minimal passive component requirements (Alammari et al., 2019). Even though the industrial applications of matrix converters have been limited by constraints such as efficiency and semiconductor drive requirements, recent developments in semiconductor technologies combined with more affordable and powerful computation devices, such as system-on-chip technologies that combine both Field Programmable Gate Array (FPGA) and microprocessors inside the same chip enabling the use of more complex control schemes, a promising future for matrix converters in a variety of applications. Fuzzy logic-based matrix converter for IM shown in figure 1.

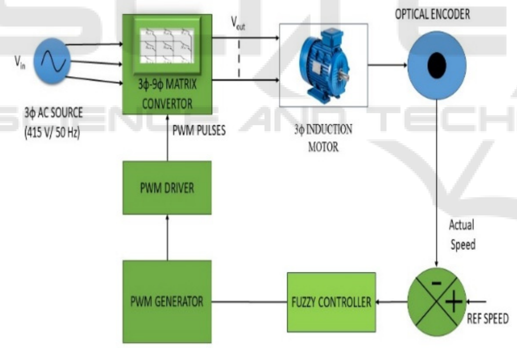

Figure 1: Fuzzy Logic Based Matrix Converter Fed IM

Matrix converters are bidirectional power topologies that allow AC/AC power conversion, without intermediate energy storage, revealing one of the most important advantages of matrix converters when compared to traditional back-to-back (B2B) voltage source converters (VSCs) (Alammari et al., 2019). The reduced filtering requirements makes the matrix converter a topology mainly dependent on power semiconductors and as a direct consequence the matrix converter is able to achieve unparalleled power densities. Matrix converters can be divided into two different families of converters, single stage or direct matrix converters (DMCs) and dual-stage or indirect matrix converters (IMC) (Khanday, 2022).

2.2 Advantages in Industrial Applications

The integration of matrix converter technology in industrial applications, such as cement manufacturing, offers a many of advantages that have the potential to significantly impact operational efficiency and sustainability (Mahmud & Gao, 2024). Firstly, matrix converters enable direct and seamless energy transfer, resulting in reduced power losses and enhanced energy efficiency (Chen et al., 2024). This translates to lower operating costs and minimized environmental impact, aligning with the cement industry's growing emphasis on sustainable and resource-efficient practices (Khanday, 2022).

The precise control capabilities of matrix converters, particularly in conjunction with induction motor drives contribute to improved dynamic response and operational flexibility. This is crucial for cement manufacturing processes that often encounter varying load demands and operational conditions, enhance the practical utility of matrix converters in optimizing motor performance and productivity in the industry (Chen et al., 2024).

Another, advantage of matrix converters is their compact and lightweight design, which minimizes physical space requirements and installation complexities (Kaleybar et al., 2024). This is especially relevant in the context of cement manufacturing facilities, where space optimization and streamlined installation processes are essential for maintaining efficient and cost-effective operations (Evangeline et al., 2024).

2.3 Challenges and Limitations

While matrix converter technology holds insist for industrial applications, including the cement industry. One of the primary challenges associated with matrix converters is the complexity of their control algorithms and modulation strategies. Achieving optimal performance and stability requires intricate control methodologies, which may pose challenges in terms of system design, implementation, and maintenance, particularly in industrial environments with exacting operational requirements and regulatory standards (Molina, 2017).

The reliability and fault tolerance of matrix converters under various operating conditions present another critical consideration.

The robustness and resilience of these systems in the face of voltage fluctuations, transient overloads, and other operational disturbances is essential for their successful integration into the demanding operational environment of cement manufacturing facilities.

The initial capital investment for implementing matrix converter technology, although offset by long-term energy savings and operational efficiencies, may present a barrier to widespread adoption within the cement industry, especially for smaller-scale producers.

Despite these challenges, advancements in control algorithms, fault tolerance mechanisms, and cost-effective manufacturing processes are continuously addressing the limitations associated with matrix converter technology, improving for its broader integration and sustained benefits in the realm of cement manufacturing.

