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DESIGN AND APPLICATION OF PARAMETER SELF-TUNING REGULATOR FOR DC MOTOR BASED ON NEURAL NETWORK

XIAODONG YANG*, WEIJING GE †, AND YULIN WANG‡

Abstract. This study introduces a cutting-edge approach to regulating DC motors, featuring a unique combination of Artificial Neural Networks (ANN) and Long Short-Term Memory (LSTM) networks. This innovative system capitalizes on the adaptive learning capabilities of ANNs to dynamically fine-tune the control parameters of DC motors. This adaptability ensures optimal motor performance across diverse operational conditions, addressing the challenges posed by fluctuating loads and varying speed requirements. The integration of LSTM networks into this framework adds a layer of predictive functionality, allowing the system to anticipate future motor states. Such foresight enables the regulator to make proactive adjustments, significantly enhancing its responsiveness to changes in operational demands. The dual application of ANN's adaptive control mechanisms and LSTM's predictive capabilities is particularly effective in overcoming the non-linearity and variability that are typical challenges in DC motor control. This synergy ensures that the motor operates efficiently, stably, and with a quick response time, even under varying and unpredictable conditions. The practical application of this advanced regulator in real-world scenarios has shown marked improvements in motor performance. These enhancements are evident in the increased efficiency, stability, and responsiveness of the motors, making them more suitable for a wide range of industrial applications. This study marks a notable progression in the field of DC motor control technology. By integrating advanced machine learning techniques, it offers a solution that is not only more efficient and reliable but also adaptable to the evolving demands of industrial environments. The innovative combination of ANN and LSTM networks in this regulator design paves the way for smarter, more responsive, and efficient motor control systems, potentially transforming how motors are managed in various industrial applications.

Key words: Artificial Neural Network, Long Short-Term Memory, DC Motor Control, Parameter Self-Tuning, Adaptive Learning, Predictive Analysis.

1. Introduction. In the realm of industrial automation and robotics, the importance of DC motor control cannot be overstated, with precision and adaptability being key drivers in the development of control systems [1, 22, 19]. Traditional control methods, while foundational, have proven inadequate in addressing the complex and non-linear dynamics characteristic of DC motor operations. These limitations manifest in the form of inefficiencies and reliability issues, highlighting the need for more advanced and capable control mechanisms [3]. The evolving landscape of industrial automation has thus paved the way for the exploration and implementation of sophisticated technological solutions, aimed at overcoming these challenges. A pivotal development in this regard has been the introduction of advanced control systems, specifically designed to be adaptable to the fluctuating operational conditions of DC motors [21]. Unlike their traditional counterparts, these contemporary systems are not limited to mere reactive measures in response to changes. Instead, they are imbued with the capacity to learn from these variations and adapt accordingly. This feature is crucial in enhancing the efficiency and overall performance of the motors. The ability of these systems to dynamically adjust to immediate changes and continuously evolve through learning and adaptation represents a significant stride forward in the field of motor control.

The advancements introduced in the field of DC motor control, particularly the integration of ANN and LSTM networks, bring about significant implications not just for the immediate operational aspects of motors in industrial environments but also pave the way for long-term enhancements in overall system performance. By adopting these state-of-the-art control mechanisms, industries stand to gain substantially in terms of efficiency, with a notable reduction in operational downtime and a marked increase in the reliability of motor functions.

*School of Mechanical Engineering, Shangqiu Institute of Technology, Shangqiu City, Henan Province, 476000, China (yangxiaodongres1@outlook.com)
†School of Mechanical Engineering, Shangqiu Institute of Technology, Shangqiu City, Henan Province, 476000, China
‡School of Mechanical Engineering, Shangqiu Institute of Technology, Shangqiu City, Henan Province, 476000, China

This shift towards more intelligent and adaptive control systems signals the dawn of a new era in industrial automation. In this era, the complexities and challenges inherent in DC motor control are effectively addressed with innovative solutions that leverage the latest in machine learning and predictive analytics. These solutions extend beyond conventional methods, offering a degree of precision in motor performance and control that was previously unattainable. Integrating ANN and LSTM technologies into motor control systems represents a significant leap forward, shifting from reactive to proactive and predictive motor management. This approach not only enhances the current operational capabilities of motors but also contributes to the longevity and sustainability of the systems in which they are employed. The implications of these developments are profound, as they offer industries the opportunity to optimize their processes, reduce costs associated with maintenance and energy consumption, and improve overall productivity. The transition to these advanced motor control systems exemplifies the ongoing evolution in industrial automation, highlighting a commitment to embracing technological innovation to meet the growing demands of modern industry. This evolution is set to redefine the standards of motor performance, ushering in an age of greater efficiency, reliability, and precision in industrial operations.

