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Ghufran Saad Mohammed

Mohammed Obaid Mustafa

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REVIEW

Intelligent Control Strategies for Permanent Magnet Synchronous Motors: A Review

Ghufran Saad Mohammed^{a,*}, Mohammed Obaid Mustafa^b

^a MSc student, Department Of Electrical Engineering, College of Engineering, University of Mosul, Mosul, Iraq

^b Department Of Electrical Engineering, College of Engineering, University of Mosul, Mosul, Iraq

ABSTRACT

Permanent Magnet Synchronous Motors (PMSMs) have been widely employed in numerous applications, on account of their high efficiency, compact structure, and high-performance torque control. Nevertheless, the dynamic and uncertain control PMSMs under the action of system perturbation and variation is a difficult problem in the field of traditional control law by using Proportional Integral Derivative controller (PID), Field oriented control (FOC) and Direct Torque Control (DTC) etc. In this article, we offer a critical survey of intelligent control methods such as Fuzzy Logic Control (FLC), Artificial Neural Networks (ANNs), Genetic Algorithms (GAs), Evolutionary Algorithms (EAs) and discuss their advantages in accommodating nonlinearity, uncertainty of the system and real-time adaptability. By these methods, the performance and energy should be comparable/more optimal, and robust to the traditional setting. Moreover, the paper also discusses practical issues such as computation complexity, hardware complexity, and power consumption, advocating hybrid or simplified control models as possible solutions. Finally, the outlook for smart PMSM control is also presented, especially in EVs and renewable areas.

Keywords: Permanent magnet synchronous motors (PMSM), Intelligent control, Fuzzy logic, Neural networks, Genetic algorithms

1. Introduction

Permanent Magnet Synchronous Motors (PMSMs) are widely used in industry due to their high efficiency, accurate torque control and compact structure. These types of motors are suitable for applications on rigorous environment and high performance, high reliable systems like as example electric vehicles (EV), industrial automation, robotics, renewable energy systems [1], Heating, Ventilation and Air Conditioning (HVAC) system. HVAC systems that control the temperature, humidity, and air quality within structures frequently use PMSMs, due to their energy efficiency and high performance. HVAC applications use PMSMs to drive fans (or blowers), compressors, and pumps because they enable efficient airflow and temperature control [2].

PMSMs offer inherent benefits, such as lower noise and vibration compared to other motor types [3], and their superior performance is largely attributed to the implementation of permanent magnet (PM) rotors, which eliminate the need for a dedicated excitation system, resulting in higher efficiencies and lower maintenance demands [4].

However, to unlock the full potential of PMSMs, advanced control algorithms are required. Traditional control techniques, including Proportional-Integral-Derivative (PID) control, Field-Oriented Control (FOC), and Direct Torque Control (DTC), have been extensively used in PMSM systems and have proven effective under nearly constant system parameters [4]. Yet, these methods encounter significant limitations when faced with time-varying loads, system disturbances, and non-linearities. In such dynamic

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* Corresponding author.

E-mail addresses: ghufran.22enp41@student.uomosul.edu.iq (G. S. Mohammed), mohammed.obaid@uomosul.edu.iq (M. O. Mustafa).

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conditions, these conventional approaches are often insufficient [5]. This challenge has led to the rise of intelligent control methods as an alternative to improve the performance, reliability, and adaptability of PMSMs. Moreover, intelligent control plays a crucial role in minimizing energy losses, maximizing efficiency, and adapting to changing operational conditions [6].

Intelligent control practices, which originate from artificial intelligence (AI), have exhibited excellent performance in addressing the intricacies and uncertainties of PMSM operation. Some of these techniques are Fuzzy Logic Control (FLC), Artificial Neural Networks (ANNs), Genetic Algorithms (GAs) and Adaptive Control [7]. Fuzzy logic controllers are an example of a systematic methodology for imprecise and uncertain information which are ideal for modeling complex systems such as a PMSMs [8]. Neural networks, on the other hand, provide with adaptive control performance learning from data [9], and can be used to cope with changes and enhance the system performance even when there is no accurate mathematical model of the motor [10].

Moreover, integrating Genetic Algorithms (GAs) into PMSM control allows for the optimization of rotor control algorithms, ensuring optimal motor operation. Adaptive control strategies, which adjust control parameters based on system feedback, enhance robustness against system dynamics, load variations, and environmental conditions [11]. These advanced control algorithms not only increase system performance but also contribute to energy savings by enabling motors to operate more efficiently across a range of conditions [12].

