



Review

Critical Review on Robust Speed Control Techniques for Permanent Magnet Synchronous Motor (PMSM) Speed Regulation

Kifayat Ullah ^{1,*} , Jaroslaw Guzinski ²  and Adeel Feroz Mirza ¹

¹ Doctoral School, Gdansk University of Technology, 80-226 Gdansk, Poland; adeel.mirza@pg.edu.pl

² Electrical and Control Engineering Faculty, Gdansk University of Technology, 80-233 Gdansk, Poland; jaroslaw.guzinski@pg.edu.pl

* Correspondence: kifayat.ullah@pg.edu.pl

Abstract: The permanent magnet synchronous motor (PMSM) is a highly efficient energy saving machine. Due to its simple structural characteristics, good heat radiation capability, and high efficiency, PMSMs are gradually replacing AC induction motors in many industrial applications. The PMSM has a nonlinear system and lies on parameters that differ over time with complex high-class dynamics. To achieve the excessive performance operation of a PMSM, it essentially needs a speed controller for providing accurate speed tracking, slight overshoot, and robust disturbance repulsion. Therefore, this article provides an overview of different robust control techniques for PMSMs and reviews the implementation of a speed controller. In view of the uncertainty factors, such as parameter perturbation and load disturbance, the H_∞ robust control strategy is mainly reviewed based on the traditional control techniques, i.e., robust H_∞ sliding mode controller (SMC), and H_∞ robust current controller based on Hamilton–Jacobi Inequality (HJI) theory. Based on comparative analysis, this review simplifies the development trend of different control technologies used for a PMSM speed regulation system.



Citation: Ullah, K.; Guzinski, J.; Mirza, A.F. Critical Review on Robust Speed Control Techniques for Permanent Magnet Synchronous Motor (PMSM) Speed Regulation. *Energies* **2022**, *15*, 1235. <https://doi.org/10.3390/en15031235>

Academic Editors: Jose Luis Calvo-Rolle, Luigi Fortuna and Oscar Barambones

Received: 13 December 2021

Accepted: 30 January 2022

Published: 8 February 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: robust speed controller; PMSM speed regulation; H_∞ robust control; SMC control; current controller

1. Introduction

The permanent magnet synchronous motor (PMSM) has outstanding advantages over brush-type motors and is progressively replacing induction motors in many fields because of their benefits, i.e., simple structure, fast dynamic response, high efficiency, high air-gap flux density, and high torque-to-inertia ratio [1]. Due to their vast application prospects, these kinds of motors are broadly used for operation in low and medium power applications. Furthermore, they are used in high-performance electric drives such as electric vehicles, robotics, aeronautical spaceframes, and machine tools [2,3]. However, the motor model is nonlinear and sensitive to many uncertainties inside and outside the speed control system during operation, making it difficult for the conventional PI control topology to convene the excessive performance control requirements of the system. Therefore, the question of how to suppress the uncertainty of the speed control system to improve the robustness of the system has become a hotspot for scholars [3,4].

Since the discovery of AC motors for speed regulation, vector control methods are the most popular, and among these methods, direct torque control (DTC) [5,6] and field-oriented control (FOC) are commonly used [7,8]. Due to the rapid and full decoupling control of torque and flux, the FOC has been widely used in PMSM motors. In the FOC method, due to their simple design structure, proportional integration (PI) controllers are typically implemented for current and speed control [9]. PI controller gain is usually determined by nominal motor parameters to assemble motor performance specifications [10]. Based on the specified model parameters and time separation assumptions, there is no guarantee of stability if there is uncertainty, load changes, or input saturation constraints.

However, where high performance and precision are required, this type of controller is not applicable [11,12].

For PMSM speed control, the control structure typically uses cascade control loops, including an external speed control loop and two internal current loops [13,14]. The benefits of the cascading control topology are enhanced disturbance resistance and superior point of tuning response performance [15]. In speed current cascading control, the relationship between the output speed and the four-axis reference current is usually defined by the first-order model. However, given that closed-loop performance may decline due to the disappearance of the relative difference in control cycles between the two loops, a second-order model relationship is also proposed [8,16]. For high-speed PMSM applications, the integration speed and current controller have been used to address the nonlinear coupling between speed and current. In [17], the authors describe the particle swarm optimization (PSO) technique for the speed control of sensorless PMSM motors.

Therefore, many advanced nonlinear control topologies have been developed in recent years to progress the speed regulation performance of PMSM motors in different applications. These methods include neural network control [18], backstepping control [19], automatic disturbance rejection control [20], fuzzy logic control (FLC) [21], predictive control [5], artificial intelligence-incorporated control [22], sliding mode control (SMC) [23], adaptive control [24], variable structure control (VSC) [25], predictive current control (PCC) [20], disturbance observer (DOB) [26], and extended state observer (ESO) [27,28]. Furthermore, for the speed regulation of the PMSM, as alternative to the conventional PI control method, H_∞ control is in operational use. In H_∞ control, external disturbances are assumed to be indeterminate parameters with bounded energy [29]. A robust speed controller based on mixed sensitivity can be used to progress the speed control for each molding in PMSM systems, as in [30,31]. An adaptive control scheme with a pre-determined H_∞ property is implemented for the PMSM control in [32]. Using the robust control principle based on signal compensation, the design method of the robust speed control system with PMSM is proposed in [33]. To comprehend PMSM speed control, a robust predictive controller is proposed [34]. Several of these methods have been used successfully in practical applications.

2. H_∞ Robust Control

Hamilton–Jacobi Inequality (HJI) system theory provides several possible control techniques for the academic circles of nonlinear disciplines and has attracted great devotion from PMSM nonlinear system scholars [35]. In the current study, several main control approaches to robust control are developed, such as quantitative feedback theory, Kharitonov, H_∞ , μ theory, and Lyapunov [36]. The H_∞ robust current control strategy based on (HJI) is proposed in [37], which improves the robustness of the current control. This method effectively solves the effect of voltage fluctuation on current control performance, but the robustness of load variation is not ideal. To control the motor drive electromagnetic synchronization, H_∞ control is used in [29,38]. However, some measurement errors still occur in the system, such as fixed space lagging and inertia that can indicate high frequency chatter. The Linear Matrix Inequality (LMI) related theory is applied to the PMSM speed control system in [39]. A robust optimal position control strategy, combined with linear quadratic regulator (LQR) and LMI theory, is proposed, resulting in optimal controller gain to ensure system robustness. The robust H_∞ sliding mode control strategy based on LMI is proposed [40], which solves the problem of mismatch interference in the system. Although this control method's effect is good, there may be changes in the system parameters caused by the controller, as well as system parameters mismatch problems, which will affect the controller's performance [41]. The decisive controller is designed through an interconnect and damping arrangement based on the main principle of energy formative and port series Hamiltonian systems [42]. In addition, the H_∞ -based current controller is proposed to suppress the voltage variation of the current loop, which improves the current control robustness [43,44]. For linear time disguise problems, the Kharitonov and H_∞ are used;



however, there is lack of theoretical evidence. On a theoretical basis, the Lyapunov method is applicable to self-sufficient nonlinear systems [45]. To efficiently suppress the disturbance of system mismatch, the robust H_∞ -SMC controller, based on LMI, is proposed in [40,46]. However, it also provides new ideas for resolving parameter mismatch between the PMSM motor and its control system.

