Advanced Electrical Motors and Control Strategies for High-quality Servo Systems - A Comprehensive Review*

Ming Cheng[1*], *Jiawei Zhou*[1], *Wei Qian*[2], *Bo Wang*[1], *Chenchen Zhao*[1] *and Peng Han*[3]

(1. School of Electrical Engineering, Southeast University, Nanjing 210096, China;

2. ESTUN Automation Co., Ltd., Nanjing 211106, China;

3. Ansys, Inc., San Jose, CA 95134, USA)

Abstract: Recent technological advancements have propelled remarkable progress in servo systems, resulting in their extensive utilization across various high-end applications. A comprehensive review of high-quality servo system technologies, focusing specifically on electrical motor topologies and control strategies is presented. In terms of motor topology, this study outlines the mainstream servo motors used across different periods, as well as the latest theories and technologies surrounding contemporary servo motors. In terms of control strategies, two well-established approaches are presented: field-oriented control and direct torque control. Additionally, it discusses advanced control strategies employed in servo systems, such as model predictive control (MPC) and fault tolerance control, among others.

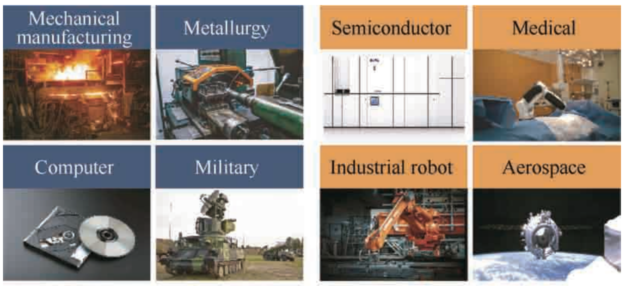
Keywords: Servo system, servo motor, control strategy, magnetic field modulation

1 Introduction

The early 20th century witnessed the influential contributions of three notable studies: Minorsky's "Directional stability of automatically steered bodies," Nyquist's "Regeneration theory," and Hazen's "Theory of servomechanisms" [1-3]. These studies laid the conceptual foundations for feedback control systems and played a crucial role in the emergence of servo systems, referred to as "servomechanisms" during that era. Consequently, the terms and concepts of servomechanisms permeated the discourse of the 1940s. A significant milestone occurred in 1948 with the publication of Brown and Campbell's monograph, "Principles of Servomechanisms," marking a significant step towards the maturation of servo systems [4].

During the initial developmental stages, servo systems were primarily utilized in manufacturing industries such as mechanical manufacturing and metallurgy. Then, the demand for high-performance military equipment escalated during World War II, leading to extensive applications of servo systems in this domain. Additionally, servo systems played a critical role in operating optical drives, which served as integral components of traditional computer systems.

In recent years, the promotion and adoption of servo products has led to substantial growth in the global servo system market. Projections suggest a market rise from \$12.2 billion in 2022 to approximately \$16.2 billion by 2028 [5]. Servo systems have not only expanded their presence in traditional sectors but have also made significant inroads into high-end industries. These industries encompass aerospace, medical equipment, industrial robotics, and semiconductor devices, as shown in Fig. 1.



(a) Traditional applications (b) Advanced applications

Fig. 1 Applications of servo systems

Manuscript received August 17, 2023; revised October 9, 2023; accepted November 13, 2023. Date of publication March 31, 2024; date of current version December 1, 2023.

* Corresponding Author, E-mail: mcheng@seu.edu.cn

* Supported by the National Natural Science Foundation of China under Major Project 51991380.

Digital Object Identifier: 10.23919/CJEE.2023.000048

Early servo systems were large mechanical systems that typically utilized rotary transformers or tacho-generator to obtain essential signals, such as angle, speed and other signals required in closed-loop control. Subsequently, control signals were generated by amplifiers to regulate the rotation of the servo motor [6]. During this stage, to achieve accurate control performance, brushed DC motors (BDCMs) (with linearized mechanical characteristics) or stepping motors (SMs) were preferred [7]. Additionally, in some fast-response applications, special motors with small electrical and mechanical time constants, such as cup-rotor induction motors (IMs), were also commonly selected [8].

With the evolution of control methods, particularly field-oriented control (FOC) and direct torque control (DTC), bulky mechanical speed control systems have been replaced by smaller and faster digital controllers [9]. Simultaneously, advancements in servo motor technology have shifted toward brushless and permanent magnetization, with brushless DC motors (BLDCMs) [10] and permanent magnet (PM) synchronous motors (PMSMs) [11] emerging as mainstream products in the middle and high-end markets.

However, advances in servo systems have not plateaued at this point, with high-end applications imposing even greater demands on these systems. For instance, lithography machines necessitate rapid and precise responses from linear servo motors, demanding a precision level at the nanometer scale [12]. Spacecraft docking, comprising of servo systems with over twenty servo motors, require not only precision and stable performance but also compact motor size and limited motor weight [13]. Consequently, researchers are compelled to pursue higher-quality servo systems to improve key technical parameters, as outlined below [14-16].

① High torque/power density.② Low-torque/ speed ripples. ③ Overload capability. ④ Wide speed range. ⑤ Fast response and wide bandwidth. ⑥ Robustness and disturbance rejection. ⑦ Fault diagnosis and fault-tolerant control (FTC).

In recent years, numerous servomotor topologies and control algorithms have emerged to satisfy these requirements. The wide variety of available options can be overwhelming, especially for newcomers to the field. Therefore, this study aims to present a comprehensive review of pertinent servo system technologies in terms of both motor topology and control strategy, offering valuable insights and guidance for both researchers and practitioners.

A general classification map of electrical motors used in servo systems is presented in Fig. 2, categorizing the topologies into three segments: conventional, advanced, and emerging types. Conventional motors include those extensively employed in early electrical servo systems, such as the BDCM, SM, IM, and hysteresis motor (HM). These motors have a long history of utilization in servo systems, still finding preference in select applications. Advanced motors include the most prominent options presently deployed in servo systems, namely BLDCMs and PMSMs. With the further development of the electrical motor theory in recent years, field-modulated motors, including vernier PM motors (VPMMs), flux-switching PM motors (FSPMMs), and flux-reversal PM motors (FRPMMs), represent promising options for future servo systems. Although not widely adopted in modern servo systems presently, these motors demonstrate superior performance compared with conventional motors, indicating their potential as future trends. Additionally, special motors such as precise direct-driven motors and multi-degree-of-freedom (multi-DOF) motors have also attracted considerable attention from researchers and industry professionals in recent years.

Fig. 3 illustrates a general classification map of the control strategies for electrical motors in servo systems, divided into conventional and advanced categories. Conventional control strategies, such as FOC and DTC are widely used in servo systems. Advanced control strategies encompass rapidly evolving technologies in servomotor control, including model predictive control (MPC), parameter estimation technology, fault diagnosis, and FTC.