The feasibility of implementing these intelligent control techniques has been greatly facilitated by the exponential growth in computational capabilities [7]. Modern real-time systems, combined with the development of high-performance microcontrollers and Digital Signal Processors (DSPs), have made the real-time execution of complex algorithms possible in embedded architectures [13]. With the continuous advancement of computing power, emerging control strategies such as deep learning and reinforcement learning are expected to play a pivotal role in the future of PMSM control [14].

The objective of this review paper is to offer a deep insight on recent smart control methods for PMSMs. This paper will review several techniques (fuzzy logic, neural networks, genetic algorithms, adaptive control) presenting strengths, weaknesses, and real-world applications. Moreover, this paper will present the difficulties of realizing these strategies and some possible solutions allowing to push the limits of control performance for current PMSM. Moreover, PMSM

control system with the genetic algorithm has the function of optimizing the rotor control algorithms and the best motor operation. In addition, adaptive control strategies enable the tuning of the control parameters with feedback of the system, thereby making it robust against system dynamics and varying loads and environment conditions as well. These sophisticated control algorithms lead to a further increase in system performance and additionally to a saving of energy – not only due to the fact that they make the motors work more efficiently at different flow rates [15].

The implementation of such intelligent control techniques have been possible due to the exponential growth of computational capabilities that allow today the real time implementation of complex algorithms in embedded architectures. Real-time systems, in combination with the development of high-performance microcontroller and digital signal processors (DSP), have made the development of these intelligent control algorithms feasible for PMSM applications, especially in industries needing high-performance and energy-saving instruments. With the growing computing power, advanced control strategies such as deep learning and reinforcement learning are foreseen to be very promising [6].

The objective of this review paper is to offer in-depth insights into smart control techniques for PMSM. The paper will review these techniques, including fuzzy logic, neural network, genetic algorithm and adaptive control, and present their advantages and limitations. Discussion will also be given about the difficulties to implement these control strategies as well as strategies to incorporate in modern computers systems to improve the control performance of PMSM.

2. Overview of control techniques

Conventional Permanent Magnet Synchronous Motors (PMSM) control has been mainly achieved with Proportional-Integral-Derivative (PID), Field-Oriented Control (FOC), and Direct Torque Control (DTC) methods for many years. Due to their simplicity and effectiveness in steady state operation [16], those methods have been broadly investigated and used in PMSM applications. Such as PID control, which is commonly applied to precision requirements and easy-to-tune systems [17]. However, the traditional control approaches are not able to deal with the more complex PMSMs in dynamic operation, like load and speed changing. These difficulties partially stem from the fact that PMSMs are inherently nonlinear, in particular under load fluctuations, motor parameter variations, and external disturbances [18].

Another common method, especially in high performance applications, is the FOC. FOC separates the motor's torque and flux control, enabling these to be independently regulated. Although FOC has good dynamic and efficiency performance [11], it has not yet solved the problem of accurately measuring the position and speed of the motor, which is very important for maintaining the stability of the system. Therefore, for FOC, the accuracy of sensor measurements has a direct impact on the performance and such parameters drift may necessitate complex estimation algorithm [1].

One alternative is Direct Torque Control (DTC) with a scheme for controlling current torque and flux from the motor side, which provides faster torque response and better efficiency [19]. DTC, however, not only needs complex algorithms but also has high computational cost. Although DTC has its own benefits, the variable switching frequency and higher torque ripples can hardly be avoided, sometimes even degrade the dynamic performance, especially in low-speed domain [20]. Moreover, DTC depends on the accurate motor modeling, which is difficult for practical application, since the motor parameters are always influenced by circumstances [21].

Although classical control methods have certain advantages, they are subjected to the requirement of exact models of the system, which are not necessarily known exactly or in real-time practical implementations [3]. To overcome these drawbacks, intelligent control strategies, which include FLC, NN and GA are increasingly studied. They are better suited to uncertainties and system dynamics, and do not require an accurate mathematical model of the system. E.G. Fuzzy Logic Controllers map input data to output data from linguistic rules to process, which makes the system very efficient in handling imprecise or incomplete information. Neural networks, however, are able to learn from data thus allowing them to adjust to different operating conditions and enhance system performance through time without the necessity of explicit mathematical modeling [4].

The introduction of GA technology into PMSM control system can improve the optimization of the system parameters. In those aspects, GAs are quite applicable in order to choose the optimal controls of motors and to adjust the parameters of the controller during real-time [22]. Such dynamic optimization of motor operational parameters can greatly enhance system efficiency and robustness [23]. Adaptive control techniques that are able to adapt system parameters based on the received feedback and for additional real-time changes to operating conditions, are further enhancements for real-time PMSM applications [18].