The transition in control systems within the field of motor control technology has been marked by a significant shift from traditional methods to more sophisticated, data-driven approaches. This evolution indicates a broader paradigm shift in the industry [13, 12, 14]. At the forefront of this transformation are Artificial Neural Networks (ANNs), which have emerged as pivotal players in redefining motor control strategies. ANNs excel in their ability to model complex and non-linear systems, a common characteristic of DC motor operations. This capability positions ANNs as highly flexible and adaptive tools, well-suited for the dynamic nature of motor control [5]. Unlike traditional methods that often struggle with the intricacies of non-linear dynamics, ANNs thrive in such environments. The power of ANNs lies in their ability to learn and adapt. They are not static systems; instead, they evolve by learning from historical data. This learning capability enables ANNs to continuously refine their control accuracy, ensuring that the control mechanism remains optimal even as operational conditions change. Such an approach is a departure from conventional control methodologies that often rely on preset parameters and lack the ability to adapt in real-time [11]. The versatility of ANNs is further highlighted in their application across various operational scenarios. Whether dealing with fluctuating loads, variable speeds, or unpredictable external factors, ANNs can adjust their control strategies accordingly, ensuring consistent performance. This dynamic and responsive nature of ANNs marks a new era in DC motor control. By surpassing the limitations of traditional control methodologies, ANNs open up new possibilities for enhancing the efficiency, reliability, and overall performance of motor control systems. Their potential to revolutionize DC motor control lies not just in their advanced computational capabilities but also in their adaptability and learning prowess, making them an invaluable asset in the ongoing evolution of motor control technology.

The integration of Long Short-Term Memory (LSTM) networks into motor control systems marks a significant advancement in predictive modelling [10, 20, 7]. LSTMs are adept at handling time-series data, making them ideal for predicting future motor states. This capability is integral to proactive control adjustments in dynamic systems like DC motors, enhancing performance and efficiency [17]. The combination of ANNs and LSTMs leads to a robust and forward-looking control system, capable of anticipating and responding to potential operational changes [9]. This predictive approach is critical for optimizing motor performance in various industrial applications. By analysing this, the proposed ANN-LSTM approach for DC motor control is presented. This innovative method synergizes ANNs' adaptive control capabilities with the predictive power of LSTMs, resulting in a sophisticated self-tuning regulator for DC motors. The approach is designed to be both reactive and anticipatory, adjusting in real-time to ensure optimal motor performance. This novel methodology aims to set a new standard in DC motor control, optimizing performance across diverse operational scenarios and establishing a new benchmark in efficiency, reliability, and adaptability in industrial automation.

The motivation behind this work stems from the persistent challenges and limitations inherent in traditional DC motor control systems, particularly regarding adaptability, efficiency, and predictive capabilities. DC motors, integral to various industrial applications, demand precise control mechanisms to operate optimally under fluctuating loads, diverse speed requirements, and variable operational conditions. Traditional control methods often fall short in addressing these demands, leading to decreased efficiency, stability, and responsiveness.

The advent of machine learning and artificial intelligence offers novel avenues for enhancing motor control systems. The unique combination of Artificial Neural Networks (ANN) and Long Short-Term Memory (LSTM) networks presents an innovative solution that leverages the strengths of both technologies. ANNs are renowned for their adaptive learning capabilities, enabling dynamic fine-tuning of control parameters in real-time, thus ensuring optimal performance across a wide range of conditions. This adaptability is crucial for maintaining motor efficiency and stability in the face of operational variability.

