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Review

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

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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.

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

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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].

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

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

$$\dot{E}(x) = x^{T}Ax + x^{T}B\left\{-B^{-1}\left[A_{2}x + \frac{1}{2}\left(1 + \frac{1}{\gamma^{2}}\right)x\right]\right\} \tag{2}$$

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

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].

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

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

$$\dot{x}' = A'x' + B'u' + M'\delta \tag{5}$$

$$y' = C'x' \tag{6}$$

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:

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

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

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

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

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.

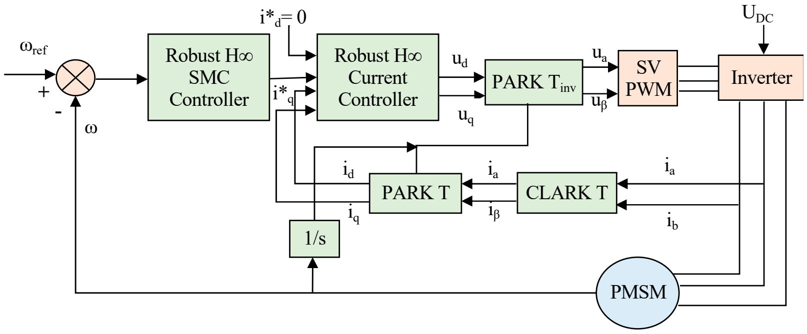

Figure 1. Principal diagram of PMSM speed regulation based on H∞ robust controller.

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.

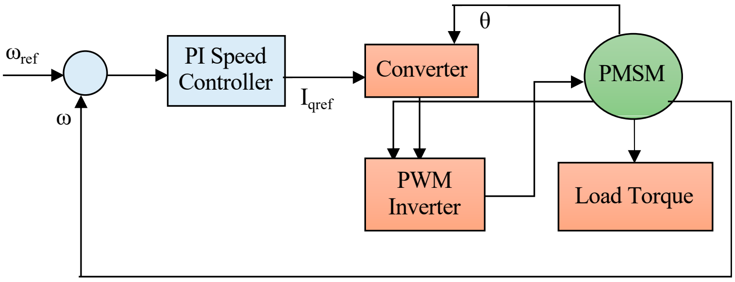

Figure 2. Basic structure of PMSM PI controller.

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.

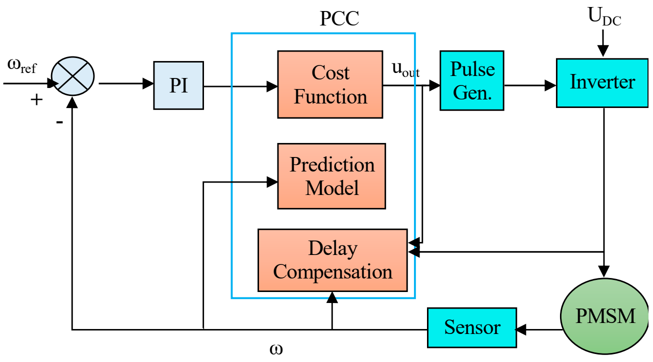

Figure 3. Basic structure of the PMSM PCC control.

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:

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

the sliding surface is given as:

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

and the SMC output can be described as:

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

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

$$sgn(S) = \begin{array}{l} +1\ if\ s > 0 \\ -1\ if\ s < 0 \end{array}$$

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.

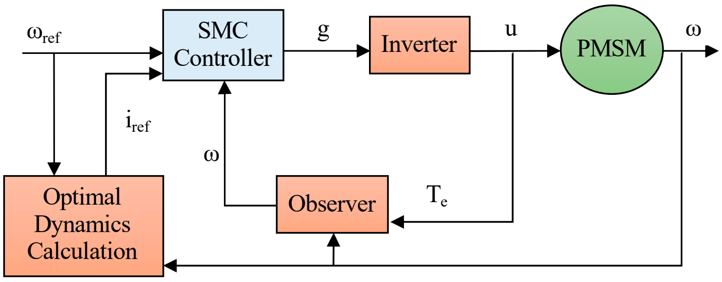

Figure 4. Basic structure of the PMSM SMC control.

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.

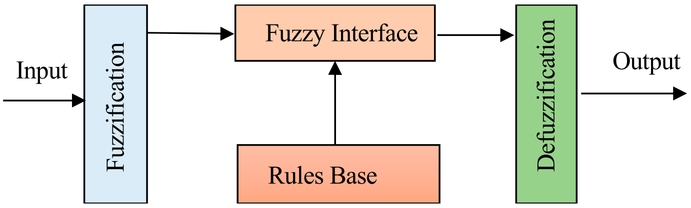

Figure 5. Basic structure of FLC.

