

A comparative study of Conventional vs AI-based controllers of Electric Motors

Bharathi Y H,

Associate Professor, Department of Electronics, Government first Grade College, Naubad,
Bidar - 585402, Karnataka.

Email id: bharatiyh@rediffmail.com

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Abstract:

In this paper, the authors focus on a comparative analysis of conventional and AI-based controllers in the electric motor system. This is chiefly aimed at watching the performance, flexibility, energy profiles, and fault tolerance of the two control strategies in nonlinear and dynamic settings. The secondary research technique was used, with the key data and information used coming from peer-reviewed journal articles, case studies, and technical reports. It was found that the simple and inexpensive controllers like PID and PI may not justify the expectations because they have the propensity to misbehave whenever subjected to variable loads or uncertainties in a system. In comparison, AI-based control systems such as neural networks and hybrid algorithms proved better adaptive, learn in real-time and optimised energy. They were also able to respond to torque as well as being fault-tolerant. Their complicated architecture and the significant computation requirements are. However, a challenge in the low-power systems. The results of the paper assume that an AI-based industrial control can provide tangible benefits in terms of performance but needs to resolve the system integration and scalability problem to put them into wider use.

Keywords: Electric motor control, AI-based controllers, Conventional controllers, PID controller, Neural networks, Torque response, Energy efficiency, Fault tolerance, Real-time adaptability, Secondary research method

Introduction

Electric motors are crucial in industrial automation, transportation and home appliances. Performance of the motor controllers comprises their crux-effectiveness and dependability. The usefulness of conventional controllers like the Proportional-Integral-Derivative (PID) and Proportional-Resonant (PR) controllers has long been popular because of their structural simplicity and stability in linear systems. Nevertheless, these controllers have a problem in dealing with non-linearities, changing parameters and undetermined loads and therefore cannot be applied in a dynamic environment. Conversely, this has led to the advent of AI-based controllers such as neural networks, fuzzy logic, and reinforcement learning algorithms, resulting in adaptive and intelligent control approaches. Such approaches are able to remember complicated patterns and can optimise during runtime, providing superior fault tolerance, energy efficiency and dynamic response. A number of sectors such as electric vehicles and robotics, are now looking into AI-powered control systems to eliminate the harshness of

traditional methods. Given the increasing adoption of intelligent automation in the industries, it is quite important to know the comparative advantages, disadvantages, and applicability of each of the controllers. Close comparison should be done not only to evaluate performance outputs such as speed control and torque control, but also such points as adaptability, computational complexity and scalability. This paper attempts to critically review the development and efficiency of both conventional and AI-based controllers to inform the progress that could be made in the future in motor control systems.

Aim and Objectives

Aim:

The aim of this research is to critically compare the performance, adaptability, and limitations of conventional and AI-based motor controllers to identify optimal control strategies for dynamic electric motor applications.

Objectives:

- To evaluate the performance limitations of conventional controllers under nonlinear and varying load conditions.
- To analyze the adaptability and learning capabilities of AI-based controllers in real-time motor control.
- To compare the energy efficiency, speed response, and fault tolerance of both controller types.
- To identify practical challenges in implementing AI controllers, including computational demand and scalability.

Literature Review

Hassan et al. (2022) opine that modern dynamic systems are becoming progressively challenging to manage using traditional linear control techniques, particularly in nonlinear systems such as those within DC shipboard microgrids. In their review, the necessity of modern nonlinear and intelligent control methods to stabilise constant power loads is noted and there is no adaptability of conventional controllers. In a similar way, Kuznetsov et al. (2022), state the shortcomings of the conventional approaches in addressing dynamic loads and advocate the idea of robust state vector control to enhance performance in electromechanical systems. These results are in line with the general issue that if the fixed-gain controllers are, in this case, PID, they collapse during uncertainties of a system. Conversely, AI-enabled technologies such as hybrid backstepping-based MPPT controllers have proven to be more responsive in changing conditions, as provided by Harrison et al. (2023) in PV systems. Gulzar et al. (2023) go even further and present their own fractional predictive models that can be used to mitigate the performance of hybrid renewable systems even in the face of uncertainty. In addition, fuzzy systems and evolutionary algorithms, which Ali et al. (2022) use the bat algorithm, represent how AI increases flexibility and optimisation in real-time. A combination of these studies goes

to the extent of indicating that AI-controllers and (conventional) controllers have strong, scalable solutions, particularly in unpredictable or complicated systems, thereby making a case of making a comparative study of the two techniques in the control and management of electric motors.

