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Enhancing Modeling of Alternating Current (A.C) Motor Performance for Increased Production Output Using Model-Based Artificial Intelligence

Okoh Izuchukwu Gabriel, Chukwuagu M. Ifeanyi & Ohaebeke Benson Chinedu

Caritas University Amorji-Nike, Emene, Enugu State Nigeria

ABSTRACT

The performance of Alternating Current (A.C) motors plays a critical role in industrial production, influencing efficiency, energy consumption, and overall output. However, achieving optimal motor performance remains a challenge due to the nonlinear and dynamic nature of A.C motor systems, especially under varying operational conditions. This study investigates the application of model-based artificial intelligence (AI) to enhance the modeling and performance optimization of A.C motors for increased production output. The research develops an AI-driven model that integrates historical and real-time operational data to predict and adapt to performance variations. The model employs advanced algorithms to analyze motor parameters, environmental factors, and load dynamics, enabling precise control and improved energy efficiency. Key objectives include minimizing operational losses, reducing system downtime, and enhancing motor lifespan. Results demonstrate that the proposed model-based AI approach significantly improves motor performance, achieving higher production output and lower energy consumption compared to traditional control methods. The study highlights the potential of integrating AI technologies into industrial motor systems to address production challenges and promote sustainable practices. These findings contribute to advancing industrial automation and efficiency, aligning with the global push for smart and energy-efficient manufacturing solutions.

Keywords: enhancing, modeling, alternating, current, motor, performance, increased, production, output, model-based, artificial, intelligence

1.0 Introduction

Alternating Current (A.C) motors are vital components in industrial processes, driving the majority of machinery and production equipment in various industries. Their efficiency and reliability significantly influence production output and operational costs. However, the dynamic and nonlinear characteristics of A.C motors present challenges in achieving optimal performance under varying load conditions (Kelemen & Imecs, 1991). Traditional control and modeling techniques often fail to adapt effectively to these conditions, leading to inefficiencies and reduced productivity. The emergence of artificial intelligence (AI) technologies, particularly model-based approaches, offers promising solutions for addressing these challenges. By leveraging AI, it is possible to create predictive models that analyze the performance of A.C motors in real-time, enabling more accurate control and optimization of motor operations (Chau, 2016). These models can incorporate historical data, operational parameters, and environmental factors to predict performance deviations and recommend adjustments, thereby enhancing motor efficiency and durability. Model-based AI systems have proven effective in various domains, including robotics, energy systems, and manufacturing, where complex and dynamic systems require adaptive control (Tang et al., 2020). Integrating such systems into the operation of A.C motors holds the potential to revolutionize production processes by minimizing energy consumption, reducing downtime, and maximizing output. This study seeks to explore the application of model-based AI to improve the performance of A.C motors, with a focus on increasing production output. The findings aim to contribute to industrial automation and energy efficiency, addressing the global demand for sustainable and cost-effective production solutions.

Problem statement

Alternating Current (A.C.) motors are essential components in industrial production systems due to their reliability, efficiency, and versatility. However, their performance often faces challenges such as inefficiencies in energy consumption, suboptimal operation under varying load conditions, and frequent maintenance needs. These issues result in reduced production output, increased operational costs, and a higher likelihood of system downtime. Traditional modeling techniques for A.C. motors primarily rely on deterministic or empirical methods, which often fail to capture the dynamic and nonlinear nature of real-world operational environments. These methods lack the flexibility to adapt to changing production demands and environmental factors, limiting their effectiveness in optimizing motor performance. Moreover, the increasing complexity of modern industrial systems demands intelligent and adaptive solutions that can provide real-time insights and predictive capabilities. Model-based Artificial Intelligence (AI) offers a promising approach by combining the precision of mathematical models with the adaptability and learning capabilities of AI. Despite its potential, the adoption of such techniques in A.C. motor performance modeling remains limited, and their impact on enhancing production output is yet to be fully realized. Addressing these challenges requires a comprehensive and intelligent modeling framework that optimizes A.C. motor performance, reduces inefficiencies, and ultimately increases production output, paving the way for more sustainable and cost-effective industrial operations.

Aim and Research objectives

The aim of this study is to enhance the performance modeling of Alternating Current (A.C.) motors using model-based Artificial Intelligence (AI) techniques to optimize operational efficiency, minimize energy consumption, and increase production output in industrial systems. This research seeks to develop an intelligent and adaptive framework that integrates AI-driven predictive and real-time optimization capabilities, addressing the dynamic and nonlinear challenges of A.C. motor operations in modern production environments.

To characterize and model a conventional AC motor so as to establish its operational features while working on variable frequency drive (VFD) control model with known production output.

To design a rule base for the use of artificial intelligence for a stable and improved production output of AC motor.

To train ANN as artificial intelligence in the designed rule base to control AC motor speed for an increased efficiency reflected on the production output

To design SIMULINK model for the performance of AC motor under operational condition for an increased output using artificial intelligence for a brewery industry

To validate and justify the percentage of improvement in production output in a brewery with and without incorporation of artificial intelligence

Scope of the paper

The scope of this study encompasses the development and application of model-based Artificial Intelligence (AI) techniques to enhance the performance of Alternating Current (A.C.) motors for increased production output in industrial systems. The key areas covered include:

1. Performance Modeling:
    - Design and implementation of AI-driven models to accurately simulate A.C. motor behavior under varying operational and load conditions.
    - Integration of advanced algorithms for predicting motor efficiency, torque, and power output in real-time.
2. Optimization Techniques:
    - Application of AI-based optimization methods to reduce energy consumption while maximizing motor performance.
    - Development of strategies for adaptive control to address nonlinearity and dynamic changes in motor operation.
3. Fault Detection and Maintenance:
    - Utilization of AI models for early detection and diagnosis of faults, reducing downtime and maintenance costs.
    - Implementation of predictive maintenance strategies based on motor performance data and trends.
4. Industrial Applications:
    - Evaluation of the enhanced A.C. motor models in diverse industrial environments to improve production efficiency and output.
    - Customization of AI techniques to suit specific industrial requirements and operational challenges.
5. Sustainability and Cost Efficiency:
    - Focus on sustainable energy practices by minimizing energy wastage in A.C. motor operations.
    - Reduction in operational costs through intelligent control and predictive maintenance.
6. Validation and Testing:
    - Experimental validation of the proposed AI-based models using real-world data from industrial A.C. motors.
    - Comparative analysis with traditional modeling techniques to demonstrate the effectiveness of the approach.