2.1. H_∞ Robust Current Controller Design

The formula to obtain the H_∞ robust current controller is given below [27].

$$\begin{cases} \dot{x} = f(x) + Z(x)\xi \\ y = h(x) \end{cases} \quad (1)$$

where $h(x)$ and $f(x)$ are nonlinear. HJI is given below, when $E(x) \geq 0$ ($E(x^*) = 0$).

$$\dot{E}(x) = x^T A x + x^T B \left\{ -B^{-1} \left[A_2 x + \frac{1}{2} \left(1 + \frac{1}{\gamma^2} \right) x \right] \right\} \quad (2)$$

$$\dot{E}(x) = x^T A_1 - \frac{1}{2} \left(1 + \frac{1}{\gamma^2} \right) x^T x < 0 \quad (3)$$

2.2. Design of Robust H_∞ Sliding Mode Speed Controller

2.2.1. Design of H_∞ Sliding Surface

The H_∞ slide surface refers to the system state that has robust stability and H_∞ disturbance attenuation γ on the slide surface [47]. Rewrite the motion equation of the SPMSM under the d-q rotation coordinate system in the form of an error, that is given below [48].

$$\dot{e}_{\omega_m} = -\frac{B_0}{J} e_{\omega_m} - \frac{3p_n \psi_f}{2J} i_q + \frac{1}{J} T_{L0} + \frac{B_0}{J} \dot{\omega}_m \quad (4)$$

At the same time, the external disturbance and parameter perturbation are considered, and the state space expression is obtained.

$$\dot{x}' = A' x' + B' u' + M' \delta \quad (5)$$

$$y' = C' x' \quad (6)$$

2.2.2. Robust H_∞ Design of the Sliding Mode Speed Control Law

For the system state to reach the slide face within a limited time, set the robust H_∞ slip mode speed control law:

$$u' = -(\Xi B')^{-1} (\|\Xi A'\| \|x'\| + \|\Xi M'\| \delta_0 + \beta) \times \text{sigmoid}(s) \quad (7)$$

where $\beta > 0$; $\text{sigmoid}(s) = \frac{2}{1-e^{-as}} - 1$, and $a > 0$ construct the Lyapunov function as:

$$V_s(t) = \frac{1}{2} s^2 \quad (8)$$

$$\dot{V}_s(t) = s \dot{s} = s \Xi (A' x' + M' \delta) + s \Xi B' u' \quad (9)$$

By substituting Equations (7) into (9), we can get the final equation of sliding mode speed control law. A diagram of the basic operation of the H_∞ controller is described in Figure 1.

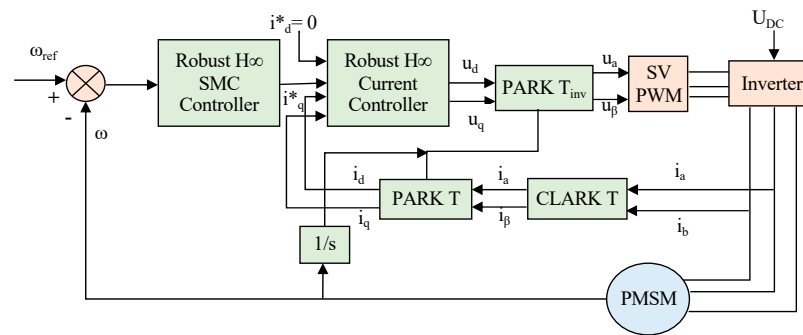


Figure 1. Principal diagram of PMSM speed regulation based on H∞ robust controller.

3. Robust Speed Control Techniques for PMSM

3.1. PI Controller

A PI controller is a traditional control strategy that is used in several industrial control developments. It includes an integrator and is responsible for accelerating the control operations and reducing the stability errors and the proportional gain, which is responsible for achieving a steady state. The disparity of the actual dignified speed ω and reference speed ω_{ref} are the inputs of the PI controller [49]. The controller’s main purpose is to minimize this inaccuracy. The relationship between the input and output parameters of the controller is given as:

$$e_0 = K_p(e) + K_i \int edt \tag{10}$$

where $e = \omega - \omega_{ref}$, and the performance of the PI speed controller depends on the values of K_p and K_i .

However, a PI controller based on the assumption of the required model parameters and time split does not deliver assured stability in the event of uncertainty, load variations, and input saturation limits [50]. When a large setup point change occurs in a PMSM control, the PI controller is being used to process the effect of the integrator end [2]. A basic operational diagram of the PI traditional controller is illustrated in Figure 2.

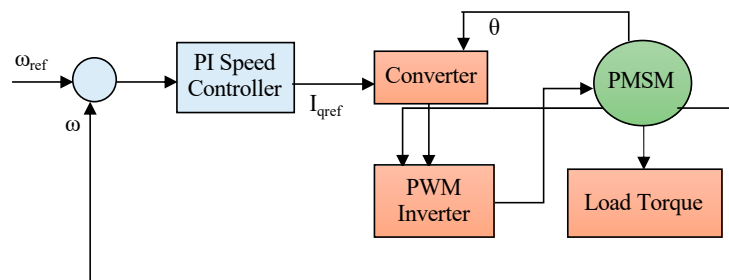


Figure 2. Basic structure of PMSM PI controller.

3.2. Predictive Current Control (PCC)

A permanent magnet synchronous motor current control strategy based on the uncertainty and disturbance estimator is proposed, which simplifies the structure of the speed control system and improves the robustness of the system to parameter disturbance. The current forecast control strategy based on the observer of the state of expansion is proposed [20,51], which effectively avoids the influence of the disturbance of the deviation of the parameters of the inductance on the robustness of the current control system. The current observer-based control strategy can overcome the effect of interference on system robustness, but it increases the complexity of the controller design, and sometimes affects system stability. In recent years, researchers have proposed new current control strategies to solve specific problems [16]. A current control strategy based on the optimization of the second-order terminal sliding mode is proposed [23], which effectively removes vibrations and improves the robustness of the current control. The current control strategy with active

resistance is proposed in [52], which improves the speed of the current ring and improves the robustness of the speed control system to the disturbance of the parameters [51]. In addition, PCC theoretically enhances the dynamic performance of the PMSM by improving the current control loop bandwidth. A basic diagram of the PCC controller is shown in Figure 3.

