IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 14 August 2024, accepted 20 August 2024, date of publication 26 August 2024, date of current version 5 September 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3450199

TOPICAL REVIEW

Speed Control Techniques for Permanent Magnet Synchronous Motors in Electric Vehicle Applications Toward Sustainable Energy Mobility: A Review

MEHDI MONADI[1], (Member, IEEE), MOHAMMAD NABIPOUR[1], FATEMEH AKBARI-BEHBAHANI[1], AND EDRIS POURESMAEIL[2], (Senior Member, IEEE)

[1]Department of Electrical Engineering, Faculty of Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Khoozestan 6135783151, Iran
[2]Department of Electrical Engineering and Automation, Aalto University, 00076 Espoo, Finland

Corresponding author: Edris Pouresmaeil (edris.pouresmaeil@aalto.fi)

ABSTRACT Electrical vehicles (EVs) play a crucial role in reducing greenhouse gas emissions and promoting environmental sustainability. To achieve stable, reliable, and satisfactory performance, these vehicles must be equipped with appropriate motor drives and control systems. Although various motors such as DC and AC induction motors can be used in EVs, the choice of motor should be based on operational features. Permanent Magnet Synchronous Motors (PMSMs) provide superior performance compared to other conventional motors used in early EV models, making them a desirable choice for EV drives. However, PMSMs require efficient drive systems and proper control schemes to ensure fast dynamic response, immunity to parameter changes, and disturbances. The choice of control method is a critical factor in enhancing motor efficiency, extending battery life, and increasing driving range. This review provides a comprehensive overview of the various speed control methods used for PMSM drives in EVs, offering insights into the key challenges and opportunities in this rapidly evolving field.

INDEX TERMS Motor drives, electrical vehicles (EVs), sustainable energy mobility, control system, power electronics.

I. INTRODUCTION

The transportation industry is a major contributor to the issue of global warming [1]. In order to achieve emission reduction targets, it is imperative to focus on the transportation sector and adopt clean transportation technologies [2]. Electric vehicles (EVs) play a crucial role in reducing greenhouse gas emissions and preserving environmental sustainability [3]. These ''zero-pollution'' vehicles offer a solution to the environmental problems caused by fossil fuel vehicles and are seen as the vehicles of the future due to their potential to mitigate rising fuel costs and air pollution [4]. To meet this future demand, EVs must be equipped with appropriate motor drive and control systems for stable, reliable, and efficient performance at various speeds. The choice of motor, such as DC or AC induction, should be based on operational characteristics.

The Permanent Magnet Synchronous Motor (PMSM) drives are widely used in a range of industrial and public applications, such as high-speed urban trains [5], and EVs [6], [7], [8]. The popularity of PMSMs is due to their high power and torque density, high efficiency, good dynamic performance, wide speed range, and simple structure [9], [10], [11]. Additionally, PMSMs are smaller, lighter, and have a high-power factor compared to other conventional motor drives [12], [13]. This, along with their superior torque-speed characteristics and quiet operation, makes PMSMs ideal for use in EVs and a preferred choice over the early DC motor drives [3].

The associate editor coordinating the review of this manuscript and approving it for publication was Nagesh Prabhu.

The PMSMs require an appropriate drive system and control scheme to achieve fast dynamic response and immunity to parameter changes and disturbances [12]. The modern variable speed drives used in EVs, pumps, fans, and air conditioners are powered by power electronics-based inverters. Voltage source inverters (VSIs) are commonly used in adjustable speed drives, and various control strategies have been proposed for them [10]. The two-level VSI, commonly used in low-power applications, has the advantage of suppressing switching harmonics and limiting circulating current [13]. This topology is also employed in the PMSM drives used in EVs [10]. The VSI connects the battery of the EV to the PMSM and modulates the three-phase current waveforms driving the PMSM motor [14]. Fig. 1 shows a two-level VSI converting DC voltage from the battery to three-phase AC voltage by modulating sinusoidal waveforms [14], [15].

The most widely used switching method to control power electronics-based drives is Pulse Width Modulation (PWM) [12]. The selection of unsuitable switching method may cause additional torque ripple and mechanical stress to the EV motor [16]. Thus, modern electrical drives must have flexible and simple control schemes to generate the required PWM signals. The control method is crucial for improving motor efficiency, extending battery life, and increasing driving range [1]. A suitable control method for adjustable speed drives can also reduce energy loss and improve EV efficiency [17].

Speed control methods for PMSMs can be broadly classified into conventional methods and artificial-intelligence (AI)-based methods. Conventional methods control PMSM through separate current and speed loops, each with its own controller. This control method is favored for its simple design, ease of implementation, and satisfactory behavior in normal operating conditions. Conventional methods include input-output feedback linearization (IOFL), model predictive control (MPC), and various types of sliding mode control (SMC). AI-based speed control methods for PMSMs include various artificial neural network (ANN) methods, including online and offline trained methods, fuzzy-based controllers, and hybrid methods. A comprehensive review of these methods will be presented in the next sections.

It is also noted that, in addition to the need to select and implement the effective control methods for PMSMs that are used in EV applications, other issues that may impact the performance of the speed controller and consequently degrade the EV comfort should also be considered when EV motor drives are designed. In this regard, the presence of the parasitic torque ripple, which cause periodic speed oscillations and mechanical vibrations, should also be known and investigated. Therefore, methods presented to realize the smooth speed control for PMSMs, by use of torque ripple reduction algorithms, are also summarized in this paper.

The rest of the paper is organized as follows: Section II introduces the construction and dynamic model of the PMSMs to facilitate understanding of the reviewed methods in the subsequent sections. Section III focuses on the conventional speed control methods for PMSMs, while Section IV provides an overview of the AI-based control schemes. Both sections compare and summarize the characteristics of the methods introduced in the respective sections using tables. Section V compares and discusses all the reviewed speed control methods. Section VI highlights the control methods presented for reducing the harmful effects of the torque ripple and current harmonics on the PMSM performance and speed control, due to their significance. Finally, the conclusions are summarized in Section VII.

II. PERMANENT MAGNET SYNCHRONOUS MOTOR

A. PMSM CONSTRUCTION

The synchronous motor is an AC electric motor that features an AC armature winding on the stator and a DC excitation component on the rotor. The three-phase balanced source powering the stator creates a variable flux in the motor air gap, rotating at a synchronous speed that depends on the supply frequency and pole number. The DC source powering the rotor generates a fixed magnetic flux, resulting in mechanical torque from the interaction of rotor and stator fluxes. The rotor rotates at a constant synchronous speed, unaffected by changes in the mechanical load. The stator windings can either be concentrated or distributed, with the latter requiring more copper but reducing current harmonics. The rotor can be constructed with excitation windings or permanent magnets, the latter being lighter and smaller and producing a fixed magnetic flux. These are referred to as wound rotor synchronous motor (WRSM) and permanent magnet synchronous motor, respectively [18].

PMSMs can have either salient or non-salient pole rotors, with magnetic flux being uniform over the air-gap in the non-salient type and concentrated along the poles in the salient type. PMSMs can further be classified into axial flux and radial flux based on the direction of the magnetic flux, where the rotor flux is in the same direction as the rotor axis in axial flux and perpendicular to the rotor axis in radial flux [19].

B. PMSM DYNAMIC MODEL

To understand the transient behavior of PMSMs, it is beneficial to convert all of their electrical parameters to the *d-q* reference frame. This simplifies the analysis of the motor. Fig. 2 illustrates the vector diagram of the PMSM fluxes in the *d-q* reference frame, which rotates at the synchronous speed. As shown in Fig. 2, the voltage equations of the PMSMs in the rotating *d-q* frame are presented as [19]:

$$v_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} - \omega_r \lambda_{qs} \tag{1}$$

$$v_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} + \omega_r \lambda_{ds} \tag{2}$$

where v_{ds}, v_{qs}, $\mathrm{i_{ds}}$, $\mathrm{i_{qs}}$, λ_{ds} and λ_{qs} represent the voltages, currents, and magnetic fluxes of the stator in the *d-q* axis, respectively. R_s is the stator resistance and ω_r is the motor speed, equal to the synchronous speed. Additionally, the flux-current relationships are expressed as:

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \quad (3)$$
$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \quad (4)$$

where L_s and L_m represent the self-inductance of the stator and the mutual inductance, respectively.

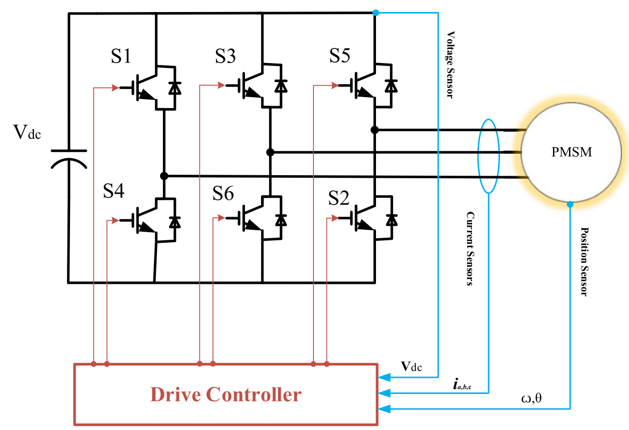

FIGURE 1. The structure of voltage source inverter fed PMSM drive [11].

The self-inductances of the d and q axis, L_d and L_q, are not always equal to Ls due to the salient pole construction of the rotor. As a result, the linkage fluxes of the d and q axis are described as follows:

$$\lambda_{ds} = L_d i_{ds} + \lambda_r \quad (5)$$
$$\lambda_{qs} = L_q i_{qs} \quad (6)$$

where, λ_r is the permanent magnet excitation of the rotor. This value is assumed to be constant and modeled as a current source, i_f, with a generated current that is zero along the q axis. The matrix form of the equations can then be expressed as follows:

$$\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = \begin{bmatrix} R_d + pL_d & -\omega_r L_q \\ \omega_r L_d & R_q + pL_q \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_r L_m i_f \end{bmatrix} \quad (7)$$

It's important to note that in (7), p represents the derivative operator ($\frac{d}{dt}$). Fig 3 illustrates the equivalent circuit of the PMSM in the d-q frame, which is generated based on equation (7). The electrical torque of the motor, on the other hand, can be expressed as:

$$T_e = \frac{3}{2}\frac{P}{2}\left\{\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}\right\} \quad (8)$$

where, P represents the number of poles.

III. CONVENTIONAL CONTROL METHODS

The conventional vector control method for PMSM drives involves the use of two loops for speed control: an inner current loop and an outer speed loop. Separate controllers are used to track each loop, and linear control is the most widely used approach due to its simplicity, ease of implementation, and favorable behavior under normal conditions [21], [22],

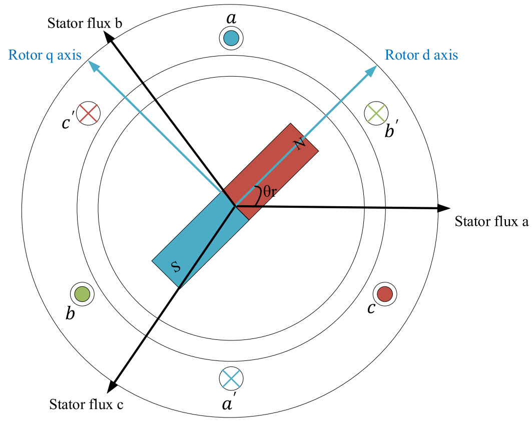

FIGURE 2. The schematic diagram of a PMSM [20].

[23]. However, when used as the main controller in a PMSM drive, its static zeros and poles can cause deviations from desired performance when the drive is subjected to uncertainties, nonlinearities, or external disturbances [24]. These deviations result in a lack of fast response, accuracy, and robustness to perturbations.

In the following sections, various conventional control methods that are used for the speed control of PMSMs are reviewed and compare.

A. INPUT OUTPUT FEEDBACK LINEARIZATION

In control systems, linearization methods are often necessary for the implementation of linear methods. The Input-Output Feedback Linearization (IOFL) is a popular alternative for linear approaches in nonlinear and perturbed environments. The goal of IOFL is to simplify the nonlinear dynamics of the plant to linear dynamics, allowing designers to use linear methods to control nonlinear systems. In [25], the IOFL approach was used to control the speed of a PMSM drive, with positive results compared to a fuzzy tuned PID method. The IOFL method was based on the assumption of a frictionless environment and only focused on tracking the reference speed command, ignoring external disturbances.

