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A Review on an Intelligent Controller for an EV Propulsion System Using Different Optimization Techniques

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Abstract
Transportation and vehicle travel are essential for socioeconomic growth because they consent communities and enterprises to operate around the world. However, major portions of the transportation sector predominantly dependent on gas-based vehicles, resulting in elevated air pollution and emission of greenhouse gas. vehicles powered by battery (EVs) provide a potential solution to transportation issues. Consequently, a strong traction motor control system is crucial to the optimization of the electric drive system. As a result, the purpose of this work is to discuss novel control approaches implemented in the traction motor system in EVs. Direct Torque management (DTC) and Indirect Field Oriented Control (IFOC) are popular control strategies because they provide enhanced management of the Induction Motor (IM) and Permanent Magnet Synchronous Motor (PMSM) used in most EVs. This paper describes different Metaheuristic Algorithms integrated with electric motor drives aim to overcome challenges in estimating real-time vehicle conditions and reduce torque ripple. An overview of the performance characteristics, strengths, and weaknesses of various motor types and control strategies are reviewed Finally, a comprehensive evaluation of various motor drives in electric vehicles using different metaheuristic algorithm-based control strategies highlights their significance and potential outcomes.

Keywords: *Control strategies; Interior Permanent Magnet Synchronous motor; Metaheuristic algorithm; Torque ripple.*

1. Introduction

The transportation sector remains a key factor driving global temperature rise [1]. To accomplish lowering emission targets, it has become critical to prioritize the automobile area and develop sustainable mobility technology [2]. EVs are showing a rising trend since they give a solution to many of the existing transportation difficulties [1] [3]. The transportation sector now relies heavily on the engines with internal combustion (ICEVs); nevertheless, this dependence offers substantial issues because ICEVs release atmospheric greenhouse gases that contribute to urban air pollution through tailpipe emissions [4], [5]. For many years, concerns regarding the environmental risks associated with the transportation sector have been the subject of ongoing debate. The transport industry accounted approximately 23-26% of all global CO2 released in 2004 as well as 74% of CO_2 released from road-going vehicles in 2007 [6]. In conjunction with CO2, ICEVs release a variety of additional pollutants, including nitrous oxide (N2O) and methane (CH4) [6, 7]. Thus, EVs play a crucial role in reducing greenhouse gas emissions and preserving environmental sustainability [3]. These “zero-pollution” vehicles offer an alternative for the environmental difficulties produced by gasoline-powered vehicles and are considered as the vehicles of the near future because to their claim to reduce increasing gasoline prices and pollutants in the air [4]. Because of their relevance, EVs require continuous improvement, and numerous mechanical design approaches can be used to increase EV performance. Optimizing electric powertrain design in EVs plays a critical role in enhancing overall efficiency and range. Electric propulsion technology is an essential component of the systems used in an EV powertrain; hence it requires ongoing attention and development. EVs require more performance from their motors compared to normal industrial applications. EV applications require electric motors having substantial power density with torque, good efficiency, a broad speed range, and with high torque capabilities. High-efficiency electric motors can be employed to improve driving range. To meet this demand, the design of an EV incorporates many considerations such as vehicle behavior, capacity, and weight along with the required speed for uphill, downhill, and regular road driving, torque, motor and range, battery type, and the DC/DC or DC/AC power converter used in order to meet future demand [5]. In EVs, electric motors and motor control techniques are major aspects impacting the range and performance of electric vehicles (EVs). Several machines powered by electricity were researched for application in electric Vehicle engine systems as EV technology has advanced [5]. Most EV systems began with DC motors, which allowed for easy integration and operation. Nevertheless, DC-powered equipment lacks the capability to meet the demanding performance standards of EV systems. As power electronics have advanced, three-phase induction and PMSM machines are presently the dominant type employed in commercially produced electric and hybrid EVs. The motor's traction control system is a critical element in the EVs powertrain, with techniques for control varied depending on the type of motor utilized. To achieve the speed and torque demands of automotive applications, three-phase induction and PMSMs sometimes require complicated vector and DTC approaches. In this paper, an extensive review of significant EV technologies and electric motor variants is presented and their control strategies is elaborated. Several further studies have been conducted to investigate enhanced motor control strategies. The authors of [6] and [7] give an overview of direct torque regulated induction motor drives. The contributors in [6] explore the fitness of DTC for EV applications, whereas the researchers in [7] discuss its numerous applications. In [8], a summary of recent DTC enhancement strategies is offered. However, the emphasis is on enhancements made to the conventional DTC system, rather than other DTC uses. In [9], the authors discuss design techniques and control tactics for energy-efficient electric machines suitable for EV applications. As a result, the topic focuses on loss minimization and control. In [10] reviews power electronics and motor drive technology for several types of EVs but does not cover traction motor control methods. In [11], researchers examine current and future propulsion technologies used in EV systems. However, unlike [10], they do not focus on the traction motor control mechanism, although discussing power electronics. Finally, the authors of [12] provide a comprehensive study of EV technologies and other pertinent information. The contributors present a brief introduction of traction motor control mechanisms. The primary contributions of this research are: (i) to review the studies that have been published in the existing literature, and (ii) review on different kinds of electric motor drives available for electric vehicles and comparison of electric motors used in traction (iii) a review on different control strategies used in electric vehicles for torque controller. (iv) Metaheuristic Technique (v) Jellyfish optimization technique, (vi) conclusions that were reached from the completion of the current study.