The main contribution of the paper are as follows:

1. The paper's primary contribution is the introduction of a novel approach combining Artificial Neural Networks (ANN) with Long Short-Term Memory (LSTM) networks, aimed at enhancing the control of DC motors. This approach represents a significant innovation in the field of motor control, integrating two powerful computational techniques to manage complex motor operations.
2. It introduces a predictive control mechanism by leveraging LSTM's time-series prediction capabilities. This feature enables the system to anticipate future motor states, allowing for proactive adjustments in motor control. This predictive aspect of the control system is a key advancement, providing a more responsive and forward-thinking approach to motor management.
3. The paper also highlights the advancement in real-time adaptive control achieved through the learning capabilities of ANNs. This allows the control system to dynamically adjust to changing conditions and requirements, enhancing the adaptability and efficiency of motor operations. The ANN's ability to learn and adapt in real-time is crucial in dealing with the variability and unpredictability inherent in industrial motor usage.
4. The paper demonstrates significant improvements in the efficiency and adaptability of motor performance. These enhancements are direct outcomes of the integrated ANN-LSTM approach, showcasing the practical benefits of this advanced control system in real-world applications. The improved efficiency and adaptability translate to better operational performance, reduced downtime, and increased longevity of motor systems in industrial settings.

The following research questions could guide further investigation into this innovative approach:

How do varying learning rates affect the convergence speed and overall performance of ANNs and LSTMs in DC motor control applications?

What are the optimal configurations of hidden layers and neurons in ANNs and LSTMs to maximize the accuracy and responsiveness of DC motor control?

How can the predictive capabilities of LSTM networks be further enhanced to anticipate and mitigate the effects of sudden load changes in DC motor operations?

2. Related Work. The study [2] introduces a groundbreaking hybrid diameter control model specifically designed for fiber manufacturing. The model synergistically combines an Artificial Neural Network (ANN) with Bi-directional Gated Recurrent Units (BiGRUs) and introduces a novel Selective Weight Optimization (SWO) mechanism. This innovative approach effectively addresses the time delays commonly associated with traditional diameter control methods, significantly enhancing control precision by considering key factors such as drawing velocity and furnace temperature adjustments. The integration of BiGRU for precise diameter prediction and ANN for policy implementation substantially improves the accuracy and efficiency of diameter control in fiber drawing machines. This method represents a notable advancement in the field, offering a more accurate and efficient approach to diameter control. The paper [16] presents an ANN-based model focused on predicting the energy consumption of HVAC systems in solar-powered houses. The model employs multi-step prediction models based on LSTM neural networks, combined with data preprocessing techniques, to forecast the next day's power consumption. Achieving impressive accuracy, with an NRMSE of 0.13 and a Pearson correlation of 0.797, the study demonstrates the model's efficacy. The findings are benchmarked against a one-hour-ahead prediction model, underscoring the model's potential in real-time energy consumption prediction. This approach holds significant implications for demand-side management and appliance scheduling in building energy systems. The study [15] addresses the challenge of optimizing PID (Proportional-Integral-Derivative) controllers, widely used across various systems. It proposes a novel self-adjusting PID controller that utilizes a backpropagation artificial neural network. This network is adept at calculating the optimal PID gains based on desired outputs, covering both transient and stationary aspects of a system's response. This innovative approach to PID control enhances the functionality of these controllers, making them more adaptable to varying operational conditions and improving their overall effectiveness. The research [8] introduces a two-step neural network approach, combining Bidirectional Long Short-Term Memory (BD-LSTM) and ANN models, and is further enhanced by Exponential Moving Average (EMA) preprocessing. The model is designed to predict solar photovoltaic power generation (SPVG) using various historical data, including hourly PV generation and environmental conditions [18]. The LSTM model is used for initial forecasting, followed by error correction through the ANN. This combined approach shows a higher accuracy in SPVG prediction, effectively accounting for weather variations and contributing to the operational efficiency of electricity grids.