Variations in the system model or using an inaccurate model can result in deviation from the desired behavior of the controlled plant. To improve the control performance, researchers have suggested combining IOFL with robust approaches such as SMC. A hybrid adaptive IOFL-SMC speed control scheme was presented in [26], in which the IOFL approach was used as the current control loop controller and the nonlinear SMC approach was utilized as the supervising controller to handle disturbances. The simulation results showed that the overall system was stable and the reference signal was tracked with the minimal error, even in the presence of numerous disturbances.

Another speed control implementation using the IOFL scheme is described in [27], with its topology depicted in Fig. 4. Like [26], the authors utilized the hybrid

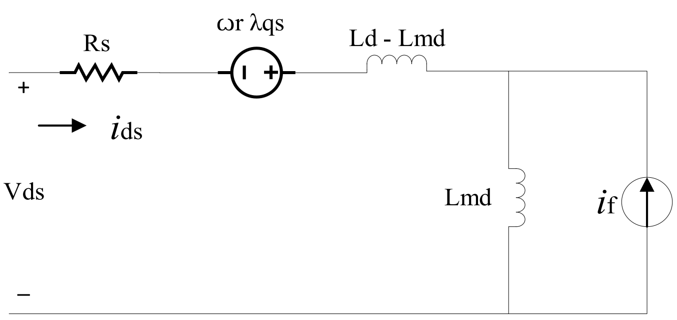

FIGURE 3. The equivalent circuit of a PMSM in the *d-q* frame.

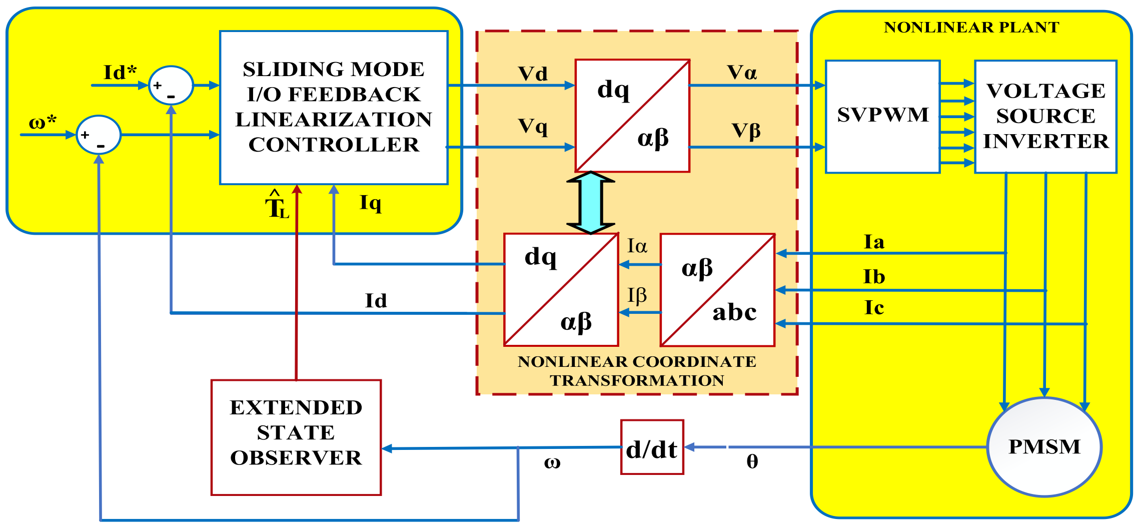

FIGURE 4. Control block diagram of PMSM drive using sliding mode input-output feed-back linearization with extended state observer [27].

IOFL-SMC method with a multi-loop control structure. Through the application of Lyapunov's stability theorem, the authors compared conventional IOFL with the proposed IOFL-SMC. The simulation results clearly demonstrate the superiority of the proposed scheme in addressing unmodeled dynamics, perturbations, and nonlinearities over the conventional IOFL.

One scheme presented in [28] involves using a feedback linearization approach to control two parallel PMSMs with one inverter (MID-PMSM). However, this scheme faces challenges such as unbalanced load torque, system nonlinearity, and coupling between the transient behaviors of the two machines, which may affect the controller performance. The approach involves linearizing the plant through order reduction, applying state feedback linearization to the reduced-order plant based on the LTI state space model, and using a state feedback controller with an integrator to separately compensate for the PMSM load torques. This method offers a closed-loop control solution and stability improvement technique for both PMSMs, even when connected to different loads simultaneously.

B. MODEL PREDICTIVE CONTROL

Model predictive control (MPC) is another widely used approach in dynamic system control. It involves generating the best control signal based on the available dynamic model of the system and by predicting its behavior in the next time step, in order to minimize a specific function [29]. MPC has several advantages such as the ability to control multivariable systems [30], good dynamic performance, and the capability to handle constraints and uncertainties [31]. As a result, MPC has been applied in various fields, including trajectory tracking [32], fuel cells [33], UAV control [34], EVs [35], and electrical drive systems [36]. There have also been efforts to implement MPC in PMSM drive control [31], [37], [38]. In one of these efforts, the researchers studied the use of MPC for automotive traction using a PMSM drive [37]. The controller designer must consider handling limitations, and the authors employed MPC control and cascade design of control loops to address this challenge. Additionally, a single-step window MPC was used to implement the proposed scheme, considering the dynamics of the inner loops, and an observer was utilized to minimize model dependence. The

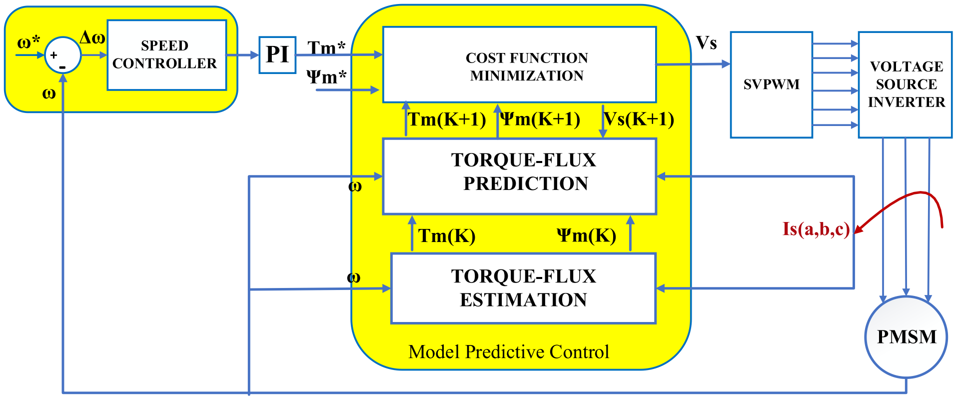

FIGURE 5. The block diagram of a PMSM drive working based on the MPC method [39], [40].

proposed scheme showed desirable tracking performance in its implementation.

Another effort to use MPC as the speed controller for a PMSM drive was presented in [38]. The researchers explored the feasibility of using MPC to control such systems, given their complexity and limitations in the under-controlled plant. To address the dependence of MPC on the plant structure, a parameter estimation method based on stability examinations was proposed. The method involves using an observer to estimate the states and selecting optimal gains. The multi-objective capability of MPC was utilized to achieve suitable control of various states under different conditions. The effectiveness of the proposed approach in controlling the PMSM drive was validated through experimental implementation.

In [31], MPC's multi-objective capabilities were utilized to achieve improved prediction, reduced model dependence, reduced construction cost, and reduced torque transient oscillations. The authors proposed adding torque-related terms to system dynamics and implementing a torque observer in the control loop, which was validated through simulation and demonstrated its effectiveness in maintaining desired PMSM drive performance.

Model dependence remains a key challenge in MPC-based control design. Additionally, MPC schemes face issues with guaranteeing stability under various operating conditions, high computational demands, and high implementation costs. Accordingly, an indirect reference-vector-based MPC is proposed in [41] to enhance MPC performance. The dynamic performance of the motor is improved through equal time-interval division and use of discrete space vector modulation, reducing current and torque ripples. The method uses a cost function based on motor current to obtain appropriate prediction vectors, and reducing calculation demands. The reference vectors are controlled by a bang-bang comparator. On the other hand, error in parameter estimation in classic MPC is known as a challenge in MPC implementation that reduces the accuracy of this control methods. To enhance the robustness of the MPC, and hence improve the controller performance, a virtual-vector MPC was presented in [42]. In this method, the negative effects of the errors in motor parameter estimation are suppressed; therefore, the motor can be used in various applications, including EVs. Moreover, in [43] an adaptive parameter observer is used in parallel with a sliding mode observer. This hybrid observer, reduce the dependency of the MPC to the model parameters and improves the MPC performance under parameter uncertainty.

MPC is also applied in applications where precise torque control is critical. Fig. 5 shows an MPC-based control scheme using the maximum torque per ampere (MTPA) method [39]. The cost function incorporates torque ripple reduction, current error reduction, switching frequency reduction, and current limitation, with empirical weighting factors for torque error and current limit violation. This reduces current harmonics and results in less torque and flux ripple. Another MPC approach, the finite set MPC with constant switching frequency (CSF), is presented in [40] and can be combined with PWM modulation. The cost function evaluations are performed based on the VSI's discrete nature and finite switching states, with the switching state having the minimum cost function being selected as the next control action. The MPC-CSF implementation on an FPGA chip offers effective cost function optimization with acceptable performance.

C. SLIDING MODE CONTROL

Variable structure control, particularly sliding mode control, is a promising alternative to conventional control methods. The SMC is known for its simple and low-cost implementation, robustness to disturbances, and fast response. The variable structure nature of SMC allows for guaranteed stability in a wide range of operating conditions with proper gain adjustments [44], [45]. As a result, SMC has been widely used as the speed controller for PMSM drives in industrial environments [46], [47], [48], [49], [50]. In [46], the authors proposed a hybrid controller combining SMC and IOFL to regulate the PMSM drive's speed. The single-loop control

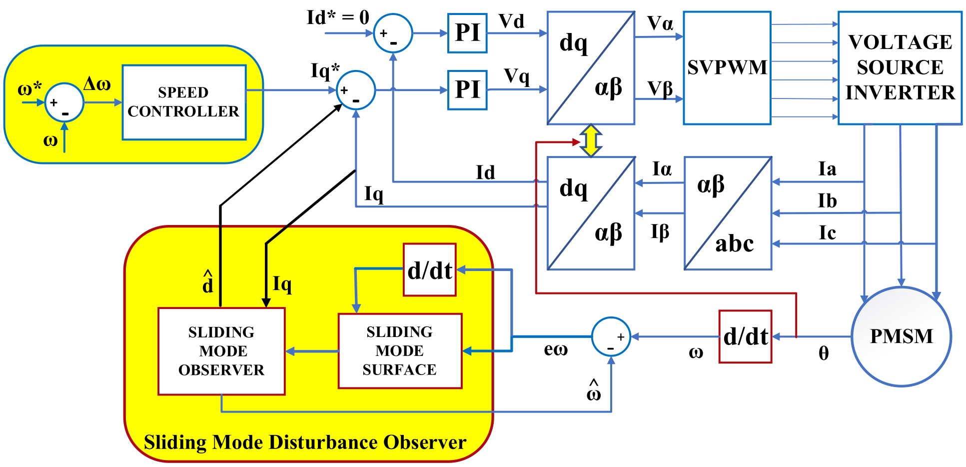

FIGURE 6. The control block diagram of a PMSM drive using a sliding mode disturbance observer [51].

of speed-current improved the controller's response speed, and the observer was used to minimize chattering's impact on drive performance. The results showed improved tracking performance with the proposed scheme and observer.

In [47], Cheema et al. explored the simultaneous control of speed and thrust in a linear PMSM. They employed a nonlinear dynamic model and integral type SMC to produce proper control signals and minimize steady-state error. To enhance reliability and accuracy while reducing implementation costs, observers were also utilized. The stability of the overall system was proven using Lyapunov's theory, demonstrating the effectiveness of the scheme in reducing tracking error in the presence of disturbances.