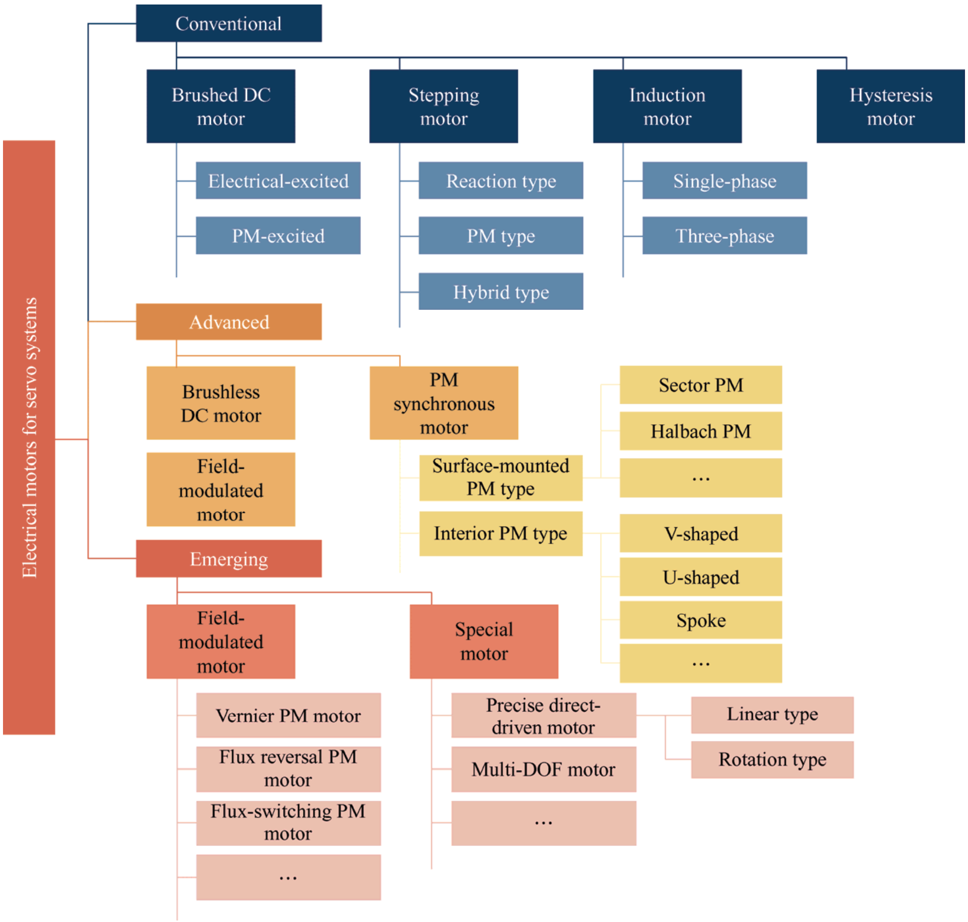


Fig. 2 Classification of electrical motors for servo systems

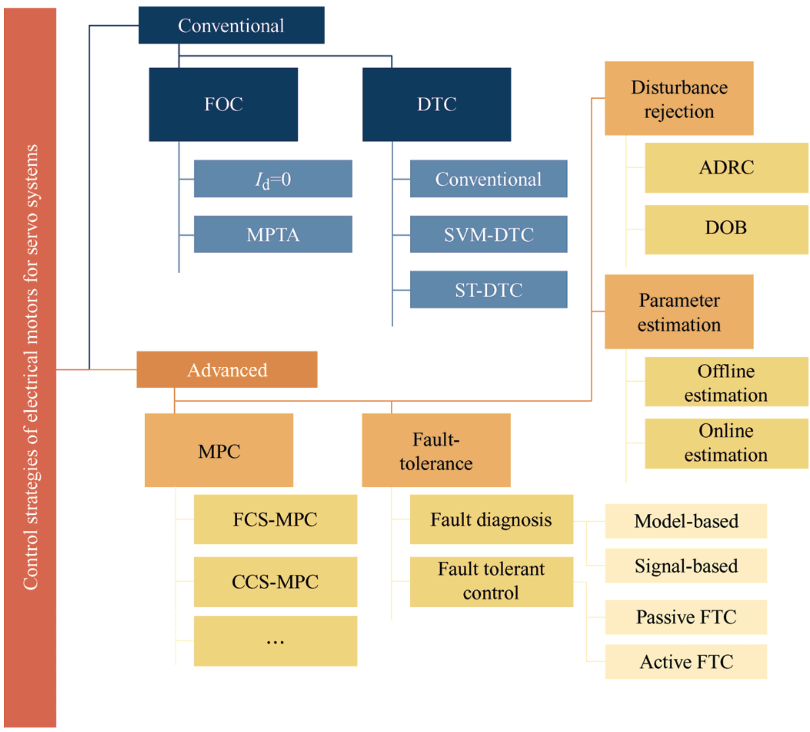


Fig. 3 Classification of control strategies of electrical motors for servo systems

2 Servo motors

2.1 Conventional motors

2.1.1 Brushed DC motor

The utilization of BDCMs in the servo field has a long history dating back to early times [6]. This preference is primarily due to its advantageous features, such as linear mechanical characteristics, wide speed range, absence of spin phenomena, and cost-effectiveness. Depending on the excitation source, BDCMs can classified into electrical-excited and PM-excited type [17]. Both types share a common rotor structure that connects the armature windings to the DC power supply via brushes and slip rings. In the PM-excited type, the stator is equipped with magnetic poles made of PMs to generate the excitation field, while the electrical-excited type the excitation field through excitation windings wound around the stator poles. The structural schematics of both types are illustrated in Figs. 4a and 4b, respectively.

To achieve more linear mechanical characteristics, BDCMs employed in servo applications typically utilize the armature control method. In this approach the excitation magnetic field is maintained constant, while the motor operates by adjusting the armature voltage.

The mechanical characteristic function of BDCMs can be represented by Eq. (1), as shown in Fig. 4c.

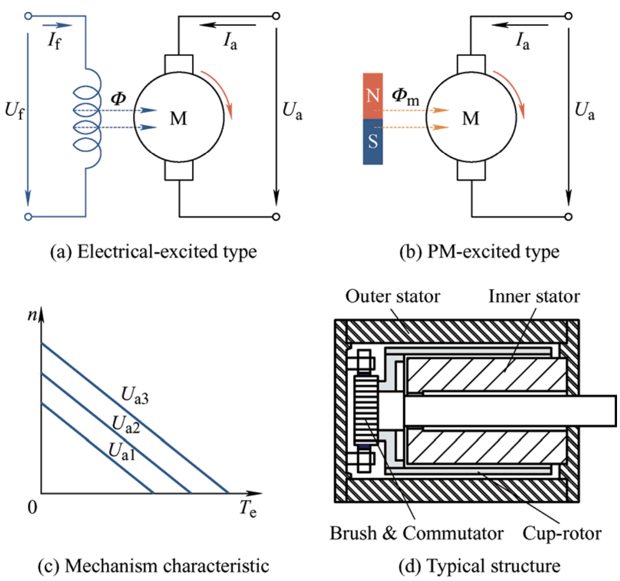


Fig. 4 Brushed DC motors

$$n = \frac{U_a}{C_e \Phi} - \frac{R_a}{C_e C_T \Phi^2} T_e \tag{1}$$

where n represents the rotor speed; U_a denotes the armature voltage; C_e and C_T are the electromagnetic and torque coefficients, respectively; R_a is the armature resistance; T_e denotes the electromagnetic torque.

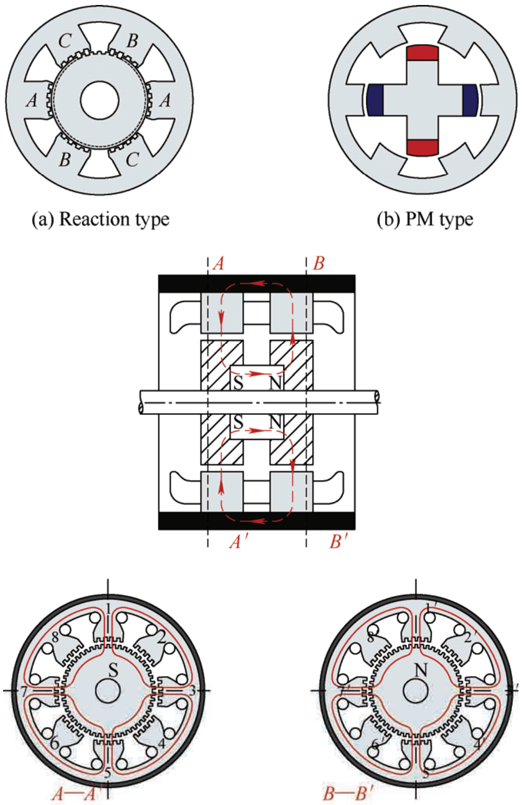
The mechanical characteristics of the BDCM exhibited linearity irrespective of variations in the armature voltage. When the armature voltage remained constant, the slope of the mechanical characteristic curve was determined solely by the armature resistance [18].

Despite the favorable mechanical and dynamic characteristics of BDCM motors, their limited power/torque density and low reliability owing to brushes/slip rings have become increasingly apparent as industrial demands have evolved. Consequently, BDCM motors have gradually lost their status as the preferred choice for servo systems, especially in high-end applications. They are now primarily employed in limited scenarios where cost considerations outweigh the need for advanced performance capabilities.

