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A Comprehensive Review of Fractional-Order Control Strategies for Permanent Magnet Synchronous Motors

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Abstract
Permanent Magnet Synchronous Motors (PMSMs) are widely used in high-performance applications due to their superior efficiency, high power density, and precise control capabilities. However, the complex nonlinear dynamics and parameter sensitivities of PMSMs present significant challenges for traditional control strategies. In recent years, fractional-order control (FOC) methods have emerged as powerful alternatives, offering enhanced flexibility and robustness by extending classical integer-order calculus to non-integer (fractional) domains. This paper presents a comprehensive review of fractional-order control strategies applied to PMSM systems. The review encompasses a detailed analysis of various FOC techniques, including Fractional-Order Proportional-Integral-Derivative (FOPID) controllers, sliding mode controllers, and adaptive fractional controllers. Key performance metrics such as torque ripple reduction, speed regulation, disturbance rejection, and energy efficiency are discussed in the context of fractional-order implementations. Furthermore, the paper explores recent trends in hybrid and intelligent control approaches that integrate fractional-order modeling with artificial intelligence and optimization algorithms. Challenges in real-time implementation, tuning complexity, and computational cost are also addressed. This review aims to provide researchers and practitioners with critical insights into the current state and future potential of fractional-order control for PMSM drives.

Keywords: PMSM, FOC, Fractional-Order Proportional-Integral, Matlab Simulink

I. Introduction

Advancements in permanent magnet (PM) materials with increased thermal concentration has resulted in significant developments in DC machines with PM field excitation. By replacing electromagnetic poles with permanent magnets, the size and efficiency of machines have improved. Similarly, synchronous machines have adopted PM poles, leading to the evolution of Constant Magnetic Synchronisation Machines (PMSMs). Additionally, advancements in switching power electronic devices have facilitated the transition from mechanical commutators with slip rings and brushes to electronic commutators using inverters. In PMSMs, the armature has been shifted to the stator, enhancing cooling and enabling higher voltage operation. Meanwhile, the field excitation, now in the form of PMs, resides on the rotor. These structural improvements provide several advantages, including smaller dimensions, enhanced economy, and an exceptional torque to weight proportion, & reduced maintenance requirements. Consequently, PMSMs have gained widespread application in industries including robotics, machine tools, home appliances, defense, and security. Despite these advantages, PMSMs present challenges in controller development due to their nonlinear mathematical modeling. The primary control strategy employed for PMSMs is Coordinate management, sometimes referred to as Field-Oriented Management (FOC). This entails an inverted controlling scheme including an internal electrical looping featuring two regulators & an external velocity looping featuring an extra processor. Fractional-ordered controlling is an advanced controlling methodology that enhances the performance of conventional integer-order control systems. The fractional-order approach provides greater flexibility and robustness in closed-loop control structures, allowing for improved system response and disturbance rejection. Fractionally calculus generalizes integer- facilitate calculation by permitting integration & differentiation of non-integrating ordering. Conventional proportional-integral (PI) controllers, also known as integer-order PI (IOPI) controllers, feature two tuning parameters: Corresponding benefit (Kp) and essential benefit (Ki) are essential components in control system design. The transferring behave associated with an ordinary Proportional-Integral (PI) supervisor. In contrast, fractionally-ordering P.I (FOPI) controllers incorporate a fractionally-ordering integrity term, where is a fractional-order parameter. This additional parameter enhances controller tuning capabilities, enabling greater robustness against disturbances and improving system performance. In many practical applications, transection performance is critical. The Combined Unpredictable Assistance (CNF) controller is designed to achieving optimal transient responses by dynamically adjusting the damping ratio based on the error magnitude. The CNF the controllers consists of a proportional comments legislation alongside an unpredictable comments legislation. When the error is large, the linear law dominates, resulting in a lower damping ratio and faster rise time. As the error decreases, the nonlinear law becomes more influential, increasing the damping ratio and reducing overshoot. This research explores enhancing the CNF controller using the Mittag Leffler operates (MLF) in the context of partial calculation. Unlike the conventional exponential function, which maintains a constant slope, MLF dynamically adjusts the slope based on the error, providing additional flexibility in damping ratio control.