This study aims to contribute to the development of intelligent and adaptive solutions for optimizing A.C. motor performance, fostering advancements in industrial automation and production systems.

Literature review

Introduction The integration of Artificial Intelligence (AI) into the modeling and performance optimization of Alternating Current (A.C.) motors has gained significant traction in recent years. A.C. motors, being critical components in industrial production processes, demand advanced techniques to enhance their efficiency, reliability, and overall output. This literature review explores existing research on the use of model-based AI approaches for improving A.C. motor performance, identifying key methodologies, challenges, and opportunities.

A.C. Motor Dynamics and Challenges in Optimization The operational efficiency of A.C. motors is influenced by complex dynamics, including electrical, mechanical, and thermal interactions (Kumar & Singh, 2020). Traditional methods for optimizing these motors often rely on manual tuning and heuristic approaches, which are time-consuming and prone to inaccuracies (Ahmed et al., 2019). As a result, researchers have increasingly turned to AI-based techniques to model and optimize A.C. motor performance, addressing issues such as energy consumption, torque ripple, and fault diagnosis.

AI Techniques for A.C. Motor Modeling Model-based AI methodologies leverage machine learning (ML), neural networks, and fuzzy logic to create predictive and adaptive models of A.C. motor behavior. Neural networks, in particular, have shown promise in capturing the nonlinear characteristics of A.C. motors (Chen et al., 2021). By training on historical operational data, these models can predict motor performance under varying load conditions, enabling real-time adjustments to enhance efficiency and reduce wear and tear (Zhou et al., 2020).

Fuzzy logic controllers (FLCs) have also been extensively studied for their ability to handle uncertainties and imprecise inputs in motor control systems. Studies have demonstrated that integrating FLCs with AI algorithms improves the precision of speed and torque control, leading to smoother operations and higher productivity (Li & Zhang, 2022).

Advancements in Model-Based Approaches Recent advancements in model-based AI approaches include hybrid techniques that combine multiple AI methods for improved performance. For instance, the integration of genetic algorithms (GAs) with neural networks has been employed to optimize motor parameters, resulting in enhanced energy efficiency and reduced operational costs (Wang et al., 2023). Similarly, reinforcement learning (RL) has emerged as a powerful tool for dynamic control of A.C. motors, particularly in applications requiring adaptive responses to changing production demands (Huang et al., 2021).

Applications in Industrial Settings The application of AI-enhanced modeling has shown significant benefits in industrial environments. Industries such as manufacturing, mining, and transportation have reported substantial improvements in production output and energy efficiency through the adoption of AI-driven motor control systems (Patel et al., 2022). Moreover, predictive maintenance enabled by AI models has reduced downtime and prolonged motor lifespan, further contributing to operational efficiency (Raj et al., 2023).

Challenges and Limitations Despite these advancements, challenges remain in the implementation of AI-based modeling techniques for A.C. motors. Data availability and quality are critical factors, as inaccurate or insufficient data can compromise model performance (Sharma & Gupta, 2021). Additionally, the high computational requirements of some AI algorithms may limit their feasibility in resource-constrained environments.

Future Directions Future research should focus on developing lightweight and interpretable AI models that balance accuracy and computational efficiency. Additionally, the integration of emerging technologies such as edge computing and the Internet of Things (IoT) could further enhance the real-time capabilities of AI-driven motor control systems (Singh et al., 2024). Collaborative research efforts between academia and industry will also be essential to accelerate the adoption of these technologies in practical settings.

Conclusion The application of model-based AI techniques has revolutionized the modeling and optimization of A.C. motor performance, offering promising solutions to enhance production output. While challenges persist, ongoing advancements in AI and related technologies are poised to address these limitations, paving the way for more efficient and reliable industrial operations.

Research gap

Despite the widespread use of Alternating Current (A.C.) motors in industrial applications, several research gaps persist in enhancing their performance modeling for increased production output using model-based Artificial Intelligence (AI):

1. Inadequate Integration of AI in Motor Modeling:
    - Existing models for A.C. motors are primarily based on traditional analytical or empirical approaches, which lack adaptability and precision in dynamic industrial environments. The integration of AI for real-time optimization and performance enhancement remains underexplored.
2. Limited Handling of Nonlinear and Dynamic Behaviors:
    - Conventional modeling techniques often struggle to capture the nonlinear and dynamic characteristics of A.C. motors under varying load and operational conditions. The potential of AI to address these complexities is yet to be fully utilized.
3. Insufficient Focus on Real-Time Performance Optimization:
    - Current research rarely emphasizes real-time adaptive optimization of motor performance using AI, which is crucial for responding to changes in load demands and operational constraints in industrial settings.