2. Electrical Motor Drives

While choosing an electric vehicle driving system, critical factors to consider include maintenance, efficiency, cost, weight, durability, reliability, size and noise level (Figure 1). According to the literature review, electric motors typically used in vehicle propulsion systems include Direct Current motors, Induction Motors (IM), Brushless DC (BLDC motors), Permanent Magnet Synchronous Machines (PMSM), and Switched Reluctance Motors (SRM)[5].

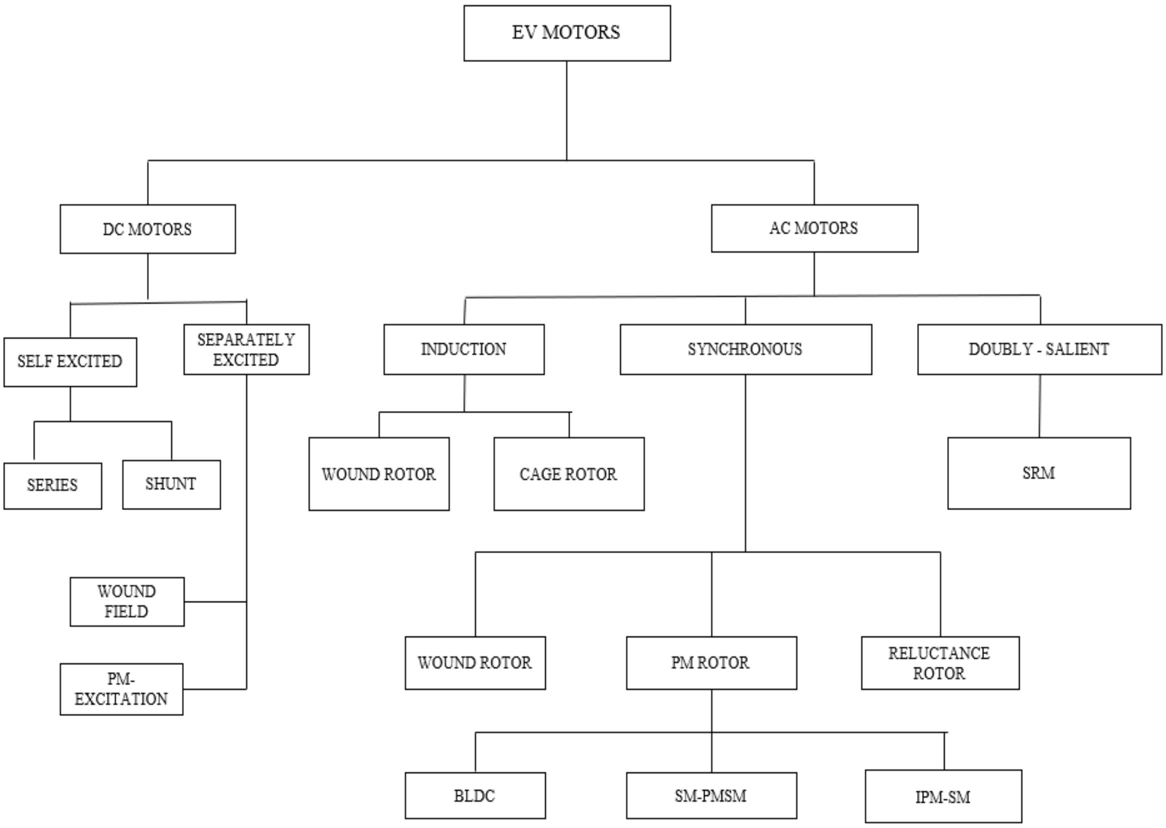

Figure 1 Classification of EV Motors

2.1. DC Motor Drives

In former times, DC motors have been the chief choice for propulsion in electric vehicles due to their ability to deliver maximum torque at low speeds and their straightforward speed control. However, these motors are relatively heavy, less dependable, and experience energy losses due to their brushes and commutators [6]. AC motor drives are preferred over DC motor drives for electric cars because of their high efficiency, enhanced dependability, higher power density, and lower maintenance requirements [7]. These parameters are critical to an electric vehicle's propulsion system.

2.2. Induction Motor Drives

Induction motors are widely utilized AC motors in electric vehicles due to their lower cost, durability, and superior dynamic performance. To improve the operational performance of induction motor drives for electric vehicle propulsion, vector control is favoured over other control strategies [8]. A decline in efficiency and a rise in losses at elevated speeds are notable limitations of induction motors.

2.3. Permanent Magnet Synchronous Motor