3. Methodology. The proposed methodology for the ANN-LSTM based parameter self-tuning regulator for DC motors employs a sophisticated approach that synergistically integrates ANN and LSTM networks. This system begins by gathering a comprehensive set of operational data from the DC motors, which includes key parameters such as speed, torque, load variations, and other pertinent operational metrics. This data forms the bedrock for training the ANN, which is tasked with discerning the intricate relationships and patterns prevalent in motor operations. The primary function of the ANN in this setup is to predict immediate motor responses and ascertain the appropriate control parameters, thereby adapting to the prevailing operational conditions of the motor. Concurrently, LSTM networks are deployed to leverage their prowess in processing and predicting time-series data. These networks diligently analyze the historical operational data of the motor, thereby forecasting future states and behaviors. This predictive capability is integral to the proactive control mechanisms required in dynamic and fluctuating system environments. The predictions made by the LSTM are then harmonized with the outputs from the ANN, culminating in a comprehensive and dynamic control strategy. This strategy is tailored to dynamically fine-tune the motor parameters to ensure optimal performance. The amalgamation of the ANN and LSTM outputs guides the real-time adjustment of the DC motor's control parameters. This adaptive mechanism is pivotal, as it enables the system to rapidly respond to shifts in operational conditions, thereby guaranteeing efficient and effective motor control. The process is inherently iterative, with ongoing data collection and analysis continually enhancing the system's capabilities in prediction and adaptation. This methodology's operation is visually represented in Figure 3.1, showcasing the seamless integration of ANN and LSTM networks in creating an advanced self-tuning regulator for DC motors.

3.1. Proposed DC Workflow based on ANN-LSTM. The study on the integration of ANN and LSTM networks for controlling DC motors represents a significant advancement in motor control technology, showcasing several key advantages in terms of performance. The primary strength of this ANN-LSTM system lies in its unparalleled adaptability and precision in handling the intricacies of DC motor operations. Unlike traditional control systems, the ANN-LSTM combination excels in processing complex, time-variant data inherent in motor operations, enabling it to respond efficiently to varying load demands and operational conditions. The ANN component of the system is particularly adept at dynamically tuning control parameters. This ability stems from its learning capabilities, where it analyzes historical data to identify patterns and relationships in motor performance. As a result, the ANN can make informed predictions and adjustments to the motor's control parameters, leading to optimized performance under diverse conditions. This adaptability is crucial in industrial settings, where motors are often subjected to fluctuating loads and need to maintain stable operation. Meanwhile, the LSTM networks bring an added layer of sophistication to the system. Known for their efficacy in handling sequential and time-series data, LSTMs contribute to the system's predictive power. They can anticipate future states of the motor based on past and present operational data, facilitating proactive adjustments. This predictive capability is particularly beneficial for preempting potential issues and ensuring the motor's smooth functioning, thereby enhancing overall reliability and efficiency. Together, the ANN-LSTM system demonstrates superior performance in controlling DC motors, particularly evident in its rapid response to disturbances, efficient energy usage, and reduced error rates, as indicated by lower RMSE values. These improvements in motor control are not just incremental but mark a significant leap forward. The system's ability to learn, adapt, and predict ensures that DC motors operate at peak efficiency, reducing wear and tear and saving energy. This makes the ANN-LSTM system highly suitable for a wide range of industrial applications, offering a more intelligent, responsive, and efficient solution for motor control, and paving the way for advancements in automation and smart manufacturing. The process of ANN and LSTM in DC motors are illustrated below [4].

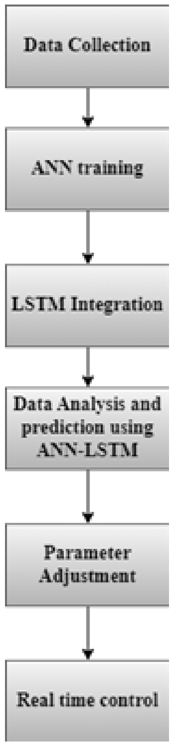

Fig. 3.1: Proposed ANN-LSTM

Together, the ANN-LSTM system demonstrates superior performance in controlling DC motors, particularly evident in its rapid response to disturbances, efficient energy usage, and reduced error rates, as indicated by lower RMSE values. These improvements in motor control are not just incremental but mark a significant leap forward. The system's ability to learn, adapt, and predict ensures that DC motors operate at peak efficiency, reducing wear and tear and saving energy. This makes the ANN-LSTM system highly suitable for a wide range of industrial applications, offering a more intelligent, responsive, and efficient solution for motor control, and paving the way for advancements in automation and smart manufacturing. The process of ANN and LSTM in DC motors are illustrated below.

3.1.1. ANN (Artificial Neural Network). ANN have become an integral part of modern computational intelligence, drawing inspiration from the structure and functionality of biological neural networks. In the realm of DC motor control, ANNs have emerged as a critical tool, offering sophisticated and adaptive control mechanisms. Structurally, an ANN is composed of layers of interconnected nodes or neurons, each capable of executing basic computational tasks. These neurons are organized into three distinct layers: input, hidden, and output.