2.1.2 Stepping motor

The SM, also known as the stepper motor, is a special motor that converts electrical pulses into discrete mechanical movements or steps. Its movement is typically proportional to the number of pulses received, allowing precise control over position and speed, even when operating under open-loop control [19].

Currently, there are three main types of SMs. The first type is the variable reluctance or reaction-type SMs, which are relatively simple in design and construction, featuring a small step angle, as depicted in Fig. 5a. Accordingly, these motors are cost-effective and find applications across various industries. The second type is the PM-type SMs [20], as illustrated in Fig. 5b, which improves the efficiency of the reaction-type SM. In addition, they exhibit good holding-torque characteristics, allowing them to maintain a stable position without requiring additional power. This feature is particularly crucial in locking mechanisms or robotic arm applications [21]. However, due to the difficulty in manufacturing small PM rotors with a large number of poles, PM-type SMs are limited to larger step sizes, typically in the range of 30°-90°. The third type is the hybrid-type SMs, which combine the key features of both variable reluctance-type and PM-type SMs. This is achieved by incorporating an axially-magnetized PM between the two rotor segments, whose construction is somewhat similar to that of a variable-reluctance SM, as depicted in Fig. 5c. The hybrid-type SM offers the benefits of a small step angle (typically 1.8°/0.9°), higher torque per unit volume, and some detent torque. Nevertheless, it tends to be more expensive compared to variable reluctance-type SMs.



(a) Reaction type (b) PM type

(c) Hybrid type

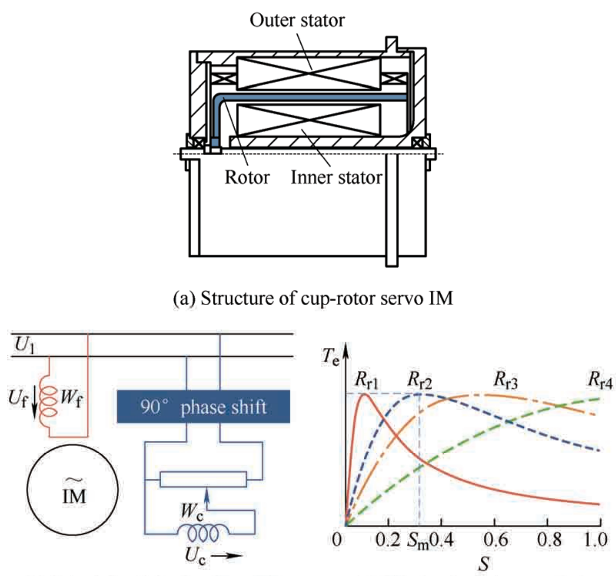
Fig. 5 Stepping motors

There are several drawbacks that have hindered the widespread adoption of SMs in servo applications. One significant limitation is their inherent nonlinear behavior, which poses challenges in achieving high-quality control and precise positioning [22]. Furthermore, SMs often exhibit lower torque density than other motor types, restricting their suitability for applications requiring high torque output [23]. Moreover, vibration and resonance effects may arise during operation, affecting the overall system performance, potentially leading to reduced accuracy and stability [24]. These drawbacks should be thoroughly considered when selecting SMs for servo applications, with supplementary measures possibly necessary to mitigate their effects and ensure optimal performance.

2.1.3 Induction motor

Given their simple rotor structure, IMs exhibit robust construction and high tolerance to harsh operating conditions, rendering them suitable for use in industrial environments. Additionally, their cost-effectiveness is a significant advantage, especially in the context of servo systems [25].

The single-phase IM is a popular servo IM type for low-power drives in various industries and commercial applications where only a single-phase supply is available. To minimize rotor inertia, a cup rotor is often preferred, as depicted in Fig. 6a. These motors are characterized by two orthogonally positioned windings: an armature winding and an excitation winding, with a 90° electrical angle shift. By controlling the amplitude and/or phase of the voltage applied to the armature winding, a rotating magnetic field was generated in the air gap, as shown in Fig. 6b. In addition, three-phase IMs also find applications in servo systems [26-27].



(a) Structure of cup-rotor servo IM

(b) Principle of single-phase IM (c) Mechanical characteristic

Fig. 6 Induction motors

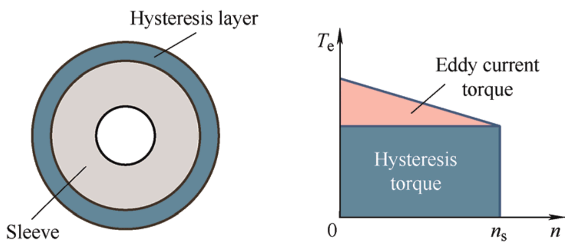
The primary challenge in further integrating IMs into servo systems lies in the inherent nonlinearity of their mechanical characteristics. Fig. 6c illustrates the typical mechanical characteristics of an IM, where S

represents the slip, and R_r corresponds to the rotor resistance. The stable operation region of IMs is limited to the interval from 0 to S_m, where their mechanical characteristics exhibit approximate linearity. With an increase in the rotor resistance, this operating region becomes wider, and the linearity improves. Generally, the rotor resistance of the servo IM should be designed to be larger, however, due to the inherent nonlinearity, achieving high precision control of IMs has remained a challenging issue, posing a considerable hurdle to their widespread application in the servo field.

2.1.4 Hysteresis motor

HMs are a special type of motors that utilize the hysteresis effect in magnetic materials to generate torque. They are characterized by their ability to perform precise positioning without cogging or torque ripple. HMs feature a unique rotor design comprising a solid rotor constructed from a high-hysteresis material (Fig. 7a). This rotor material retains a specific level of magnetic flux even after the excitation field has traversed, resulting in smooth and continuous torque production [28-29].

When the rotation speed of the HM is below the synchronous speed, the relative motion between the rotor and the rotational magnetic field produces an eddy current torque (Fig. 7b). Thus, the starting torque of HMs is relatively high, a crucial characteristic that made them well-suited for servo applications. However, the applied scenarios for HM are limited, considering the relatively low power/torque density and significant inefficiency.



(a) Structure of HM (b) Torque of HM

Fig. 7 Hysteresis motors

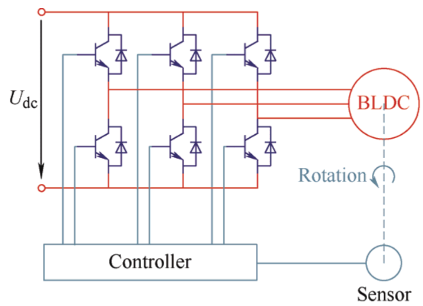
2.2 Advanced motors

The development of power electronic technologies and advancements in PM materials have ushered in the era of brushless motors, including BLDCMs and PMSMs. These motors have been rapidly integrated into the servo domain and currently stand as the preferred choice for servo motors due to their remarkable attributes, including high power density, high efficiency, and substantial torque output.

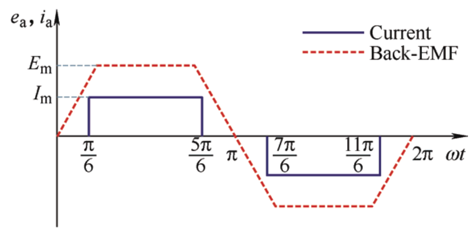
2.2.1 Brushless DC motor

In terms of the motor structure, BLDCMs share several similarities with BDCMs. However, a key difference lies in the absence of mechanical commutators in BLDCMs. Instead, the commutation function is assigned to an external circuit, typically a three-phase full-bridge inverter, as illustrated in Fig. 8a. This circuit, controlled by a digital controller, generates switching signals to convert DC power into AC power, which is then supplied to the armature windings of the motor.

In reality, BLDCMs and PMSMs exhibit numerous similarities in terms of external circuit and internal structure. However, the primary distinguishing factor lies in the shape of their back-EMF waveforms. BLDCMs typically exhibit a trapezoidal back-EMF waveform [30-31], visualized in Fig. 8b, whereas PMSMs feature a sinusoidal waveform. This distinction in back-EMF waveforms allows for different control strategies and operational characteristics between the two motor types [32]. To match the back-EMF, the BDCM is usually driven by a square wave current, as indicated by the curve in Fig. 8b, while the PMSM is usually driven by a sinusoidal current.