Fig. 6 depicts the general structure of SMC-based controllers for PMSM drives [51]. The SMC-based method presented in [51] aims to control the speed of PMSM by using a sliding mode observer (SMDO). Generally, sliding mode observers are efficient tools used for estimating the states of dynamic systems and improving the performance of control systems. On the other hand, in industrial applications, PMSM drives are usually faced with various external disturbances that reduce the effectiveness and the accuracy of the speed control loop of the drive systems. Accordingly, the SMDO is added to the control system of Fig. 6 to estimate the external load disturbance, and apply a corresponding compensation term to the output of the speed controller. Indeed, the SMDO offers a real-time estimation of load disturbance, and reduces the effects of this external disturbance on the dynamic performance of the speed controller. In this observer, the estimated load disturbance ($\hat{d}$) as well as the estimated motor speed ($\hat{\omega}$) are calculated based on equation (8).

$$\begin{bmatrix} \dot{\hat{d}} \\ \dot{\hat{\omega}} \end{bmatrix} = \begin{bmatrix} -\frac{B}{J} & -\frac{1}{J} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{d} \\ \hat{\omega} \end{bmatrix} + \begin{bmatrix} \frac{1}{J} \\ 0 \end{bmatrix} T_e + \begin{bmatrix} 1 \\ l \end{bmatrix} \mu(e_\omega) \quad (9)$$

where B is friction coefficient, J is moment of inertia, T_e is the electromagnetic torque, l is the observer gain, $\mu(e_\omega)$ is the sliding mode control function, and e_ω is the speed observation error.

By use of this well-designed SMDO unit advantages such as fast dynamic responses, disturbance rejection, and strong robustness are achieved for the PMSM drive controller.

On the other hand, although the SMCs are typically used for speed regulation in PMSM applications, these types of controllers can also be used to obtain accurate position control. For example, in [49] an integrated sliding mode control (ISMC) is introduced to regulate both speed and position of the PMSMs. Indeed, the presented approach simultaneously tracks the speed and position references, and minimizes the tracking errors by use of a differential evolution (DE) algorithm. In this method, the DE optimization method is used to find the optimal control gains. Compared to other optimization methods, the DE algorithm, which is a simple and robust optimization method, needs less calculations and time to determine the optimized values of the controller gains. Therefore, the approach improved PMSM performance and addressed two challenges of SMC design: convergence to the sliding surface and minimizing chattering.

Chattering phenomena; however, is the key issue in the applications of SMCs because this phenomenon may cause mechanical wear in the PMSMs. Therefore, various methods are presented to mitigate this phenomenon. For example, an observer-based sliding mode control was presented in [52] to be used in the speed control on the PMSMs. In this method, a novel reaching law was used for chattering attenuation in which the law is adjusted by a hyperbolic tangent function of the sliding variable. By use of this method, unlike the existing auto-tuning power rate reaching law, a guaranteed reaching time is achieved which is not dependent on the initial conditions.

1) SUPER-TWISTING SLIDING MODE CONTROL

In addition to the chattering phenomena, slow time convergence is another main issue related to implementation of the classical SMCs. Using high-order SMC methods is effective to overcome this issue; in this method a discontinues function is added onto the integral term of the SMC. Super-twisting algorithm (STA) is a well-known high-order SMC used in various applications [53]. Moreover, the variable gains super-twisting sliding mode (VGSTSM) control proposed in [54] is insensitive to external disturbances because the super-twisting gains are adopted according to the system states and online bounds of the perturbations. This method, however, needs large switching gains [55]. Due to their advantages, the STA-based methods were improved and used in [55] and [56] to control the speed of PMSMs.

In [55], a terminal term was introduced into the super-twisting SMC; hence, an improved super-twisting SMC (ISTSMC) was introduced to enhance the convergence speed, dynamic performance, and switching gains. The method also uses a time-varying two-time scale disturbance observer (TV-TTSDO) to estimate the system disturbances, including PMSM parameter uncertainty and load varying, and increase the system robustness by providing compensation signals. The control scheme of [55] consist of a single-loop controller and ISTSMC; therefore, it provides a simple structure, in compare with the conventional cascade control structure, that its implementation does not increase difficulties in the practical applications. Another type of super-twisting SMC was introduced in [53] in which, similar to [55], controller gains are adjusted according to the system states to enhance the transient response and reduce the chattering. However, in the control strategy of [53], the presented adaptive gain STA block is put on both speed and current control loops. In addition, the method of [53] is equipped with a filtered high-gain observer to not only estimate the lumped disturbances but also reduce the effects of measurement noises on the performance of the controllers.

Although the method presented in [55] uses the proper sensors for determining the rotor speed/position, sensorless controllers are also used in the PMSM drives. In the model-based sensorless control methods, that are used for rotor position/speed estimation of PMSMs, an observer is used to estimate the back-EMF of the motor, and extract the rotor position and speed information by use of a phase-looked loop (PLL). In this regard, the sliding mode observers (SMOs) based sensorless control methods are suggested due to their robustness for parameter variation and simple implementation. However, as mentioned before, the inherent chattering of the classic SMOs will affect the accuracy of the rotor position/speed estimation. To address this issue, an adaptive super-twisting algorithm for the back-EMF estimation was presented in [56], which employs linear terms and adaptive laws for the SMC. According to the rotor speed, the IAST algorithm adjusts the observer gains to enhance the estimation accuracy in a wide range of motor speed. It is noted that, in implementation of the sensorless-based-observers, the high-frequency noises of the back-EMF should be eliminated. Moreover, a PLL is needed to obtain the rotor position. Low pass filters (LPFs) can eliminate the high-frequency noises; however, they may reduce the estimation accuracy by adding the phase delay. Accordingly, in [56], an improved super-twisting quadrature signal generator (IST-QSG) was designed and used instead of the LPFs. Using the presented IST-QSG, which works as the front stage of the PLL, the fundamental frequency signal is extracted without phase delay and speed feedback estimation issues.

2) TERMINAL SLIDING MODE CONTROL

An important weakness of the classic SMC is slow convergence time [A5]; however, in the terminal sliding mode, a non-linear term is introduced to the sliding surface of the SMC to achieve fast and finite time convergence [50]. Accordingly, another weakness of classical SMC can be solved by the use of well-designed terminal sliding mode (TSM) control methods.

The authors in [57] propose a discrete compound integral terminal sliding mode control (C-ITSMC) technique to control the speed of PMSM. This approach combines ITSMC, extended state observer (ESO), and predictive control. Disturbances caused by uncertain parameters, non-ideal conditions, and external factors are treated as a lumped disturbance and estimated by the ESO. To overcome the chattering, a lower switching gain is employed while maintaining robustness in the system. Predictive control is utilized to generate optimized control signals by improving the transient response and reducing the tracking error.

A PMSM drive's speed control in the presence of structural disturbances has been improved using a cascade control structure and a sliding mode observer in [48]. The authors extracted a system model and used the cascade control structure to generate control signals, and reported that the SMO has reduced chattering. The proposed scheme was compared to conventional linear approaches and showed better disturbance rejection.

When a system is suffered from severe parameter uncertainty and external disturbances, model-based control methods cannot provide required robustness and model-free controllers are more applicable. Therefore, in [58], a model-free TSM controller was presented to gain an effective control for the PMSMs. This method, moreover, uses a fast TSM-based observer to improve the dynamic performance of the controller and limit the effects of the phase delay seen in the SMC-based methods. Indeed, the control strategy of [58] combines a model-free controller and fast integral TSM method to establish a fast and anti-disturbance control method and reduce the torque ripple without requiring to know the precise model of the PMSM.

The performance of the discussed controllers is shown in Table 1.

IV. ARTIFICIAL-NETWORKS-BASED METHODS

AI approaches were considered as alternatives to conventional linear and variable structure schemes due to their flexibility, reliability, and robustness against disturbances [59].

TABLE 1. Conventional control approaches for PMSM drives.

	Author/s	Publishing date	Remarks
IOFL	Fazeli et.al	2008	✓ Control using a hybrid IOFL-SMC in a multi-loop formation ✓ IOFL is used as the base and linearizing controller, and SMC as the supervising approach to guarantee robustness
	Wang et.al	2013	✓ Cascade control of current and speed by a hybrid IOFL-SMC with Lyapunov's stability examinations
	Izad and Ghanbari	2015	✓ Speed control of a PMSM drive in an ideal environment with no disturbances ✓ No stability check
MPC	Formentini et.al	2015	✓ Multi-objective MPC speed and state controller with examined stability and state observer
	Carpiuc and Lazar	2016	✓ MPC speed controller with cascade loops ✓ Minimized model dependence by observer
	Liu et.al	2019	✓ Simultaneous control of speed, torque oscillation, construction cost and etc. ✓ Torque term is added to multi-loop control formation with observers to guarantee stability
SMC	Cheema et.al	2017	✓ Simultaneous control of speed and thrust by an integral type SMC. ✓ Benefiting from observers and Lyapunov's theory to minimize chattering.
	Liu et.al	2018	✓ PMSM speed controller based on terminal type SMC ✓ A combination of SMC and IOFL in a single loop formation to control speed and currents. ✓ Minimized chattering by estimated disturbances.
	Zhao et.al	2019	✓ PMSM speed control in presence of structural disturbances based on an extracted system model ✓ Cascade control structure and an SMO used to reduce chattering.
	Zhang et.al	2021	✓ Enhancing the convergence time ✓ increase the system robustness by providing compensation signals ✓ simple structure

AI control methods can be grouped into three categories: evolutionary algorithms, artificial neural networks (ANN), and fuzzy logic (FL). Evolutionary algorithms primarily serve tuning and optimization, while ANN and FL are considered individual control methods.

A. ANN-BASED METHODS

ANN is a leading AI method. It is modeled after the human brain and made up of parallel neural networks. The ANN processes signals to produce the desired control output. Its potential for training makes it capable of generating specific control outputs for particular inputs. ANN can also imitate the characteristics of a system by being trained on inputs and outputs of the plant it's controlling. During training, connections between neurons are established and the neural network structure is determined. Proper training enables ANN to model complex unknown plants, reducing the need for an accurate system model [60], [61]. ANN has proven successful in various applications such as classifications [62], pattern recognition [63], predictions [64], estimations [65], and control of PSMSs [66]. From a training perspective, ANNs can be classified as offline or online-trained [67], [68]. With regards to their dependence on the system model, ANNs can be divided into model-dependent and model-free approaches [69], [70]. In model-dependent ANNs, an accurate representation of the system being controlled is necessary. The data is fed to the plant and the ANN is trained to imitate the plant's behavior before the controller is implemented. The accuracy of the ANN is directly related to the quality of the training data. Examples of model-dependent ANN training can be found in [71] and [72].

1) OFFLINE TRAINED ANNs

ANNs have also been applied in PMSM speed control. In [37], the vector speed control of a PMSM drive was explored. The aim was to improve speed control performance compared to conventional methods by increasing control accuracy and optimizing control response, adaptability, and robustness against disturbances, and developing a practical platform. The ANN was trained based on general PMSM parameters and the control performance was improved by minimizing an approximate dynamic programming (ADP) cost function. Compared to linear schemes, the proposed ANN approach performed better in terms of response speed and quality, particularly in tracking tasks.

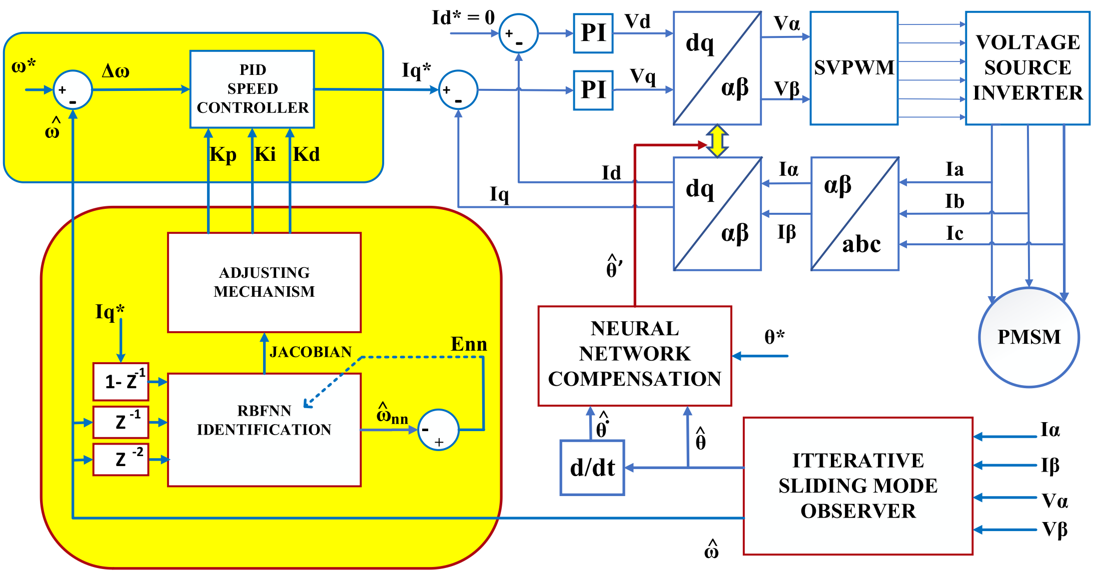

FIGURE 7. The control block diagram of a PMSM drive using the RBFNN-based self-tuning PI controller [77], [78].