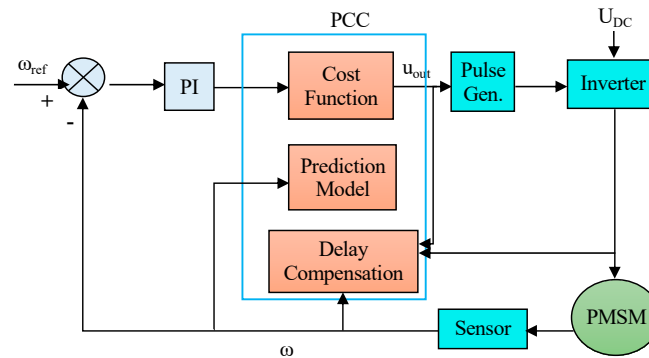


Figure 3. Basic structure of the PMSM PCC control.

3.3. Sliding Mode Control (SMC)

SMC is a widely used robust speed control method for PMSM; it is used in several applications researched in the literature [53] and is applied to multiple systems with different approaches. SMC is a nonlinear control method that is insensitive to changes in motor parameters and loads. SMC enables the system to track a predefined path (sliding surface) on the phase line, and for this purpose, a switching algorithm is used. Theoretically, it is controlled by adjusting the dynamic behavior of the closed loop to match the sliding surface [54,55]. The torque equation of the PMSM model is given as:

$$\dot{\omega}_r(t) = \frac{1.5 \times P \times \lambda \times i_q - B \times \omega - T_L}{J} \quad (11)$$

the sliding surface is given as:

$$S = e(t) + \frac{3 \times P \times \lambda}{2 \times J} \int e(t) dt \quad (12)$$

and the SMC output can be described as:

$$i \times q = qe + f \times \text{sgn}(S) + \frac{2 \times J}{3 \times P \times \lambda} \dot{\omega} \quad (13)$$

where T_L is load torque, ' J ' is variation in moment of inertia, and ' q ' and ' f ' are gains. Function $\text{sgn}(S)$ is called a sign function, and is describe as [56]:

$$\text{sgn}(S) = \begin{cases} +1 & \text{if } s > 0 \\ -1 & \text{if } s < 0 \end{cases}$$

However, the weakest point of SMC is the chatter affected by the switching function after it multiplies the sliding mode, which is the one aspect that needs to be avoided in some applications, like industrial robots and machine tools [57].

Many scholars have devised better SMC solutions to this problem, such as SMC reaching law, fractional order sliding mode control (FROSMC), and the boundary layer method [58]. These overall SMC control techniques do not fully reduce the chattering, but it is concentrated by the external interference [56]. Therefore, it has become an important area of research for scholars to observe disturbance, and at the same time the SMC controller is compensated appropriately. A structure diagram of the MCC traditional controller is given in Figure 4, below.

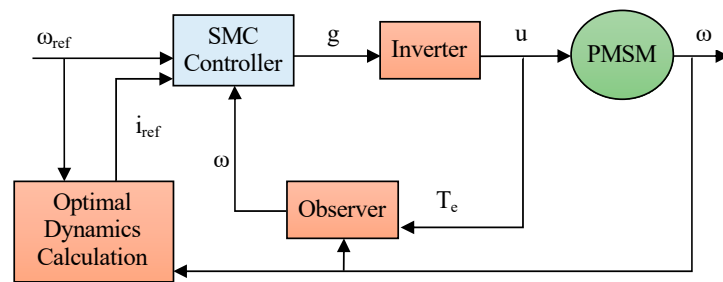


Figure 4. Basic structure of the PMSM SMC control.

3.4. Fuzzy Logic Control (FLC)

Over the past few years, many scholars have been involved in the fuzzy logic control system. Fuzzy logic has numerous advantages, one of which is that it utilizes language information rather than numerical tools to simulate complicated industrial procedures. Compound fuzzy sliding mode controllers have been used in many applications [59] due to the fact that they can consistently approach any nonlinear function that cannot be linearly paralyzed or designed. Based on the under-control process, the fuzzy system depends on intellectual algorithms through human intelligence [60]. The study in [61] extensively applied the Takagi Sugeno (TS) fuzzy system to an estimate of unconstructed or unknown system explosives in the PMSM speed control system. The use of fuzzy logical inference systems for revenue requires member functions to be dense enough, accurate, and sufficient to reduce sensitivity to noise. In addition, the error change rate Δe_ω and error speed e_ω of the fuzzy logic controller, where e_ω and Δe_ω can be expressed as [62], are as follows:

$$e_\omega = k_e(\omega^* - \omega) \tag{14}$$

$$\Delta e_\omega = k_c = \frac{de}{dt} \tag{15}$$

where ‘e’ is the error in speed between the feedback and reference speed, $e = \omega^* - \omega$. The theoretical range of e_ω and Δe_ω is given respectively as $(-2,2)$, $(-3,3)$.

The fuzzy controller produces superior speed tracking compared to other control techniques used for PMSM speed control, but the fuzzy and membership function primarily relies on expert proficiency [63]. The fuzzy prediction control of the current predictive deadbeat technique, which can offset the deficiency of parameters in real time by weight constant, is proposed in [60,64]. A basic internal structure diagram of the FLC is given in Figure 5, and a structure diagram of the FLC controller is shown in Figure 6.

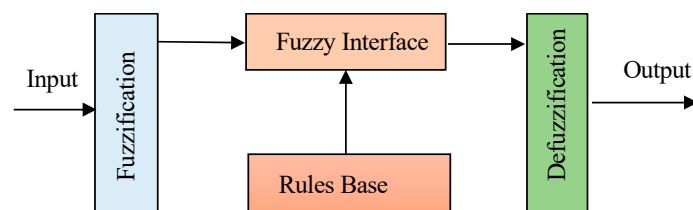


Figure 5. Basic structure of FLC.

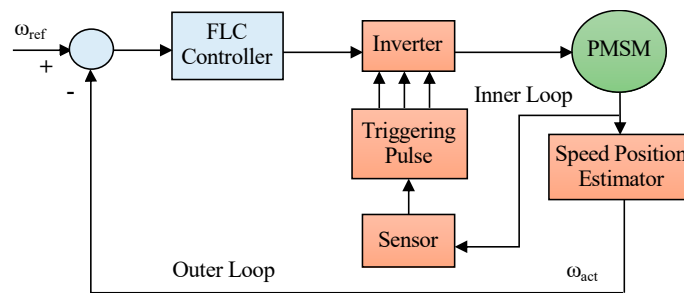


Figure 6. Basic structure of the PMSM FLC control.