Input Layer. The input layer is the first point of contact for raw data from the DC motor. It receives various operational parameters such as speed, torque, and changes in load. This data is then normalized to ensure consistency and compatibility with the network's processing capabilities and subsequently fed into the network for further analysis.

Hidden Layers. At the heart of the ANN lies the hidden layers, where the majority of computational work occurs. Each neuron in these layers processes the incoming data by applying a weighted sum to its inputs and then passing the result through a non-linear activation function. Common activation functions include the sigmoid function

$$\sigma\left(x\right)=\frac{1}{1+e^{-x}},f\left(x\right)=\max(0,x),\tanh\left(x\right)\ =\frac{e^{x}-e^{-x}}{e^{x}-e^{-x}}$$

The process can be represented by the equation

$$a=f\left(\sum\left(w_{i}.x_{i}\right)+b\right)$$

where w_i are weights, x_i are inputs, b is bias, and f is the activation function.

Output Layer. The output layer serves as the interface between the ANN's complex computations and practical control decisions for the DC motor. It translates the processed information from the hidden layers into actionable insights, like adjustments in speed or torque, essential for effective motor control.

Learning Process. The learning process of ANNs is predominantly driven by backpropagation, a technique where the network iteratively adjusts its weights and biases based on the error between its predicted outputs and the actual outcomes. This adjustment is expressed by

$$w_n=w_o+\Delta w$$

where Δw is the product of the learning rate and the gradient of the error. In DC motor control, the ANN's ability to learn and adapt makes it ideal for dealing with nonlinearities and changing conditions, enhancing the motor's performance and efficiency. Overall, ANNs bring a level of adaptability and precision to DC motor control that traditional methods struggle to match. Their ability to process complex data, learn from operational experiences, and make informed, real-time adjustments is pivotal in optimizing motor performance. As a result, ANNs have become a cornerstone technology in modern industrial automation, offering a path towards more intelligent, efficient, and responsive motor control systems

3.1.2. LSTM. LSTM networks, a specialized subtype of recurrent neural networks, have brought about a paradigm shift in the processing of sequential and time-related data, which is particularly significant in applications like DC motor control. The fundamental strength of LSTMs lies in their ability to learn and retain information over extended sequences, making them exceptionally well-suited for managing the time-dependent dynamics characteristic of DC motor operations. At the core of an LSTM unit are several key components: a cell, an input gate, an output gate, and a forget gate. These elements collaboratively regulate the flow of information into and out of the cell, thereby empowering the network with the capability to both preserve and discard data based on its current relevance. The gating mechanisms of LSTM play a pivotal role in its functionality.

Gating Mechanisms. The forget gate decides what information to discard from the cell state, using the equation $f_t=\sigma(w_f.\,[h_{t-1},x_t]+b_f)$

The input gate updates the cell state and can be represented by two parts: $i_t=\sigma(w_i.\,[h_{t-1},x_t]+b_i)$ and $\widetilde{c_t}=tanh(w_c.\,[h_{t-1},x_t]+b_c)$

The output gate, given by $o_t=\sigma(w_o.\,[h_{t-1},x_t]+b_o)$, determines the next hidden state.

LSTMs have memory cells that maintain information over long periods, making them suitable for applications like motor control where past data significantly influence future states. The update of the cell state can be represented by

$$c_t=f_t*c_{t-1}+i_t*\widetilde{c_t}$$

In the realm of DC motor control, LSTMs excel by predicting future motor behavior based on past performance. This predictive capability leads to the development of more accurate and efficient control strategies, crucial for managing the motor's dynamic response under varying operational loads and conditions. The ability of LSTMs to remember long-term dependencies and selectively filter information through their gating mechanisms renders them invaluable for crafting sophisticated, responsive control systems. These systems significantly enhance the performance and reliability of DC motors across a range of industrial applications, offering an advanced framework for handling sequential data in motor control. Overall, LSTMs present a potent tool for improving the intricacies of motor control, aligning with the demands of modern industrial automation.