In [73], the speed control of a spherical PMSM drive was investigated with the existing decoupling taken into consideration. The authors leveraged the adaptability of the ANN approach and built a prototype system using it. The uncertainties were estimated to reduce the impact of un-modeled dynamics, and the estimates were then incorporated into the main control loop as a feed-forward signal.

In studies similar to [74] and [75], researchers attempted to address the challenge of controlling the speed of a PMSM drive in the presence of decoupling. The authors of these papers set two main design objectives. The first objective was to generate an accurate model of the system to minimize decoupling effects, which was achieved by using accurate dynamic equations of the plant. The second objective was used to improve the robustness of the drive against un-modeled environmental disturbances. Due to the nonlinearities and couplings present in PMSM drive dynamics, the research results showed significant improvement in control performance with regards to robustness and quality of reference tracking.

In [76], the authors focused on the estimation application of ANN, using a Chebyshev type neural network as a disturbance estimator and presenting an observer based on neural network principles. They also proposed a hybrid neural network and backstepping approach which, despite its higher complexity, showed improved performance compared to standalone ANN and backstepping controllers. The hybrid approach was able to overcome the drawbacks of backstepping and filtering while preserving the advantages of both controllers. The proposed approach was evaluated in simulations, and the results showed acceptable performance in controlling the speed of the PMSM drive in the presence of disturbances and immeasurable states.

2) ONLINE TRAINED ANNs

In comparison to conventional AI methods, model-dependent approaches, which require offline training, often result in lower control precision. On the other hand, while online-trained, model-free ANNs improve control, they also come with an increased number of parameters that need tuning, leading to a higher computational burden. In contrast to the simple PID approach, which only requires tuning three parameters, model-free ANNs, as stated in [79], [80], and [81] require tuning ten parameters. Despite efforts to minimize training data and online tuning, dependence on system dynamics, time-consuming training, high computation demand, and expensive implementation remain major challenges in the controller design process.

Besides offline tuning, online adaptation of the ANN using gradient descent method is also implemented to minimize modeling errors and improve drive performance. The results show improvement in maintaining the desired output and evaluating the system based on factors such as response speed, tracking error, and other control factors. However, it should be noted that high computational power is necessary to train the neurons online at each sampling interval.

In [82], a combination of model-free and model-based approaches is presented as the main controller for a PMSM drive. The ANN is initially optimized using particle swarm optimization (PSO) to converge to an optimal structural solution, and then trained and tuned using the gradient descent method. The combination of PSO and gradient descent improves the ANN controller's convergence and performance. The authors evaluate the drive's response speed, tracking error, and other control factors to show the improvement in maintaining the desired output.

In [83], the impact of dynamic coupling terms in PMSM model with uncertain and time-variant parameters was addressed by using a radial basis function neural network (RBFNN). An adaptive decoupling controller (ADEC) based on Lyapunov stability theory was used in conjunction with the RBFNN to optimize the uncertain parameters. This approach resulted in a fast-response closed-loop torque control method, which prevented large fluctuations in torque and current over a wide range of speeds. The optimization of the uncertain parameters was carried out using the gradient descent method.

In [78], a sensorless PMSM drive scheme is presented using an RBFNN. The system employs an extended Kalman filter as a stochastic observer to estimate the system's state and RBFNN to self-tune PI controllers, as illustrated in Fig.7. The effectiveness of the algorithm is validated with an FPGA-based implementation. Similarly, in [77], RBFNN is used for PI self-tuning in a sensorless PMSM drive. The method employs a sliding mode observer with a phase locked loop to estimate the rotor's speed and position and a strategy to start the motor when the back-EMF signal is insufficient. The scheme is implemented with a digital signal processor and shows good tracking response and low current ripple.

B. FUZZY-BASED METHODS

Fuzzy logic (FL), a control approach based on human linguistic behavior, is considered as reliable and attractive among various AI methods due to its high efficiency, simple implementation, desirable dynamics and steady state characteristics, and low model dependence [84], [85], [86], [87]. It has been widely used in various fields such as electric drives [88], EV application [89], and power electronics [90].

The study in [91] combined Fuzzy and conventional control methods to enhance the performance of a PI controller. The inefficiency and inaccuracies of linear control when facing disturbances and nonlinearities were addressed by proposing a fuzzy-based method. The stability of the system was guaranteed using a dynamic model and tuning the gains with linear matrix inequality (LMI) and Lyapunov's theory. The controlled system was implemented and showed desirable performance under various torque variations. In [92], fuzzy logic was used to present an observer-based method that considered additional sources of disturbance such as friction, uncertain parameters, viscous force, and noise. The fuzzy controller was used for online tuning of PI parameters with suitable if-then rules.

In reference [93], a PMSM sensorless control strategy was presented based on a fuzzy sliding mode observer (FSMO) using a sigmoid function with adaptive coefficient adjustment to handle the nonlinearity and discontinuity of the SMO. This results in faster response, reduced chattering, and improved observation performance. An adaptive law was employed to improve the estimation of speed and position by reducing the error signal in the back-EMF of the motor. A tangent function PLL was also utilized to enhance the control loop performance during speed direction changes.

In [94], a fuzzy-based multi-variable optimization approach was proposed to improve the performance of PMSM drives in the face of uncertainty in motor parameters and load torque variations. The method describes motor parameters, such as the viscosity friction coefficient and moment of inertia, using fuzzy set theory instead of probability theory. A performance index, incorporating cost controls and steady-state performance, was defined using fuzzy uncertain parameters. A multi-variable optimization approach was then applied to find optimal parameters and ensure robust PMSM performance despite uncertainties.

1) HYBRID FUZZY CONTROLLERS

In [95], researchers turned to hybrid fuzzy controllers to take advantage of multiple control schemes and reduce their drawbacks. In [96], a hybrid approach was proposed to regulate the speed of a six-phase PMSM drive using a combination of NN, SMC, and backstepping controllers integrated with FL. The method started with a dynamic model of the problem, and a hybrid approach combining backstepping, SM, and nonlinear $H\infty$ was designed to address disturbances and nonlinearities. The authors then utilized a hybrid fuzzy-neural observer to estimate uncertainties, improve tracking performance, and reject disturbances, with the NN learning process being performed online to minimize the impact of uncertainties and disturbances. The proposed method was validated through simulation and experimental results.

In [97], a hybrid FL-neural-SMC approach is implemented to control both speed and current loops. The study prioritizes minimizing chattering during speed control, improving steady-state performance, and minimizing tracking errors. States and disturbances are estimated using an ESO and the desired control signal is generated in the current loop. Simulation results confirm the success of the proposed approach in achieving its design goals.

In [98], a hardware/software co-design approach using a PID-type fuzzy controller is presented to solve the uncertain parameter problem and load torque variation. The current control algorithm is implemented in hardware on an FPGA, while the speed control algorithm is implemented in software. In [99], a combination of fuzzy and PI controllers is presented to exploit the advantages of each controller in different conditions (shown in Fig. 8). The fuzzy controller is used in transient conditions and the PI controller in steady-state conditions to provide improved performance and less computational time. An optimal switching function is chosen by combining the fuzzy and PI outputs to generate the weights of the controllers.

2) ONLINE AND OFFLINE TUNING OF THE MFs

In fuzzy controllers, the membership function (MF) shapes and number are determined by the fuzzy rules. However, conventional fuzzy-based approaches have issues with handling

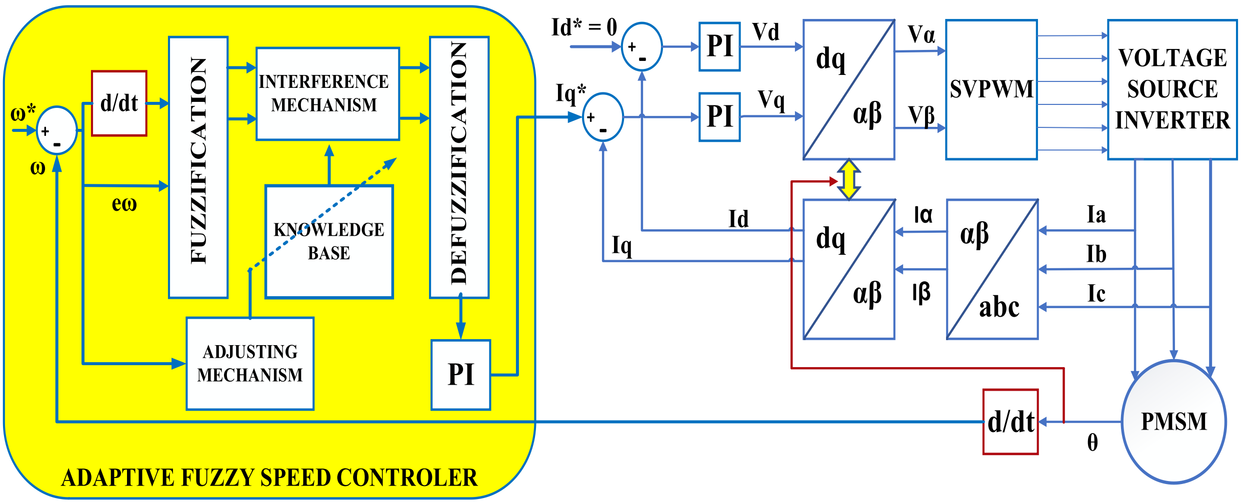

FIGURE 8. Block diagram of a PMSM drive using an adaptive fuzzy-based controller [98], [99].

rule uncertainties, especially for complex plants [100], [101]. To address this, tuning antecedent and consequent membership functions with offline evolutionary approaches has been suggested to minimize these drawbacks [100]. However, this approach can be time-consuming, require large amounts of training data, and have a heavy computation burden, and may also need regular tuning. Online adaptation of membership functions is a solution to improve FL performance [100], where antecedent membership functions are typically tuned offline using evolutionary algorithms or the designer's experience, while consequent membership functions are adapted in real-time using methods like Lyapunov's theory. These FL approaches are called self-tuned FLs. In [102], a comparison was made between the optimally-tuned conventional FL, linear controller, and self-tuned FL in controlling the speed of a PMSM drive. This study, similar to others found in references [103], [104], [105], presents a comprehensive comparison between various AI methods. The results showed that the self-adaptive fuzzy approach was superior in terms of accuracy, least tracking error, shortest offline training duration, simple structure, and simple input-output relations, compared to the other methods.

3) DIRECT AND INDIRECT FUZZY LOGIC

The implementation of FLs can be divided into two categories: direct fuzzy logic (DFL) and indirect fuzzy logic (IFL) [106], [107], [108]. In DFL, the control output is generated directly through the defuzzification process. There are various examples of implementing DFL in different fields, such as drilling [109], descriptor systems [110], maximum power point tracking (MPPT) [111], torque control [112], power electronics [113], and valve control [114].

In IFL control, the FL can serve as a solitary controller or be integrated with other control techniques in a hybrid setup. IFL is a popular choice in many fuzzy-based control schemes due to its versatility and effectiveness. The main use of IFL is to estimate unknown functions through global estimation theory [115]. Examples of IFL control implementations can be found in [91], [116], and [117].

In [116], an IFL control approach was employed in the speed controller of a PMSM drive to estimate unknown and un-modeled dynamics and uncertainties. The IFL approach was able to minimize approximation errors in inner speed and current loops, as demonstrated through comparison with conventional linear controllers. The proposed method was shown to have improved control characteristics and a simpler implementation than conventional linear approaches, as confirmed through both simulation and practical results.