(a) Operation structure of BLDCMs



(b) Back-EMF and current waveform of BLDCM

Fig. 8 Brushless DC motors

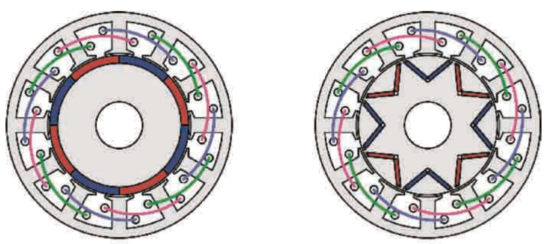
The main difference between the BLDCM and PMSM is listed in Tab. 1. It is important to emphasize that the characteristics mentioned in Tab. 1 represent typical cases and may vary depending on specific motor designs and applications. For instance, there are PMSMs that utilize full-pitch concentrated windings [33], resulting in a sinusoidal back-EMF waveform. However, due to the ease of achieving a trapezoidal back-EMF waveform with full-pitch concentrated windings, the majority of BLDCMs adopt this winding configuration [34], which can be considered a significant feature of BLDCMs.

Tab. 1 Differences between BLDCMs and PMSMs

Items	BLDCM	PMSM
Back-EMF waveform	Trapezoidal	Sinusoidal
Stator winding	Full-pitch concentrated	Short-pitch distributed
Current waveform	Square	Sinusoidal
Sensor	Hall	Encoder, rotatory transformer
Control method	Six-step commutation	FOC, DTC

2.2.2 Permanent magnet synchronous motor

PMSMs are the most widely used type of motors in servo systems currently. The sinusoidal waveforms of the back-EMF and current enable them to produce a remarkably smooth torque output, contributing to enhanced control accuracy. Depending on the location of the PMs, PMSMs can be categorized as surface-mounted PM motors (SPMMs) or interior PM motors (IPMMs), their typical structures are shown in Fig. 9.



(a) SPMM (b) IPMM

Fig. 9 PM synchronous motors

In response to the growing demands placed on servo systems in various industries, there has been a significant research focus on optimizing the traditional structure of PMSMs to meet the requirements of high-quality servo applications. This ongoing research aims to enhance various performance indicators that are crucial for assessing the quality of PMSMs, including power/torque density, torque ripple, and thermal dissipation.

Power/torque density is a metric that measures the power or torque output capability per unit volume or mass. In multiple industrial applications, space constraints impose strict requirements on the size and weight of servo equipment, necessitating compact and lightweight servo motors/drives. Consequently, high-power/torque-density servomotors have consistently been a key research focus in servo products.

Tab. 2 presents the power/torque densities of the main servo products available on the market. Notably, these data signify the maximum values of the corresponding motor series and may not be achievable for every motor in the series. Advanced servo products can realize a power output of at least 1 kW or a torque output of at least 3 N • m per unit volume. This high performance can be attributed to the targeted and optimized performance design of the motors.

Tab. 2 Power/torque density of main servo products

Brand	Series	Power density/ (kW/L)	Torque density/ (N • m/L)	Power density/ (kW/kg)	Torque density/ (N • m/kg)
Panasonic	A6	1.23	5.85	0.36	1.72
Delta	A3	1.05	3.36	0.29	1.22
Inovance	MS1-R	1.32	5.81	0.4	1.66
Inovance	MS1-Z	1.32	4.49	0.39	1.5
Yaskawa	∑-X	1.87	6.41	—	—

Optimizing the magnet and winding arrangement, and improving the magnet materials are effective ways to enhance the power/torque density. Currently, commonly used optimized magnet arrangements include spoke-type [35-36], Halbach-type [37-38], U-type [39] and V-type [40-42] magnet arrangements. These magnetic arrangements generally enhance the power/torque density by optimizing the magnetic flux paths and increasing the fundamental magnetic flux density. Nevertheless, these enhancements often lead to aggravated torque ripples in permanent magnet motors. Hence, it is essential to find new methods to minimize the impact of torque ripple on the performance of servo systems, while maximizing the power/torque output per unit size.

Torque ripple refers to periodic fluctuations or variations in output torque during operation. This undesirable phenomenon adversely affects the performance, efficiency, and overall quality of servo systems. Modern servo products, such as Delta's A3 series motors, can achieve a torque ripple of below 1.5%. Notably, Yaskawa claimed that ∑-X series motors can achieve almost zero speed ripple.

The source of the torque ripple is complex. It is not only influenced by the motor itself but also by the inverter and control algorithms. The optimization methods related to motor structure can be categorized into three types.

(1) Magnet shape modification: In Ref. [15], the impact of magnet shape on the torque capability was discussed, with sine harmonic compensation and inverse cosine harmonic compensation methods applied to modify the magnet shape. The torque ripple was reduced by 15% compared to that of the original motors, whereas the average torque reduction was only 4%. Similarly, a "butterfly" shape magnet was proposed in Ref. [43] to achieve high torque output and low torque ripple. The results indicated that the proposed design sacrificed only 5% of the power density for an essentially zero torque ripple.

(2) Modification of the stator/rotor shape: In Ref. [44], the rotor surface of the IPM motor was designed to have a special shape, reducing both the rotor core loss and torque ripple. In Ref. [45], the assisted poles were applied and the cogging torque was decreased from 0.48 N • m to 0.1 N • m. Additionally, skewing or segmental skewing is also an effective and wide-applied method. Zhao et al. [46] combined both skewing and sinusoidal PM configurations to modify spoke-type IPM motors. The simulation results revealed that the cogging torque was reduced by more than 60%, and the total torque ripple decreased by 40%.

(3) Winding optimization: The influence of the partitioned winding is discussed in Ref. [47], where the torque ripple of the proposed motor was only 1.57%. In Ref. [48], a star and delta hybrid connection method for the fractional-slot concentrated-winding PM motor was proposed, and the torque ripple was significantly reduced by employing this winding connection method.

In addition to power density and torque ripple, servomotor performance indicators include factors such as back-EMF sinusoidality and thermal dissipation. These indicators have corresponding optimization measures. Considering the numerous optimization targets for servomotors, multi-objective optimization has become a popular topic of research in recent years.

Multi-objective optimization refers to a motor structure optimization method that considers multiple interrelated objective functions or performance metrics in an optimization project. Owing to the strong coupling relationship between various electromagnetic characteristics, optimizing one aspect of performance often leads to a trade-off with other aspects.

Ref. [49] proposed a multi-objective optimization method based on an extreme learning motor considering the thrust, thrust ripple, and THD of the back electromotive force. The experimental results indicated that this method increased the average thrust by 12.17%, decreased the thrust ripple by 84.78%, and reduced the THD by 46.62%. To solve the computational problems caused by the finite-element analysis, an analytical model was proposed in Ref. [50] to address the electromagnetic, thermal, and structural behaviors of a servomotor. In addition, Zhu et al. [51] proposed a multi-objective method based on the airgap field modulation theory to achieve a higher output torque and lower torque ripple.

2.3 Emerging servo motor technologies

To further enhance the servomotor performance to improve the overall system quality and meet the increasing demand in modern industrial applications, researchers have undertaken a variety of studies and investigations, with particular emphasis on the following areas.

2.3.1 Direct-driven servo systems

A direct-driven servo system refers to a servo system in which the workbench is directly powered by a motor. Such systems eliminate the reduction gear and other mechanical transmission components, thereby streamlining the powertrain and enhancing transmission efficiency [52-53].

The omission of conventional mechanical transmission mechanisms eliminates the need for inertial matching, resulting in reduced system response times and increased bandwidth. Moreover, although complex mechanical structures can be employed to mitigate the precision errors inherent in traditional equipment, the design and fabrication of such structures often incur substantial costs. By contrast, direct-driven systems offer the potential for improved positioning accuracy while reducing system costs. Furthermore, conventional mechanical transmission structures typically exhibit substantial volumes and masses, consequently limiting the power-torque density of the system. However, direct-driven systems can achieve remarkably high power-torque densities by obviating the need for mechanical transmission elements.