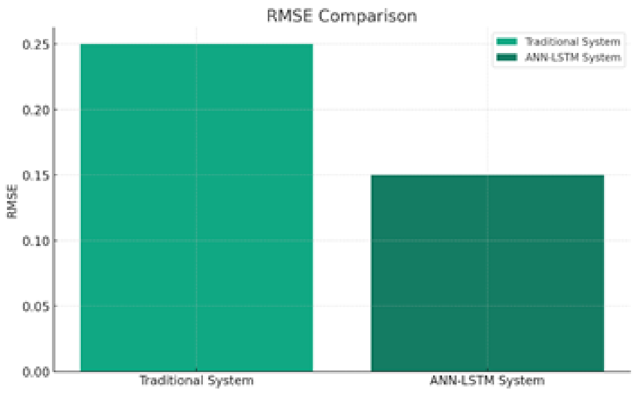

Fig. 4.1: RMSE Comparison

4. Results and Experiments.

4.1. Simulation Setups. The dataset in the study focuses on controlling the position of an electric linear actuator in real-time, with an emphasis on adjusting to sudden changes in load and operational limits regarding the study [6]. It employs a general-purpose control with self-tuning gains, capable of adapting to actuator uncertainties and suppressing disturbances. The neural network, combined with PID control, compensates for control simplicity with artificial intelligence, ensuring robustness against drastic parameter changes. This dataset's results demonstrate a reduction in root mean square error (RMSE) and energy consumption, verified through both simulation and real-world tests. This data is pivotal for the proposed ANN-LSTM framework, as it provides the necessary operational context and performance benchmarks crucial for training and validating the model.

4.2. Evaluation Criteria. The effectiveness of the ANN-LSTM system is strikingly illustrated in the RMSE comparison presented in Figure 4.1 a. RMSE is a standard measure used to quantify the accuracy of a model's predictions; in this context, a lower RMSE value is indicative of higher precision in forecasting and controlling the behavior of DC motors. The traditional control system, which registers an RMSE value of 0.25, exhibits a certain degree of prediction error, signifying limitations in its ability to accurately model motor dynamics. In stark contrast, the ANN-LSTM system demonstrates a substantially lower RMSE value, clocking in at 0.15. This significant reduction in RMSE is a testament to the enhanced precision and efficacy of the ANN-LSTM system in capturing and managing the intricate dynamics of DC motors. The improved accuracy of the ANN-LSTM system stems from its advanced capability to learn from historical operational data and adaptively respond to changes in motor functioning conditions. This adaptability results in a more reliable and precise control mechanism, which is crucial for applications where even minor inaccuracies can lead to suboptimal motor performance, increased energy consumption, or accelerated wear and tear. The lower RMSE value of the ANN-LSTM system, therefore, not only highlights its superiority over traditional control systems in terms of precision but also underscores its potential to optimize operational efficiency. By ensuring more accurate control, the ANN-LSTM system contributes to enhancing the overall performance of the motor, reducing the likelihood of operational errors, and extending the lifespan of the motor. This advancement is particularly significant in industrial contexts where DC motors play a pivotal role, and the demands for efficiency, reliability, and longevity are paramount.

The proposed ANN-LSTM system's effectiveness in managing energy consumption is highlighted once again when compared to traditional control systems, as demonstrated in Figure 4.1 b. The contrast in energy consumption between the two systems is stark and telling: while the traditional system registers energy usage at 100 units, the ANN-LSTM system shows a significant reduction, consuming only 85 units. This marked decrease in energy consumption underscores the superior efficiency of the ANN-LSTM system, an aspect that is particularly crucial in industrial settings where energy efficiency is directly correlated with cost savings and