3 INDUCTION MOTOR DRIVES IN CEMENT INDUSTRIES

3.1 Characteristics of Induction Motors in Cement Manufacturing

In the context of cement manufacturing, induction motors play a crucial role due to their robustness, reliability, and ability to operate under varying load conditions. These motors are often subjected to high starting torque requirements and fluctuating loads, making them indispensable for driving equipment such as crushers, conveyors, and fans in cement plants. Their simple and rugged construction makes them well-suited for the harsh operational environment of cement manufacturing, where dust, high temperatures, and vibration are common challenges. The ability of induction motors to operate efficiently across a wide range of speeds further enhances their suitability for diverse applications in the cement industry.

3.2 Traditional Drive Systems and Their Limitations

Induction motor drives in cement industries have relied on fixed-speed drive systems, resulting in suboptimal energy efficiency and limited control over motor operation. Such traditional drive systems often suffer from inherent limitations in adapting to fluctuating load demands and optimizing energy usage, leading to inefficiencies and increased operational costs (Kim et al., 2024). The lack of advanced control features and the inability to dynamically adjust motor speed and torque according to process requirements further restrict the overall performance and flexibility of these drive systems in cement manufacturing (Swami et al., 2016).

3.3 Need for Advanced Drive Solutions

The cement industry's demand for advanced drive solutions is motivated by the need to improve energy efficiency, productivity and sustainability, while also addressing operational difficulties. Advanced drive solutions incorporating modern control technologies, such as variable frequency drives and advanced control algorithms, can address the shortcomings of traditional drive systems and unlock substantial performance improvements (Xie et al., 2021). By enabling precise control over motor speed and torque these advanced drive solutions can optimize energy usage. To minimize mechanical stress on equipment and support the adoption of sustainable operational practices within cement manufacturing facilities. Moreover, the integration of advanced drive solutions can contribute to reducing maintenance requirements and extending the operational lifespan of critical equipment, aligning with the industry's pursuit of enhanced reliability and cost-effective operations (Swami et al., 2016).

4 MATRIX CONVERTER-FED INDUCTION MOTOR DRIVES

Industrial applications, particularly in the province of cement manufacturing, have seen a growing integration of matrix converter technology due to its significant advantages and potential to optimize operational efficiency and sustainability (Vinil Dani & Jobin Christ, 2024).

4.1 Integration of Matrix Converter Technology in Industrial Drives

The integration of matrix converter technology in industrial drives presents a transformative approach to power conversion and motor control (Rissman et al., 2020). By directly converting AC power from the grid into variable-frequency AC output for the induction motors, matrix converters eliminate the need for intermediate DC-link components resulting in a seamless energy transfer with reduced power losses (Gong et al., 2024). This not only enhances energy efficiency but also enables precise control over motor speed and torque, addressing the variable load demands inherent in cement manufacturing processes.

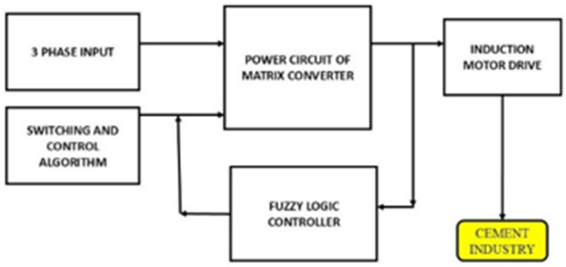

Figure 2: Proposed AI-based Matrix Converter Fed Induction Motor Drive

The compact and lightweight design of matrix converters also makes them well-suited for the space-constrained environments of cement manufacturing facilities, where efficient space utilization is crucial for operational productivity. The proposed model of AI based Matrix Converter Fed Induction Motor Drive is shown in figure 2.

4.2 Technical Considerations and Challenges in Implementation

Despite the substantial advantages offered by matrix converter technology. Its implementation in industrial drives, particularly in cement industries poses several technical considerations and challenges. The complexity of control algorithms and modulation strategies, essential for achieving optimal performance and stability, requires meticulous system design, implementation and maintenance to ensure seamless integration into the demanding operational environment of cement manufacturing facilities.