Currently, direct-driven systems primarily encompass two common orientations: rotational and linear direct-driven [54-55]. The distinctions between these orientations and conventional rotational servo systems, as well as linear servo systems, are illustrated in Fig. 10. The diagram clearly shows that when adopting direct-driven approaches, both rotary and linear servo systems offer significant advantages in terms of space efficiency and complexity reduction.

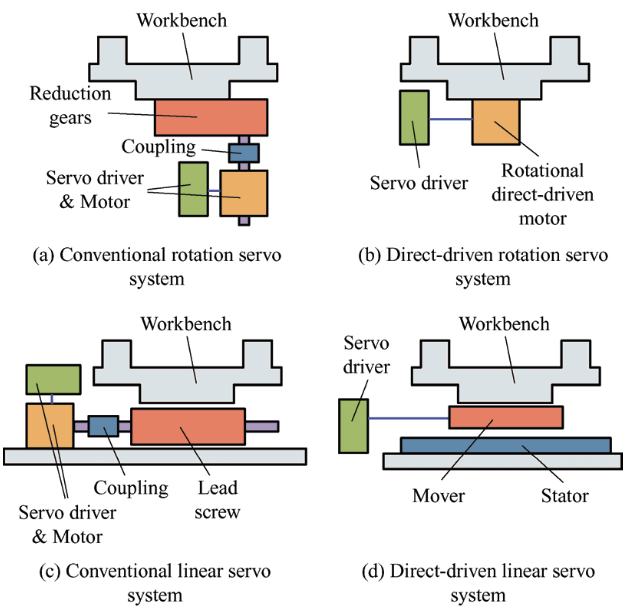


Fig. 10 Comparison of conventional servo systems and direct-driven servo systems

This combined advantage positions direct-driven servo devices as efficient, accurate, and durable solutions, thereby garnering significant attention from researchers and manufacturers.

2.3.2 Multi-DOF systems

In contexts such as intelligent manufacturing, biomimetic robot joints, and cannon elevation platforms, the requirement for achieving motion with two or more degrees of freedom often arises. Conventional approaches for driving multi-DOF motion typically involve multiple motors working in coordination, resulting in larger system volumes and weights, while demanding intricate coordination among the motors. Consequently, researchers have proposed solutions that employ a single motor to achieve multi-DOF motion [56]. Prominent schemes include two-DOF and spherical motors [57], as presented in Fig. 11. Multi-DOF motors offer the advantage of significantly reduced system volume and weight, albeit with heightened demands on the control system. Although servo systems based on these motors have not yet been widely adopted in practical applications, they show significant potential and are one of the development directions for advanced servo systems.

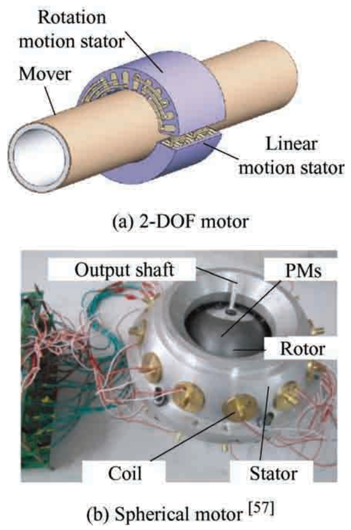


Fig. 11 Multi-DOF motors

2.3.3 Emerging topologies

With the continuous expansion of servo system application scenarios and the emergence of harsh operating conditions, the limitations of the two traditional PMSM structures have become apparent. Field-modulated motors have re-emerged as the focus of researchers. They have become a popular topic in servomotor research due to their high power/torque density arising from their multi-harmonic operation principle. Notably, the VPMM, characterized by rotor-PMs, and the FSPMM and (FRPMM), both featuring stator-PMs, have gained attention in the field; their typical structures are shown in Fig. 12.

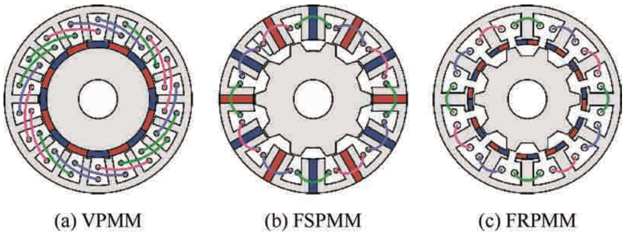


Fig. 12 Emerging motor structures

The VPMM has garnered significant attention owing to its high torque density and low torque ripple [58]. Because of its special structure, the speed of the armature magnetic field is equal to that of the air-gap magnetic flux, which exceeds the rotor speed. Consequently, the air gap acts as a magnetic gear, allowing a high-speed armature magnetic field to achieve higher output torque at low speeds [59]. It is anticipated that VPMM could replace conventional PMSMs for servo applications. For instance, ESTUN implemented a 6-kW flux-modulated PM motor for forging applications. This motor has demonstrated a nominal torque density of 10.14 N • m/L, with a maximum torque density reaching 25.2 N • m/L, surpassing that of conventional PMSMs.

Owing to the advantages of the stator-PM structure in thermal dissipation and high-speed operation, the FSPMM and FRPMM are also considered to have some prospects in servo fields; however, at present, they still face certain problems (such as large torque ripple and low efficiency) that need to be resolved [60-61].

2.3.4 Electrical motor theory

The invention of emerging structural machines has inspired the development of new electrical machine theories. Conversely, the advancement of electrical machine theory serves as a guide for optimizing the conventional motors and promoting new motor topologies. This process creates mutually beneficial iterations of progress and innovation in the machinery field.

Over the past hundred years, numerous machine theories have been proposed, with some typical theories of servomotors listed in Tab. 3. In 1925 and 1926, rotating magnetic field and cross-field theories were introduced, providing methods for a deeper understanding of the operating principles of synchronous motors [62-63]. Park [64] proposed the famous Park transformation that is still widely applied in the field of servomotor control. In 1975, Adkins et al. [65] presented a general theory for AC machines by deriving equations for current, voltage, and the relationship between torque and current. This theory established a unified mathematical model for solving problems related to AC machines. All these theories offer valuable guidance for the analysis and design of conventional servomotors.

However, it should be noted that most of these theories were proposed half a century ago. Consequently, they may be outdated and fall short in properly analyzing the emerging structure motors. In 2017, based on the research and analysis of the winding function theory [66] and the magnetic gear principle [67], Cheng et al. [68-70] proposed the general airgap field modulation theory (GAFMT) for electrical machines. The GAFMT considers all machines as a cascade of three elements, namely excitation sources, modulators, and filters, thus unifying the principle analysis and performance calculation of all machine types.

Tab. 3 Classical machine theories

Year	Theory	Author
1925	Rotating magnetic field theory [62]	K. L. Hansen
1926	Cross-field theory [63]	H. R. West
1929	Park transformation [64]	R. H. Park
1975	General theory of AC machines [65]	B. Adkins
1990	Winding function theory [66]	T. A. Lipo
2017	General airgap field modulation theory [68-70]	M. Cheng

Currently, the GAFMT is applied to motor design, analysis, and optimization. For example, Xu et al. [71] proposed a field-harmonic optimization approach to improve the power factor of VPMM. Fang et al. [72] proposed a novel VPMM by using a coded tooth. In Ref. [73], the characteristics of the FSPMM were analyzed using GAFMT. Zhou et al. [74-75] evaluated the torque ripple characteristics of an SPM motor and a V-shaped interior PM machine, and presented a novel control method to suppress it. In addition, Poudel et al. [76] applied the GAFMT to the cogging-torque analysis and optimization of the SPMM.

2.3.5 Analysis methods

Although finite element analysis (FEA) software has proven to be effective in the motor design process, it cannot reveal the operating mechanism directly and requires significant computational resources. Therefore, fast analysis or numerical analysis methods that can reveal the mechanisms of electric motors have always been a popular research topic.