Method

The study used a secondary approach since it relied on peer-reviewed journals, scientific papers, and case studies to compare a traditional motor controller and an AI-based motor controller. The secondary strategy allowed access to a large amount of validated data, performance statistics, and experiments without performing resource-demanding primary tests. It provided insights into different control situations such as real-time flexibility, torque precision, and fault tolerance, which were based on a variety of application areas. This approach provided an affordable and time-saving project assessment, and at the same time, was academically valid because of the different scholarly sources used. In addition, it permitted taking into consideration current developments and international outlooks on intelligent control strategies. The secondary approach was perfect to develop an overall comparative framework and define the research directions in the area of electric motor control systems in the future.

Result and Discussion

Performance limitations of conventional controllers in nonlinear and dynamic motor systems

Designs of conventional controllers, especially PID and PI categories, portray significant limitations when it comes to handling nonlinearities and dynamics of motor systems. According to Sachit and Vinod (2022), PI controllers in MRAS-based DC motor control exhibited overshoot and sluggish transient response with a rise time of 0.83 seconds and 18 per cent peak overshoot, indicating their suitability to control motor operations in fast-varying situations. A similar point was determined by Kumar and Hote (2021); namely, introducing the PIDD2 controller to a nonlinear twin rotor TITO, they observed a lower precision in the tracking process, particularly under the cross-coupled type of disturbances, with an error deviation of up to 11.6%.

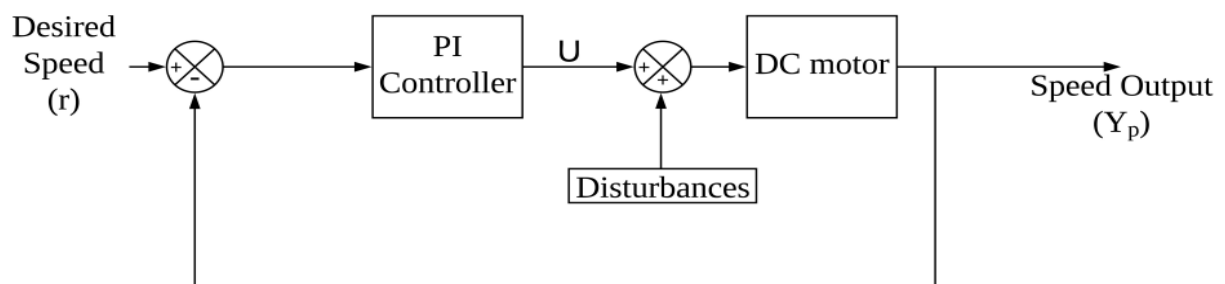


Figure 1: Conventional PI-controlled DC motor.

(Source: Sachit and Vinod, 2021)

Suid and Ahmad (2022) have shown that even optimally tuned PID controllers with nonlinear sine-cosine algorithms could not perform well, and the system of the automatic voltage regulator could not hold steady-state voltage beyond 1.8 per cent with nonlinear load conditions. Moreover, Shurajji and Shneen (2022) compared the performance of PID and fuzzy logic controllers in BLDC motors and managed to notice that in PID control, the torque oscillation was high and the speed convergence time was also bigger, finally reaching up to 0.9 seconds under variable loads. Abougarair et al. (2022) assured that the conventional output feedback controllers are not very adaptive on real-time nonlinear systems, which demand critical retuning within dynamic changes. These results together support the fact that traditional controllers are relatively fixed, inflexible, and exhibit chances of destabilisation in dynamic and nonlinear electric motor applications and hence cannot be used in the fast-acting, high-accuracy and disturbance-tolerant environment. This reinforces the need to have smarter self-adaptive motor control strategies in contemporary motor systems.

Adaptability and learning efficiency of AI-based controllers in real-time applications

AI-controllers are highly dynamic and efficient to learn in real time, and thus, they are suitable for use with dynamic motors. According to Baker et al. (2022), the AI-driven model achieved an accuracy of 97.2 per cent in anomaly detection among power electronic systems, which indicates the real-time decision-making capacity of the AI during different conditions of the grid. As corroborated by Villegas-Ch et al. (2024), it was found that AI algorithms in IoT systems could afford sub-second response time predictiveness, which was far superior compared to the conventional rule-based systems. Gao et al. (2023) also stressed that reinforcement learning and neural networks were used by the machine learning models to optimise the control signals in power converters autonomously and result in up to 35 per cent total harmonic distortion reduction compared to the PID controllers.