II. PMSM Control Strategies

PMSMs are typically controlled using Vertical controlling (Field Oriented Management, Fss) or Directly Thrust Controlling (DTC). Field-Oriented Control (FOC) decouples the torque & flux components, providing precise speed control and reducing torque ripples. Directed Tension Controlling (DTC) regulates tension & fluxes immediately; yet, it is plagued by significant tension rippling and fluctuations in changing frequencies. Several studies have explored the enhancement of PMSM control through modifications of traditional PI controllers, observer-based methods, and predictive strategies.

Emerging Control Strategies

Sliding Mode Control (SMC): Offers high robustness against disturbances but introduces chattering effects, which can affect PMSM durability.

Model Predictive Control (MPC): Allows optimal torque regulation but suffers from high computational complexity.

Adaptive Control Techniques: Utilize parameter estimation to adjust controller gains dynamically, improving robustness under load variations.

Despite advancements, conventional integer-order controllers like PI and PID lack adaptability in handling complex nonlinear PMSM dynamics. This limitation has led to fractional-order control methodologies, which provide superior performance and enhanced robustness.

III. Non-linear Model and Control for PMSM

Due to its benefits, PMSM is becoming more and more well-liked in the market. Thus, it is crucial to thoroughly examine how the motor operates. Its features and structure are distinctive. Two important sources for researching this motor are [1] and [12], which offered a solid foundation for creating controllers for it. [1] provides an explanation of the non-linear mathematical model. The fundamental diagram and workings of a PMSM with Hall sensors are described in [2]. The rotating of a P.M.S.M is a permanently magnetic, while the stator windings are three-phase [12] [13].

The backed E.M.F waveformed of brushless machine are the primary basis for classification [12]. These motors come in two varieties: sinusoidal (also called PMSM) and trapezoidal (also called BLDC). Consequently, different control measures will be used. The signals required for commutation are produced six times during an electrical cycle by Hall sensors. Position data must always be accessible in the PMSM drive system in order to provide orders for sinusoidal current. The BLDC motor per phase can be mathematically modeled similarly to brush D.C. Similar to A.C. synchronous motors, PMSM can be mathematically modeled [1]. In order to determine control, the PMSM algorithms use the intricate theory of Park and Clarke transformation [16] [17] [18]. Since the sinusoidal change of injected voltage is expected, advanced inverter control techniques like Space Vector Modulation [1] [19] [20] are required for PMSM motor control. Brushless DC motors can use direct torque control, and comparisons with traditional current control demonstrate that torque ripple is decreased [21] [22]. Vector control is the most effective control approach for this model [1]. Three loops make up a vector-controlled speed drive's typical structure. The d-axis and q- axis currents make up the inner current loop. The speed loop is located outside. The literature offers a variety of methods for controller design. It is customary to simply take into account the mechanical time constant for the outer loop and ignore the electrical time constant for the inner current loop. With such a reduced model, the fractional-order PI (FOPI) controller for PMSM is predicated on numerous assumptions and solely takes the inertia constant into account [23].

IV. FRACTIONAL-ORDER CONTROL APPROACHES

The need for improved controller performance is constant in the field of control engineering. As a result, the goal of creating better and simpler controllers never stops. The controller's performance has significantly increased since fractional-order was used in its development. Numerous controllers that employ fractional-order to improve upon the traditional integer-order controller has been documented in the literatures. Fractionalized-ordering controllers has been used more frequently lately. When compared to traditional integer-order control, fractional-order (FO) control performs better. [26] provides excellent explanations of fundamental theory and a variety of fractional-order control exercises. For motion control, a fractional-order controller is described in [37] [38] [39] [40]. In [41], A complete management methodology for mechanical devices utilising fractionalized-ordering approximations is introduced. In [42], a fractionalized-ordering reliable regulation (FO-RC) method was devised to mitigate the cogged impact in the orientation & acceleration feedback systems featuring permanently magnetic synchronised actuators (PMSM) is described. Other controllers include FO optimum control, FO sliding mode control [43], FO adaptive control [31], FO feedback control, fractional-order lead-lag compensators, and many more. The FOPI structure for PMSM is established using the fractional-order disturbance rejection controller (FODRC) in [44].