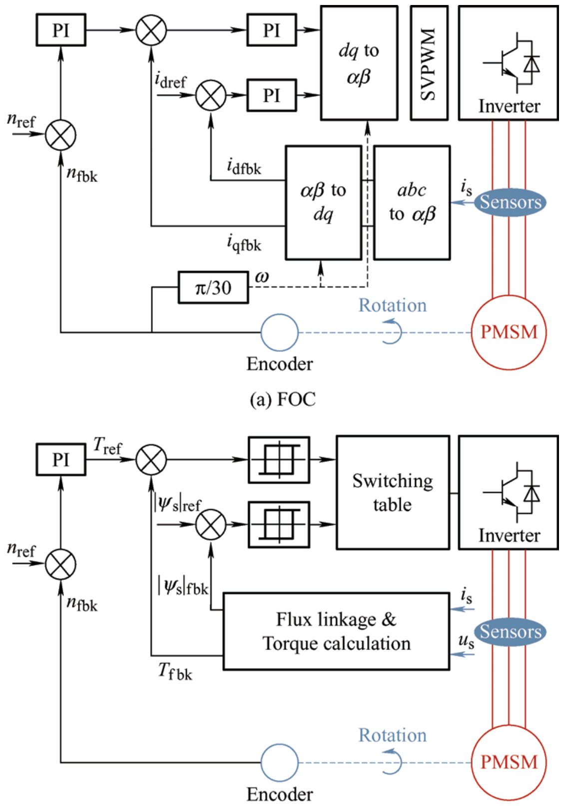
In Ref. [77], the torque generation mechanism of a dual-PM-excited VPMM was analyzed based on the GAFMT, which elucidated the torque increase phenomenon of the motor. In Ref. [78], the relationship between stator core loss and flux modulation behavior was investigated. On this basis, two approaches to suppress the stator core loss have been proposed. To solve the power factor problem of VPMMs, the airgap magnetic field harmonic was analyzed, and a prototype motor was manufactured based on the analysis results [79]. In Ref. [80], a novel meshless generalized finite-difference method was proposed to analyze the electromagnetic performance of SPMM. It has been claimed that this method can significantly reduce time consumption and improve the utilization of computational resources compared to traditional analytical models. Yan et al. [81] observed and revealed the spatial-temporal coupling relationship of the magnetic field in motors. Accordingly, a torque ripple-reduction method was proposed [81]. Considering the slotting effect, rotor saliency, and iron nonlinearity, a hybrid subdomain model was developed to analyze the electromagnetic performance of an IPMM in Ref. [82]. Using an intermediate-flux linkage, the analytical relationship among the supply voltage, current, and structural parameters of the PMSM was clearly deduced in Ref. [83].

3 Control strategies of electrical motors for servo systems

Considering that PMSM occupy the mainstream of the servo market nowadays, several advanced control algorithms were designed based on the PMSM platform. Therefore, in this section mainly focuses on PMSM control strategies.

3.1 Conventional control strategies

In 1968, Dr. Hasse from the Darmstadt University of Technology initially proposed the idea of the FOC. In 1972, Blaschke [84] presented the first study on the FOC for IMs. Several years later, Takahashi et al. [85-86] introduced DTC, and Depenbrock [87] presented the direct self control (DSC). Today, FOC- and DTC-based control methods have gained widespread application in servo systems, as shown in Fig. 13. Over the past several decades, the structures of FOC and DTC have been continuously optimized, and numerous modifications have been developed to achieve better control performance.



(a) FOC

(b) DTC

Fig. 13 Conventional control strategies

Compared with the SPMM, the output torque of the IPMM contains not only the electromagnetic torque but also the reluctance torque. Hence, to obtain a larger torque output, the IPMM is usually controlled by maximum torque per ampere (MTPA) algorithms, whereas the SPMM is controlled by i_d=0 algorithms.

In addition, novel control algorithms, such as two-degrees-of-freedom (2DOF) PI [88-90], model-reference adaptive control [91], fuzzy control [92], and sliding mode control [93] have been applied to further improve the control accuracy and quality of servo systems. Among these, sliding mode control (SMC) has emerged as a prominent research focus because of its simple structure and fast dynamic response. For example, Wang et al. [94] and Yu et al. [95] independently proposed two composite sliding-mode speed controllers. Both approaches use a fast-reaching law and disturbance compensation to improve the response speed of the system. The experimental results revealed that this composite structure based on sliding mode control achieved a maximum improvement of 8% in response speed, while exhibiting good disturbance rejection abilities.

At the same time, in order to solve the problems of large torque ripple, uncontrollable switching frequency and large current distortion brought by the traditional hysteresis DTC strategy, researchers have formulated several methods to ensure the DTC strategy meets the demands of high-quality servo systems [96-97]. Among them, the space vector modulation DTC (SVM-DTC) strategy has attracted considerable attention due to its ability to provide a fast torque response and low torque and flux ripples [98-99]. In addition, the switching-table DTC (ST-DTC) strategy has been widely researched owing to its fewer computational requirements, ease of implementation, and lower switching frequency [100-101].

3.2 Advanced control strategies

In this section, several advanced control strategies that are already being used in advanced servo products such as Yokogawa's Σ-X series are introduced and proposed by researchers to solve several key problems faced by conventional servo systems and help improve the performance of modern servo systems from different insights. Some of them are structural subversions of the conventional control strategy, while others can be used as a patch to combine with the conventional control strategy. Regardless of the case, they all improve the quality of the servo system and represent developmental directions for the modern servo industry. For instance, MPC is a completely novel control structure that is widely recognized for improving the dynamic response of a system. Fault diagnosis and FTC can ensure the safe and reliable operation of a system in case of failure. Parameter identification techniques offer the possibility of recognizing system parameters under different operating conditions, and can be used to achieve better control performance. Disturbance rejection control helps resist multisource disturbances faced by the system and maintains high-precision and stable operation.

3.2.1 Model predictive control

The MPC is known for its fast response and adaptability to digital controllers. Consequently, numerous researchers have attempted to apply it to servo systems to achieve a larger system bandwidth. Currently, two types of MPCs are widely used in servo systems: finite-control-set MPC (FCS-MPC) and continuous-control-set MPC (CCS-MPC) [102-103]. Typical control block diagrams are shown in Fig. 14. The FCS-MPC strategy calculates a finite number of voltage vectors, which are usually six effective voltage vectors and two zero-voltage vectors, for a two-level inverter through the cost function. The CCS-MPC strategy can produce precise and arbitrary voltage vectors because it uses the PWM algorithm. In addition, the reference voltage provided to the SVPWM module was produced using an optimized controller. Owing to the different operating principles of these strategies, their control performances are quite different. As shown in Tab. 4, in general, the control performance of CCS-MPC is better than that of FCS-MPC; however, the optimization problem in CCS-MPC has no explicit solution, and it is difficult to determine the optimal resolution in a short time using an iterative solution, which limits the application of the CCS-MPC strategy in servo systems [104].

Therefore, researchers have attempted to overcome these limitations. For instance, a separate split flux torque cost function for FCS-MPC was proposed to simplify the design of the weight coefficient [104]. Multi-vector FCS-MPC [105] and multistep FCS-MPC [106] have also emerged as interesting topics in research focusing on improved FCS-MPC. However, generalized predictive control [107] and explicit MPC [108] are the main directions for improving CCS-MPC.