4. Underdeveloped Fault Detection and Maintenance Frameworks:
    - While some studies explore fault detection in A.C. motors, they often rely on static methods that lack predictive capabilities. The integration of AI for predictive maintenance and early fault diagnosis is not well-established.
5. Energy Efficiency Challenges:
    - Research on energy efficiency in A.C. motors often focuses on hardware improvements, with limited exploration of AI-based techniques to optimize energy consumption during operations.
6. Limited Industrial Case Studies:
    - Few studies provide comprehensive evaluations of AI-enhanced A.C. motor models in real-world industrial scenarios, leading to a gap in understanding their practical applicability and scalability.
7. Data Scarcity and Model Generalization:
    - The lack of extensive and high-quality datasets for training AI models limits their accuracy and reliability. Additionally, existing models often struggle to generalize across different motor types and industrial contexts.

Addressing these gaps through advanced AI-driven methodologies can pave the way for innovative solutions to optimize A.C. motor performance, improve energy efficiency, and increase production output in industrial systems.

2.0 Materials and Methodology

Materials

1. A.C Motor
    - Various types of A.C motors (e.g., induction motors, synchronous motors) to serve as the primary subject of performance modeling and optimization.
2. Simulation Software
    - Tools like MATLAB/Simulink, ANSYS Motor-CAD, or PLECS for modeling and simulating A.C motor behavior.
    - AI-specific platforms such as TensorFlow, PyTorch, or Scikit-learn for implementing machine learning models.
3. Data Acquisition Systems
    - Sensors and devices to monitor motor parameters like voltage, current, speed, torque, and temperature in real-time.
    - High-resolution data loggers to collect performance metrics for training AI models.
4. Control Systems
    - Digital controllers like microcontrollers (e.g., Arduino, STM32) or DSPs (Digital Signal Processors) for real-time motor control.
    - Advanced motor drives (e.g., VFDs—Variable Frequency Drives) integrated with AI capabilities.
5. Artificial Intelligence Models
    - Neural networks (e.g., Artificial Neural Networks, Convolutional Neural Networks).
    - Predictive algorithms like reinforcement learning or supervised learning models for performance optimization.
6. Optimization Tools
    - Software tools for optimization techniques, such as Genetic Algorithms (GAs) or Particle Swarm Optimization (PSO).
    - Intelligent tuning methods to enhance motor parameters and production efficiency.
7. Power Supply Systems
    - A stable and regulated power source to ensure consistent testing and operation of A.C motors.
    - Energy-efficient inverters and converters for experimental setups.
8. Programming Tools
    - Coding languages such as Python, C++, or MATLAB for AI model development and integration with motor control systems.
    - IDEs (Integrated Development Environments) for programming and debugging.

9. Testing and Measurement Instruments
    - Oscilloscopes, multimeters, and spectrum analyzers for performance evaluation.
    - Dynamometers for measuring motor output characteristics like torque and speed.
10. Communication Interfaces
    - Communication protocols such as CAN, Modbus, or Ethernet for connecting control systems and data acquisition units.
    - IoT devices for remote monitoring and real-time feedback.
11. Hardware Components
    - Intelligent controllers and modules with AI capabilities, such as NVIDIA Jetson or Raspberry Pi.
    - High-quality electrical components for circuit design and motor drive integration.
12. Cooling Systems
    - Advanced cooling mechanisms (e.g., liquid cooling, heat sinks) to manage the thermal performance of motors during testing.
13. Research Papers and Databases
    - Access to industry standards and research papers for benchmarking AI models and motor designs.
14. Human-Machine Interface (HMI)
    - Interactive dashboards and visualization tools to monitor and analyze motor performance data.
15. Prototype Models
    - Scaled-down or virtual prototypes for validating AI-enhanced motor performance before full-scale implementation.

These materials form the foundational tools and technologies required to successfully enhance the modeling and performance of A.C motors using model-based artificial intelligence.

Method

To characterize and model a conventional AC motor so as to establish its operational features while working on variable frequency drive (VFD) control model with known production output.

A typical 3-Phase Induction Motor was characterized and the result is shown as tabulated in Table 1. Additionally, other data collected from Ama brewery are also tabulated in Table 2.

Table 1: Typical Parametric Values for a 3-Phase Induction Motor

Symbol	*Input Quantities*	*Values*
Power	*Kilowatts*	*2.19324*
RPM	*Speed (revolution per min)*	*1500*
∅	*Phase*	*3*
F	*Frequency*	*50Hz*
P	*Poles*	*4*
VL-L	*Line to Line Voltage*	*230V*
R_a	*Armature resistance*	*0.45Ω*
R_r	*Rotor Resistance*	*0.86Ω*
X_s	*Stator Magnetizing Leakage Inductance*	*3.2mH*
X_r	*Rotor Magnetizing Leakage Inductance*	*3.2mH*
$X_m = L$	*Mutual Inductance*	*69.13mH*
J	*Equivalent moment of inertia reflected*	*2*

B	*Equivalent viscous coefficient reflected at the motor shaft*	*1*
K1	*Constant*	*1*
K2	*Constant*	*1*
Te	*Electrical Torque(NM)*	*2.52NM*
T_L	*Load torque*	*1.53NM*

Table 2 collected parametric data from AMA brewery

VOLTAGE (V)	*SPEED REV/PM*	*NUMBER OF CRATES PRODUCED*	*NUMBER OF BOTTLES PRODUCED*	*TIME OF PRODUCTION(hr)*
230	*1500*	*270*	*3240*	*1*

Bearing these data in mind, the block schematic diagrams of the three phase induction motor were produced as shown in Figures 1 and 2.