As technology advances, permanent magnet motor drives are increasingly being chosen over Induction motor drives for use in EV propulsion systems. Utilization of extremely strong permanent magnets minimizes size and weight with enhancing power density. These kinds of motors are more efficient than induction motors because they do not experience rotor copper losses, and they provide greater reliability when contrasted with various motor drives. The insufficient supply of rarefied magnets and their elevated price constitute significant challenges to the broader adoption of these motors in the affordable electric vehicle market. [9]. PMSM can be categorized into Surface Mounted type PMSM (SPM) and Interiors Permanent Magnet (IPM) types depending on the positioning of the permanent magnets on or within the rotor. When comparing these motors, IPM motors exhibit a higher capacity for overload, reduced noise during operation, and are

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increasingly preferred for mobility applications [10].

2.4. Brushless DC Motors

The arrangement of this kind of motors resembles that of PMS motors. Rather than employing a sinusoidal power supply, these type motors are typically driven through a rectangular AC power source. The most significant advantage of using these motors is the absence of brushes. Furthermore, PMBLDC motors provide a higher torque performance under defined peak current and voltage conditions compared to other motor types. Due to their excellent power density and efficacy, permanent magnet Brush-less DC motors hold great potential employed in electric vehicle drive systems. [11]. The permanent magnet configuration raises the expenses associated with these type motors, and the magnets are affected by temperature.