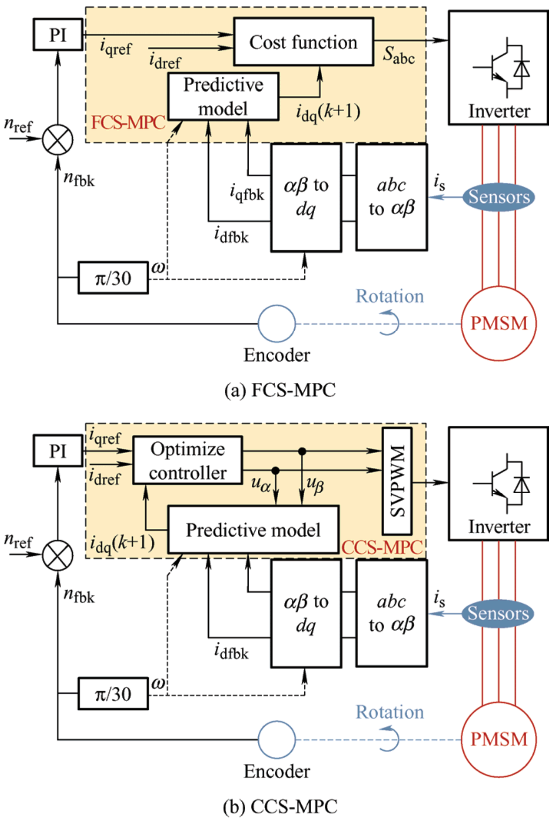


Fig. 14 MPC strategies

Tab. 4 Comparison of FCS-MPC and CCS-MPC

Items	FCS-MPC	CCS-MPC
Algorithm complexity	Normal	Complicated
Steady-state performance	Normal	Good
Robustness	Parameter sensitive	Good
Anti-disturbance	Good	Normal
Output voltage vector	Finite	Arbitrarily
Modulation process	Not required	Required

3.2.2 Fault-tolerance control

Fault diagnosis and FTC of the system can ensure the continuity of the production process, reduce the impact of equipment failure on production, and reduce losses and are therefore of increasing concern to servo users [109].

Fault diagnosis and FTC in servomotor systems aim to continuously monitor the state of the system, promptly detect potential faults, and implement appropriate control strategies to maintain system stability and performance. The objective of fault diagnosis is to identify and assess potential faults or abnormal conditions by monitoring and analyzing the input, output, and internal state data. In contrast, FTC aims to address fault situations by employing advanced signal processing, data analysis, and control strategies, ensuring that the system can either continue operating or safely stop operating when faults occur. By enhancing system reliability, availability, and maintenance efficiency, FTC guarantees the continuity of production processes [110-111].

Currently, the most commonly used diagnostic methods are based on processed electrical signals such as current [112-113], voltage [114], and leakage flux [115]. Sometimes, mechanical signals, such as vibrations [116], can also be used as the source signal. The source signals were analyzed in the frequency or time domain. The frequency-domain methods are simple, inexpensive, and can be used online, whereas the time-domain methods are fast and can make full use of the diagnostic signal [117-119].

Diagnostic methods based on mathematical modeling are also extensively used. They employ circuit models, FEM-based models, and FEM-circuit models to observe fault signals [120-121]. Meanwhile, owing to the rapid development of artificial intelligence (AI) technology, diagnostic methods combining mathematical models and AI have become a rapidly growing area of research [122-123].

Conversely, the FTC method is also an important part in modern servo systems. Generally, FTC methods can be divided into two categories: passive fault-tolerant control (PFTC) and active fault-tolerant control (AFTC) [124]. PFTC methods do not utilize fault diagnosis and are based on robust control techniques such as adaptive theory, predictive control, and AI methods [125]. AFTC methods employ fault diagnosis and switch regulators according to the diagnostic results. AFTC methods are currently more applicable and have given rise to specific AFTC methods targeting various fault issues, such as those related to voltage inverter faults [126], inter-turn short circuit faults [127], and sensor failures [128].

3.2.3 Parameter estimation

Unlike the FOC, MPC, or DTC algorithms, parameter estimation technologies cannot be used to control the motor alone but can be used as a patch in these control algorithms to improve their control performance [129]. Owing to minor variations in the manufacturing process, even for motors in the same production batch, their parameters are inconsistent [130]. Thus, motor-parameter estimation methods have become popular research topics in recent years.

Currently, the commonly identified motor parameters include rotor inertia, stator resistance, inductance, and frictional torque [131-133]. Parameter estimation methods can be broadly categorized into two types: offline and online estimation [134], as shown in Fig. 15.

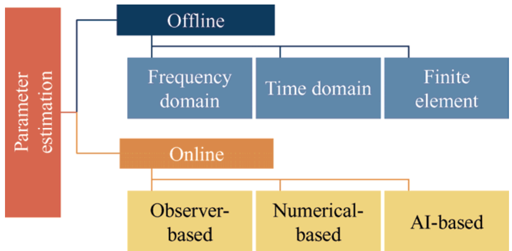


Fig. 15 Classification of parameter estimation techniques

Offline estimation methods include frequency-domain, time-domain, and finite element methods. Frequency-domain methods usually utilize the standstill frequency-response test to identify motor parameters in the standstill state [135-136], whereas time-domain methods utilize the time-based responses of an imposed perturbation or excitation signal on the motor for parameter identification [137-138]. The finite element method differs from the two aforementioned methods in that it uses FEA software to simulate the motor and analyze the parameters [139].

Online estimation methods, including numerical, observer-based, and AI-based methods, have gained increasing attention in recent years.

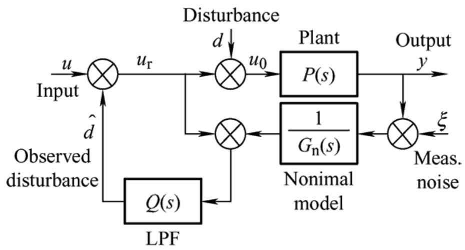
Numerical methods include the recursive least square method [140], affine projection method [141], extended Kalman filter method [142], and model reference adaptive system method [143]. Numerical methods are widely applied and can be used to estimate both electrical and mechanical parameters. They require relatively fewer computational resources but are generally more complex, demanding a deep understanding of the motor model.

Observer-based methods include adaptive observers [144], sliding-mode observers [145], and disturbance observers [146]. They offer a relatively simpler implementation and better integration with controllers, but can cause stability issues.

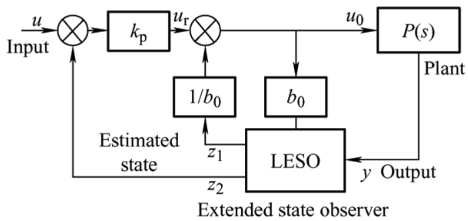
AI methods, including neural networks [147], genetic algorithms [148], and particle swarm optimization [149], represent a novel research direction with powerful capabilities but require significant computational resources and lengthy training periods.

3.2.4 Disturbance rejection

Disturbances and uncertainties exist widely in servo systems and have adverse effects on their performance and stability [150]. A good disturbance rejection capability is an important indicator of high-quality servo systems. The sources of disturbances vary and primarily include external load variations, torque ripple, sensor errors, mechanical friction, and inertia. Fig. 16 shows two widely-used disturbance rejection control strategies, including the disturbance observer (DOB) and the active disturbance rejection control (ADRC).



(a) DOB



(b) Linear ADRC

Fig. 16 Anti-disturbance control strategies

Research on disturbance rejection control strategies in servo systems is expected to focus on two primary approaches. The first is to conduct specific analyses of disturbances from different sources, considering their characteristics, and propose targeted solutions accordingly [151-152]. The second approach leverages the periodic nature of disturbances in servo systems, treats multiple sources of disturbances as lumped disturbances, and develops more advanced periodic controllers [153].

4 Trends and conclusions

As shown in Tab. 5, the future directions of servo system development can be divided into four main aspects. The first is control, which focuses on solving response bandwidth, intelligence, and other issues. The second is topology, which focuses on the power/torque density, speed range, and other indicators. The third is theory, which provides more advanced theoretical guidance for the analysis and optimization of servo systems. Finally, the system level includes mobility, integration, and miniaturization. Some of the key points are as follows.

Tab. 5 Development trends of high-quality servo systems

Classification	Key points
Control	Response bandwidth, intelligence, ···
Topology	Power/torque density, speed range, ···
Theory	Field modulation theory, vector magnetic theory, ···
System	Mobility, integration, ···

(1) Response bandwidth: The response bandwidth is, and will continue to be, a major focus of servo systems. It determines the performance, stability, and ability of a system to respond accurately and rapidly to changes in the input signal. In practical applications, numerous factors impose constraints on the bandwidth, presenting pivotal considerations for researchers. For instance, the sensor bandwidth is inherently bounded, and a limited sensor bandwidth can cause measurement inaccuracies, thereby decreasing the overall system performance. Efforts to maintain high bandwidth within the confines of limited sensor bandwidth are critical for high-quality systems. Furthermore, a high response bandwidth tends to amplify the extant noise within the system, thereby precipitating instability in the system behavior. Hence, methods to suppress noise and extract meaningful information within high-bandwidth systems have emerged as essential avenues of inquiry. In addition, a high bandwidth necessitates a higher switching frequency, which directly contributes to amplified losses in these components. Moreover, these devices have inherent limitations in terms of how quickly they can be switched on and off. Thus, achieving the maximal bandwidth within hardware-constrained environments is an imperative area for further investigation. Numerous similar factors can limit the response bandwidth of a system, and a higher bandwidth will always be a key objective pursued by researchers.