Taken together, smart control methods have provided substantial advantages in terms of enhanced performance, reliability and real-time adaptability in PMSM applications, although conventional control techniques are still commonly utilized.

2.1. Artificial intelligence control techniques

With the capabilities of dealing with uncertainty, non-linearity and system dynamics, AI, especially in control systems, has played an effective role in some of the complex systems such as Permanent Magnet Synchronous Motors (PMSMs). of the AI control, ANN, GA and evolutionary algorithm based intelligent controller are noted as being the most powerful techniques in enhancing PMSM control.

2.2. Artificial neural networks (ANNs):

Artificial Neural Networks (ANNs) are computational models inspired by the biological neural network found in the human brain. These networks are composed of layers of interconnected nodes, or neurons, which process input data in a manner similar to the human brain's approach to information processing. ANNs are highly versatile and can approximate complex, non-linear functions without the need for a physical model of the system being controlled [25]. In PMSM control, ANNs can be trained to learn the motor's behavior under various operating conditions, enabling their application in real-time tasks such as fault detection, load estimation, and control optimization [26].

ANNs operate by taking in sensor data in real-time, such as motor speed, torque, and current, and then processing this information through multiple layers of neurons to predict optimal control actions [27]. This process allows the ANN to adjust the motor control parameters dynamically, such as the rotor flux or the torque-producing current, based on the detected system variations. One of the primary strengths of ANNs is their ability to continuously learn and adapt to changing conditions without requiring explicit mathematical models of the motor, making them especially useful for non-linear systems like PMSMs [28].

An important advantage of ANNs is their capability to enhance system performance, particularly when traditional control methods, such as PID, Field-Oriented Control (FOC), or Direct Torque Control (DTC), struggle due to the complexity or non-linearity of the system [29]. This adaptability of ANNs becomes especially useful when handling dynamic load variations or external disturbances, where classical controllers may fail to maintain the desired motor performance [30].

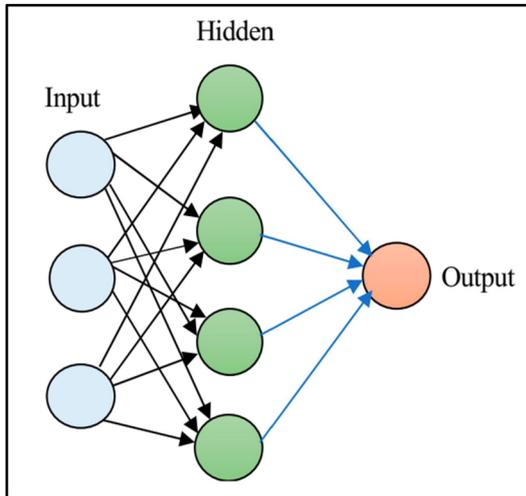


Fig. 1. Feedforward artificial neural network (ANN).

For example, in PMSM control, ANNs can be trained to manage both torque and speed. When there is a change in the load, the ANN adjusts the control parameters, such as voltage and current, in real time to maintain the motor’s desired performance [31]. This self-adjusting behavior shown in Fig. 1 is crucial during transient operating conditions where the system faces sudden changes, ensuring that the motor can stabilize and maintain the same performance despite the disturbances [32].

Such flexibility is also advantageous in enhancing PMSM operation under varying load conditions and improving response time and stability during transient conditions [33]. The ANN’s learning capability enables it to predict and adapt to these changes in a way that traditional methods struggle with, making it an ideal choice for highly dynamic and non-linear environments [34].

2.3. Genetic Algorithms (GA):

Genetic Algorithms (GAs) are evolutionary optimization techniques inspired by the process of natural selection. In GA, a **population of potential solutions** (also called **individuals**) is evolved through **generations** using genetic operators such as **selection**, **crossover**, and **mutation** [33]. These operators mimic the principles of **natural evolution**, allowing the algorithm to explore large solution spaces efficiently. Over time, the population evolves towards **optimal or near-optimal solutions** for complex problems shown in Fig. 2 [34].