3.5. Artificial Neural Network (ANN)

Numerous techniques of designing a controller based on an ANN have been proposed [62], because it has the ability to generate an ultimate nonlinear control signal due to the capability to express arbitrary nonlinear mapping, self-adaptation, and real-time online training. A PMSM with the vector control method based on ANN's online self-adjusting speed control is proposed in [65]. Various types of recurrent NN and Elman NN are proposed in [66] to form a controller system for a PMSM drive. However, the novel ENN is not accurately closed to superior order system dynamics and does not converge very quickly. Therefore, it is not suitable for applications based on critical time. To overcome these weaknesses, many improved ENN methods have been developed to improve the robustness and fusion of the traditional ENN [67]. Different approaches of ANN adaptive controllers are proposed in the literature [68,69]. The neuro fuzzy adaptive following control (MFC) is proposed in [70], where the NFC controller is trained online based on the errors that occur between the reference model output signal and the control system. In [62], a PD-improved nonlinear controller is described. The modification only includes disparity components that calculate feedback signals. In [67], a RENN-based adaptive speed controller is designed to achieve the robust speed control of a PMSM. A diagram of the basic internal ANN layers is given in Figure 7, below, and a structure diagram of the ANN controller for PMSM speed regulation is shown in Figure 8 [68].

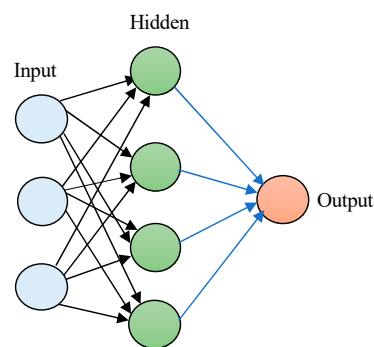


Figure 7. Structure of ANN layers.

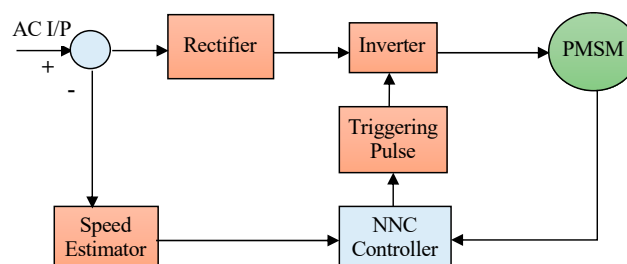


Figure 8. Basic structure of the PMSM NNC control.

3.6. Extended State Observer (ESO)

In [71,72], an ESO is developed. This has benefits over traditional observers, i.e., accuracy, robustness, and better dynamic performance independent of the mathematical model. An ESO has the capability of approximating unidentified disturbance affected by high precision and inductance mismatch. Another ESO control method for observing disturbances has been broadly used and is proposed in [73,74]. The ESO groups disturbances, including internal and external disturbances, as a new state variable that builds the novel extensive state equation, and formerly evaluates the state variables of the extensive state equation [75]. The ESO is an actual perturbation observer; it does not require the direct measurement of the perturbation and disturbance model. Active disturbance rejection control (ADRC) [76] is broadly used in power converter control, PMSM, and robotic control systems, etc. For the PMSM control system, a second order model is proposed for speed regulation in [77,78]; furthermore, active feed forward compensation is also proposed to minimize the chatter of the SMC and enhance the robustness. High accuracy position assessment is achieved by using linear ESO in [79]. For robustness in the full speed variety, LESO is implanted in the current controller. The ESO's ADRC controller is designed for elevator traction machines. It is observed that nonlinear disturbance in the elevator turn on condition can increase the dynamic reaction exclusive of using a weight sensor [80]. A basic structure diagram of the PMSM ESO-based controller is illustrated in Figure 9.

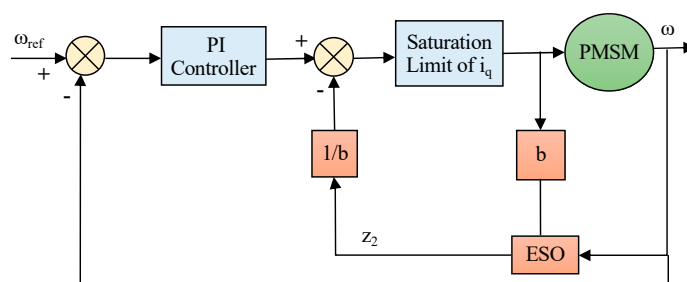


Figure 9. Basic structure of the PMSM ESO control.

4. Comprehensive Analysis

In [81], the researchers discussed the role of a H_∞ robust control strategy based on a surface permanent magnet synchronous motor vector control system. In the design of the speed controller, the LMI-based H_∞ slip surface and slide control law are constructed, and the robust H_∞ SMC speed controller is obtained, which simplifies the calculation and ensures the robustness of the speed control. In the current controller design, the H_∞ robust current controller based on HJI is designed to consider the perturbation factor, which improves the robustness of the current control topology.

As the authors have illustrated, the H_∞ robust control for the PMSM system must have good inhibition of uncertainty and external perturbation. It can improve the system stability, but it fails to properly overcome the robust performance of the system. LTR is a simple and effective way to solve the design of a robust feedback system, i.e., according to the characteristics of the accused object, pre-set the performance of the system (target transfer function) so that the design of the feedback controller and the object model in a series of open-loop transmission functions to the target transfer function. Therefore, designing a comprehensive control method of H_∞ -LTR with an observer means designing a robust H_∞ control law to meet the performance requirements of the system, thus making the target loop transfer function recover after the system is introduced into the observer [29].

In addition, the authors express that the structural uncertainty of the system makes the design of the H_∞ controller more conservative, and the μ control theory can make up for the shortcomings of the H_∞ controller [37,65]. However, by using μ theory, the mathematical calculation conditions are not satisfied. Furthermore, the convergence speed is slow. The μ - H_∞ speed controller is designed to assist in the removal of the orthogonal hypothesis of the H_∞ controller, starting with the upper boundary of the structured singular value μ ,

through the H_∞ control theory to compress the singular value. This modified controller increases the stability and robust performance of the PMSM speed regulation system [82]. Comparative analysis of different control techniques used for PMSM is given in Table 1.

Table 1. Comparative analysis of different speed control techniques used for PMSM speed regulation.