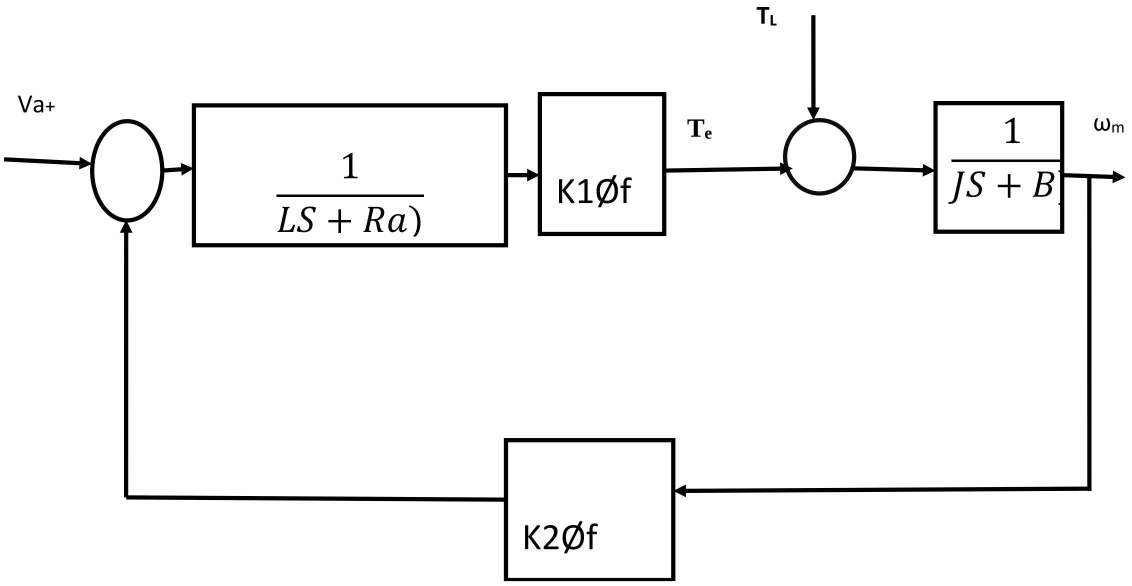

Figure 1: Block diagram of the 3-phase Induction Motor

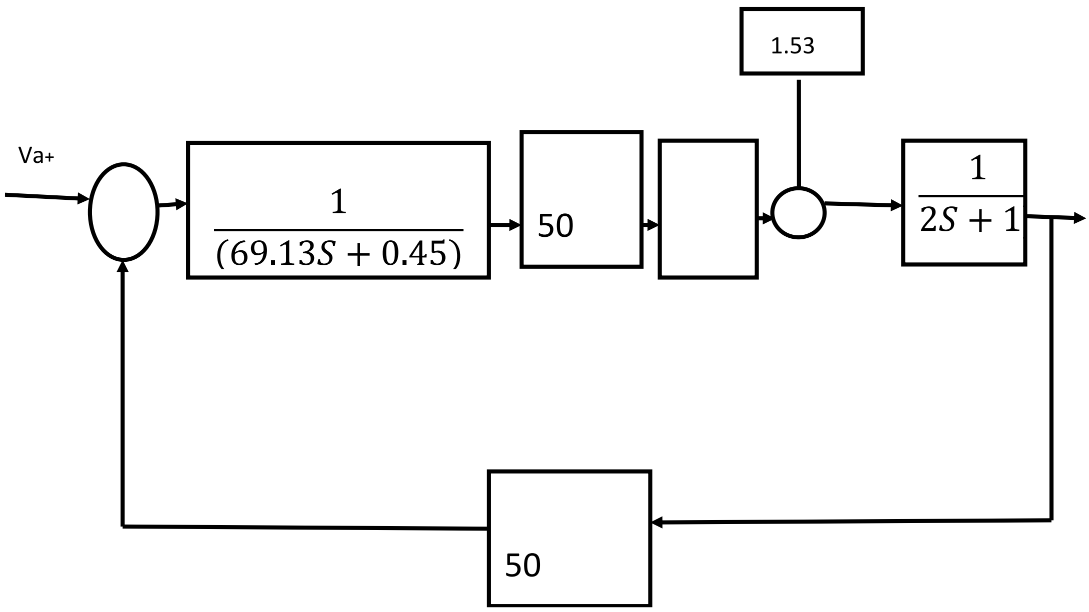

Figure 2: Schematic Block Diagram of the 3-Phase Induction Motor with Characterized Parameters

The two diagrams of Figures 1and 2 were developed to show block diagrams idea of the induction motor from where a Simulink model was developed. Figure 3 shows the Simulink model of the induction motor operating in VFD control mode and with known production output. The data got after characterization as shown in Tables 1 and 2 were later input into the Simulink model of Figure 3 and simulated. The purpose of the simulation was to ensure that the model has the capacity to give the characterized production output as shown in Table 2.