2.5. Switched Reluctance Motor

Switched-Reluctance Motors (SRMs) have recently sparked significant interest from researchers for applications that demand high dynamic performance. In comparison to Induction Motors (IM) and Permanent Magnet Synchronous Motors (PMSMs), SRMs stand out for their reliability, capability for high-speed operation, tolerance to high temperatures, and operation without gears. The consistent power range can be enhanced by bumping up the basic speed by 6-7 times. Although SRMs exhibit lower efficiency than PMSMs when operating at maximum velocity and torque levels, they outperform other electric motors in terms of efficiency across a broader range of speed and torque. However, these motors come with disadvantages such as noise, intricate design, and complicated control systems. [12]. Table 1 displays the performance evaluations for the motors previously mentioned. A range of motor drives has been evaluated across various criteria in this part. PM-brushless motors offer the highest efficiency among motor drives. From the perspective of reliability, PM-brushless motor drives rank highest, succeeded by induction motor (IM) and switched reluctance motor drives (SRM). PM-brushless motors excel in terms of power density. Induction motors are the most cost-effective option to use. In contrast to all the other motors, PM-brushless motors incur the highest costs. [13]. Numerous claims have been made regarding IPM topologies, particularly concerning their saliency torque contribution, resistance to demagnetization, reduced magnet mass, broad flux-weakening capacity, and excellent operational efficiency. Such characteristics have been evaluated and contrasted for a widely recognized IPM design and a corresponding SMPM design [14].

Table 1 Overview of the Most Widely Used Propulsion Motors.

Index	Brushless DC	Series	PMSM	SRM	IM
Expense	Greater	Low	Greater	Med	Med
Weight	Light	Bulky	Med	Med	Med
Controller Cost	Extremely high	Minimal	High	High	High
Maintenance Requirement	Negligible	Brushed wear	Negligible	Negligible	Negligible

Efficiency	High	Less	High	Less than PMDC	High
Starting torque	>175% of rated	>175% of rated	>200% of rated	Up to 200% of rated	High
Speed Range	Excellent	Limited by brushes	Controllable	Controllable	Controllable
Commutation	Internal Electronic	Mechanical	External Electronic	External Electronic	External Electronic
Pros	Good torque and Speed, fast response, tremendous power, long life	Inexpensive field weakening, maintains Constant speed, higher starting torque	No torque ripple, more torque, better performance, greater reliability, and fewer noisy.	Small inertia, adaptable to specific applications, runs cool.	Excellent efficiency
Cons	Expensive	Bulky, limited speed, requires large field winding	Complex control, Costly	Require position sensor, high acoustic noise, vibration, high torque ripple	Complex Controller

3. Torque Controller

Control techniques for Permanent Magnet Synchronous Motors (PMSMs) utilized in electric vehicle (EV) applications are critical for improving performance, efficiency, and reliability. This section examines the different control algorithms suggested for PM Synchronous motor drives that aim to minimize torque ripple. Permanent magnets are used in PMSM instead of rotor windings. Thereby, the rotor flux remains unchanged, and the current equals zero [15]. The direct axis stator current generally affects any change in air gap flux value [12]. The motor's equation is a series of nonlinear time-varying equations linked to the rotor's instantaneous location, making studying its dynamic aspects challenging in the α-β system [13]. Consequently, the mathematical

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representation of the PM Synchronous motor in this system of coordinate was not used in the evaluation. Thus, the dynamic representation of the PMSM system is defined in a revolving d-q reference frame coupled to the rotor, as is common for motor control.

$$y_{ds} = L_{ds} i_{ds} + Y_m \quad (1)$$

$$y_{qs} = L_{qs} i_{qs} \quad (2)$$

$$V_{ds} = R_s i_{ds} + L_{ds} \frac{di_{ds}}{dt} - \omega_r L_{qs} i_{qs} \quad (3)$$

$$V_{qs} = R_s i_{qs} + L_{qs} \frac{di_{qs}}{dt} + \omega_r (L_{ds} i_{ds} + \Psi_m) \quad (4)$$

$$T = \frac{3}{2} P (\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds})$$