In [117], a fuzzy-based speed controller was introduced that utilizes IFL as the base controller. The IFL approach in this method focuses on enhancing control robustness by tuning a repetitive control approach. The authors identified various disturbances that impact the PMSM drive's performance, and evaluated the proposed approach's ability to minimize these effects. The results from simulations and practical implementation showed that the proposed controller improved the robustness and disturbance rejection compared to conventional linear approaches.

V. COMPARISON AND DISCUSSION

The choice of an appropriate AI control approach between ANN and FL remains a challenge for control system designers. To address this challenge, various comparative studies have been conducted, including [102], [103], [104]. In [103], the authors compared the performance of ANN and FL in tracking applications using a robotic arm. They found that the tuned FL outperformed ANN in terms of tracking performance in various operational conditions. In [104], the authors concluded that the performance of ANN may deviate from expectations due to variations in the plant model and requires routine training of neurons. On the other hand, the tuned FL showed superior tracking performance,

TABLE 2. Control characteristics of PMSM drives.

	Linear	Predictive	SMC	ANN	Conv FL	Optimal FL	Adaptive FL
Advantages	✓ Easy Implementation ✓ Low computation burden	✓ Robust ✓ Fast convergence ✓ Multi-objective ✓ Low implementation cost	✓ Robust ✓ Fast convergence ✓ Good tracking with perturbation presence ✓ Low model dependence	✓ More efficient ✓ Fast convergence ✓ Good tracking with perturbation presence	✓ High robustness ✓ Low model dependence ✓ Fast response ✓ More efficient than ANN	✓ High robustness ✓ Low model dependence ✓ Fast respons ✓ More efficient than ANN	✓ Adaptive ✓ Minimum Initial tuning ✓ Minimum plant knowledge ✓ Fast response ✓ More efficient than ANN ✓ High robustness
Disadvantages	✓ Model dependent ✓ Periodic tuning ✓ Low reliability at presence of perturbation	✓ Periodic tuning ✓ Prior plant Knowledge ✓ heavy calculations	✓ Periodic tuning ✓ Prior plant ✓ Knowledge ✓ Chattering	✓ Periodic tuning ✓ Costly ✓ Prior plant knowledge ✓ Large set of data ✓ Complex ✓ High computation burden ✓ Implementation ✓ Low reliability at presence of perturbations	✓ Periodic tuning ✓ Costly ✓ Prior plant ✓ knowledge ✓ Complex implementation	✓ Periodic tuning ✓ Costly ✓ Prior plant ✓ knowledge ✓ Complex implementation ✓ heavy calculations	✓ Costly ✓ Complex

TABLE 3. Comparing reviewed control approaches.

	Linear	IOFL	Predictive	VSC	ANN	Conv FL	Optimal FL	Adaptive FL
Response speed	Slow	Fast	Fast	Fast	Fast	Fast	Very Fast	Very Fast
efficiency	Low	Good	Good	Good	High	High	High	Very High
Prior Training	no	no	no	no	yes	no	yes	no
Model Dependence	High	Very high	Very high	low	Very high	Medium	Low	low
Learning Capability	NO	No	no	yes	yes	no	no	yes
Hardware Complexity	Analogue-Digital	Digital	Digital	Digital	Digital	Digital	Digital	Digital
Software Complexity	Low	High	Very High	Medium	Medium	Medium	Very High	High
Overall Cost	Low	Medium	High	Medium	High	Medium	Medium	Medium

considering the effects of nonlinearities and disturbances, in terms of dynamics and steady-state characteristics. Table 2 [105] summarizes the characteristics of the reviewed control approaches.

The comparisons between various control methods for PSMS speed control are presented in Fig. 9 [59], [104], [105], [118]. Fig. 9(a) compares the response speeds of the reviewed methods, with the adaptive fuzzy and optimal fuzzy showing the highest response speeds, and other approaches having lower speeds. Fig. 9(b) ranks the controllers based on efficiency, with the adaptive FL approach ranking the highest. Model dependency and software complexity are compared in Fig. 9(c) and Fig. 9(d), respectively, with the adaptive FL and SMC showing the least model dependency, and the linear control approach having the lowest software complexity. The overall design cost comparisons are presented in Fig. 9(e), with the linear controller having the lowest design cost and the ANN and MPC approaches having the highest. Table 3 provides a summary of these results, including the added factors of "prior training," "hardware complexity," and "learning capability."

VI. SPEED RIPPLE CONTROL

The presence of the torque ripple is one of the main weakness of PMSMs that directly cause mechanical vibration, speed oscillations, and acoustic noise, especially when the motor speed is low [7], [119]. Torque ripple may cause more severe impact on the performance of the EV controllers, and reduce the car comfort [119]. Therefore, the drive of the PMSMs, used in the EV applications, should be equipped with proper control methods/ devices to reduce the effects of the mentioned torque ripple, and provide smooth speed control.

The torque ripple arises from cogging torque due to stator slots design, flux harmonics, and stator current harmonics.

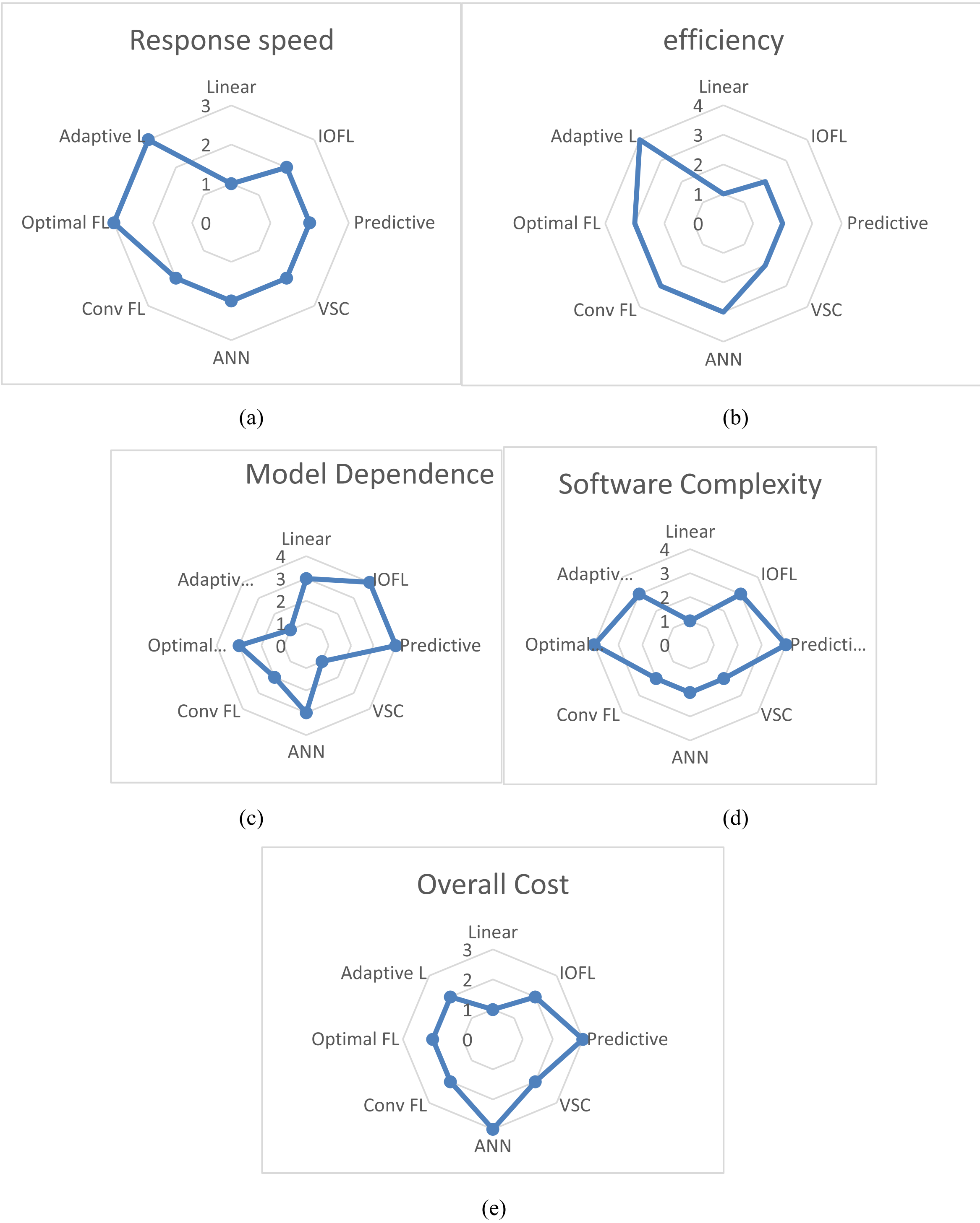

FIGURE 9. **Comparison of the reviewed control approaches: (a) response speed, (b) efficiency, (c) model dependence, (d) software complexity, and (e) overall cost.**

Machine design can reduce the cogging torque and permanent magnet contributions, but a control system is necessary to reduce the share of stator current harmonics.

Torque ripple reduction methods can be divided into feedback-based and feedforward-based methods [120]. In feedforward-based methods, an accurate model of torque ripple is crucial. However, this model is not always available, and changes in machine behavior due to core saturation, temperature changes, and parameter variations can make it difficult to provide such a model. Predictive control and AI-based control methods may face challenges in overcoming these issues [120]. In [121], a detailed model of torque ripple was presented that considered harmonics of rotor and stator flux, as well as harmonics of stator voltage and current. An adaptive filter using the least-mean-square algorithm was used to extract the desired harmonic, and an optimal harmonic current calculation was performed in the rotor reference frame to minimize stator losses. A harmonic current controller was also presented to control the magnitude of injecting harmonic currents. This method performs well for both steady-state and transient modes at a wide range of motor speeds, but its effectiveness is dependent on the accuracy of the model.

On the other hand, since the torque harmonic is directly proportional to the same order speed harmonic, speed harmonics can be used as the feedback control signal of the current controller. In [120], a FL-based current controller was presented that uses speed measurement and harmonic detection. The dominant cogging torque component is detected by measuring the speed harmonic of the same order, and this component is minimized by injecting the appropriate current harmonic. This reduces torque ripple efficiently, but requires accurate speed measurement, limiting its applications to steady-state mode or low-speed motors.

It is noted that, in most of harmonic-injection-based methods, the controller only adjusts the amplitude of the compensating harmonic, while phase compensation is not considered. This can lead the system to instability [119]. However, in the method presented in [119] both injected harmonic amplitude and phase are adjusted. Moreover, two PI controllers are used in this method to remove steady-state error.

The disturbance-observer-based methods are of other solutions for reducing the effects of harmonic disturbances. For example, in [122] an external harmonic state observer (EHSO) was presented to achieve an accurate and fast torque ripple estimation. This observer, moreover, adds compensation terms to the speed control loop of the PMSM. Indeed, in this method, disturbance estimation and compensation signal generation are done by the introduced EHSO. Another compensating technique for torque ripple reduction in the low-speed operation of the PMSMs is presented in [123]. In this method, a proper compensating signal is added to the q-axis current component of the conventional filed-oriented control (FOC) of the PMSM. Selecting a proper compensating term has a critical role on the effectiveness of this method; therefore, the q-axis current is modified according to the identified current disturbance and fed to the inner PI controller of the conventional FOC. Accordingly, the method can remove low-frequency disturbances without adding complexity to the control scheme.

As an alternative approach, the minimizing torque ripple method in [124] simplifies the controller design by utilizing two separate PI controllers for the magnitude and phase angle of the current, with another PI controller coordinating their operation. Additionally, a speed harmonic detector is employed to reduce torque ripple through harmonic injection. The authors also addressed the issue of power losses by implementing a harmonic controller that is based on optimal references and regulates the q-axis current while controlling the d-axis current.

Another application of speed harmonic measurement is maximizing the torque per ampere (MTPA), which is particularly useful for interior PMSMs. This strategy aims to maximize the output torque by determining the MTPA angle that minimizes copper losses. The direct calculation of MTPA angle using speed measurement is described in [125]. This method obtains the MTPA angle without considering machine parameters. A harmonic controller decouples the magnitude and phase controllers, and the speed harmonic's phase angle is detected for harmonic injection. This approach is fast, efficient, and effective for reducing copper losses. However, increasing iron losses at high speeds may compromise efficiency.