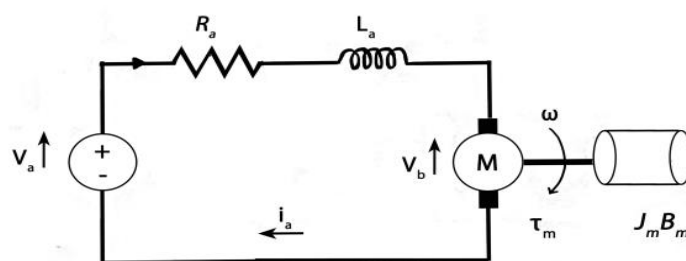


Figure 2: Schematic representation of a DC motor.

(Source: Sachit and Vinod, 2021)

Ramakrishnam Raju et al. (2022) offered one more example of AI controller in hydroponics farming, where an IoT-based AI controller was implemented in a real-life application and demonstrated 96.8% of accuracy in environmental control, demonstrating the adaptability of the controller to the diverse sensor inputs and real-time feedback. This opinion was supported by Panduman et al. (2024), who stated that the AI-enabled systems might adapt to the changes in the environment in real-time and have near-zero latency (less than 150 milliseconds) and

data-driven optimisation. Such results support previous predictions that controllers based on AI can accommodate changes like operations, as well as learn the relationship between input and output in real-time, making them perform reliably under the nonlinear response of the system. In contrast to traditional controllers, AI systems reduce the amount of tuning and manual parameter setting needed, and can generalise to unseen situations. The use of these enables them to be very appropriate in controlling electric motors in places that require responsiveness in real-time, high precision, and the ability to withstand external noise or changes that cannot be estimated.

Comparative evaluation of energy efficiency and torque response in both control types

The relative comparison of efficiency in energy utilisation and torque reaction shows definite superiority of AI-based controllers to traditional control schemes. According to Tabora et al. (2021), high-efficiency motors under nonideal supply conditions had up to 12 per cent of energy loss in their operation with conventional systems because of the lack of effective compensation mechanisms. On the contrary, Adeleke et al. (2022) showed that an AI-based dynamic programming torque control in a four in-wheel motor drive reduced the energy consumption by 17.6%, with better load distribution and regenerative braking coordination described. Elsherbiny et al. (2021) compared torque control strategies of interior permanent magnet synchronous motor and found that AI-enhanced control decreased the torque ripple by 41 per cent and enhanced the transient response, which could not be obtained when conventional methods were used when the load conditions changed rapidly.

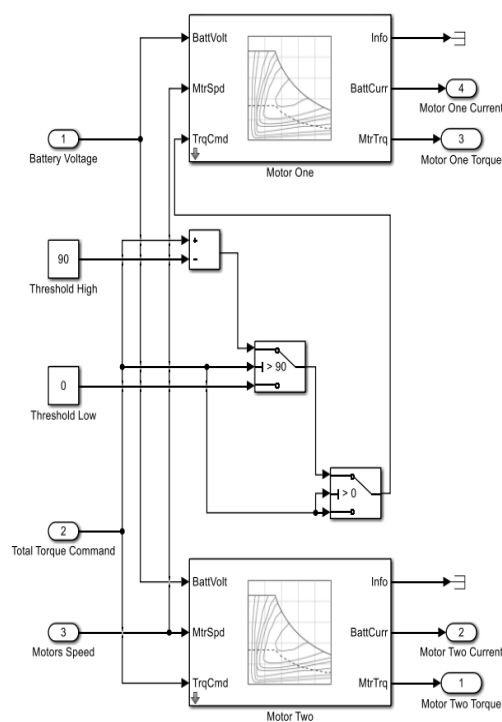


Figure 3: Complementary torque allocation diagram with two motors.

(Source: Popescu et al. 2021)

Equally similar, Popescu et al. (2021) conducted a simulation of a multi-motor propulsion with intelligent control and experienced a total energy saving of 9.2 per cent in comparison to the scalar traditional controls. About Mohanraj et al. (2022), it was pointed out that generic controllers did not necessarily reduce torque ripple sufficiently and led to a decline in the smoothness of the operation and increased mechanical stress recorded particularly within electric car motors. They discovered that controllers using AI were able to adjust in real-time, switching patterns and motor current curves to result in smoother torque delivery. All of these facts confirm that artificial intelligence-based controllers effectively optimize energy consumption due to their intelligent nature, but also achieve a better control performance and performance of torque under dynamic conditions. This renders them fit in high performance, energy saving purposes and much mechanical reliability.