Controller	Merits	Demerits	Reference
H_∞ robust controller	<ul style="list-style-type: none"> Better load disturbance rejection capability Short settling time duration Good tracking capabilities Effectively attenuates both match and mismatch disturbance conditions 	<ul style="list-style-type: none"> Slight increase in overshoot Complexity in the drive system 	[2]
HJI based H_∞ current controller	<ul style="list-style-type: none"> Improves the robustness of current control Decreases maximum overshoot Fast tracking precision 	<ul style="list-style-type: none"> Slow convergence speed Longer settling time 	[41]
LMI based H_∞ SMC controller	<ul style="list-style-type: none"> Simplifies the calculation Ensures the robustness of speed regulation Smaller settling time Fast tracking precision 	<ul style="list-style-type: none"> System is complex Larger overshoot 	[43]
Combination of μ theory- H_∞ controller	<ul style="list-style-type: none"> Increases stability of control system and robustness performance of speed regulation Smaller overshoot 	<ul style="list-style-type: none"> Small steady-state tracking error Large settling time compared to SMC H_∞ 	[82]
H_∞ -LTR	<ul style="list-style-type: none"> Improves target loop transfer function Improves robust feedback system 	<ul style="list-style-type: none"> Larger overshoot Speed tracking errors 	[48]
PI controller	<ul style="list-style-type: none"> Easy to design Easy to implement in practical applications 	<ul style="list-style-type: none"> Longer settling time Larger overshoot Higher fluctuation in the speed 	[21]
ESO controller	<ul style="list-style-type: none"> Better dynamic response and stability than PID Perfectly appraises the lumped external and internal disturbances of the system 	<ul style="list-style-type: none"> Slow tracking efficiency and high overshooting System chattering 	[30]
SMC controller	<ul style="list-style-type: none"> Simple design structure Requires smaller maximum control Low steady state error Easy design and implementation 	<ul style="list-style-type: none"> Insufficient settling time and convergence rate 	[24]
FLC controller	<ul style="list-style-type: none"> Fast dynamic response Shorter settling time High efficiency Decreases the possibility of high-speed sagging due to immediate change occurring in load 	<ul style="list-style-type: none"> System is complex Slight overshoot 	[25]
ANN controller	<ul style="list-style-type: none"> Can model difficult functions No overshooting Can be used in several operations Significantly reduces steady state oscillation 	<ul style="list-style-type: none"> ANN methods make it difficult to relate network Constructions to physical processes 	[26]
PCC controller	<ul style="list-style-type: none"> Simple structure compared with robust controller 	<ul style="list-style-type: none"> Longer settling time Slow convergence speed 	[10]

5. Conclusions

An extensive review of different widely used robust control strategies for the speed regulation of PMSMs have been proposed in detail. Each of the control techniques is briefly described and analyzed individually. Different controllers designed with H_∞ robust control theory, i.e., a combination of μ theory- H_∞ controller, HJI based H_∞ current controller, LMI based H_∞ SMC controller, and other control methods for the speed control of PMSMs are highlighted. This paper also reviews the significant features and demerits of the previous research. The analysis of the current situation of this research area is also discussed. Later, a



comparative analysis of the different speed control techniques is tabled in detail, including their merits and demerits. It can be concluded from the comparative analysis that each technique is practically suitable for PMSM speed regulation in their own way, but some are complex in design and are costly. However, the reference analysis of the different techniques used by researchers is also highlighted. Based on the analysis, it is advised that future work focuses on the controllers that can be used in practical applications and are less costly, such as SMC, FLC, PI, and ESO controllers.

Author Contributions: K.U. designed and investigate this work and perform the analysis. A.F.M. optimize the figures and table for this work. J.G. supervise this work and improve the grammar of the manuscript. K.U. jointly wrote this manuscript and the manuscript was edited by the J.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Fan, S.; Tong, C. Model predictive current control method for PMSM drives based on an improved prediction model. *J. Power Electron.* **2020**, *20*, 1456–1466. [[CrossRef](#)]
2. Wang, W.; Shen, H.; Hou, L.; Gu, H. H_{∞} Robust Control of Permanent Magnet Synchronous Motor Based on PCHD. *IEEE Access* **2019**, *7*, 49150–49156. [[CrossRef](#)]
3. Ma, Y.; Li, Y. Active Disturbance Compensation Based Robust Control for Speed Regulation System of Permanent Magnet Synchronous Motor. *Appl. Sci.* **2020**, *10*, 709. [[CrossRef](#)]
4. Zheng, Y.; Zhao, H.; Zhen, S.; Sun, H. Fuzzy-set theory based optimal robust constraint-following control for permanent magnet synchronous motor with uncertainties. *Control Eng. Pract.* **2021**, *115*, 104911. [[CrossRef](#)]
5. Zhen, S.; Peng, X.; Liu, X.; Li, H.; Chen, Y.-H. A new PD based robust control method for the robot joint module. *Mech. Syst. Signal Process.* **2021**, *161*, 107958. [[CrossRef](#)]
6. Wu, H.; Zheng, L.; Li, Y.; Zhang, Z.; Yu, Y. Robust Control for Active Suspension of Hub-Driven Electric Vehicles Subject to in-Wheel Motor Magnetic Force Oscillation. *Appl. Sci.* **2020**, *10*, 3929. [[CrossRef](#)]
7. Pillay, P.; Krishnan, R. Modeling, simulation, and analysis of permanent-magnet motor drives. I. The permanent-magnet synchronous motor drive. *IEEE Trans. Ind. Appl.* **1989**, *25*, 265–273. [[CrossRef](#)]
8. Kim, S.-K.; Lee, J.-S.; Lee, K.-B. Robust speed control algorithm with disturbance observer for uncertain PMSM. *Int. J. Electron.* **2018**, *105*, 1300–1318. [[CrossRef](#)]
9. Sudwilai, P.; Oka, K.; Sano, A.; Hirokawa, Y. 2A12 Vibration Control with Linear Actuator Permanent Magnet System using Robust Control. In Proceedings of the Symposium on the Motion and Vibration Control, Tokyp, Japan, 17–20 August 2010; pp. _2A12-1_–_2A12-11_. [[CrossRef](#)]
10. Hassaine, S.; Moreau, S.; Ogab, C.; Mazari, B. Robust Speed Control of PMSM using Generalized Predictive and Direct Torque Control Techniques. In Proceedings of the 2007 IEEE International Symposium on Industrial Electronics, Vigo, Spain, 4–7 June 2007; pp. 1213–1218. [[CrossRef](#)]
11. Chou, H.-H.; Cheng, S.; Ting, C.-M. 2A23 H_{∞} Observer for Sensorless Velocity Control of Permanent Magnet Synchronous Motors. In Proceedings of the Symposium on the Motion and Vibration Control, Tokyp, Japan, 17–20 August 2010; pp. _2A23-1_–_2A23-10_. [[CrossRef](#)]
12. Mayo, P.; Saenz-Aguirre, A.; Martín, F.; Vadillo, J. FOC-Droop control strategy for PMSM fed paralleled multi-inverter power systems oriented to aeronautical applications. *Electr. Power Syst. Res.* **2020**, *185*, 106369. [[CrossRef](#)]
13. Wang, X.; Suh, C.S. A nonlinear time–frequency control based FOC for permanent magnet synchronous motors. *Int. J. Dyn. Control* **2020**, *9*, 179–189. [[CrossRef](#)]
14. Cai, R.; Zheng, R.; Liu, M.; Li, M. Optimal selection of PI parameters of FOC for PMSM using structured H_{∞} -synthesis. In Proceedings of the IECON 2017-43rd Annual Conference of the IEEE Industrial Electronics Society, Beijing, China, 5–8 November 2017; pp. 8602–8607. [[CrossRef](#)]
15. Zhang, W.; Cao, B.; Nan, N.; Li, M.; Chen, Y. An adaptive PID-type sliding mode learning compensation of torque ripple in PMSM position servo systems towards energy efficiency. *ISA Trans.* **2020**, *110*, 258–270. [[CrossRef](#)] [[PubMed](#)]
16. Nazelan, A.; Osman, M.K.; Samat, A.; Salim, N.A. PSO-Based PI Controller for Speed Sensorless Control of PMSM. *J. Phys. Conf. Ser.* **2018**, *1019*, 012027. [[CrossRef](#)]