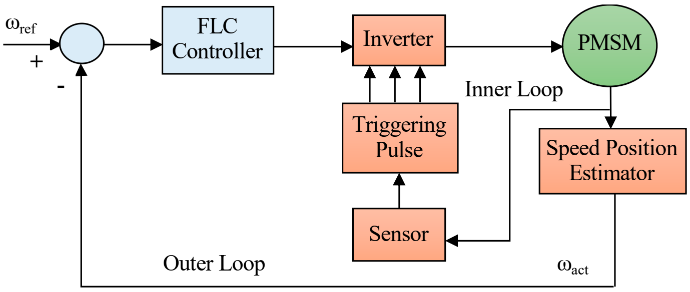

Figure 6. Basic structure of the PMSM FLC control.

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].

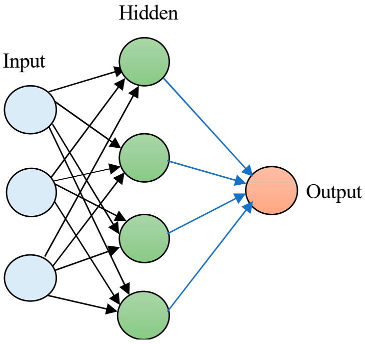

Figure 7. Structure of ANN layers.

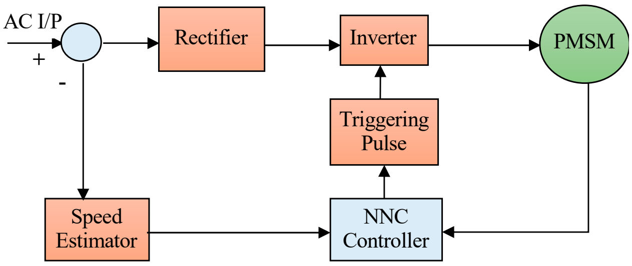

Figure 8. Basic structure of the PMSM NNC control.

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.

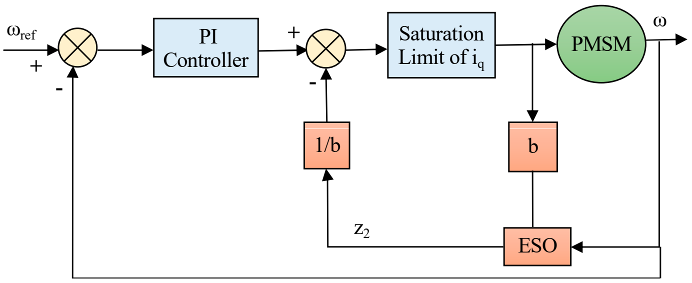

Figure 9. Basic structure of the PMSM ESO control.

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	• Better load disturbance rejection capability • Short settling time duration • Good tracking capabilities • Effectively attenuates both match and mismatch disturbance conditions	• Slight increase in overshoot • Complexity in the drive system	[2]
HJI based H∞ current controller	• Improves the robustness of current control • Decreases maximum overshoot • Fast tracking precision	• Slow convergence speed • Longer settling time	[41]
LMI based H∞ SMC controller	• Simplifies the calculation • Ensures the robustness of speed regulation • Smaller settling time • Fast tracking precision	• System is complex • Larger overshoot	[43]
Combination of μ theory-H∞ controller	• Increases stability of control system and robustness performance of speed regulation • Smaller overshoot	• Small steady-state tracking error • Large settling time compared to SMC H∞	[82]
H∞-LTR	• Improves target loop transfer function • Improves robust feedback system	• Larger overshoot • Speed tracking errors	[48]
PI controller	• Easy to design • Easy to implement in practical applications	• Longer settling time • Larger overshoot • Higher fluctuation in the speed	[21]
ESO controller	• Better dynamic response and stability than PID • Perfectly appraises the lumped external and internal disturbances of the system	• Slow tracking efficiency and high overshooting • System chattering	[30]
SMC controller	• Simple design structure • Requires smaller maximum control • Low steady state error • Easy design and implementation	• Insufficient settling time and convergence rate	[24]
FLC controller	• Fast dynamic response • Shorter settling time • High efficiency • Decreases the possibility of high-speed sagging due to immediate change occurring in load	• System is complex • Slight overshoot	[25]
ANN controller	• Can model difficult functions • No overshooting • Can be used in several operations • Significantly reduces steady state oscillation	• ANN methods make it difficult to relate network • Constructions to physical processes	[26]
PCC controller	• Simple structure compared with robust controller	• 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.

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