In the context of **PMSM control**, GA can optimize various system parameters, including **controller gains** (P, I, D) and motor operation settings. The GA starts by initializing a random population of

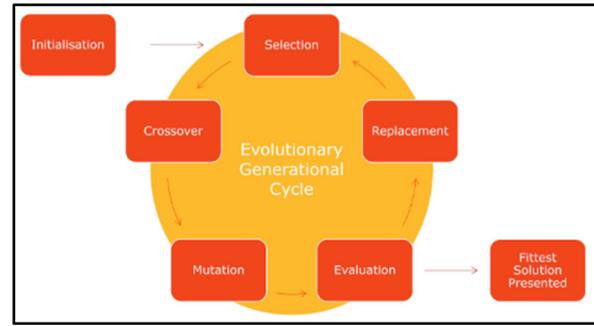


Fig. 2. The evolutionary cycle of a typical evolutionary algorithm.

candidate solutions, which represent different combinations of the parameters [35]. These solutions are then evaluated based on their **fitness**, which reflects how well they perform in terms of system efficiency and other performance metrics [36]. The GA iteratively breeds new solutions by selecting the best individuals (based on their fitness), applying crossover to combine the best features, and using mutation to introduce diversity in the population. This process continues until the **optimal control parameters** are found [34].

For example, in **PMSM applications**, GA can be used to **tune the PID controller parameters** to achieve the best system performance under varying load conditions. When the load on the motor changes, the GA can **adjust the control parameters** in real time to ensure the motor operates efficiently, reducing **energy transmission losses** and improving the motor’s dynamic characteristics [37]. The adaptability of GA enables it to optimize control parameters continuously, even as the system’s operating conditions evolve. This is particularly useful for maintaining **high efficiency** and **system robustness** under diverse and unpredictable conditions, such as **varying loads** and **environmental disturbances** [38].

GA is especially powerful in scenarios where **large-scale optimization problems** exist with many variables (such as in PMSM systems), and traditional optimization methods struggle due to high dimensionality [39]. Compared to other techniques, GA has a distinct advantage in finding near-optimal solutions across vast solution spaces [40].

2.4. Evolutionary Algorithms (EA):

Evolutionary Algorithms (EAs) shown in Fig. 3, such Genetic Algorithms (GAs), are optimization algorithms inspired by the principles of natural evolution. Unlike conventional, rule-based algorithms, EAs are adaptive and evolve through iterative processes that mimic natural selection [41]. The key operators

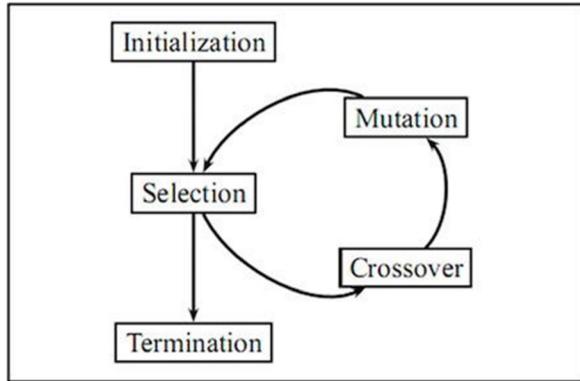


Fig. 3. Evolutionary algorithm cycle.

in an EA are selection, mutation, and crossover (recombination) [42]. These operators enable the algorithm to evolve a population of solutions by selecting the best candidates, combining their characteristics, and introducing random changes to maintain diversity in the population [43]. Through these iterations, EAs are able to explore large and complex solution spaces effectively, eventually converging on near-optimal solutions for difficult problems [44].

In the context of PMSM control, EAs are particularly useful because they can handle the complex dynamics of PMSM systems. As the system operates, EAs continually adapt the control parameters, such as PID controller gains (P, I, D), in response to changes in system dynamics (such as load variations, speed changes, and environmental influences) [45]. The iterative nature of EAs, where each generation of solutions builds on the best-performing candidates from the previous generation, makes them highly suitable for online tuning of control parameters in real time [46].

For example, in PMSM applications, when the load on the motor changes, the evolutionary algorithm can quickly adjust the control strategy to maintain optimal motor performance. This is achieved by the EA evaluating the performance of different control parameter combinations (e.g., PID gains) and selecting the optimal configuration that minimizes system errors, such as torque ripple or speed deviations. The mutation operator introduces randomness into the

control strategy, allowing the EA to explore new solutions that may improve system performance, while crossover combines the best aspects of existing solutions to refine the controller [38].

Additionally, adaptive control can be implemented through EAs, where the system learns from its past actions and previous performance [10]. This learning process enables the system to adapt its operation continuously, optimizing performance even in the presence of external disturbances or internal variations (e.g., motor wear, temperature changes). By constantly evolving and improving control strategies, EAs make PMSMs more robust, allowing them to respond effectively to unpredictable and dynamic environments, such as those found in electric vehicles and industrial automation systems. [47].

Table 1 provides a qualitative comparison of several strategies as they are applied to PMSMs in terms of essential performance criteria, namely efficiency, response, speed regulation, consumption and implementation complexity.