17. Elhafyani, M.L.; Fadil, H. Fuzzy-PI controller applied to PMSM speed controller: Design and experimental evaluation. *Int. J. Power Electron.* **2020**, *11*, 102. [[CrossRef](#)]
18. Pyrkin, A.; Bobtsov, A.; Ortega, R.; Vedyakov, A.; Cherginets, D.; Ovcharov, A.; Petranovsky, I. Robust nonlinear observer design for permanent magnet synchronous motors. *IET Control Theory Appl.* **1994**, *2*, 524. [[CrossRef](#)]
19. Xu, D.; Gao, Y. A simple and robust speed control scheme of permanent magnet synchronous motor. *J. Control Theory Appl.* **2004**, *2*, 165–168. [[CrossRef](#)]
20. Pyrkin, A.; Vedyakov, A.; Bobtsov, A.; Bazylev, D.; Sinetova, M.; Ovcharov, A.; Vladislav, A. Adaptive Full State Observer for Nonsalient PMSM with Noised Measurements of the Current and Voltage: The work was written with the support of the Ministry of Science and Higher education of the Russian Federation, project unique identifier RFMeFI57818X0271. *IFAC-PapersOnLine* **2020**, *53*, 1652–1657. [[CrossRef](#)]
21. De Soricellis, M.; Da Ru, D.; Bolognani, S. A Robust Current Control Based on Proportional-Integral Observers for Permanent Magnet Synchronous Machines. *IEEE Trans. Ind. Appl.* **2017**, *54*, 1437–1447. [[CrossRef](#)]
22. Ahmed, W.A.E.M.; Adel, M.M.; Taha, M.; Saleh, A.A. PSO technique applied to sensorless field-oriented control PMSM drive with discretized RL-fractional integral. *Alex. Eng. J.* **2021**, *60*, 4029–4040. [[CrossRef](#)]
23. Jie, H.; Zheng, G.; Zou, J.; Xin, X.; Guo, L. Adaptive Decoupling Control Using Radial Basis Function Neural Network for Permanent Magnet Synchronous Motor Considering Uncertain and Time-Varying Parameters. *IEEE Access* **2020**, *8*, 112323–112332. [[CrossRef](#)]
24. Sheng, L.; Xiaojie, G.; Lanyong, Z. Robust Adaptive Backstepping Sliding Mode Control for Six-Phase Permanent Magnet Synchronous Motor Using Recurrent Wavelet Fuzzy Neural Network. *IEEE Access* **2017**, *5*, 14502–14515. [[CrossRef](#)]
25. Liu, X.; Zhang, Q. Robust Current Predictive Control-Based Equivalent Input Disturbance Approach for PMSM Drive. *Electronics* **2019**, *8*, 1034. [[CrossRef](#)]
26. Girovský, P. Fuzzy control of synchronous motor with permanent magnet. *Acta Electrochim. Inform.* **2016**, *16*, 17–20. [[CrossRef](#)]
27. Yang, J.-Z.; Li, Y.-X.; Tong, S. Adaptive NN finite-time tracking control for PMSM with full state constraints. *Neurocomputing* **2021**, *443*, 213–221. [[CrossRef](#)]
28. Zaihidee, F.M.; Mekhilef, S.; Mubin, M. Robust Speed Control of PMSM Using Sliding Mode Control (SMC)—A Review. *Energies* **2019**, *12*, 1669. [[CrossRef](#)]
29. Pewmaikam, C.; Srisertpol, J.; Khajorntraidet, C. Adaptive Fuzzy Logic Compensator for Permanent Magnet Synchronous Motor Torque Control System. *Int. J. Model. Optim.* **2012**, *2*, 141–146. [[CrossRef](#)]
30. Xiong, J.; Gu, H. Research on a Sliding Mode Variable Structure Control FOC of PMSM for Electric Vehicles. In Proceedings of the 2018 IEEE 9th International Conference on Software Engineering and Service Science (ICSESS), Beijing, China, 23–25 November 2018; pp. 1088–1091.
31. Ma, X.; Zhang, J.; Huang, R. Disturbance observer based adaptive sliding mode controllers for fuzzy systems with mismatched disturbance. In Proceedings of the 2016 35th Chinese Control Conference (CCC), Chengdu, China, 27–29 July 2016; pp. 3391–3396. [[CrossRef](#)]
32. Wang, Y.; Yu, H.; Che, Z.; Wang, Y.; Zeng, C. Extended State Observer-Based Predictive Speed Control for Permanent Magnet Linear Synchronous Motor. *Processes* **2019**, *7*, 618. [[CrossRef](#)]
33. Jon, R.; Wang, Z.; Luo, C.; Jong, M. Adaptive robust speed control based on recurrent elman neural network for sensorless PMSM servo drives. *Neurocomputing* **2017**, *227*, 131–141. [[CrossRef](#)]
34. Benfriha, E.; Mansouri, A.; Bendiabdellah, A.; Boufadene, M. Nonlinear adaptive observer for sensorless passive control of permanent magnet synchronous motor. *J. King Saud Univ.-Eng. Sci.* **2019**, *32*, 510–517. [[CrossRef](#)]
35. Zhao, N.; Ge, B.-M. H_{∞} robust control of permanent magnet synchronous motor used in electric vehicle. *Electr. Mach. Control* **2007**, *5*, 462–466.
36. Zhou, B.; Xia, Y. H_{∞} control for speed control of permanent magnet synchronous motor based on Matlab. In Proceedings of the 2012 International Conference on System Simulation (ICUSS 2012), Shanghai, China, 12–15 June 2012; p. 147. [[CrossRef](#)]
37. Gambhire, S.J.; Kishore, D.R.; Londhe, P.S.; Pawar, S.N. Review of sliding mode based control techniques for control system applications. *Int. J. Dyn. Control* **2020**, *9*, 363–378. [[CrossRef](#)]
38. Majidabad, S.S.; Zafari, Y. Robust flux observer and robust block controller design for interior permanent magnet synchronous motor under demagnetisation fault. *Int. J. Model. Identif. Control* **2018**, *30*, 206. [[CrossRef](#)]
39. Lee, Y.; Lee, S.-H.; Chung, C.C. LPV H_{∞} Control with Disturbance Estimation for Permanent Magnet Synchronous Motors. *IEEE Trans. Ind. Electron.* **2017**, *65*, 488–497. [[CrossRef](#)]
40. Liu, B. Research on H infinity Robust Tracking Controller for Permanent Magnet Synchronous Motor Servo System. In Proceedings of the 2009 International Conference on Information Engineering and Computer Science, Wuhan, China, 31 March–2 April 2009; pp. 1–5.
41. Vadivel, R.; Joo, Y.H. Reliable fuzzy H_{∞} control for permanent magnet synchronous motor against stochastic actuator faults. *IEEE Trans. Syst. Man Cybern. Syst.* **2019**. [[CrossRef](#)]
42. Mousavi, M.H.; Karami, M.E.; Ahmadi, M.; Sharafi, P.; Veysi, F. Robust speed controller design for permanent magnet synchronous motor based on gain-scheduled control method via LMI approach. *SN Appl. Sci.* **2020**, *2*, 1–15. [[CrossRef](#)]