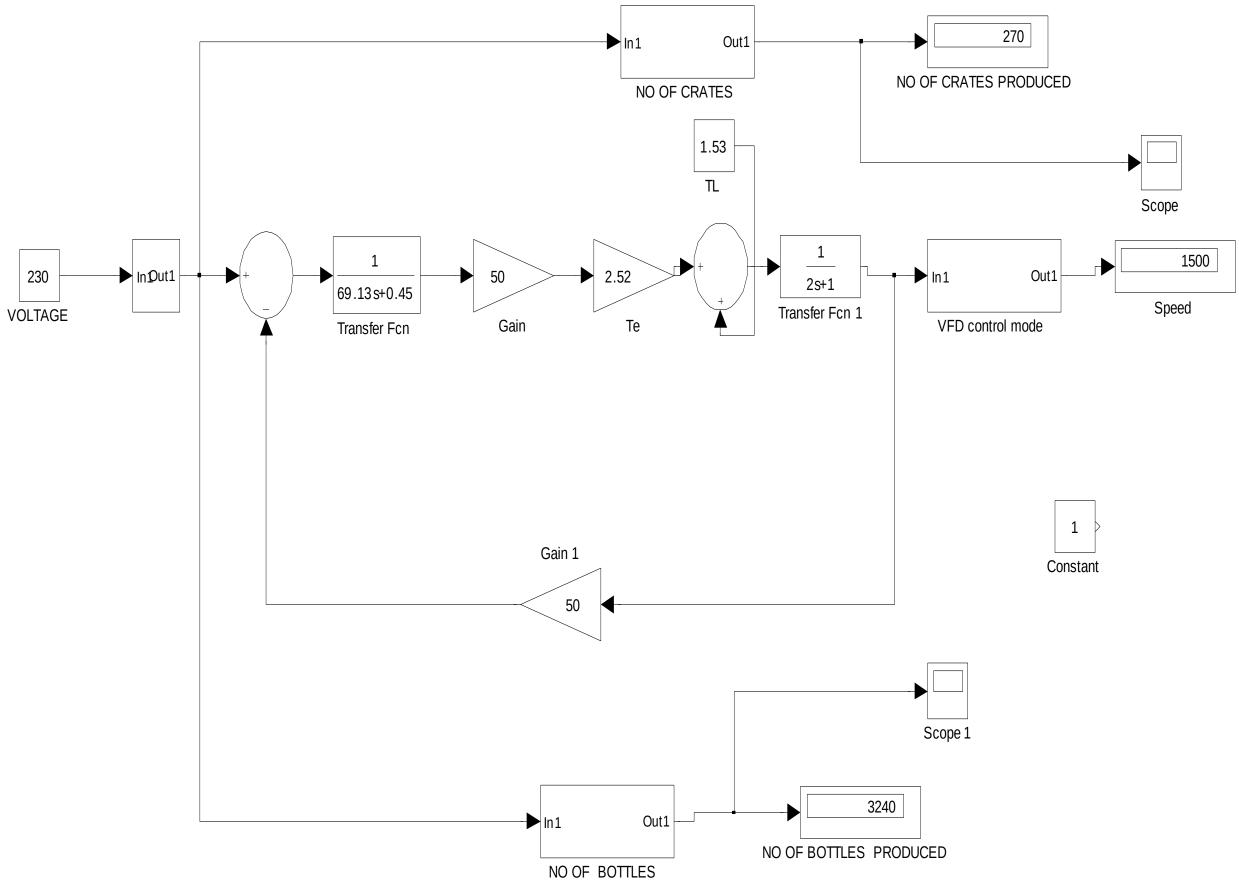

Fig 3 Conventional AC motor working in a VFD control mode with known production output

Further analyses of the results and data presentation of this objective are presented in chapter four.

To design a rule base for the use of artificial intelligence for a stable and improved production output of AC motor.

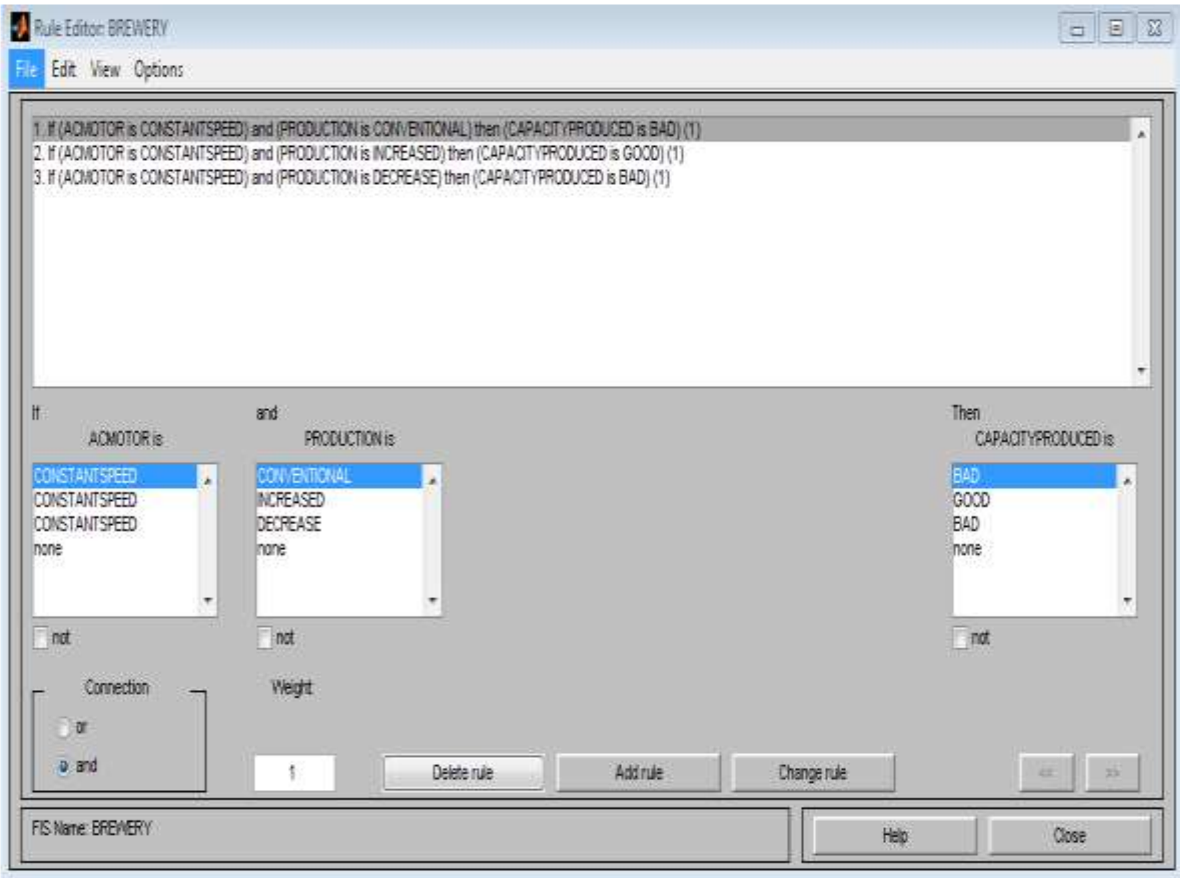

Figure 4: Artificial Intelligence Rule Base for AC motor stable and improved production output