Traditional PID control has moderate control effect, but slow response, and bad control effect with variable load. Although it is easy to implement, it is not versatile and robust in environment described by nonlinearity [29].

The Fuzzy Logic control structure is effective on the improvement of performance in both efficiency and dynamic respectively, on the other hand has the medium time response and the good speed stability. It is applicable to imprecise knowledge systems and knowledge gradient systems and the computational workload is not dearer than PID [48].

Despite the good performance of ANNs across most of these measures, their speed of response and stability are some of the best, rendering them a prime candidate for use in complex system real-time control. But they are computationally expensive and complex and are not well suited for cost effective applications [49].

Genetic algorithms (GAs) have the merit of high efficiency, quick response and the ability of being adaptive to variation situations. Though computationally expensive, they are very efficient in dynamic control parameter optimization and energy minimization,

Table 1. Qualitative comparison of intelligent and conventional control strategies for PMSMs.

Control Method	Efficiency (%)	Torque Ripple(%)	Response Time (ms)	Speed Stability	Energy Consumption	Computational Cost	Implementation Complexity	References
Conventional PID	85	5.2	50	Low	Moderate	Low	Low	[29]
Fuzzy Logic (FLC)	90	3.1	35	Moderate	Low	Medium	Medium	[48]
Neural Network (ANN)	95	1.2	20	High	Low	High	High	[49]
Genetic Algorithm (GA)	92	0.8	25	High	Very Low	Very High	Very High	[50]

Table 2. Mapping of PMSM control techniques to application contexts.

Control Method	Key Features	Most Suitable Applications	References
PID / Classical FOC / DTC	Simple structure, easy to implement, well-understood; limited adaptability	General industrial drives, household appliances, low-cost EVs	[51]
Fuzzy Logic Control (FLC)	Handles nonlinearities, requires no precise model, interpretable rule base	Electric vehicles (smooth torque control), robotics (flexible operation)	[52]
Artificial Neural Networks (ANN)	Learns from data, strong nonlinear mapping, adaptive to varying conditions	Electric vehicles (efficiency optimization), renewable energy converters, robotics (trajectory tracking)	[53]
Genetic / Evolutionary Algorithms (GA/EA)	Global optimization, robust parameter tuning, slower response times	Offline controller design/parameter tuning for EVs and wind turbines	[54]
Hybrid Control (e.g., ANN + FLC, Fuzzy-PID)	Combines strengths of multiple methods, balances robustness and stability	Electric vehicles (complex drive cycles), wind energy systems (variable speed), industrial automation	[55]
Adaptive Control	Real-time parameter adjustment, compensates for system changes	Aerospace/robotics (dynamic environments), renewable energy converters	[10]
Model Predictive Control (MPC)	Predictive optimization, constraint handling, computationally intensive	High-performance EV drives, robotics with safety constraints	[56]

and hence are application for high-performance, adaptive control for PMSM [50].

In sum, intelligent control algorithms perform better than conventional solutions in terms of adaptability, precision and energy consumption at the expense of increased implementation complexity. Accordingly, the selection of control strategy should take into account the system requirements and computational resources.

While each control method for PMSM offers distinct strengths and trade-offs, their suitability also depends on the application context. For instance, electric vehicles demand high efficiency and smooth torque control, while wind energy systems operate under variable and uncertain conditions. To provide a consolidated view, Table 2 summarizes the main intelligent and classical control methods and links them to the application domains where they are most effectively deployed.

3. Applications in improving system response under variable load conditions

One of the most challenging tasks in control of PMSM is to keep stable and efficient operation under loads which may be changing. It is well known that a good solution to the problem of response improvement on flat topped wavefronts in AON systems is intelligent control methods such as ANN's, GA's and evolutionary algorithms. For example, in the PMSM application for electric vehicle, the load can change dramatically under different driving conditions, so that the smart control system can monitor the motor's characteristics continuously and adapt the control strategy in real-time that limits the waste of power, the performance of optimal output of the motor, or

the motional order of steadiness of torque. Similarly, in industrial automation practices, among the electro-mechanical actuators, PMSMs are always used for withstanding different loads exerted by different machine tools; intelligent control strategies can improve the adaptability of the system. By tuning control parameters according to the feedbacks from the system, these methods guarantee maximal performance of motor, no matter how the load varies. This provides for a more rugged and higher functioning system to cover a broad performance range with smaller losses and improved overall system durability, performance life and reliability [57].

4. Challenges and proposed solutions

Intelligent control of Permanent Magnet Synchronous Motors (PMSMs) gives a number of benefits such as improved performance, robustness, and adaptability. Nevertheless, incorporating these systems faces several difficulties which needs to be addressed for efficient and practical operation. These challenges are associated with complexity of computation, Realtime processing, energy requirement and requirement of specialized hardware.