Moreover, ensuring the reliability and fault tolerance of matrix converters under various operating conditions, especially in the face of voltage fluctuations and transient overload common in industrial settings, is critical for the sustained performance of these systems (Javaid et al., 2021) (Swami & Kumar, 2020).

Additionally, while the long-term energy savings and operational efficiency achieved through matrix converter technology justify the initial capital investment. The cost implications may pose a barrier to widespread adoption, particularly for smaller-scale cement producers.

In navigating these challenges, ongoing advancements in control algorithms, fault tolerance mechanisms, and cost-effective manufacturing processes are crucial in addressing the limitations associated with matrix converter technology, thereby fostering its broader integration within the cement industry and unlocking its full potential for driving sustainable improvements in energy usage and motor performance.

5 FUZZY LOGIC CONTROL IN DRIVE SYSTEMS

Fuzzy logic control is a powerful and intuitive control system that operates on the principles of fuzzy logic, allowing for the representation of imprecise and non-linear relationships between inputs and outputs. Unlike traditional binary logic, where inputs are either true or false, fuzzy logic allows for degrees of truth, enabling a more nuanced and flexible control approach (Vinil Dani & Jobin Christ, 2024).

FLC utilizes linguistic variables and fuzzy rules to process input data and generate output control signals, making it particularly well-suited for complex and uncertain systems such as motor drives in the cement industry.

Novel fuzzy logic-based controller development of AI based Matrix converter fed Induction motor drive model will be developed by using MATLAB/SIMULINK environment. After that the effectiveness of purposed fuzzy logic-based controller will be tested under different operating conditions (Swami et al., 2022).

Also, ensure the reliable and stable operation of the cement industries. The application of fuzzy logic control in motor drives within the cement industry offers several advantages. FLC be excellent in handling the non-linear and uncertain load characteristics of cement manufacturing equipment (Zhang et al., 2018).

It can adaptively adjust motor speed and torque based on imprecise or fluctuating process requirements, thereby enhancing the overall operational efficiency and performance of the drive systems.

Additionally, the ability of FLC to handle imprecise input data, such as varying material properties in crushers or fluctuations in conveyor loads, enables precise and responsive control, contributing to improved equipment reliability and process stability.

5.1 Advantages of Fuzzy Logic Control in Cement Industry Applications

The cement industry can benefit significantly from the implementation of FLC in drive systems. Fuzzy logic control enables adaptive and intelligent control over motor drives, allowing for seamless adaptation to changing operating conditions and load demands (Utvic et al., 2023).

This adaptability not only enhances energy efficiency by optimizing motor operation based on real-time requirements but also contributes to the continuity of drive system components by minimizing stress (Diaz et al., 2020).

The inherent ability of FLC to handle imprecise and uncertain data empowers drive systems to operate reliably amidst the challenging environmental conditions of cement manufacturing, ultimately supporting sustainable and cost-effective operations.

The advantages of FLC enable cement plants to achieve greater process stability, energy savings, and overall operational reliability, aligning with the industry's goals of efficiency and sustainability.

6 PERFORMANCE EVALUATION AND CASE STUDIES

6.1 Methods for Evaluating Drive Performance

Evaluating the performance of drive systems, particularly those integrated with matrix converter technology, requires the assessment of various standard. Key parameters such as energy efficiency, dynamic response, and torque control precision serve as fundamental indicators of drive performance. Energy efficiency can be quantified through measurements of power losses and energy consumption, while dynamic response reflects the drive system's ability to adjust rapidly to load changes.

Additionally, torque control precision assesses the accuracy of the motor's response to varying torque demands, crucial for meeting the operational requirements of cement manufacturing processes.

Simulation and testing methodologies play an integral role in evaluating drive performance. Utilizing advanced simulation software allows for virtual analysis of system dynamics and control strategies under diverse operating conditions, providing insights into energy utilization and system response.

Complementing simulations with controlled testing in real-world environments further validates the performance of matrix converter-fed induction motor drives, enabling the verification of energy efficiency improvements and dynamic response capabilities in actual operational scenarios.