The variables ids, iqs, Vds, Vqs, Ψds, and Ψqs, represent motor currents voltages, and fluxes, in the dq reference frame. T represents Electromagnetic torque, Ψm represents flux due to permanent magnet, ωr represents electrical angular velocity, Rs represents resistance of the stator, Lds represents direct axis stator inductance, and $\boldsymbol{Xqs}$ represents stator inductance in quadrature axis. In surface mounted PM (SMPM) motors, Lds = $\boldsymbol{Xqs}$ [14]. While in interior PM motor $Lds < \boldsymbol{Xqs}$. Here are the technical equations for the motor:

$$J \frac{d\omega_m}{dt} = T - T_1 - B\omega_m \quad (6)$$

$$\omega_r = P\omega_m \quad (7)$$

J denotes the total moment of inertia for both motor and load, Tl indicates the load torque, and ωm stands for the angular speed of the motor in mechanical terms. The expression for motor torque (5) can be expressed in another form.

$$T = \frac{3}{2} P \frac{\Psi_s \Psi_m}{L_s} \sin\delta \quad (8)$$

Equation (8) indicates that motor torque is directly proportional to flux of stator, magnet flux, and the sine of the angle amid them. In [16] [17] Field-Oriented Control (FOC) is commonly utilized because it offers accurate regulation of torque and flux through the conversion of three-phase currents into a rotating reference frame. This enables decoupled control of the motor's magnetic and torque-producing components, ensuring smooth operation and high dynamic response. The [17] benefit of FOC lies in its exceptional precision and effectiveness in regulating the torque and speed of the motor [18] and presents a comparison of various control algorithms with respect to their performance parameters (Figure 2).

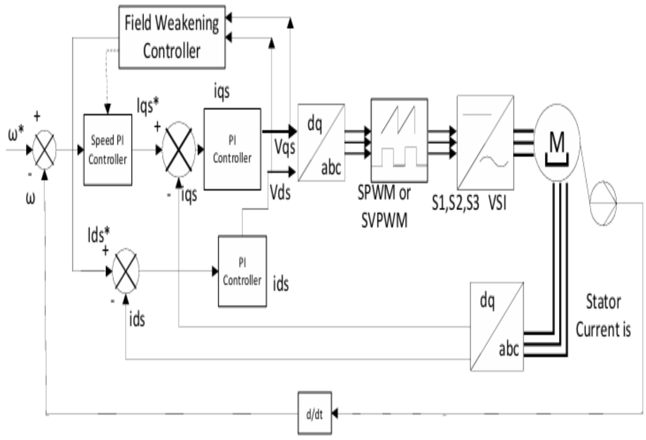

Figure 2 Block Structure of FOC for PMSM Drive

An entire field-oriented control (FOC) system functions as a cascading closed-loop control, comprising two inner PI current controllers and a speed PI controller at the outer loop. Internal PI controllers calculate control voltage references (Vds and Vqs) by comparing current references (ids and iqs ∗) to measured currents (ids and iqs), which are derived by transforming the stator current into a synchronous d-q reference frame. The exterior PI controller calculate the current reference by comparing the rotor speed reference (ω∗) and real speed (ω) [5]. A position sensor measures the rotor's position in real-time. Cascaded closed-loop control employs time constants that enable inner current loops to react more rapidly than outer speed loops. The outputs of the PI controllers are limited to ensure that voltages and currents remain within their specified ratings [12]. The voltage references (Vds and Vqs) are converted into three-phase signals that function as control voltages for Space Vector Pulse Width Modulation or Sinusoidal Pulse Width Modulation (SPWM). The gated signal attained using SVPWM or SPWM is used to control the output voltage of the PMSM via the inverter. In addition to field weakening control, Maximum Torque per Ampere (MTPA) control helps boost vehicle efficiency. FOC suffers from certain disadvantages including a greater switching frequency, a slow reaction, and a limited bandwidth. Direct Torque Control (DTC), on the other hand,

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simplifies the control process by directly regulating torque and flux, offering faster dynamic response. Nevertheless, DTC suffers from higher torque ripple and increased switching losses, [14] which can impact efficiency and motor longevity.