4.1. Computational complexity and real-time execution

High computational complexity of executing advanced algorithms in real time is one of the main obstacles of application of intelligent control strategies to PMSMs. AI control strategies like ANNs, GAs and FLC are computationally intensive in view of their high level of complexity [50new]. Indeed, beyond the structural differences, large-scale optimization

algorithms, such as neural networks' optimization (e.g. by training significantly large networks of thousands of parameters) and GAs (evaluate multiple individuals at each iteration) share a common property: due to their high computation and memory requirements, it is impossible to run these algorithms in parallel to obtain a performance benefit by running them faster. The associated computation burden can be considerable, particularly when the control system is required to act upon high volume data at fast response rates for the purpose of accommodating vary operating conditions [58].

In real-time operation, if the control signals are processed with such a delay, This latency can impact response time of the system, causing challenges in maintaining fine control over the motor, especially in dynamic environments when the load, speed, or other parameters change quickly. Control delay, as one factor affecting the performance and stability of the system, is highly demanding for the high-performance applications, for instance E-vehicles that need instantaneously control torque and speed [59].

This real-time execution problem is exacerbated by the fact that dynamic operations such as start-up, speed control, torque control under load fluctuations, etc. are typically required for PMSM systems. To implement real-time control in such applications, the intelligent algorithms must be effective as well as computationally efficient since losing the precision or time delays of the controller can reduce performance.

4.2. Need for powerful hardware

This leads to the need for high-performance hardware for realizing AI-based control strategies. Traditional control algorithms such as PID and FOC control can be implemented with simple micro-controllers or processors, while intelligent algorithms such as ANNs, GAs require high processing power [60]. These algorithms are computationally intensive and, in many cases, necessitate specialized hardware in the form of Digital Signal Processors (DSPs), Field-Programmable Gate Arrays (FPGAs), or application-specific integrated circuits (custom ICs) [61].

This dedicated hardware is designed to take advantage of parallel computations, one of the critical requirements of AI algorithms, but they might be costly and not available for all PMSM applications [61]. The expense of such hardware, as well as the difficulty of incorporating such sophisticated processors into existing motor control systems, can be a major obstacle to the use of intelligent control algorithms, particularly in cost-sensitive applications,

such as appliances, household, or low-cost industrial motors [62].

Further, the system becoming increasingly complicated also increases the time cost on re-engineering motor control systems compatible with AI-based controllers [63]. The re-design of the controller in order to incorporate powerful processors and efficient communication channels (as well as system compatibility) is also an issue [64].

4.3. Energy consumption of intelligent control systems

On the other hand, advanced control strategies of PMSMs, such as intelligent control system, are likely to greatly improve the performance, at the cost of the energy consumption. AI algorithms, and especially those adapted in neural networks and evolutionary algorithms) are energy intensive through their computational requirements. In applications such as electric vehicles and renewable energy systems, wherein efficiency is an important factor, the increase in power required to run these algorithms can be greater than the potential benefits of improved control.

For example, if executing the complex AI models is used for continuously tuning (modifying) the control parameters of the motor, such continuous tuning of the control parameters of the motor may result in excessive energy consumption of the motor system if the motor system is not adequately energy-efficient. In addition, the energy consumption in real time execution of such algorithms may be prohibitive in applications where minimal energy consumption is a primary concern, such as battery powered systems [14].

5. Proposed solutions

For the intelligent control of PMSM, some strategies were found to tackle the computation burden problem, the hardware demand and the energy consumption issues:

5.1. Simplification of algorithms

To reduce computation complexity, scholars have paid attentions to the algorithm's simplification with keeping the system performance available. One route may be to reduce the size of the parameter space in ANNs through a shallow network or fewer hidden layers. These simpler structures can reduce the requirement for computing capacity and remain satisfactory for control performance of the PMSMs in most practical applications.

Moreover, approximation approach can be applied to ease the computations of algorithms including the fuzzy logic, and decrease the complexity of inference operations. The number of rules and memberships shall be reduced with a view to the fact that the fuzzy logic system can function quicker, while the control precision can be guaranteed.