6.2 Comparative Analysis with Traditional Drive Systems

Conducting a comparative analysis between matrix converter-fed induction motor drives and traditional drive systems reveals the significant improvements in energy efficiency and operational costs achievable with the former (Swami et al., 2022). By eliminating the need for intermediate DC-link components and offering seamless energy transfer, matrix converters exhibit superior energy efficiency conversion capabilities, resulting in reduced power losses and enhanced overall efficiency. This comparative analysis serves to underscore the economic benefits and long-term operational cost advantages associated with the adoption of matrix converter technology in cement industries.

Table 1: Performance comparison of control strategies used in matrix converter fed induction motor drive

Control Strategy	Principle	Description	Advantages
Direct Torque Control (DTC) (Peng et al., 2021)	Controls torque and flux directly.	Directly controls motor torque and flux using hysteresis controllers	High dynamic performance, no need for modulation indexes
Field-Oriented Control (FOC) (Bi et al., 2021)	Decouples torque and flux control.	Decouples torque and flux control using coordinate transformations	Precise control, good dynamic response
Scalar Control (V/f Control) (Swami & Kumar, 2020)	Maintains constant voltage-to-frequency ratio.	Controls motor speed by maintaining a constant voltage-to-frequency ratio	Simple implementation, cost-effective
Fuzzy Logic Control (FLC)(Bajpai et al., 2024)	Uses heuristic rules for control.	Uses fuzzy logic rules to handle non-linearities and uncertainties in the control system.	Robust to parameter variations, good for non-linear systems
Model Predictive Control (MPC)(Peng et al., 2021)	Predicts and optimizes future control actions.	Predicts future behaviour of the motor to optimize control inputs	High performance, handles constraints explicitly

Space Vector Modulation (SVM)(Bajpai et al., 2024)	Optimizes switching sequences.	Uses space vector theory to generate optimized PWM signals for the matrix converter	High efficiency, low harmonic distortion
Neural Network Control (NNC)(Delille et al., 2012)	Learns and adapts to system dynamics.	Employs neural networks to learn and control motor behaviour dynamically	Adaptive, handles complex non-linearities
Sliding Mode Control (SMC)(Nahin et al., 2023)	Uses a discontinuous control signal.	Uses a sliding surface to drive system states to desired values	Robust to disturbances and parameter variations
Hybrid Control Strategies(Swami & Kumar, 2020)	Combines multiple control methods.	Combines two or more control strategies to leverage their strengths and mitigate their weaknesses.	Balances robustness and precision.

Table 2: Continuation of Table 1

Disadvantages	Applications	Remark
Torque ripple, complex implementation	Industrial drives needing fast response	DTC offers very high dynamic response but at the cost of higher torque ripple.
Requires accurate motor parameters, complex	High-performance applications.	FOC offers precise control, good dynamic response
Poor dynamic performance, limited to steady-state	Fans, pumps, low-cost drives.	Easy to implement but lacks dynamic performance and robustness.
Complex design, computationally intensive	Systems requiring robust control.	FLC balances ease of understanding and robustness but requires careful rule tuning.
High computational burden, complex to design	Advanced systems requiring precision.	MPC provides top-notch performance across the board but demands high computational power and complexity.
Complex implementation, requires precise calculation	High-performance, low distortion needs.	SVM offers very low harmonic distortion and excellent performance but involves complex implementation.
Requires extensive training, high computational effort	Adaptive control systems.	NNC is adaptive and handles complex dynamics well but requires extensive computational resources and training data.
Chattering effect, requires high-frequency switching	Systems with large uncertainties.	SMC is highly robust and performs well dynamically, but can be complex and potentially introduces chattering
Complex design and integration.	Applications needing versatile control.	Specific needs but involve managing the complexities of multiple methods.

7.1 Parameter Optimization Using Fuzzy Logic Control

Fuzzy logic control enables the optimization of parameters, such as motor speed, torque, and energy consumption, based on real-time requirements. By employing FLC, the drive systems can dynamically adapt to fluctuating conditions, leading to improved equipment reliability, enhanced energy efficiency, and minimised stress and wear on the drive system.