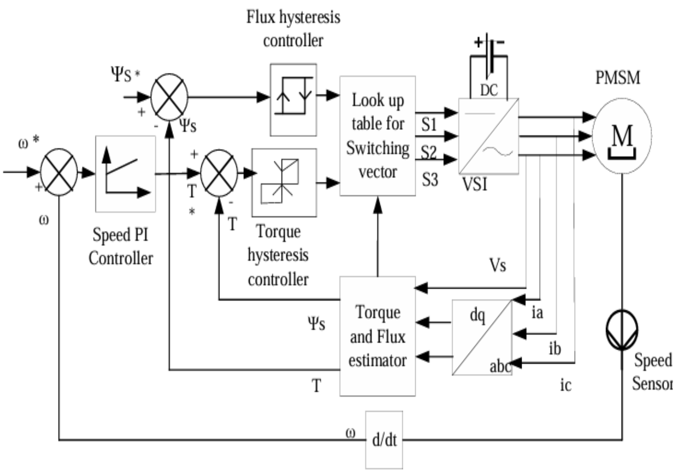

Figure. 3 Block Diagram of Direct Torque Control of PMSM

Figure 3 depicts the PMSM's Direct Torque Control block diagram. The rotor's position and the currents in the stator phases are fed into an estimator, which computes the stator flux, torque, and speed. To compute stator flux, the three-phase stator current is first converted to two-phase, and then from d-q to α-β. The reference values for stator flux and torque are compared against the estimated values, leading to discrepancies that are fed into a two-level flux hysteresis controller and a three-level torque hysteresis controller, correspondingly. The result generated by the hysteresis comparator is directed into the lookup table, which identifies the appropriate voltage vector to apply into the inverter. This lookup table depends on the stator voltage vector location, which is extracted from the estimator block. The bandwidth of the flux hysteresis primarily influences the distortion of motor current through lower-order harmonics. The torque hysteresis bandwidth has a considerable influence on switching frequency and losses [5]. Variable switching frequency in DTC causes significant current and torque ripple, necessitating more investigation. Although some authors presented strategies to lessen current and torque ripple, these challenges remained unresolved. Model Predictive Control (MPC) has recently gained appeal as a dependable control approach. MPC approaches use a system model to predict output responses, allowing for the optimal control action to minimize desired cost functions. Many efforts have been made in the power electronics sector over the last decade to use MPC in electrical drives. Electrical drive systems are fundamentally a subset of power electronics since electric machine drives, or Power converters are one form of power electronics application. Model Predictive Control has advantages in managing electrical drives, including a simpler design approach, faster dynamics, a simplified structure and implementation. MPC has been widely implemented across multiple applications, such as grid-connected converters, machine drive, power quality, and regulated power supplies. MPC is basically separated as two categories: Continuous Control Set MPC (CCS-MPC) and Finite Control Set MPC. In CCS-MPC, a modulator is needed to generate the inverter's switching state. In FCS-MPC, no need for a modulator because the inverter is optimized with a finite number of switching states. Though greater computational work is required, it can be applied to scenarios requiring continuous reference voltage vectors, which is a drawback of traditional FCS-MPC, which generates only discrete switching states. FCS-MPC outperforms CCS-MPC in terms of nonlinearity and constraint control (Figure 4).

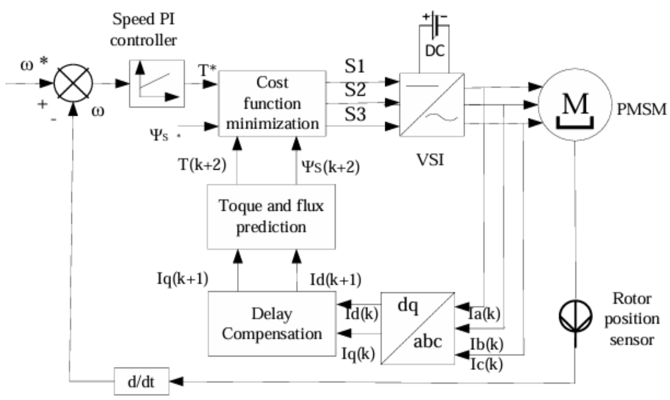

Figure 4 Block Diagram of MPC for PMSM Drive

Model Predictive based Direct Torque Control (MPDTC) combines the predictive modelling strengths of Model Predictive Control (MPC) with