Another method is model reduction, in which the system dynamics are replaced with a simplified model to decrease the computational complexity. These simplified models can be integrated with control techniques, allowing the system to behave well under changes in load or speed without being burdened by complex calculations [65]. In real-world applications, simplifying algorithms to reduce computational complexity can significantly enhance performance without compromising control effectiveness. For instance, in controlling Permanent Magnet Synchronous Motors (PMSMs) for industrial automation, using shallow Artificial Neural Networks (ANNs) with fewer hidden layers can reduce the computational load while maintaining satisfactory motor control performance [66]. Similarly, fuzzy logic systems can be simplified by reducing the number of rules and membership functions, allowing faster inference operations in applications like automotive adaptive cruise control, where quick decision-making is essential [67]. Additionally, model reduction techniques can be applied in robotics and drones, where simplified models of system dynamics enable efficient real-time control despite variations in load or speed [68]. These simplifications ensure that systems remain responsive and resource-efficient, even in computationally constrained environments [69].

5.2. Hardware acceleration and parallel processing

Parallel processing techniques have been proposed to overcome the demand for a powerful machine. This control law can be performed with several algorithms simultaneously executed, which minimizes the execution time in modern microcontrollers, GPUs, and FPGAs [70]. The general benefit of GPU acceleration is that for tasks like training neural nets or doing optimization in real time, parallelism can be absurdly fast [71].

In addition, multi-core processor use can distribute the processing load among the cores, which, in turn, can increase system responsiveness [72]. All of these processors can cooperate to compute various parts of the control algorithm in parallel, and thusly closely approximate real-time control decisions [73].

The design of dedicated hardware devices, which could be hardware accelerators like ASICs for PMSM-

control for instance, may well become relevant for breaching hardware limitations of intelligent systems. These chips are developed especially for controlling PMSMs and so they minimize the energy cost and computation time. [47].

5.3. Energy-efficient control systems

One of the methods for lowering the power requirement of intelligent controllers is to provide an energy-efficient hardware implementation. The power consumption of intelligent controllers can be further reduced via low-power microcontrollers or dedicated low-energy AI processing circuits [74]. Furthermore, adaptive control techniques are exploited, so that the system adapts the number of computational resources according to the operating condition of the motor. At steady-state, the system can minimize computing resources, but can dynamically upshift resources if the motor is experiencing different loading or operating conditions [75].

Furthermore, hybrid control structures, in which conventional methods are merged with intelligent algorithms, present another alternative. One example is where a hybrid controller applies a classical PID controller to provide baseline control and an AI-based algorithm that adjust parameters more precisely, or optimize the motor performance [76]. It can not only have the simplicity, efficiency and energy saving characters of the conventional control, but also possess the flexibility of the intelligent control, which can decrease the energy consumption and the complexity of the system [65].

6. Future applications of intelligent control in PMSM

Smart controllers for Permanent Magnet Synchronous Motors (PMSMs) are considered to be promising candidates in next-generation advanced applications, especially in renewable power plants and electric vehicles (EVs) [77]. These industries are demanding more PMSMs because of their attracting efficiency, reliability and compact structure. With the increasing demand of energy-saving, low carbon and eco-friendly technology, intelligent control strategies are expected to be a new solution for the PMSMs performance improvements in terms of load change, system uncertainty and real time optimization [78].

6.1. Renewable energy systems

Regarding to the renewable energy generation application, PMSMs are widely implemented in the

wind and solar power generation systems because of high efficiency and low maintenance requirements. The development of intelligent control solutions for such systems is essential in order to minimize the bounty required for the systems process that enhance energy conversion rate and system robustness [79]. For example, PMSMs in wind turbines need to have very accurate torque and speed control for adjusting to altering wind conditions. Intelligent control systems, such as fuzzy control and neural network techniques can be utilized to dynamically control the turbine performance, so that power is maximized by varying the motor action in response to changing conditions of wind speed and load [80]. In addition, in solar applications PMSMs need to track the position of the sun in an efficient manner, and artificial control systems can be used to achieve a motor move that follows the optimal angle for the sun's radiation in a dynamic way throughout the day [81].

The main advantage of intelligent control for renewable energy system is to maximize the energy harvesting with the minimum loss in the system. Since renewable energy reservoirs are usually alternative in nature, intelligent control strategies also enable to provide a stable and ecological power supply system by adaptively changing PMSM parameters according to environmental factors, such as solar insolation or wind speed [82]. Such capability would enable renewable energy systems to be significantly more robust and reliable where they can more easily couple into the grid and generate power in a continuous manner despite coffee variations [3].

6.2. Electric vehicles (EVs)

Electric car is one of the potential applications for the PMSMs because of its high efficiency and less pollution suspension compared to the internal combustion engine. Advanced control strategies play a vital role in improving the performance, safety, and energy efficiency of electric vehicles [83]. PMSMs used in EVs must perform accurate control of torque, speed, and regenerative braking when the vehicle is accelerating, decelerating or slope changes. Based on the feedback, smart control can realize the real-time adjustment of motor parameters which will help to optimize the torque and guarantee smooth operation under complex driving situation [84].