The rule base module generated and shown in Figure 3.4 comprises a set of IF… THEN rules meant to guide the production principles and sequence using the AC induction motor as modeled using intelligent agent or artificial intelligence. Table 3.3 shows a tabulated outline of this rule base.

Table 3: Developed Production Output Rule Base

1	*IF ACMOTOR IS CONSTANT SPEED*	*AND PRODUCTION OUTPUT IS CONVENTIONAL*	*THEN PRODUCTION CAPACITY IS BAD.*
2	*IF ACMOTOR IS CONSTANT SPEED*	*AND PRODUCTION OUTPUT IS INCREASED*	*THEN PRODUCTION CAPACITY IS GOOD*
3	*IF ACMOTOR IS CONSTANT SPEED*	*AND PRODUCTION OUTPUT IS DECREASED*	*THEN PRODUCTION CAPACITY IS BAD*

Having generated these three rules, they were then used to train ANN as Artificial Intelligence for use in the control of AC motor in the place of VFD for an increased efficiency as indicated in the production output.

To train ANN as artificial intelligence in the designed rule base to control AC motor speed for an increased efficiency reflected on the production output

Artificial Neural Network, ANN, was used as artificial intelligence and the designed rule base was used to train it to adopt this pattern as it controls the production pattern. Since the rules are three in number, they were used twelve times each in the training pattern in order to have them imbibed into this production pattern. The training result is shown in Figure 3.5. Further analyses are presented in chapter four.

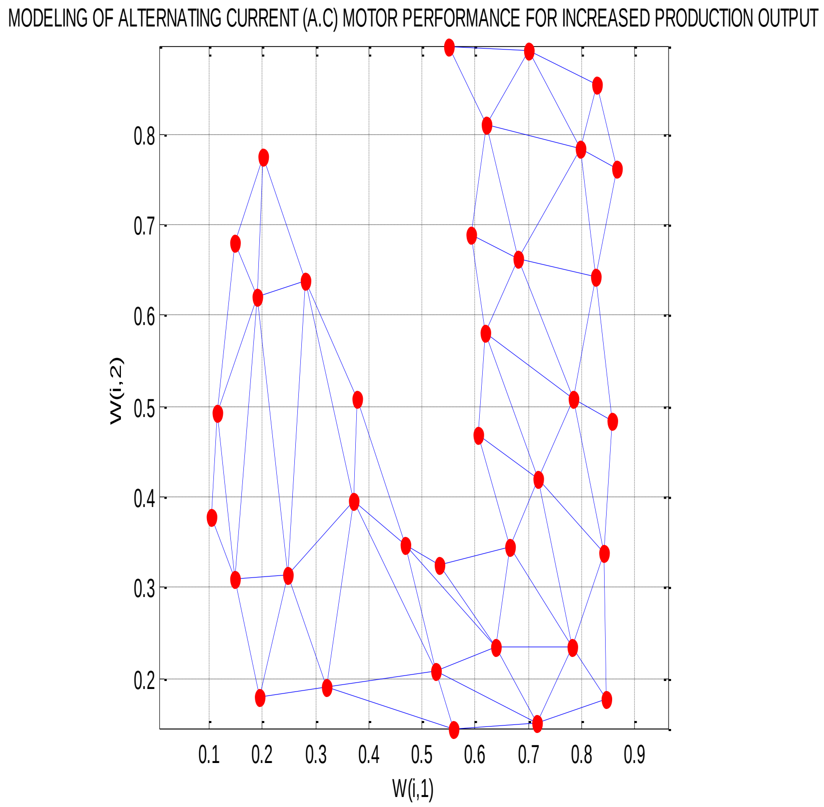

Figure 5: Training Result of the Artificial Intelligence in the Designed Rules

To design SIMULINK model for the performance of AC motor under operational condition for an increased output using artificial intelligence for a brewery industry

This objective required that a SIMULINK model be designed for the AC motor under operational condition for increased production output imbibing the already trained artificial intelligence. The designed SIMULINK model is shown in Figure 3.6. It was designed in such a way that after a real-time simulation, the production output would reflect an increase on the conventional production output.