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the simplicity of DTC, achieving superior torque ripple reduction, faster response, and enhanced efficiency. Despite its advantages, MPDTC demands significant computational power and a highly accurate motor model for real-time implementation. In [9] One notable feature of Sliding Mode Control (SMC) is its resilience to changes in parameters and external disturbances, making it reliable under challenging conditions. However, its tendency to cause chattering [10] introduces potential efficiency and durability concerns. [13] This study meticulously examines and contrasts the torque control techniques of interior permanent magnet synchronous motors (IPMSM) utilized in EVs. The choice among these techniques depends on specific EV application priorities, such as performance, computational resources, and system robustness. In [17], various control methods for PMSM are analyzed with respect to current, speed, and torque fluctuations as performance measures for vehicles.

4. Metaheuristic Technique

Over the decades many metaheuristic algorithms have been evolved. Out of which some may provide clues from nature, and some may not provide clues for metaheuristics. The four main types of nature inspired metaheuristic algorithms are: human-based, physics-based swarm based, and evolutionary algorithms. Modern metaheuristic algorithms have started exhibiting their effectiveness in solving complex optimization issues in recent years. These metaheuristics have been shown to be effective and efficient in locating nearly ideal solutions in a reasonable amount of time when applied to a range of optimization problems [18]. Genetic algorithms (GA), artificial neural networks (ANN) and Fuzzy logic (FL), are utilized extensively in machine control and power electronics. In the literature, a novel artificial intelligence-based control method has been proposed. By either replacing the switching table with intelligent controllers or changing the hysteresis band, these methods improve the dynamic performance of DTC control. One kind of artificial intelligence is fuzzy logic, or uncertainty handling in general. The FL-DTC principle operates similarly to conventional DTC; the sole distinction is that a fuzzy logic controller substitutes the torque hysteresis loop to minimize fluctuations of torque. It addresses the challenges of nonlinear high torque at low speeds through the application of fuzzy rules. [19]. Neural networks (ANNs) are excellent tools for mapping nonlinear mathematical functions. They can estimate any nonlinear system without understanding its intrinsic structure [20]. These neural networks have a wide range of applications, including classification, image and audio processing, estimate, process identification, and electrical system management. In fact, ANN-based intelligent control gives the driving system great adaptability [21]. Multiple papers have recommended for ANN-based DTC to decrease torque ripple and speed estimation inaccuracies at low speeds. In [22], the researchers used ANN in an induction machine's DTC to improve the drive system's dynamic behavior in the event of a faulty switch. In [23], Awasthi et al. proposed a unique ANN controller for managing the speed of a linear induction motor with low complexity and high performance. The suggested ANN-DTC approach excels at trajectory tracking and is a cost-effective speed controller for linear induction motors. Neural networks in DTC offer effective dynamic torque and flux control with a set switching frequency in both transient and long term circumstances [24, 25]. Genetic algorithms (GA) are a type of stochastic optimization method that employs natural evolution approaches to evaluate a wide search space and find several solutions [26]. They offer high-quality solutions to diverse issues with minimal effort and computational resources [27]. The utilization of genetic algorithms (GA) as an alternate strategy for optimizing PI controllers is the prevailing approach for research on high-performance electric machines [28, 29, 30]. In [31], For five-level DTC control of IM, the authors employed a genetic algorithm-optimized PI controller (PI-GA). This approach outperformed the standard DTC in terms of response time. Numerous benefits were demonstrated, including reduction of overshoot, flux and torque ripple reduction, and response time. In [32], GA is utilized to enhance the reference torque calculation by optimizing PI controller gain parameters. The GA-PI-based DTC increases the high-speed accordance by 100% and the low-speed accordance by 50%. Reference [33] compares adaptive neural network (ANN) and genetic algorithm (GA)-based DTC

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control of an electric vehicle propulsion motor. The GA torque controller outperforms the PI and ANN controllers in terms of torque ripple at higher speeds and energy consumption, as demonstrated by simulation results. These tendencies have recently been detailed in several optimization techniques, a summary of which is provided in Table 2.