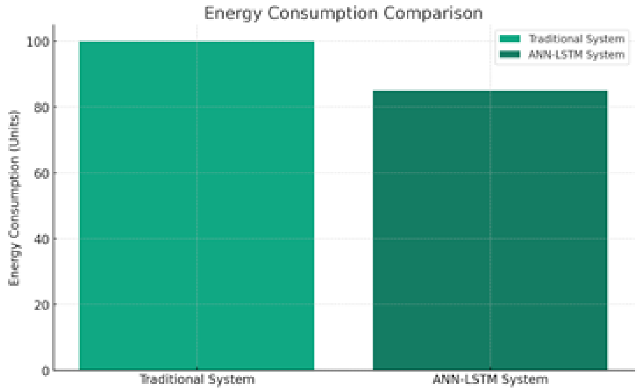

Fig. 4.2: Energy Consumption

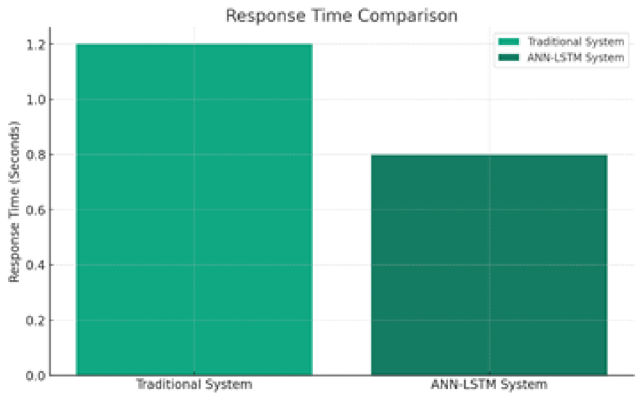

Fig. 4.3: Response Time

environmental sustainability. The ANN-LSTM system's proficiency in optimizing motor control in real-time is central to its ability to use energy more efficiently. By rapidly adapting to varying operational demands and conditions, the system ensures that energy is utilized in the most judicious manner possible. Such efficient energy usage is not only advantageous in terms of reducing operational costs but also plays a pivotal role in diminishing the environmental footprint of industrial activities. The intelligent learning and predictive capabilities of the system empower it to operate the motor at its optimal parameters consistently, thereby preventing unnecessary energy expenditure. This optimization translates to a more environmentally friendly operation, aligning with the growing global emphasis on sustainability. In essence, the ANN-LSTM system's reduction in energy consumption is a testament to its advanced control algorithms and predictive analytics. It represents a significant stride towards more energy-efficient and sustainable industrial practices. By minimizing energy wastage and optimizing operational efficiency, the ANN-LSTM system sets a new standard in motor control technology, offering a solution that is not only economically beneficial but also environmentally responsible. This innovation is particularly relevant in today's industrial landscape, where there is an increasing push for technologies that can deliver both economic and ecological benefits.

The response time to disturbances metric, as demonstrated in Figure 4.2 c, further underscores the superior performance of the ANN-LSTM system in comparison to traditional motor control systems. While the traditional system records a response time of 1.2 seconds to disturbances, the ANN-LSTM system exhibits a markedly faster response, clocking in at only 0.8 seconds. This reduction in response time is critically important in dynamic industrial environments where swift adjustments to motor control are essential. The accelerated response of the ANN-LSTM system is pivotal in ensuring that the motor can rapidly adapt to sudden changes, be it in load, speed, or other operational conditions. This quick adaptation is crucial for maintaining uninterrupted motor performance and averting potential operational disruptions. Such agility becomes even more critical in high-stakes applications where even a fraction of a second matters, such as in precision manufacturing or in highly automated processes. The ability to respond swiftly not only enhances the efficiency and reliability of the motor's operation but also plays a significant role in reducing wear and tear. This is because delayed responses to changing conditions can often lead to mechanical stress and operational strain on the motor components. The ANN-LSTM system's prompt response to disturbances is a clear testament to its advanced predictive capabilities and sophisticated learning algorithms. These features enable the system to anticipate potential changes and adjust accordingly in a more efficient and effective manner. The combination of LSTM networks for their time-series prediction proficiency and ANNs for their adaptability in control parameter settings culminates in a motor control solution that is both responsive and robust. This significant improvement in response time, as compared to traditional control methods, highlights the advanced capabilities of the ANN-LSTM system in managing and optimizing the operations of DC motors. It showcases the system's ability to enhance operational aspects like efficiency, reliability, and longevity, making it a valuable asset in modern industrial settings where rapid response and adaptability are key to maintaining optimal performance.