(2) Power/torque density: Similar to the bandwidth challenge, the issue of the power/torque density in servomotors has garnered significant attention. This density concern has assumed greater importance owing to the expanding utilization of servomotors in high-end fields, such as robotics and aerospace. In addition to conventional optimization strategies, emerging research directions encompass the utilization of direct-driven motors that circumvent the inclusion of gear mechanisms and the exploration of field-modulated motors that operate by multiple field harmonics. However, these innovative trajectories encounter certain challenges. For instance, direct-drive motors exhibit relatively modest rated speeds, as evidenced by Yaskawa's ∑-X series of direct-driven motors, all of which maintain ratings below 300 r/min. This limits the dynamic responsiveness of the system. Furthermore, field-modulated motors face notable issues, including suboptimal power factors and relatively large torque ripples, which constrain their wider applicability in the context of servo applications.

(3) Intelligence: In the field of servo systems, the role of AI is to emulate human cognition to supply certain decision-making processes. For example, AI can swiftly select and match responsive control parameters to address tuning challenges under varying product loads and operating conditions. This paradigm can be construed as a data-driven control strategy underpinned by abundant data reserves to ascertain the optimal control parameters for the present moment. Furthermore, as previously indicated, AI has attained specific outcomes in the realm of fault diagnosis. However, it remains at a relatively rudimentary stage, with the utilization of data still proving inadequate. However, the potential for expansive development remains promising.

(4) Mobility: In recent years, mobile servo products have attracted significant attention in this burgeoning domain. These products find applications in various contexts such as household appliances and mobile robots for tasks such as parcel sorting, where the equipment is no longer statically positioned but requires dynamic mobility. Such equipment is frequently powered by single-phase low-voltage machines or low-voltage direct-current batteries. Consequently, the demand for substantial power output leads to an elevated current flow, thereby

posing substantial challenges to both the thermal management and insulation integrity of electric motors. Moreover, these mobile devices are subject to stringent spatial constraints, which necessitate high power/torque densities. Presently, a predominant choice for these applications is low-voltage BLDC motors; thus, substantial avenues for refinement and enhancement persist and might herald a pivotal direction for future investigation.

(5) Vector magnetic circuit theory: An electrical motor functions as a device that transforms electrical energy into kinetic energy using a magnetic field. The comprehensive analysis and optimization of motors necessitate an extensive exploration of the inherent characteristics of magnetic fields or magnetic circuits. Consequently, achieving a breakthrough in magnetic circuit theory is of heightened significance. For example, the proposal of the GAFMT has greatly expanded our understanding of field-modulated motors, which has led to field-modulated motors gaining considerable attention in recent years. Recently, Cheng et al. [154-155] proposed a novel notion of “magductance” (or magnetic-inductance) from the fundamental physical properties to represent the eddy current effect in magnetic materials. More recently, they proposed another component of “hysteretance” (or virtual magnetic capacitance) to characterize the hysteresis effect of magnetic materials [156]. With the defined parameters of magductance and hysteretance, the traditional scalar magnetic circuit theory with sole reluctance is promoted to the vector magnetic circuit theory. This reveals and expresses the phase shift between the magnetomotive force and magnetic flux owing to the eddy current and hysteresis effects in the iron core of the electrical motors. Furthermore, an analytical model for the eddy current and hysteresis losses is established in terms of the magductance and hysteretance. In Refs. [157-158], the vector magnetic circuit theory was applied to improve the accuracy of the high-frequency current injection method and the performance of predictive control. The simulation and experimental results demonstrated the feasibility and effectiveness of these novel methods. Thus, this novel perspective provides fresh insights into the intricate magnetic circuits operating within motors, with the potential to significantly elevate the precision of motor analysis and the performance of servo controllers.

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Ming Cheng received the B.Sc. and M.Sc. degrees from the Department of Electrical Engineering, Southeast University, Nanjing, China, in 1982 and 1987, respectively, and the Ph.D. degree from the Department of Electrical and Electronic Engineering, University of Hong Kong, Hong Kong, China, in 2001, all in Electrical Engineering.

Since 1987, he has been with Southeast University, where he is currently a Chief Professor at the School of Electrical Engineering and the Director of the Research Center for Wind Power Generation. From January to April 2011, he was a Visiting Professor with the Wisconsin Electric Machine and Power Electronics Consortium, University of Wisconsin, Madison, WI, USA. His teaching and research interests include electrical machines, motor drives for EV, renewable energy generation, and servo motor & control. He has authored or co-authored more than 500 technical papers and 7 books, and is the holder of 150 patents in these areas.

Prof. Cheng is a Fellow of the Institution of Engineering and Technology. He has served as the Chair and an Organizing Committee Member for many international conferences. He was a Distinguished Lecturer of the IEEE Industry Application Society in 2015/2016.

Jiawei Zhou was born in Jiangsu, China, in 1993. He received the B.Sc. and M.Sc. degree in Electrical Engineering from Yangzhou University, Yangzhou, China, in 2015 and 2018, respectively. He is currently working toward the Ph.D. degree in the School of Electrical Engineering, Southeast University. His current research interests include the analysis and control of electrical machines.

Wei Qian received the B.Sc. and Ph.D. degrees from Southeast University, Nanjing, China, in 1985 and 1992 respectively, in Electrical Engineering.

Dr. Wei Qian is currently a CTO of Estun Automation Group in leading the company's R&D activities. He was an Associate Professor (1994-1999) of the Department of Electrical Engineering at Southeast University and was a Director (1999-2015) of Advanced Technology Lab of Rockwell Automation at Shanghai, China. He is also now a Board Director of Jiangsu Association of Automation (JSAA). His main areas of research are on the general motion control and robotics.

Bo Wang received the B.Eng. and M.Sc. degrees in Electrical Engineering from Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2009 and 2012, respectively and the Ph.D. degree in Electronic and Electrical Engineering from the University of Sheffield, Sheffield, UK, in 2018.

From 2012 to 2014, he served as a Senior Engineer in the Delta Electronics Co., Ltd. From 2017 to 2018, he was a Research Associate at the Department of Electronic and Electrical Engineering, University of Sheffield. Since 2018, he has joined the School of Electrical Engineering, Southeast University as an Associate Research Fellow. From 2020 to 2022, he joined Hong Kong Polytechnic University under the Hong Kong Scholar program. His research interests include the permanent magnet machine drives, electric traction and fault tolerant systems.

Chenchen Zhao was born in Nanchong, China, in 1996. She received the B.Sc. and M.Sc. degree in Electrical Engineering from the China University of Petroleum (East China), Qingdao, China, in 2018 and 2021, respectively. She is currently working toward the Ph.D. degree with the School of Electrical Engineering, Southeast University, Nanjing, China. Her research interests include the electromagnetic vibration and noise analysis of electric machines.

Peng Han received the B.Sc. and Ph.D. degrees in Electrical Engineering from the School of Electrical Engineering, Southeast University, Nanjing, China, in 2012 and 2017, respectively.

From November 2014 to November 2015, he was a joint Ph.D. student funded by China Scholarship Council with the Department of Energy Technology, Aalborg University, Aalborg, Denmark, where he focused on the brushless doubly-fed machines for wind energy conversion and high-power drive. He was a Postdoctoral Researcher with the Center for High Performance Power Electronics (CHPPE), Department of Electrical and Computer Engineering, the Ohio State University, and later the SPARK Laboratory, Department of Electrical and Computer Engineering, University of Kentucky. He is currently working at Ansys, Inc. as an Application Engineer. His current research interests include electric machines, power electronics, and renewable energy.