Second, intelligent control can make a positive contribution to battery life by optimizing motor operation and driver in order to minimize power consumption [85]. Methods such as model predictive control (MPC) and adaptive control can be employed to forecast the future behavior of the motor and battery system, dynamically updating parameters for

the desired operation in order to minimize the energy consumption and lengthen the life of the battery [86]. Furthermore, the regenerative braking of EVs can be intelligently controlled, such as modifying the braking force derived from the EV's speed, load and road state, thereby enhancing energy recovery and prolonging the life of the braking components [87].

With the development of the EV market, advanced flexible intelligent control strategies must be well handled in order to keep the charging time low, increasing vehicle efficiency and performance. These advances in PMSM drive will enhance the competition levels of electric vehicles against conventional vehicles in performance and operational costs, and hence further promote the sustainable transportation technology for broad applications [88].

7. Conclusion

From this review, it has been demonstrated that intelligent control approaches, neural, fuzzy, and evolutionary algorithms, provide an enhanced tracking, disturbance rejection, and energy efficiency for PMSM drives working under nonlinear, uncertain, and disturbances compared to standard PID/FOC/DTC methodologies. Yet, the advantages mentioned above come at the price of practical costs such as additional design complexity, higher computational effort, larger hardware requirements and excessive implementation overhead. Translating research prototypes into production form with far fewer bits is going to require simple algorithms in addition to heavy reliance on hardware accelerators (e.g., FPGAs or ASICs) and hybrid architectures that couple a light-weight classical controller for nominal operation with an adaptive intelligence layer that is called on only as necessary to balance between performance and deploy ability in battery-powered machinery (electric vehicles, renewable-energy inverters, etc.). There is also an immediate need for shared benchmark datasets and metrics, full cost-benefit analysis (including the controller's own energy overhead), and long-term testing in the field to assess reliability; future work should focus on ultra low power implementation, standardized comparative performance evaluation and realistic demonstrators proving a life-cycle gain in efficiency, lifetime and maintainability, the latter being crucial for wide acceptance of smart PMSM control technologies.

7.1. Key findings

The primary message from state-of-the-art intelligent control of PMSMs is the capability of these

methods for dealing with uncertainties and for the on-the-fly system performance optimization. In previous studies, intelligent control strategies have been successfully applied to system non-linearity, load disturbances, and uncertain operating conditions. For instance, neural networks can acquire the dynamic of PMSMs, genetic algorithms can identify an optimized control of parameters and fuzzy logic can deal with vague data and environments uncertainty. These characteristics are important for the application of PMSMs in practical circumstances, particularly in real time systems, such as wind generators, solar cells, and electric vehicles.

Another major conclusion is the significance of energy efficiency. Due to the PMSMs often being utilized in energy-sensitive systems, such as renewable energy systems and electric vehicles, energy-efficient intelligent controller becomes more important. Certain control strategies based on Artificial Intelligence (AI) have a high potential for minimizing energy consumption with little degradation in performance. With the dynamic changing of motor control parameters, intelligent controllers can realize the maximum energy consumption especially in the case of changeable load.

8. Future directions

The future development of intelligent control techniques for PMSMs will likely focus on several key areas:

1. Improved computational performance: With the growing complexity of control algorithms, the trend in future studies is to enhance the computational performance of AI control approaches. This may require either streamlined algorithms or the use of extreme hardware acceleration (e.g., GPUs or FPGAs) in order to support the increasing requirements for real-time control.
2. Compatibility with future and emerging technology: Combining PMSM control with IoT (Internet of Things) and big data analytics to do predictive maintenance and real-time tuning. Smart sensors and predictive algorithms can analyse the behavior of the PMSM from the acquired big data, to improve performance and prevent future malfunction beforehand, which can keep the failure time of the PMSM used in air conditioner within the design life, increasing the reliability and lifespan of the PMSM system.
3. Hybrid systems: Hybrid control systems joining classical control and intelligent control techniques will increasingly play an important role, as such systems can provide a good trade-off

among performance, computational complexity, and energy consumption. They also allow to obtain more effective, responsive and energy-aware systems by bringing together the robustness of traditional controllers and pattern-driven AI-based approaches.

However, there is no doubt that the future of intelligent control for PMSMs will explore the performance, and energy utilization and promote the wider use of sustainable technologies. With increasing penetration of automation, renewable energy and electric vehicles in various industries, smart and intelligent control systems hold even greater significance in achieving optimal system performance and reducing environmental footprints.

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