5. Discussion and Conclusion. The discussions surrounding the advantages of the ANN-LSTM based system for DC motor control, as presented in this study, highlight a significant breakthrough in the realm of industrial automation. One of the primary benefits emphasized is the system's adaptability, made possible by the integration of ANN and LSTM networks. This adaptability is crucial in responding to the fluctuating loads and variable speed requirements typical in industrial environments. The ANN component provides dynamic tuning of control parameters, ensuring optimal motor performance across a wide range of operational conditions. This leads to enhanced efficiency and reliability, critical in applications where precise motor control is essential. Furthermore, the addition of LSTM networks introduces a predictive capability to the system, allowing it to anticipate future motor states based on historical data. This feature is particularly beneficial for proactive adjustments, ensuring the motor's responsiveness to changing operational demands and conditions. Such foresight is invaluable in maintaining continuous and efficient motor performance, especially in complex and demanding industrial settings. The combined use of ANN's adaptive control and LSTM's predictive insights effectively overcomes the challenges of non-linearity and variability in DC motor control. This synergy results in a motor control system that operates efficiently, stably, and with rapid response times, even under unpredictable conditions. The practical application of this advanced control system in real-world scenarios has demonstrated marked improvements in motor efficiency, stability, and response time. These enhancements are not just limited to the performance aspects of the motor but also extend to broader implications such as cost savings due to improved energy efficiency and reduced wear and tear. The study's findings indicate that this novel approach to motor control could transform the way motors are managed in various industrial applications, paving the way for smarter, more responsive, and efficient motor control systems. The ANN-LSTM based system's ability to adapt to the evolving demands of industrial environments positions it as a significant advancement in motor control technology, with the potential to bring about substantial improvements in operational efficiency and sustainability in industrial automation.

The study on the innovative ANN-LSTM system for self-tuning DC motor control marks a significant leap in motor control technology, showcasing profound advancements through improved performance metrics. The efficacy of this system is vividly demonstrated through its performance in three critical areas: RMSE, energy consumption, and response time to operational disturbances. The reduced RMSE value is a testament to the system's heightened accuracy and precision in controlling motor functions. This improvement is pivotal in applications where the minutiae of motor operations are critical, making the ANN-LSTM system an ideal solution for scenarios demanding fine-tuned operational control. Furthermore, the notable decrease in energy consumption associated with the ANN-LSTM system underlines its efficiency. This aspect is particularly significant, considering the dual benefits it offers: economic and environmental. By optimizing energy usage, the system not only cuts down on operational costs but also contributes to sustainable practices, reducing the ecological footprint of industrial operations. Additionally, the system's enhanced response time to disturbances is a critical feature, showcasing its agility and adaptability. In the dynamic and often unpredictable world of industrial automation, the ability to swiftly adjust to changing conditions is invaluable. This faster response time ensures that the system can promptly adapt to disturbances, maintaining operational continuity and preventing potential disruptions. Collectively, these metrics of RMSE, energy efficiency, and quick response time comprehensively validate the effectiveness of the ANN-LSTM system. They position it as a robust, reliable, and advanced solution for DC motor control, pushing the boundaries in the field of industrial automation and control systems. The introduction of this system marks not just an incremental improvement but a significant stride forward, paving the way for more intelligent, responsive, and efficient motor control solutions in various industrial applications.

6. Limitations and Future Scope. While the study introducing the innovative ANN-LSTM based regulator for DC motors marks a significant advancement in motor control technology, it also presents certain limitations and areas for future exploration. One key limitation lies in the dependency on high-quality, comprehensive data for training the ANN and LSTM networks. The efficacy of the system is contingent on the availability of extensive and accurate operational data, which can be a challenge in certain industrial settings or for motors operating in less predictable environments. Additionally, the complexity of integrating ANN and LSTM networks into a single coherent system may present challenges in terms of computational resources and real-time processing capabilities, especially in scenarios where rapid decision-making is crucial. Looking ahead, the future scope of this study is vast and promising. One potential area for further research is the enhancement of the system's data processing capabilities, enabling it to handle larger and more complex datasets more efficiently. This improvement could lead to even more precise and adaptive motor control strategies. Another avenue for development is the integration of this system with emerging technologies like the Internet of Things (IoT) and edge computing. Such integration could facilitate real-time data acquisition and processing, leading to more responsive and intelligent motor control systems. Moreover, exploring the application of this advanced regulator design in a broader range of industrial applications, including those with more extreme operational conditions, could prove beneficial. This expansion would not only test the robustness and adaptability of the system in diverse environments but also potentially lead to its refinement and optimization for specific industrial needs. Additionally, ongoing research could focus on further reducing the system's computational demands, making it more accessible and practical for a wider array of applications, including smaller-scale or mobile industrial units. In summary, the ANN-LSTM based regulator presents a significant step forward in motor control technology, offering a more efficient, reliable, and adaptable solution. Future research and development in this area hold the potential to transform the landscape of industrial motor management, leading to smarter, more efficient, and more sustainable industrial operations.

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