Finally, it is noted that, in some especial cases, the PWM-based switching methods that are used to control the switching of the drive inverter of the PMSM, may cause extra type of torque ripple not seen in general applications. Typically, the switching frequency of the drive inverter is significantly higher than the fundamental frequency. However, if in an especial application, the switching frequency was not high-enough, undesirable sideband harmonics may be generated due to the inverter switching [7]. These harmonics, in turn, add additional negative impact on the controller performance. To prevent this phenomenon, it is recommended to be sure that the high-enough switching frequency is always selected for the drive controller. For the cases that high frequency switching is not applicable, [7] suggest to use an additional sideband harmonic compensator in the speed control loop of the PMSM. Moreover, in this case, another observer is also needed to estimate the generated sideband harmonics. Indeed, in this case two separated observers and compensators are needed to be added to the control speed loop.

VII. CONCLUSION

In this paper, various control methods used for PMSM control were analyzed and presented. These methods, including conventional and AI-based approaches, are applicable for PMSM drives used in various applications, including EVs, which play a crucial role in the future green transportation system. Hence, this study's results are of great interest for EV manufacturers, engineers, and academics in the field of power electronics and drives. As seen in previous sections, fuzzy-based controllers provide the fastest response and better efficiency, while adaptive fuzzy controllers and SMC-based methods are less model dependent. On the other hand, conventional methods such as IOFL and MPC are highly model dependent. In terms of software complexity, the linear control approach has the lowest complexity, while MPC and fuzzy-based methods require more processing power.

REFERENCES

[1] T. Sutikno, N. R. N. Idris, and A. Jidin, "A review of direct torque control of induction motors for sustainable reliability and energy efficient drives," *Renew. Sustain. Energy Rev.*, vol. 32, pp. 548–558, Apr. 2014.

[2] M. Monadi, H. Farzin, M. R. Salehizadeh, and K. Rouzbehi, "Integrated control and monitoring of a smart charging station with a proposed data exchange protocol," *IET Renew. Power Gener.*, vol. 16, no. 3, pp. 532–546, Feb. 2022.

[3] C. Sain, A. Banerjee, and P. K. Biswas, *Control Strategies of Permanent Magnet Synchronous Motor Drive for Electric Vehicle*. Boca Raton, FL, USA: CRC Press, 2022.

[4] H. Farzin and M. Monadi, "Reliability enhancement of active distribution grids via emergency V2G programs: An analytical cost/worth evaluation framework," *Scientia Iranica. Trans. D, Comput. Sci. Eng., Elect.*, vol. 26, no. 6, pp. 3635–3645, 2019.

[5] X. Wang, Y. Luo, Y. Zhou, Y. Qin, and B. Qin, "Hybrid energy management strategy based on dynamic setting and coordinated control for urban rail train with PMSM," *IET Renew. Power Gener.*, vol. 15, no. 12, pp. 2740–2752, Sep. 2021.

[6] Y. Zhao, X. Liu, H. Yu, and J. Yu, "Model-free adaptive discrete-time integral terminal sliding mode control for PMSM drive system with disturbance observer," *IET Electric Power Appl.*, vol. 14, no. 10, pp. 1756–1765, Oct. 2020.

[7] Y. Lee, J. Gil, and W. Kim, "Velocity control for sideband harmonics compensation in permanent magnet synchronous motors with low switching frequency inverter," *IEEE Trans. Ind. Electron.*, vol. 68, no. 4, pp. 3434–3444, Apr. 2021.

[8] K. Kakouche, A. Oubelaid, S. Mezani, D. Rekioua, and T. Rekioua, "Different control techniques of permanent magnet synchronous motor with fuzzy logic for electric vehicles: Analysis, modelling, and comparison," *Energies*, vol. 16, no. 7, p. 3116, Mar. 2023. [Online]. Available: https://www.mdpi.com/1996-1073/16/7/3116

[9] M. S. Rafaq and J.-W. Jung, "A comprehensive review of state-of-the-art parameter estimation techniques for permanent magnet synchronous motors in wide speed range," *IEEE Trans. Ind. Informat.*, vol. 16, no. 7, pp. 4747–4758, Jul. 2020.

[10] C. Xia, X. Qiu, Z. Wang, and T. Shi, "Predictive torque control for voltage source inverter-permanent magnet synchronous motor based on equal torque effect," *IET Electric Power Appl.*, vol. 10, no. 3, pp. 208–216, Mar. 2016.

[11] F. Naseri, E. Schaltz, K. Lu, and E. Farjah, "Real-time open-switch fault diagnosis in automotive permanent magnet synchronous motor drives based on Kalman filter," *IET Power Electron.*, vol. 13, no. 12, pp. 2450–2460, Sep. 2020.

[12] J. Li, J. J. Yu, and Z. Chen, "A review of control strategies for permanent magnet synchronous motor used in electric vehicles," *Appl. Mech. Mater.*, vols. 321–324, pp. 1679–1685, Jun. 2013.

[13] R. Akhil, V. Mini, N. Mayadevi, and R. Harikumar, "Modified flux-weakening control for electric vehicle with PMSM drive," *IFAC-PapersOnLine*, vol. 53, no. 1, pp. 325–331, 2020.

[14] L. H. Opsahl, "Design and testing of voltage source inverter and motor control system for electric vehicle," M.S. thesis, NTNU, Trondheim, Norway, 2015.

[15] D. Wang, T. Yuan, X. Wang, X. Wang, and Y. Ni, "Performance improvement of servo control system driven by novel PMSM-DTC based on fixed sector division criterion," *Energies*, vol. 12, no. 11, p. 2154, Jun. 2019.

[16] M. Monadi, A. A. Astaraki, and P. C. Nia, "Analysis and comparison of SVPWM and SPWM methods used for indirect rotor flux-oriented control of EV applications," *J. Power Technol.*, vol. 104, no. 2, pp. 99–115, May 2024.

[17] C. M. F. S. Reza, M. D. Islam, and S. Mekhilef, "A review of reliable and energy efficient direct torque controlled induction motor drives," *Renew. Sustain. Energy Rev.*, vol. 37, pp. 919–932, Sep. 2014.

[18] B. Wu and M. Narimani, *High-Power Converters and AC Drives*. Hoboken, NJ, USA: Wiley IEEE Press, 2017.

[19] A. Balashanmugham and M. Maheswaran, "Permanent-magnet synchronous machine drives," Tech. Rep., 2019.

[20] M. De Soricellis and H. Rapp, "Current and voltage shaping method via modified d–q transformation for the torque ripple compensation in PMSMs," *J. Eng.*, vol. 2019, no. 17, pp. 3812–3817, Jun. 2019.

[21] S.-K. Kim, J.-S. Lee, and K.-B. Lee, "Self-tuning adaptive speed controller for permanent magnet synchronous motor," *IEEE Trans. Power Electron.*, vol. 32, no. 2, pp. 1493–1506, Feb. 2017.

[22] H.-W. Kim, S.-M. Park, S.-J. Kim, and J. Y. Choi, "Adaptive backstepping speed control for PMSM with mechanical parametric uncertainties," in *Proc. IEEE 25th Int. Symp. Ind. Electron. (ISIE)*, Jun. 2016, pp. 427–430.

[23] M. Morawiec, "The adaptive backstepping control of permanent magnet synchronous motor supplied by current source inverter," *IEEE Trans. Ind. Informat.*, vol. 9, no. 2, pp. 1047–1055, May 2013.

[24] H. H. Choi, E. K. Kim, D. Y. Yu, J. W. Jung, and T. H. Kim, "Precise PI speed control of permanent magnet synchronous motor with a simple learning feedforward compensation," *Electr. Eng.*, vol. 99, no. 1, pp. 133–139, Mar. 2017.

[25] S. Izad and M. Ghanbari, "Speed control of permanent magnet synchronous motor using feedback linearization method," *Indian J. Fundam. Appl. Life Sci.*, vol. 5, no. S1, pp. 3293–3298, 2015.

[26] S. M. Fazeli, H. A. Zarchi, J. Soltani, and H. W. Ping, "Adaptive sliding mode speed control of surface permanent magnet synchronous motor using input–output feedback linearization," in *Proc. Int. Conf. Electr. Mach. Syst.*, 2008, pp. 1375–1380.

[27] L. Wang, H. Zhang, and X. Liu, "Sliding mode variable structure I/O feedback linearization design for the speed control of PMSM with load torque observer," *Int. J. Innov. Comput., Inf. Control*, vol. 9, no. 8, pp. 3485–3496, 2013.

[28] T. Liu, X. Ma, F. Zhu, and M. Fadel, "Reduced-order feedback linearization for independent torque control of a dual parallel-PMSM system," *IEEE Access*, vol. 9, pp. 27405–27415, 2021, doi: 10.1109/ACCESS.2021.3057876.

[29] Y. Zhang, I. I. Sirmatel, F. Alasiri, P. A. Ioannou, and N. Geroliminis, "Comparison of feedback linearization and model predictive techniques for variable speed limit control," in *Proc. 21st Int. Conf. Intell. Transp. Syst. (ITSC)*, Nov. 2018, pp. 3000–3005.

[30] P. Kakosimos and H. Abu-Rub, "Predictive speed control with short prediction horizon for permanent magnet synchronous motor drives," *IEEE Trans. Power Electron.*, vol. 33, no. 3, pp. 2740–2750, Mar. 2018.

[31] M. Liu, K. W. Chan, J. Hu, W. Xu, and J. Rodriguez, "Model predictive direct speed control with torque oscillation reduction for PMSM drives," *IEEE Trans. Ind. Informat.*, vol. 15, no. 9, pp. 4944–4956, Sep. 2019.

[32] G. Ganga and M. M. Dharmana, "MPC controller for trajectory tracking control of quadcopter," in *Proc. Int. Conf. Circuit, Power Comput. Technol. (ICCPCT)*, Apr. 2017, pp. 1–6.

[33] Q. Ouyang, J. Chen, F. Wang, and H. Su, "Nonlinear MPC controller design for AIR supply of PEM fuel cell based power systems," *Asian J. Control*, vol. 19, no. 3, pp. 929–940, May 2017.

[34] L. Wang, W. Tang, Y. Wang, J. Liang, Z. Li, and M. Cui, "A comparative study of gust load alleviation of UAV based on LPV and MPC controller," in *Proc. Chin. Control Conf. (CCC)*, 2019, pp. 8091–8096.

[35] L. Yuan, H. Zhao, H. Chen, and B. Ren, "Nonlinear MPC-based slip control for electric vehicles with vehicle safety constraints," *Mechatronics*, vol. 38, pp. 1–15, Sep. 2016.

[36] F. Wang, X. Mei, J. Rodriguez, and R. Kennel, "Model predictive control for electrical drive systems—An overview," *CES Trans. Electr. Mach. Syst.*, vol. 1, no. 3, pp. 219–230, Sep. 2017.

[37] S.-C. Carpiuc and C. Lazar, "Real-time multi-rate predictive cascade speed control of synchronous machines in automotive electrical traction drives," *IEEE Trans. Ind. Electron.*, vol. 63, no. 8, pp. 5133–5142, Aug. 2016.

[38] A. Formentini, A. Trentin, M. Marchesoni, P. Zanchetta, and P. Wheeler, "Speed finite control set model predictive control of a PMSM fed by matrix converter," *IEEE Trans. Ind. Electron.*, vol. 62, no. 11, pp. 6786–6796, Nov. 2015.

[39] L. N. Ramya and A. Sivaprakasam, "Application of model predictive control for reduced torque ripple in orthopaedic drilling using permanent magnet synchronous motor drive," *Electr. Eng.*, vol. 102, no. 3, pp. 1469–1482, Sep. 2020, doi: 10.1007/S00202-020-00968-X.

[40] Z. Ma, S. Saeidi, and R. Kennel, "FPGA implementation of model predictive control with constant switching frequency for PMSM drives," *IEEE Trans. Ind. Informat.*, vol. 10, no. 4, pp. 2055–2063, Nov. 2014, doi: 10.1109/TII.2014.2344432.

[41] S. Niu, Y. Luo, W. Fu, and X. Zhang, "An indirect reference vector-based model predictive control for a three-phase PMSM motor," *IEEE Access*, vol. 8, pp. 29435–29445, 2020, doi: 10.1109/ACCESS.2020.2968949.