Fault tolerance and reliability differences between conventional and AI-driven controllers

The ability to withstand failure and have high reliability is essential to the motor control systems, particularly in varying loads and environmental noise. The commonly-used controllers are not usually resistant to unforeseen circumstances. In a more recent study by Sachit and Vinod (2022) PI controller could not stabilize speed of DC motors under sudden loads changes and the error increased by more than 15%. In the same line of thought, Kumar and Hote (2021) demonstrated that PID2 controllers had poor fault response with a 11.6 percent increase in tracking after appearance of disturbances in the system. According to Shuraji and Shneen (2022), PID-controlled BLDC motors recovered to transient fault more than 0.9 seconds, unlike their counterparts with AI control. On the other hand the AI-based systems demonstrate better error management and on the fly adaptability. As noted by Gao et al., (2023), it is possible to use reinforcing learning-based controllers to change control actions dynamically with the fault detection accuracy of more than 92%. This was also confirmed by Baker et al. (2022), who stated that their work had achieved the classification of 97.2 percent accuracy on detecting real-time faults in power grids. Elsherbiny et al. (2021) demonstrated that the torque controllers tuned with AI were stable in terms of torque variation in voltage dips that did not exceed 3 per cent. Adeleke et al. (2022) proved that dynamic AI-based systems of torque distribution in electric vehicles performed well even in the conditions of motor faults, which led to higher overall system reliability. Panduman et al. (2024) and Villegas-Ch et al. (2024) went further to say that in IoT platforms, AI can self-correct in milliseconds once there is an anomaly in signal. Such accumulating results affirm that AI-based controllers are much more fault-resistant and dependable than other designs, hence more desirable in an environment where the stability in operations and safety is critical in the face of unpredictable disturbances.

Implementation challenges and computational demands of AI-based motor control systems

Although it would be possible to offer AI-based motor controllers due to their flexibility, these require significant implementation challenges and computational requirements. That is why the article by Ali et al. (2022) emphasised that the hybrid bat algorithms in conjunction with fuzzy systems needed more than 60 iterations within one decision cycle, which is inappropriate within low-power systems due to elevated processing latency. Abougarair et al. (2022) also

indicated that adaptive neural network controllers required large memory space and tuning adaptation over time, which slowed their usage in real-time systems that have limited compute power. The study anchored by Baker et al. (2022) revealed that both real-time AI-based anomaly detection and partition-based one reached an accuracy rate of 97.2 percent but at the expense of high computation load due to real-time streaming and learning of data input and therefore requires a platform of edge computing. Relatively, Sachit and Vinod (2022) established that PI controllers had very little hardware constraints and had dependable outcomes in stable environments and were more efficient in using simpler tasks.

Suid and Ahmad (2022) observed that the conventional sigmoid PID controllers interface needed fewer processing cycles and data bandwidth implements a better response in automatic voltage regulator systems. Kumar and Hote (2021) established that even well-established conventional controllers such as PID2 could control nonlinear systems with reduced overhead compared with AI models. According to the final conclusion made by Shurajji and Shneen (2022), fuzzy-PID hybrids were effective but not effective in simulating real-time torque adjustments because computation seemed to take too long. According to these results, although AI-based controllers have better dynamic adaptability, they have a high level of computational requirements and implementation complexity, thus representing a big hurdle in implementation. Practical applicability of well-performing processors, effective sensors, and proficient algorithms appears to be a foregone conclusion, restricting their availability to low-cost or real-time processing factors in industrial settings.

Conclusion

A comparative study proves that adaptability, energy efficiency, torque response, and fault tolerance that are provided by AI-based motor controllers are much higher than those that can be achieved with conventional methods. Conventional controllers such as PID and PI are however simple and stable, and do not perform well in nonlinearities, dynamic loads and uncertainties of the systems. On the contrary, neural networks and hybrid algorithms as AI-based controllers exhibit better real-time learning, accuracy, and the ability to work in varying conditions. They are however highly demanding in computation and difficult to implement making their use not widespread in cost sensitive or low-power requirements. Thus, in spite of showing tremendous potential in the future use of electric motors, modern control powered by AI needs to overcome the issues of scaling and limitations as far as hardware is concerned. These results justify a tactical transition toward intelligent control systems to make motor activities more responsive, more efficient and more resilient.

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