43. Khodamoradi, A.; Heydari, M.; Hasanzadeh, S. Design of Robust H_∞ Controller based on Nonlinear Observer for Sensorless PMSM using LMIs. In Proceedings of the 7th International Conference on Control, Instrumentation and Automation (ICCIA), Tabriz, Iran, 23–24 February 2021. [\[CrossRef\]](#)
44. Ghafarri-Kashani, A.R.; Yazdanpanah, M.J.; Faiz, J. Robust speed control of pmsm using mixed nonlinear h_∞ /smc techniques. *IEAC Proc.* **2008**, *41*, 8413–8418. [\[CrossRef\]](#)
45. Huang, G.; Li, J.; Fukushima, E.F.; Zhang, C.; He, J.; Zhao, K. An improved equivalent-input-disturbance approach for PMSM drive with demagnetization fault. *ISA Trans.* **2020**, *105*, 120–128. [\[CrossRef\]](#)
46. Choi, J.; Nam, K.; Bobtsov, A.; Pyrkin, A.; Ortega, R. Robust Adaptive Sensorless Control for Permanent-Magnet Synchronous Motors. *IEEE Trans. Power Electron.* **2016**, *32*, 3989–3997. [\[CrossRef\]](#)
47. Lee, H.; Lee, Y.; Shin, D.; Chung, C.C. H_∞ control based on LPV for load torque compensation of PMSM. In Proceedings of the 2015 15th International Conference on Control, Automation and Systems (ICCAS), Busan, Korea, 13–16 October 2015. [\[CrossRef\]](#)
48. Yang, J.; Fa, N.; Chen, R. H_∞ Robust Controller Based on Local Feedback Recurrent Neural Network for Permanent Magnet Linear Synchronous Motor. In Proceedings of the 2006 CES/IEEE 5th International Power Electronics and Motion Control Conference, Shanghai, China, 14–16 August 2006. [\[CrossRef\]](#)
49. Mesloub, H.; Boumaaraf, R.; Benchouia, M.; Goléa, A.; Goléa, N.; Srairi, K. Comparative study of conventional DTC and DTC_SVM based control of PMSM motor—Simulation and experimental results. *Math. Comput. Simul.* **2018**, *167*, 296–307. [\[CrossRef\]](#)
50. Kung, Y.-S.; Thanh, N.P.; Wang, M.-S. Design and simulation of a sensorless permanent magnet synchronous motor drive with microprocessor-based PI controller and dedicated hardware EKF estimator. *Appl. Math. Model.* **2015**, *39*, 5816–5827. [\[CrossRef\]](#)
51. Kuz'Menko, A.A. Robust Control of Permanent Magnet Synchronous Motor: Synergetic Approach. *Mehatronika Avtom. Upr.* **2020**, *21*, 480–488. [\[CrossRef\]](#)
52. Ye, S. Design and performance analysis of an iterative flux sliding-mode observer for the sensorless control of PMSM drives. *ISA Trans.* **2019**, *94*, 255–264. [\[CrossRef\]](#) [\[PubMed\]](#)
53. Yuan, G.; Zuo, M. Improved PMSM speed control based on a novel sliding-mode load disturbance observer. In Proceedings of the 2019 22nd International Conference on Electrical Machines and Systems (ICEMS), Harbin, China, 11–14 August 2019; pp. 1–5. [\[CrossRef\]](#)
54. Lu, E.; Li, W.; Wang, S.; Zhang, W.; Luo, C. Disturbance rejection control for PMSM using integral sliding mode based composite nonlinear feedback control with load observer. *ISA Trans.* **2021**, *116*, 203–217. [\[CrossRef\]](#) [\[PubMed\]](#)
55. Wu, S.; Zhang, J. A Terminal Sliding Mode Observer Based Robust Backstepping Sensorless Speed Control for Interior Permanent Magnet Synchronous Motor. *Int. J. Control Autom. Syst.* **2018**, *16*, 2743–2753. [\[CrossRef\]](#)
56. Siddhapura, K.; Jadeja, R. Design and Simulink Modelling of an Adaptive Gain Variation Sliding-Model Control Algorithm for Sensorless Permanent Magnet Synchronous Motor Drive. *Mater. Today Proc.* **2018**, *5*, 596–609. [\[CrossRef\]](#)
57. Liu, Y.; Zhou, B.; Fang, S. Sliding mode control of PMSM based on a novel disturbance observer. In Proceedings of the 2009 4th IEEE Conference on Industrial Electronics and Applications, Xi'an, China, 25–27 May 2009; pp. 1990–1994. [\[CrossRef\]](#)
58. Jiang, D.; Yu, W.; Wang, J.; Zhao, Y.; Li, Y.; Lu, Y. A Speed Disturbance Control Method Based on Sliding Mode Control of Permanent Magnet Synchronous Linear Motor. *IEEE Access* **2019**, *7*, 82424–82433. [\[CrossRef\]](#)
59. Li, Y.; Zhang, B.; Xu, X. Robust control for permanent magnet in-wheel motor in electric vehicles using adaptive fuzzy neural network with inverse system decoupling. *Trans. Can. Soc. Mech. Eng.* **2018**, *42*, 286–297. [\[CrossRef\]](#)
60. Zheng, Y.; Zhao, H.; Zhen, S.; He, C. Designing Robust Control for Permanent Magnet Synchronous Motor: Fuzzy Based and Multivariable Optimization Approach. *IEEE Access* **2021**, *9*, 39138–39153. [\[CrossRef\]](#)
61. Bouguenna, I.F.; Azaiz, A.; Tahour, A.; Larbaoui, A. Robust neuro-fuzzy sliding mode control with extended state observer for an electric drive system. *Energy* **2018**, *169*, 1054–1063. [\[CrossRef\]](#)
62. Lakshmipriya, N.; Ananthamoorthy, N.; Ayyappan, S.; Hema, P. An intelligent fuzzy PI controller based 33 level switched capacitor multilevel inverter for PMSM drives. *Mater. Today Proc.* **2021**, *45*, 2861–2866. [\[CrossRef\]](#)
63. Ma, J.; Zhao, J.; Sun, J.; Yan, C. A novel PMSM speed control scheme based on sliding-mode and fuzzy disturbance observer. In Proceedings of the IECON 2017-43rd Annual Conference of the IEEE Industrial Electronics Society, Beijing, China, 29 October–1 November 2017; pp. 1704–1710. [\[CrossRef\]](#)
64. El-Sousy, F. Robust adaptive H_∞ position control via a wavelet-neural-network for a DSP-based permanent-magnet synchronous motor servo drive system. *IET Electr. Power Appl.* **2010**, *4*, 333–347. [\[CrossRef\]](#)
65. Lin, C.-H.; Wu, R.-J. Modified Elman neural network control for PMSM direct-driven PMSG/Battery renewable energy system. In Proceedings of the 2013 IEEE 10th International Conference on Power Electronics and Drive Systems (PEDS), 22–25 April 2013; pp. 651–656. [\[CrossRef\]](#)
66. El-Sousy, F.F. Intelligent optimal recurrent wavelet Elman neural network control system for permanent-magnet syn-chronous motor servo drive. *IEEE Trans. Ind. Inform.* **2012**, *9*, 1986–2003. [\[CrossRef\]](#)
67. Ghamri, A.; Boumaaraf, R.; Benchouia, M.; Mesloub, H.; Goléa, A.; Goléa, N. Comparative study of ANN DTC and conventional DTC controlled PMSM motor. *Math. Comput. Simul.* **2019**, *167*, 219–230. [\[CrossRef\]](#)
68. Lin, F.-J.; Tan, K.-H.; Tsai, C.-H. Improved differential evolution-based Elman neural network controller for squirrel-cage induction generator system. *IET Renew. Power Gener.* **2016**, *10*, 988–1001. [\[CrossRef\]](#)