[42] X. An, Z. Liu, Q. Chen, and G. Liu, "Robust virtual-vector model predictive control of permanent-magnet motor considering D-Q axis inductance parameter uncertainty," *IET Electric Power Appl.*, vol. 18, no. 1, pp. 76–89, Jan. 2024.

[43] T. Liu, Q. Zhao, K. Zhao, L. Li, and G. Zhu, "Sensorless model predictive control of permanent magnet synchronous motor based on hybrid parallel observer under parameter uncertainty," *IET Power Electron.*, vol. 17, no. 3, pp. 438–449, Feb. 2024.

[44] S. Masumpoor, H. Yaghobi, and M. A. Khanesar, "Adaptive sliding-mode type-2 neuro-fuzzy control of an induction motor," *Exp. Syst. Appl.*, vol. 42, no. 19, pp. 6635–6647, Nov. 2015.

[45] B. Castillo-Toledo, S. Di Gennaro, A. G. Loukianov, and J. Rivera, "Discrete time sliding mode control with application to induction motors," *Automatica*, vol. 44, no. 12, pp. 3036–3045, Dec. 2008.

[46] X. Liu, H. Yu, J. Yu, and L. Zhao, "Combined speed and current terminal sliding mode control with nonlinear disturbance observer for PMSM drive," *IEEE Access*, vol. 6, pp. 29594–29601, 2018.

[47] M. A. M. Cheema, J. E. Fletcher, M. Farshadnia, D. Xiao, and M. F. Rahman, "Combined speed and direct thrust force control of linear permanent-magnet synchronous motors with sensorless speed estimation using a sliding-mode control with integral action," *IEEE Trans. Ind. Electron.*, vol. 64, no. 5, pp. 3489–3501, May 2017.

[48] K. Zhao, T. Yin, C. Zhang, J. He, X. Li, Y. Chen, R. Zhou, and A. Leng, "Robust model-free nonsingular terminal sliding mode control for PMSM demagnetization fault," *IEEE Access*, vol. 7, pp. 15737–15748, 2019.

[49] Z. Yin, L. Gong, C. Du, J. Liu, and Y. Zhong, "Integrated position and speed loops under sliding-mode control optimized by differential evolution algorithm for PMSM drives," *IEEE Trans. Power Electron.*, vol. 34, no. 9, pp. 8994–9005, Sep. 2019.

[50] F. Mohd Zaihidee, S. Mekhilef, and M. Mubin, "Robust speed control of PMSM using sliding mode control (SMC)—A review," *Energies*, vol. 12, no. 9, p. 1669, May 2019. [Online]. Available: https://www.mdpi.com/1996-1073/12/9/1669

[51] Y. Deng, J. Wang, H. Li, J. Liu, and D. Tian, "Speed control of PMSM with sliding mode disturbance observer," in *Proc. IEEE Int. Conf. Mechatronics Autom. (ICMA)*, Aug. 2018, pp. 2311–2315, doi: 10.1109/ICMA.2018.8484457.

[52] Q. Zou, X. Li, and D. Chen, "Observer based sliding mode control of PMSM speed regulation system with a novel reaching law," *IET Power Electron.*, vol. 15, no. 10, pp. 886–900, Aug. 2022.

[53] X. Lin, B. Zhang, S. Fang, R. Xu, S. Guo, and J. Liu, "Adaptive generalized super twisting sliding mode control for PMSMs with filtered high-gain observer," *ISA Trans.*, vol. 138, pp. 639–649, Jul. 2023, doi: 10.1016/J.ISATRA.2023.02.008.

[54] T. Gonzalez, J. A. Moreno, and L. Fridman, "Variable gain super-twisting sliding mode control," *IEEE Trans. Autom. Control*, vol. 57, no. 8, pp. 2100–2105, Aug. 2012.

[55] Z. Zhang and X. Liu, "An improved super-twisting sliding mode single-loop control with current-constraint for PMSM based on two-time scale disturbance observer," *IEEE Trans. Transport. Electrific.*, early access, Oct. 9, 2023, doi: 10.1109/TTE.2023.3322687.

[56] D. Wang and X. Liu, "Sensorless control of PMSM with improved adaptive super-twisting sliding mode observer and IST-QSG," *IEEE Trans. Transport. Electrific.*, early access, Apr. 30, 2024, doi: 10.1109/TTE.2024.3395318.

[57] Y. Ma, D. Li, Y. Li, and L. Yang, "A novel discrete compound integral terminal sliding mode control with disturbance compensation for PMSM speed system," *IEEE/ASME Trans. Mechatronics*, vol. 27, no. 1, pp. 549–560, Feb. 2022, doi: 10.1109/TMECH.2021.3068192.

[58] K. Zhao, W. Liu, R. Zhou, W. Dai, S. Wu, P. Qiu, Y. Yin, N. Jia, J. Yi, and G. Huang, "Model-free fast integral terminal sliding-mode control method based on improved fast terminal sliding-mode observer for PMSM with unknown disturbances," *ISA Trans.*, vol. 143, pp. 572–581, Dec. 2023.

[59] T. Pajchrowski and K. Zawirski, "Application of artificial neural network to robust speed control of servodrive," *IEEE Trans. Ind. Electron.*, vol. 54, no. 1, pp. 200–207, Feb. 2007.

[60] S. Brock, J. Deskur, and K. Zawirski, "Modified sliding-mode speed controller for servo drives," in *Proc. IEEE Int. Symp. Ind. Electron. (ISIE)*, vol. 2, 1999, pp. 635–640.

[61] B. Burton, F. Kamran, R. G. Harley, T. G. Habetler, M. A. Brooke, and R. Poddar, "Identification and control of induction motor stator currents using fast on-line random training of a neural network," *IEEE Trans. Ind. Appl.*, vol. 33, no. 3, pp. 697–704, Aug. 1997.

[62] H. Fathabadi, "Novel filter based ANN approach for short-circuit faults detection, classification and location in power transmission lines," *Int. J. Electr. Power Energy Syst.*, vol. 74, pp. 374–383, Jan. 2016.

[63] S. Buhan, Y. Özkazanç, and I. Çadirci, "Wind pattern recognition and reference wind mast data correlations with NWP for improved wind-electric power forecasts," *IEEE Trans. Ind. Informat.*, vol. 12, no. 3, pp. 991–1004, Jun. 2016.

[64] M. Matos, S. Pinho, and V. Tagarielli, "Predictions of the electrical conductivity of composites of polymers and carbon nanotubes by an artificial neural network," *Scripta Mater.*, vol. 166, pp. 117–121, Jun. 2019.

[65] R. N. Milion, J. C. Paliari, and L. H. B. Liboni, "Improving consumption estimation of electrical materials in residential building construction," *Autom. Construction*, vol. 72, pp. 93–101, Dec. 2016.

[66] S. Li, H. Won, X. Fu, M. Fairbank, D. C. Wunsch, and E. Alonso, "Neural-network vector controller for permanent-magnet synchronous motor drives: Simulated and hardware-validated results," *IEEE Trans. Cybern.*, vol. 50, no. 7, pp. 3218–3230, Jul. 2020.

[67] T. Pajchrowski and K. Zawirski, "Synthesis of robust speed controller based on artificial neural network for permanent magnet synchronous motor," *Przeglad Elektrotechniczny*, vol. 82, no. 2, pp. 57–61, 2006.

[68] T. Pajchrowski and K. Zawirski, "Robust speed controller for PMSM based on artificial neural network," in *Proc. Eur. Conf. Power Electron. Appl.*, 2005, p. 9.

[69] J. P. Catalão, *Electric Power Systems: Advanced Forecasting Techniques and Optimal Generation Scheduling*. Boca Raton, FL, USA: CRC Press, 2016.

[70] A. D. Anastasiadis, G. D. Magoulas, and M. N. Vrahatis, "An efficient improvement of the Rprop algorithm," in *Proc. 1st Int. Workshop Artif. Neural Netw. Pattern Recognit. (ANNPR)*, 2003, pp. 197–201.

[71] E. T. Mohamad, R. S. Faradonbeh, D. J. Armaghani, M. Monjezi, and M. Z. A. Majid, "An optimized ANN model based on genetic algorithm for predicting ripping production," *Neural Comput. Appl.*, vol. 28, no. S1, pp. 393–406, Dec. 2017.

[72] M. Khandelwal, A. Marto, S. A. Fatemi, M. Ghoroqi, D. J. Armaghani, T. N. Singh, and O. Tabrizi, "Implementing an ANN model optimized by genetic algorithm for estimating cohesion of limestone samples," *Eng. Comput.*, vol. 34, no. 2, pp. 307–317, Apr. 2018.

[73] C. Xia, C. Guo, and T. Shi, "A neural-network-identifier and fuzzy-controller-based algorithm for dynamic decoupling control of permanent-magnet spherical motor," *IEEE Trans. Ind. Electron.*, vol. 57, no. 8, pp. 2868–2878, Aug. 2010.

[74] C. Guo and C. Xia, "A dynamic decoupling control algorithm for Halbach array permanent magnet spherical motor based on computed torque method," in *Proc. IEEE Int. Conf. Robot. Biomimetics (ROBIO)*, Dec. 2007, pp. 2090–2094.

[75] H. Shenghua, T. Xingshi, and L. Jinming, "Mechanical model of three dimensional motor and its decoupling control," *Trans. Chin. Electrotech. Soc.*, vol. 11, no. 1, pp. 12–16, 1996.

[76] S. Lu and X. Wang, "Observer-based command filtered adaptive neural network tracking control for fractional-order chaotic PMSM," *IEEE Access*, vol. 7, pp. 88777–88788, 2019.

[77] H.-K. Hoai, S.-C. Chen, and H. Than, "Realization of the sensorless permanent magnet synchronous motor drive control system with an intelligent controller," *Electronics*, vol. 9, no. 2, p. 365, Feb. 2020. [Online]. Available: https://www.mdpi.com/2079-9292/9/2/365

[78] H. Than and Y.-S. Kung, "FPGA-realization of an RBF-NN tuning PI controller for sensorless PMSM drives," *Microsyst. Technol.*, vol. 28, no. 1, pp. 25–38, Jan. 2022, doi: 10.1007/S00542-019-04347-W.

[79] L. Grzesiak, V. Meganck, J. Sobolewski, and B. Ufnalski, "DTC-SVM driver with ANN-based speed controller," *Przeglad Elektrotechniczny*, vol. 82, no. 2, pp. 118–122, 2006.

[80] C. Igel and M. Hüsken, "Improving the Rprop learning algorithm," in *Proc. 2nd Int. ICSC Symp. Neural Comput. (NC)*, 2000, pp. 115–121.

[81] M. Riedmiller and H. Braun, "A direct adaptive method for faster backpropagation learning: The RPROP algorithm," in *Proc. IEEE Int. Conf. Neural Netw.*, Sep. 1993, pp. 586–591.

[82] Z. Ali, Z. Frijet, and M. Chtourou, "An adaptive neural network controller based on PSO and gradient descent method for PMSM speed drive," *Int. J. Power Electron. Drive Syst. (IJPEDS)*, vol. 9, no. 3, p. 1412, Sep. 2018.

[83] H. Jie, G. Zheng, J. Zou, X. Xin, and L. Guo, "Adaptive decoupling control using radial basis function neural network for permanent magnet synchronous motor considering uncertain and time-varying parameters," *IEEE Access*, vol. 8, pp. 112323–112332, 2020, doi: 10.1109/ACCESS.2020.2993648.

[84] A. Boulkroune, "A fuzzy adaptive control approach for nonlinear systems with unknown control gain sign," *Neurocomputing*, vol. 179, pp. 318–325, Feb. 2016.

[85] K. Hornik, M. Stinchcombe, and H. White, "Multilayer feedforward networks are universal approximators," *Neural Netw.*, vol. 2, no. 5, pp. 359–366, Jan. 1989.

[86] L.-X. Wang and J. M. Mendel, "Fuzzy basis functions, universal approximation, and orthogonal least-squares learning," *IEEE Trans. Neural Netw.*, vol. 3, no. 5, pp. 807–814, Aug. 1992.

[87] H. Ying, "Li xin Wang's adaptive fuzzy systems and control: Design and stability analysis," *J. Intell. Fuzzy Syst.*, vol. 3, no. 2, pp. 187–188, 1995.