Table 2 Comparative Study Various Methods

	Fuzzy	ANN	GA
Performance in transient state	High	High	High
Torque and flow ripple	Very low	Very low	Medium
Switching frequency	Constant	Constant	Constant
Parameter sensitivity	Insensitive	Insensitive	Insensitive
Dynamic response of torque	Very fast	Very fast	Very fast
Harmonic distortion of the current	Low distortion	Low distortion	Low distortion
Complexity of the algorithm	More complex	More complex	Complex

A comparison of metaheuristic algorithms based on various factors, including computational complexity, convergence speed, robustness, and solution accuracy is made. Among these algorithms, the Jellyfish Optimization (JFO) technique stands out as the most effective. Its superior performance can be attributed to its balanced exploration and exploitation mechanisms, which prevent premature convergence while ensuring a comprehensive search of the solution space. Additionally, JFO adapts dynamically to the optimization landscape, making it particularly suitable for complex, nonlinear problems like torque ripple minimization in PMSMs. This adaptability and efficiency position JFO as a preferred choice for achieving optimal results in demanding applications such as electric vehicles.

4.1. Jellyfish Optimization Technique

The Jellyfish Algorithm (JA) is an optimization technique based on swarm intelligence, drawing inspiration from the motion of jellyfish. Introduced by Wang and Guo in 2014, it serves as a fresh method for addressing intricate optimization challenges. This algorithm follows the movement patterns of a jellyfish swarm, which is made up of individuals that work together to find food and evade threats. In JA, the jellyfish swarm is represented just like a collection of entities, every single entity describing a potential solution for a given optimization problem. The jellyfish's mobility is governed by a system of behavioral norms that include food attraction, predator avoidance, and swarm alignment. These guidelines are turned into mathematical functions that update the position and velocity of the entire population. The Jellyfish Algorithm (JA) offers numerous benefits compared to other optimization techniques, such as its capability to manage multiple objectives and constraints, its rapid convergence speed, and its resilience against noise and uncertainties. It has been effectively utilized in a variety of practical optimization challenges, highlighting image segmentation, feature selection, and power system optimization. Jellyfish inhabit ocean depths beneath surface levels across all continents. They are bell-shaped and vary in size from under a centimeter in diameter to significantly larger. Each distinct species shows unique adaptations to the marine environment. These animals can almost appear any place in the ocean due to a process that synchronizes each jellyfish's movements with surrounding tidal currents, leading to the formation of jellyfish blooms. A jellyfish would identify the best location by evaluating the availability of food as it fluctuates in different areas. Consequently, a novel approach is developed, inspired by the foraging and swimming patterns of jellyfish in the ocean. The following sections will provide a theoretical analysis of jellyfish behaviour and movement. Subsequently, an optimization technique based on a numerical model will be introduced.

Conclusion

The Jellyfish Optimization technique presents a promising approach for reducing torque ripple in Permanent Magnet Synchronous Motors designed to apply for EVs. The implementation of this technique not only minimizes torque fluctuations but also improves efficiency and overall operational stability of the PMSM. This innovative optimization method, inspired by the natural foraging behaviour of jellyfish, not only effectively reduces torque fluctuations but also contributes to enhanced motor efficiency and operational reliability. By optimizing the design parameters and control strategies, this technique facilitates improved torque consistency, resulting in a smoother driving experience and increased vehicle performance. As the EV market continues to evolve, the application of such bio-inspired methodologies will be crucial in meeting the demands for higher efficiency and performance. Future work can focus on using Deep Learning (DL)-based predictive control and Reinforcement Learning (RL)-based Field-Oriented Control (FOC) to further improve motor control. Combining AI with optimization techniques and using hardware-in-the-loop (HIL) testing can make the system more efficient, reliable, and suitable for real-world mobility applications.

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