7.2 Strategies for Improving Efficiency and Performance

In addition to FLC, there are various strategies for improving efficiency and performance in drive systems. These may include the use of advanced sensor technologies for accurate data acquisition, predictive maintenance techniques to predict potential issues, and the integration of machine learning algorithms for continuous performance optimization (Phoon et al., 2022). These strategies enable the drive systems to operate at peak efficiency, contributing to overall process stability and cost-effectiveness.

7.3 Real-Time Adaptation and Optimization Methods

In addition Real-time adaptation and optimization methods involve the integration of advanced control algorithms and predictive analytics to continuously monitor and adjust the motor drives based on real-time data. By using real-time data and advanced optimization algorithms, the drive systems can adapt to changing conditions, ensuring optimal performance and energy efficiency (Phoon et al., 2022). These methods provide the cement industry with the ability to achieve sustainable and reliable operations while also supporting the industry's goals of efficiency and sustainability.

As the cement industry continues to pursue advancements in optimization techniques, the integration of real-time adaptation and optimization methods, in conjunction with FLC, presents an approach to drive system optimization, ultimately driving continual improvements in motor performance and operational excellence. Various types of the control strategies used in matrix converter fed induction motor drive are shown in Table 1 and Table 2.

8 FUTURE DIRECTIONS AND EMERGING TRENDS

The future of matrix converter technology holds significant promise for advancing the energy efficiency, operational flexibility, and reliability of drive systems, particularly in the context of cement industries. As technological advancements continue to unfold, the potential advances in matrix converter technology are poised to revolutionize the landscape of motor drives and power conversion within industrial settings.

8.1 Potential Advances in Matrix Converter Technology

The ongoing research and development in matrix converter technology are expected to lead to increased power density, enhanced fault tolerance, and expanded compatibility with various motor types. Advancements in semiconductor materials and switching technologies are expected to contribute to the further miniaturization and increased efficiency of matrix converter topologies.

The integration of advanced control strategies and fault-diagnostic algorithms is also anticipated to enhance the fault tolerance and reliability of matrix converter-fed induction motor drives in the cement industry.

Moreover, the exploration of novel modulation techniques and advanced thermal management solutions is poised to address the challenges associated with high-power density and heat dissipation, thereby paving the way for the deployment of matrix converters in higher-capacity drive applications within cement manufacturing facilities.

These potential advances hold the promise of optimizing energy utilization, enabling seamless integration with smart grid systems, and fostering the evolution of robust and resilient motor drive solutions tailored to the specific requirements of the cement industry.

8.2 Potential Advances in Matrix Converter Technology

In charting the future trajectory of matrix converter-fed induction motor drives in cement industries, the prospects for further research and development are multifaceted and encompass diverse areas of exploration. With a focus on enhancing grid compatibility, mitigating harmonic distortion, and advancing robust control methodologies, research endeavors are poised to elevate the grid-interfacing capabilities of matrix converter technology, fostering harmonious integration with the existing grid infrastructure and supporting the seamless exchange of power with minimal electromagnetic interference.

Additionally, the pursuit of enhanced cybersecurity measures, fault-tolerant design frameworks, and interoperable communication standards stands to underpin the development of secure, resilient, and standardized matrix converter-driven drive systems.

This proactive approach serves to fortify the operational integrity and reliability of drive systems, aligning with the imperatives of safety, continuity, and adaptability within the dynamic industrial landscapes of cement manufacturing.

9 CONCLUSIONS

The integration of advanced control strategies, fault-diagnostic algorithms, and novel modulation techniques is anticipated to enhance the reliability and efficiency of matrix converter-fed induction motor drives, thereby fostering the evolution of robust and resilient motor drive solutions tailored to the specific requirements of the cement industry.

The implications of integrating matrix converter technology with cement industries extend to energy optimization, smart grid systems integration, and the establishment of responsive production processes. Implementing fuzzy logic control can further enhance the adaptability and robustness of motor drives, facilitating smooth transition towards smart manufacturing principles.

Additionally, the adoption of advanced communication protocols such as Time-Sensitive Networking and 5G connectivity is recommended to bolster the interoperability and scalability of matrix converter-driven drive systems within the broader ecosystem of smart manufacturing infrastructure.

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