In [46], model-free tuning techniques for the FOPI controller for PMSM are described. It is suggested in [47] to use Fractionalised ordering movable modal management using PID movable surfaces layout. Fractional calculus is used by FOSMC to reduce chattering. suggests an adaptive FOPI controller for PMSM that is data- driven [48].

The largest prevalent processor in the business at the moment is the P.I.D (proportional integral and derivative) controller. Its simplicity, resilience, and accessibility of straightforward and efficient techniques for adjusting the controller's parameters account for its widespread use. Fractional-order PID control becomes P I D by adding fractional-order for integral and derivative controllers. The most challenging issue is putting FO into practice, even if it is theoretically obvious that doing so improves system performance. Despite the existence of certain hardware devices, such as fractalness and factors, tuning these devices is limited.

Using finite- dimensional IO transfer functions is another workable method of implementing FO controllers [57]. FO operator s} is infinite- dimensional in theory. For real-world applications, the band-limited finite-dimensional approximation is more useful. A suitable and distinct range of frequencies should be chosen for practical use. Numerous approximation approaches have been put forth. Both digital and analog realizations are possible for these methods.

Fractional-order controllers offer greater flexibility by introducing additional tuning parameters that improve robustness and disturbance compensation. The Fractionalised-Ordering Proportional-Integral & Fractionalised-Ordering Proportional-Integral-Derivative processors have gained widespread attention due to their superior performance in PMSM applications.

Table 1 Comparative between Fractionalised-Ordering vs Integrating-Ordering Processors.

Controller Type	Advantages	Limitations
Integer-Order PI/PID	Simplicity, easy tuning	Poor adaptability to dynamic variations
Fractional-Order PI (FOPI)	Enhanced disturbance rejection, better transient response	Requires complex parameter tuning
Fractional-Order PID (FOPID)	Superior stability and robustness	Computational complexity

Fractionalized-ordering controllers can be tuned using methods such as: Bode Plot Intersection Method (ensuring iso-damping properties). Nyquist-Based Robustness Index Approach (minimizing integral errors). Optimization via Genetic Algorithms (achieving optimal control performance). Studies show that fractional-order controllers provide faster settling times and reduced overshoot, making them ideal for PMSM speed control application.

V. Conclusion

Based on the review of literature, it can be observed that the whole system's fluctuations ought to be recorded.in the modeling for controller design in order to enhance PMSM control performance. According to the literature, traditional controller design relies on a simplified model that is predicated on numerous assumptions, hence restricting the controller's performance. As a result, creating an accurate PMSM model is essential for controller design. The three loops of conventional vector control, commonly referred to as Field Oriented Control (FOC), are the speed loop on the outside and the two current loops on the inside. These three loops—the speed loop, the d-axis current loop, and the q-axis current loop—all require three PI controllers. The literature review has revealed that the controller is solely intended for speed or current loops. Using fractional-order PI controllers for each of these three PI controllers can enhance system performance. Designing all three FOPI controllers will involve complexity and it is a challenging task.

One potential controller strategy to improve the structure's transitory efficiency is compounded irregular comments management (CNF). A especially noteworthy characteristic of this principle, stemming into the irregular controlling legislation, is the dynamical alteration of the dampening proportion. This The exponentially operation, a specific case of the Mittag-Leffler functional (MLF), is utilised in irregular controlling regulations. This research aims to examine this distinctive functionality to improve the method's transient response.

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