[88] A. M. Zaki, M. El-Bardini, F. A. S. Soliman, and M. M. Sharaf, "Embedded two level direct adaptive fuzzy controller for DC motor speed control," *Ain Shams Eng. J.*, vol. 9, no. 1, pp. 65–75, Mar. 2018.

[89] S. Sajilamol, E. Paul, and M. Thomas, "Fuzzy controller based boost PFC converter for EV application," *Int. J. Advance Res., Ideas Innov. Technol.*, vol. 4, no. 3, pp. 1–5, 2018.

[90] G. Jothimani, S. K. Natarajan, and Y. Palanichamy, "Fuzzy controller based power quality improvement in three level converter with multiloop interleaved control for marine AC/DC applications," *Indian J. Geo Mar. Sci.*, vol. 46, no. 9, pp. 1908–1919, Sep. 2017.

[91] Y.-C. Chang, C.-H. Chen, Z.-C. Zhu, and Y.-W. Huang, "Speed control of the surface-mounted permanent-magnet synchronous motor based on Takagi–Sugeno fuzzy models," *IEEE Trans. Power Electron.*, vol. 31, no. 9, pp. 6504–6510, Sep. 2016.

[92] K. Suleimenov and T. D. Do, "Design and analysis of a generalized high-order disturbance observer for PMSMs with a fuzy-PI speed controller," *IEEE Access*, vol. 10, pp. 42252–42260, 2022, doi: 10.1109/ACCESS.2022.3167429.

[93] H. Ding, X. Zou, and J. Li, "Sensorless control strategy of permanent magnet synchronous motor based on fuzzy sliding mode observer," *IEEE Access*, vol. 10, pp. 36743–36752, 2022, doi: 10.1109/ACCESS.2022.3164519.

[94] Y. Zheng, H. Zhao, S. Zhen, and C. He, "Designing robust control for permanent magnet synchronous motor: Fuzzy based and multivariable optimization approach," *IEEE Access*, vol. 9, pp. 39138–39153, 2021, doi: 10.1109/ACCESS.2021.3056890.

[95] S. Ye, "Fuzzy sliding mode observer with dual SOGI-FLL in sensorless control of PMSM drives," *ISA Trans.*, vol. 85, pp. 161–176, Feb. 2019.

[96] L. Sheng, G. Xiaojie, and Z. Lanyong, "Robust adaptive backstepping sliding mode control for six-phase permanent magnet synchronous motor using recurrent wavelet fuzzy neural network," *IEEE Access*, vol. 5, pp. 14502–14515, 2017.

[97] I. F. Bouguenna, A. Azaiz, A. Tahour, and A. Larbaoui, "Robust neuro-fuzzy sliding mode control with extended state observer for an electric drive system," *Energy*, vol. 169, pp. 1054–1063, Feb. 2019.

[98] Y.-S. Kung and M.-H. Tsai, "FPGA-based speed control IC for PMSM drive with adaptive fuzzy control," *IEEE Trans. Power Electron.*, vol. 22, no. 6, pp. 2476–2486, Nov. 2007, doi: 10.1109/TPEL.2007.909185.

[99] A. V. Sant and K. R. Rajagopal, "PM synchronous motor speed control using hybrid fuzzy-PI with novel switching functions," *IEEE Trans. Magn.*, vol. 45, no. 10, pp. 4672–4675, Oct. 2009, doi: 10.1109/TMAG.2009.2022191.

[100] M. Moradi, M. H. Kazemi, and E. Ershadi, "Direct adaptive fuzzy control with membership function tuning," *Asian J. Control*, vol. 14, no. 3, pp. 726–735, May 2012.

[101] S. Barkat, A. Tlemçani, and H. Nouri, "Noninteracting adaptive control of PMSM using interval type-2 fuzzy logic systems," *IEEE Trans. Fuzzy Syst.*, vol. 19, no. 5, pp. 925–936, Oct. 2011.

[102] D. Kukolj, F. Kulic, and E. Levi, "Design of the speed controller for sensorless electric drives based on AI techniques: A comparative study," *Artif. Intell. Eng.*, vol. 14, no. 2, pp. 165–174, Apr. 2000.

[103] P. D. Giri and S. K. Shah, "Fuzzy logic controller and neural network controller as a power system regulator implemented on GUI," in *Proc. Int. Conf. Soft Comput. Problem Solving (SocProS)*. Springer, 2011, pp. 243–256.

[104] F. Chekired, A. Mellit, S. A. Kalogirou, and C. Larbes, "Intelligent maximum power point trackers for photovoltaic applications using FPGA chip: A comparative study," *Sol. Energy*, vol. 101, pp. 83–99, Mar. 2014.

[105] P. Joshi and S. Arora, "Maximum power point tracking methodologies for solar PV systems—A review," *Renew. Sustain. Energy Rev.*, vol. 70, pp. 1154–1177, Apr. 2017.

[106] Y. Li, S. Tong, and T. Li, "Direct adaptive fuzzy backstepping control of uncertain nonlinear systems in the presence of input saturation," *Neural Comput. Appl.*, vol. 23, no. 5, pp. 1207–1216, Oct. 2013.

[107] Y. Chen, Z. Zhou, J. Zhang, Y. Li, and X. Wang, "A new error estimation approach based on fuzzy logic system for H-R adaptive boundary element method," *Appl. Math. Comput.*, vol. 218, no. 5, pp. 2167–2177, Nov. 2011.

[108] M. B. Kadri, "Control structures for multiplicative input disturbance rejection using adaptive direct fuzzy controllers," *Arabian J. Sci. Eng.*, vol. 38, no. 6, pp. 1427–1435, Jun. 2013.

[109] M. Imanian, A. Ghassemi, and M. Karbasian, "Bit pressure control during drilling operations using a direct fuzzy adaptive controller," *Int. J. Fuzzy Syst.*, vol. 21, no. 2, pp. 488–502, Mar. 2019.

[110] N. F. Shamloo, A. A. Kalat, and L. Chisci, "Direct adaptive fuzzy control of nonlinear descriptor systems," *Int. J. Fuzzy Syst.*, vol. 21, no. 8, pp. 2588–2599, Nov. 2019.

[111] S. Mishra, S. Shukla, and N. Verma, "Comprehensive review on maximum power point tracking techniques: Wind energy," in *Proc. Commun., Control Intell. Syst. (CCIS)*, 2015, pp. 464–469.

[112] S. Fahas, H. Le-Huy, and I. Kamwa, "Fuzzy direct adaptive direct torque control of switched reluctance motors," in *Proc. 42nd Annu. Conf. IEEE Ind. Electron. Soc.*, Oct. 2016, pp. 2809–2814.

[113] X. Zheng, H. Zaman, X. Wu, H. Ali, and S. Khan, "Direct fuzzy logic controller for voltage control of standalone three phase inverter," in *Proc. Int. Electr. Eng. Congr. (iEECON)*, Mar. 2017, pp. 1–4.

[114] R. Thompson and A. Dexter, "A fuzzy decision-making approach to temperature control in air-conditioning systems," *Control Eng. Pract.*, vol. 13, no. 6, pp. 689–698, Jun. 2005.

[115] O. Nelles, *Nonlinear System Identification: From Classical Approaches to Neural Networks and Fuzzy Models*. Berlin, Germany: Springer, 2013.

[116] R. H. Du, Y. F. Wu, W. Chen, and Q. Chen, "Adaptive fuzzy speed control for permanent magnet synchronous motor servo systems," *Electric Power Compon. Syst.*, vol. 42, no. 8, pp. 798–807, Jun. 2014.

[117] J. Wang, "Fuzzy adaptive repetitive control for periodic disturbance with its application to high performance permanent magnet synchronous motor speed servo systems," *Entropy*, vol. 18, no. 9, p. 261, Sep. 2016.

[118] A. Youssef, M. El-Telbany, and A. Zekry, "The role of artificial intelligence in photo-voltaic systems design and control: A review," *Renew. Sustain. Energy Rev.*, vol. 78, pp. 72–79, Oct. 2017.

[119] X. Wang, C. Jiang, F. Zhuang, C. H. T. Lee, and C. C. Chan, "A harmonic injection method equivalent to the resonant controller for speed ripple reduction of PMSM," *IEEE Trans. Ind. Electron.*, vol. 69, no. 10, pp. 9793–9803, Oct. 2022.

[120] G. Feng, C. Lai, and N. C. Kar, "A closed-loop fuzzy-logic-based current controller for PMSM torque ripple minimization using the magnitude of speed harmonic as the feedback control signal," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 2642–2653, Apr. 2017, doi: 10.1109/TIE.2016.2631524.

[121] J. Qu, J. Jatskevich, C. Zhang, and S. Zhang, "Torque ripple reduction method for permanent magnet synchronous machine drives with novel harmonic current control," *IEEE Trans. Energy Convers.*, vol. 36, no. 3, pp. 2502–2513, Sep. 2021, doi: 10.1109/TEC.2021.3056557.

[122] M. Hu, W. Hua, Z. Wang, S. Li, P. Wang, and Y. Wang, "Selective periodic disturbance elimination using extended harmonic state observer for smooth speed control in PMSM drives," *IEEE Trans. Power Electron.*, vol. 37, no. 11, pp. 13288–13298, Nov. 2022.

[123] A. Houari, A. Bouabdallah, A. Djerioui, M. Machmoum, F. Auger, A. Darkawi, J.-C. Olivier, and M. F. Benkhoris, "An effective compensation technique for speed smoothness at low-speed operation of PMSM drives," *IEEE Trans. Ind. Appl.*, vol. 54, no. 1, pp. 647–655, Jan. 2018.

[124] G. Feng, C. Lai, and N. C. Kar, "Speed harmonic based decoupled torque ripple minimization control for permanent magnet synchronous machine with minimized loss," *IEEE Trans. Energy Convers.*, vol. 35, no. 4, pp. 1796–1805, Dec. 2020, doi: 10.1109/TEC.2020.2992487.

[125] C. Lai, G. Feng, J. Tjong, and N. C. Kar, "Direct calculation of maximum-torque-per-ampere angle for interior PMSM control using measured speed harmonic," *IEEE Trans. Power Electron.*, vol. 33, no. 11, pp. 9744–9752, Nov. 2018, doi: 10.1109/TPEL.2017.2789245.

MEHDI MONADI (Member, IEEE) received the Ph.D. degree (Hons.) in electrical engineering from the Technical University of Catalonia (UPC), Barcelona, Spain, in 2016. In 2015, he was a Visiting Ph.D. Student with the KTH Royal Institute of Technology, Stockholm, Sweden, where he was a Researcher, in 2016. Since 2018, he has been an Assistant Professor with the Shahid Chamran University of Ahvaz, Ahvaz, Iran, where he also works as a Supervisor with the Modernization of Electrical Installations and Systems Research Group (MoernISR Group). His research interests include the protection of active/smart distribution systems, power electronics drives, and dc distribution and transmission systems.

MOHAMMAD NABIPOUR received the Ph.D. degree in electrical engineering from the Shahid Chamran University of Ahvaz, Ahvaz, Iran, in 2018. Since 2019, he has been an Assistant Professor with the Shahid Chamran University of Ahvaz. His research interests include power electronics drives, electrical motors, and power electronics.

FATEMEH AKBARI-BEHBAHANI received the B.Sc. degree in electrical engineering from the Shahid Chamran University of Ahvaz, Ahvaz, Iran, in 2020, where she is currently pursuing the M.Sc. degree. She is also a member of the Modernization of Electrical Installations and Systems Research Group (ModernISR Group), Shahid Chamran University of Ahvaz. Her research interests include the protection of HVDC and MVDC systems and power electronics drives.

EDRIS POURESMAEIL (Senior Member, IEEE) received the Ph.D. degree (Hons.) in electrical engineering from the Technical University of Catalonia, BarcelonaTech (CITCEA-UPC), Barcelona, Spain, in 2012. He is currently an Associate Professor with the Department of Electrical Engineering and Automation and the Head of the Renewable Energies for Power Systems Group, Aalto University, Finland. His research expertise lies in the operation and control of power electronics in power systems, integrating renewable energy sources into power grids, microgrids operations and control, and modeling and development of hybrid energy storage systems reliant on green hydrogen and batteries. He serves as an Associate Editor for IEEE Systems Journal, IEEE Open Journal of the Industrial Electronics Society, IEEE Open Journal of Power Electronics, *IET Generation, Transmission & Distribution*, and *IET Renewable Power Generation*.