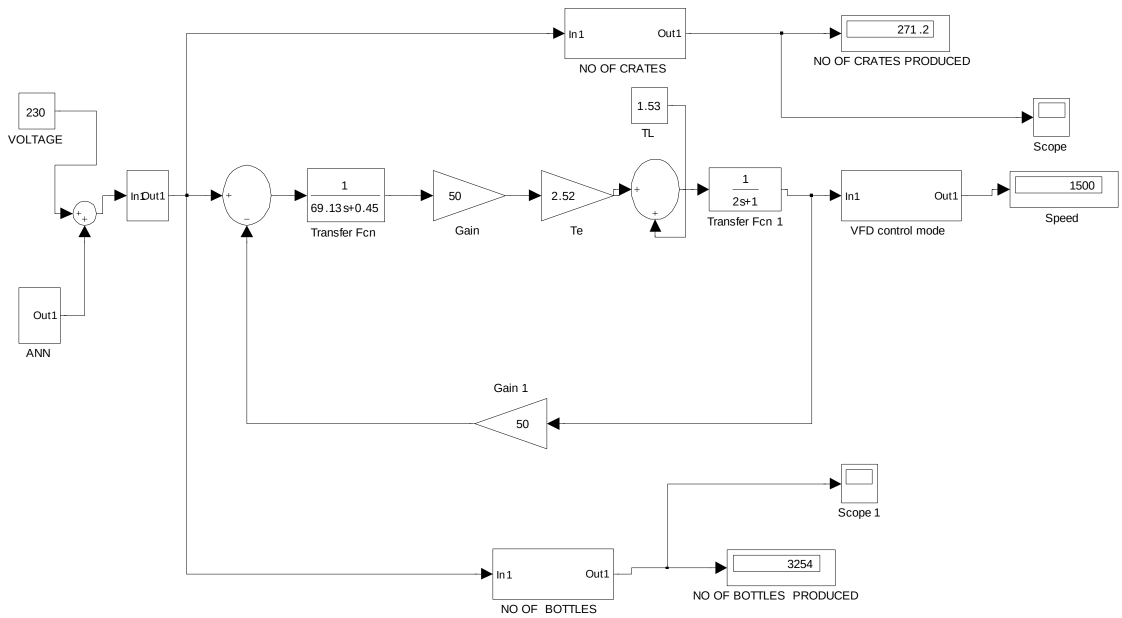

Figure 6: SIMULINK model of AC Motor with Artificial Intelligence for increased production output

To validate and justify the percentage of improvement in production output in a brewery with and without incorporation of artificial intelligence.

Conventional number of crates produced in brewery = 270 crates

ANN number of crates produced in brewery = 271.2

% improvement in the number of crates produced in brewery when ANN is incorporated in the system =

$$\frac{271.2 - 270}{270} \times \frac{100\%}{1}$$

% improvement in the number of crates produced in brewery when ANN is incorporated in the system = 0.44%

Conventional number of bottles produced in brewery = 3240 bottles

ANN number of bottles produced in brewery = 3254 bottles

% improvement in the number of bottles produced in brewery when ANN is incorporated in the system =

$$\frac{3254 - 3240}{3240} \times \frac{100\%}{1}$$

% improvement in the number of bottles produced in brewery when ANN is incorporated in the system = 043%

3.0 Results and discussion

Table 4 Comparison of conventional and ANN number of bottles of beer produced in brewery

Time(s)	Conventional quantity of bottles of beer produced in brewery(bottles)	ANN quantity of bottles of beer produced in brewery(bottles)
0	0	0
1	2000	2100
2	2700	2800
3	3200	3204
4	3240	3254
10	3240	3254

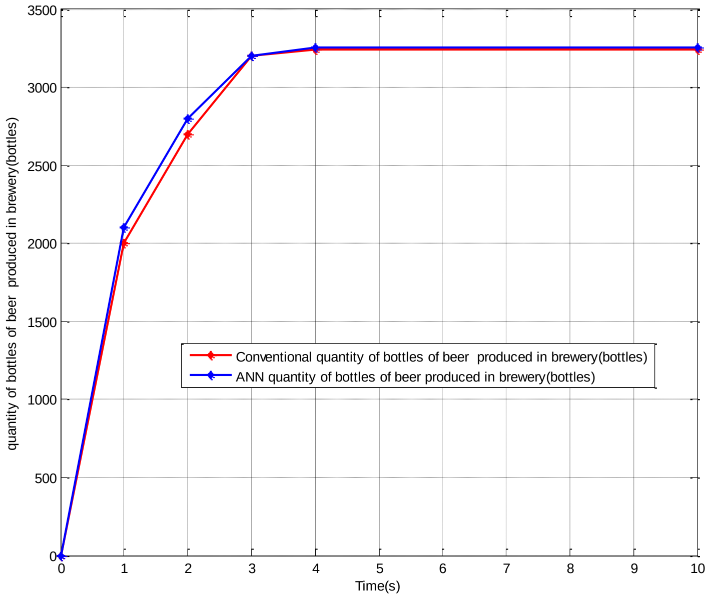

Fig 7 Graph of conventional and ANN number of bottles of beer produced

Fig shows a graph of conventional and ANN number of bottles of beer produced in brewery. In figure 7 the highest conventional quantity of bottles of beer produced was 3240 while that of ANN was 3254.

Table 5 Comparison of conventional and ANN number of crates of beer produced.

Time(s)	Conventional quantity of crates of beer produced in brewery(crates)	ANN quantity of crates of beer produced in brewery(crates)
0	0	0
1	167	175
2	225	233
3	267	267
4	270	271
10	270	271