69. Song, W.; Gang, Y.; Zhi-Jian, Q.; Shuang-shuang, S.; Chao, C. Identification of PMSM based on EKF and elman neural network. In Proceedings of the 2009 IEEE International Conference on Automation and Logistics, Shenyang, China, 5–7 August 2009; pp. 1459–1463.
70. Tety, P.; Konate, A.; Asseu, O.; Soro, E.; Yoboue, P.; Kouadjo, A.R. A Robust Extended Kalman Filter for Speed-Sensorless Control of a Linearized and Decoupled PMSM Drive. *Engineering* **2015**, *7*, 691–699. [[CrossRef](#)]
71. He, C.; Hu, J.; Li, Y. Robust cascade-free predictive speed control for PMSM drives based on Extended State Observer. *IET Electr. Power Appl.* **2021**, *15*, 214–230. [[CrossRef](#)]
72. Xia, P.; Deng, Y.; Wang, Z.; Li, H. Speed Adaptive Sliding Mode Control with an Extended State Observer for Permanent Magnet Synchronous Motor. *Math. Probl. Eng.* **2018**, *2018*, 1–13. [[CrossRef](#)]
73. Qian, J.; Xiong, A.; Ma, W. Extended State Observer-Based Sliding Mode Control with New Reaching Law for PMSM Speed Control. *Math. Probl. Eng.* **2016**, *2016*, 1–10. [[CrossRef](#)]
74. Liu, B. Speed control for permanent magnet synchronous motor based on an improved extended state observer. *Adv. Mech. Eng.* **2018**, *10*, 168781401774766. [[CrossRef](#)]
75. Herbst, G. A Simulative Study on Active Disturbance Rejection Control (ADRC) as a Control Tool for Practitioners. *Electronics* **2013**, *2*, 246–279. [[CrossRef](#)]
76. Zhao, Y.; Liu, X.; Zhang, Q. Predictive Speed-Control Algorithm Based on a Novel Extended-State Observer for PMSM Drives. *Appl. Sci.* **2019**, *9*, 2575. [[CrossRef](#)]
77. Rifaq, M.S.; Nguyen, A.T.; Choi, H.H.; Jung, J.-W. A Robust High-Order Disturbance Observer Design for SDRE-Based Suboptimal Speed Controller of Interior PMSM Drives. *IEEE Access* **2019**, *7*, 165671–165683. [[CrossRef](#)]
78. Liu, H.; Li, S. Speed Control for PMSM Servo System Using Predictive Functional Control and Extended State Observer. *IEEE Trans. Ind. Electron.* **2011**, *59*, 1171–1183. [[CrossRef](#)]
79. Zhang, Y.; Jin, J.; Huang, L. Model-Free Predictive Current Control of PMSM Drives Based on Extended State Observer Using Ultra-Local Model. *IEEE Trans. Ind. Electron.* **2020**, *68*, 993–1003. [[CrossRef](#)]
80. El-Sousy, F.F.M.; Amin, M.; Mohammed, O.A. Adaptive H_∞ -Based Variable Structure Control for Permanent-Magnet Synchronous Motor-Driven Uncertain Linear Stage via Self-Learning Recurrent Fuzzy-Wavelet-Neural-Network. In Proceedings of the 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA, 29 September–3 October 2019; pp. 4069–4076.
81. Cheng, S.; Huang, Y.-Y.; Chou, H.-H.; Ting, C.-M.; Chang, C.-M.; Chen, Y.-M. PDFF and H_∞ Controller Design for PMSM Drive. In *Novel Algorithms and Techniques in Telecommunications, Automation and Industrial Electronics*; Springer: Dordrecht, The Netherlands, 2008; pp. 237–241. [[CrossRef](#)]
82. Xie, L. Output feedback H_∞ control of systems with parameter uncertainty. *Int. J. Control* **1996**, *63*, 741–750. [[CrossRef](#)]