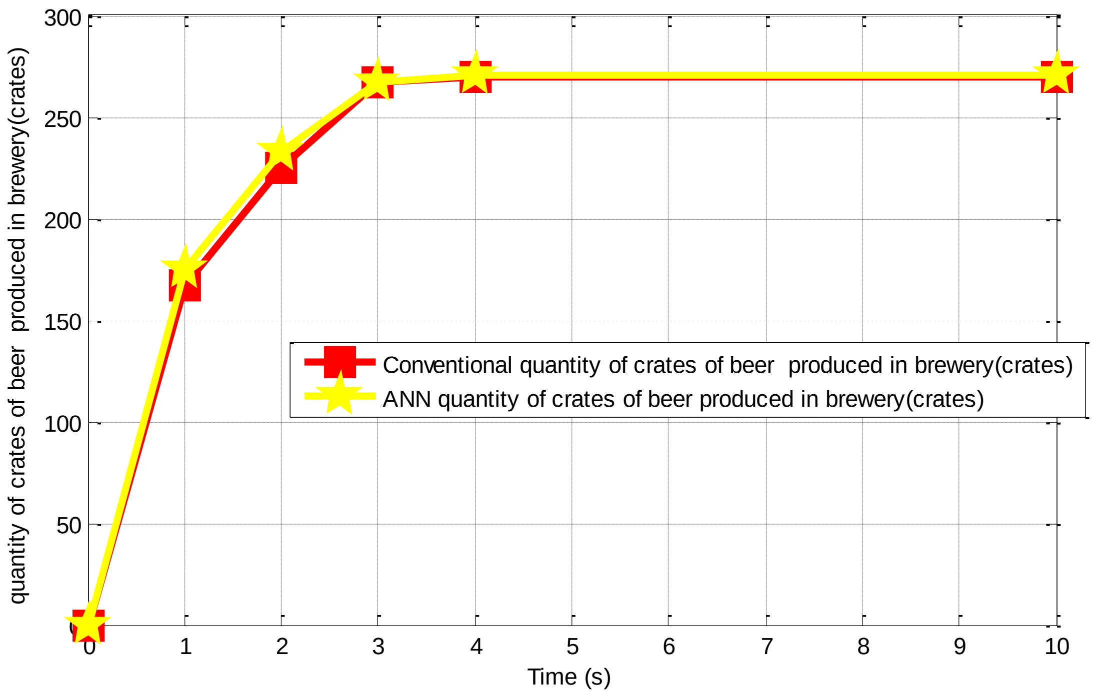

Fig 8 Graph of conventional and ANN quantity of crates of beer produced

The conventional quantity of beer produced was 270 crates. On the other hand, when ANN was incorporated in the system, it simultaneously increased to 271crates. The percentage improvement in modeling of alternating current motor performance for increased production output when model-based artificial intelligence was incorporated in the system was 0.33%.

Contribution to knowledge

This study provides significant contributions to the field of A.C. motor performance enhancement and industrial automation through the application of model-based Artificial Intelligence (AI):

1. Development of Intelligent Models:
   - Introduces advanced AI-driven models that accurately simulate and optimize A.C. motor performance under varying load conditions, offering a more adaptive and precise alternative to traditional approaches.
2. Addressing Nonlinear and Dynamic Behaviors:
   - Provides innovative solutions for modeling and managing the nonlinear and dynamic operational characteristics of A.C. motors, improving their responsiveness to industrial demands.

3. Real-Time Optimization Framework:
    - Develops a real-time optimization framework that integrates AI algorithms to enhance motor efficiency, reduce energy consumption, and maximize production output.
4. Enhanced Fault Detection and Predictive Maintenance:
    - Implements AI-based techniques for early fault detection and predictive maintenance, minimizing downtime and extending motor lifespan.
    - Offers actionable insights into fault patterns, enabling proactive industrial maintenance strategies.
5. Sustainability and Cost-Effectiveness:
    - Promotes sustainable industrial practices by reducing energy wastage through intelligent motor control.
    - Demonstrates cost-effective solutions by optimizing motor operations and reducing maintenance expenses.
6. Practical Industrial Applications:
    - Validates the proposed AI-based models in real-world industrial environments, providing a scalable and adaptable solution for diverse applications.
    - Bridges the gap between theoretical research and practical implementation in industrial systems.
7. Comprehensive Data Utilization:
    - Creates robust datasets and AI models that enhance the understanding of A.C. motor behavior across various contexts, improving the generalization and scalability of intelligent systems.

By addressing critical gaps in A.C. motor performance modeling, this research advances the state-of-the-art in industrial automation and establishes a foundation for future studies on integrating AI into motor control and optimization systems.

4.0 Conclusions

This study demonstrates the significant potential of model-based artificial intelligence (AI) in enhancing the performance of Alternating Current (A.C) motors for increased production output. By leveraging advanced AI algorithms, the proposed approach addresses the nonlinear and dynamic characteristics of A.C motor systems, enabling precise modeling, efficient control, and adaptive optimization under varying operational conditions. The findings highlight several key benefits, including improved energy efficiency, reduced operational losses, minimized downtime, and extended motor lifespan. These improvements translate to higher production output, reduced costs, and enhanced sustainability, making the integration of AI into industrial motor systems a viable and transformative solution for modern manufacturing challenges. The study underscores the importance of adopting intelligent systems in industrial automation, aligning with the global push for smart, energy-efficient, and sustainable production processes. Future work can explore the scalability of the proposed model across different motor types and industries, as well as the integration of emerging AI technologies such as deep learning and edge computing to further enhance system performance and adaptability. The manner by which this was done was as stipulated herein *characterizing and modeling a conventional AC motor so as to establish its operational features while working on variable frequency drive (VFD) control model with known production output, designing a rule base for the use of artificial intelligence for a stable and improved production output of AC motor, train ANN as artificial intelligence in the designed rule base to control AC motor speed for an increased efficiency reflected on the production output, designing SIMULINK model for the performance of AC motor under operational condition for an increased output using artificial intelligence for a brewery industry and validating and justifying the percentage of improvement in production output in a brewery with and without incorporation of artificial intelligence. The results obtained were* conventional and ANN number of bottles of beer produced in brewery were the highest conventional quantity of bottles of beer produced was 3240 while that of ANN was 3254. The conventional quantity of beer produced was 270 crates. On the other hand, when ANN was incorporated in the system, it simultaneously increased to 271crates. The percentage improvement in modeling of alternating current motor performance for increased production output when model-based artificial intelligence was incorporated in the system was 0.33%.

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