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Review

A Review of Axial-Flux Permanent-Magnet Motors: Topological Structures, Design, Optimization and Control Techniques

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Abstract: Axial-flux permanent-magnet (AFPM) motors are a kind of important motor with compact structure, high power density and high torque density. In this review, the progress of AFPM motors and their key technologies are analyzed and described, with emphasis on the topological structures, design and optimization methods and control techniques. Based on these analyses, the main findings of the review are the following: (1) the yokeless and segment armature (YASA)-type motors have great potential for development; (2) the multi-objective optimization design theories can be integrated and applied to optimize the design of AFPM motors; and (3) optimal control and sensorless control have important value in improving system reliability and reducing cost. Finally, highlights and prospects are provided for further advancing AFPM motors.

Keywords: axial-flux permanent-magnet motors; topological structures; design and optimization methods; control techniques

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1. Introduction

Axial-flux permanent-magnet (AFPM) motors are now attractive choices for various applications, such as new energy vehicles [1], aerospace [2], marine [3] and other industrial applications [4,5]. The reason is that AFPM motors have the advantages of compact structure, high torque density and high power density [6]. Compared with the conventional radial-flux permanent-magnet (RFPM) motors, AFPM motors can be made in a smaller volume under the same power demand, which is more suitable for compact applications. Additionally, AFPM motors can obtain better dynamic response performance [7]. In view of the many advantages of AFPM motors, studying the progress of AFPM motors is of great significance.

In order to improve the comprehensive performance of AFPM motors, some studies have presented the novel topological structures, design and optimization methods and control techniques [8–10]. In terms of the topological structures, studies mainly focus on the rotor shape optimization, stator design, winding structure and permanent magnet selection and evaluate the air gap flux intensity, back electromotive force, flux linkage, cogging torque and torque ripple performances of the designed topological structure of AFPM motors [11–13]. In addition, in terms of the design and optimization methods, cogging torque reduction, flux leakage reduction and torque ripple reduction are important issues which demand attention of designers during design process [14,15], and the size design and electromagnetic model of AFPM motors are the basis of design optimization, which demands attention as well. Furthermore, in terms of the control techniques, the controlled system and control algorithm are proposed to increase torque density and decrease the cogging torque of AFPM motors [16–18], and the studies mainly focus on simplifying the structure of controlled system and improving the precision of control algorithm to achieve effective dynamic performance and high reliability. Based on the above, this paper mainly focuses on three aspects: (i) topological structures; (ii) design and optimization; and (iii) control techniques, and Figure 1 depicts a summary of the major points of this paper.

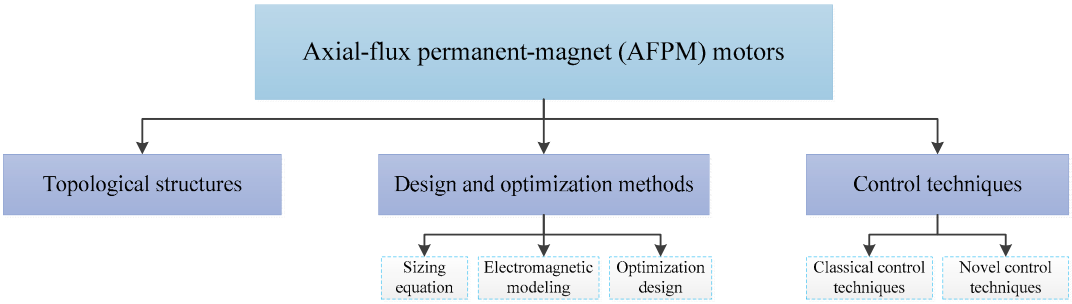


Figure 1. The major points of this paper.

1.1. Literature Survey

In recent years, many studies on key technologies for AFPM motors have been published, which provides references for this paper. The scope, keywords and results of the literature survey in this paper are given in Table 1. A total of 126 related studies were referred to in this review, of which 69.05% were published in the last 5 years (see Figure 2).

Table 1. List of literature survey.

Scope	Keywords	Results
Web of Science and Engineering Village (Publisher: MDPI, Elsevier, IEEE, etc.)	➢ axial flux permanent magnet ➢ topological structure ➢ ovel ➢ design ➢ modeling ➢ optimization ➢ improved ➢ control algorithm	✧ journal articles (100) ✧ conference articles (23) ✧ website reports (3)

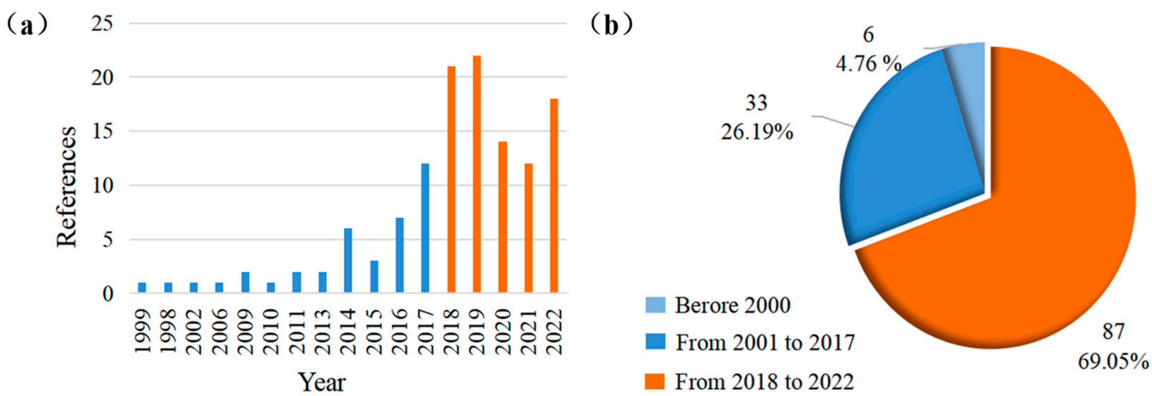


Figure 2. Analysis of references: (**a**) classified by year and (**b**) proportion in past 5 years.

1.2. Motivations and Contributions

Based on the abovementioned information and the literature survey, AFPM motors are important and widely used, and certain progress has been made in key technologies. However, to date, only a few reviews on AFPM motors have been published [7,19,20]. In light of this, we review the research progresses of AFPM motors in this paper. We not only summarize the research progresses of AFPM motors in topological structures, design and optimization methods and control techniques but also put forward the prospects in the future development of AFPM motors.

In order to advance the understanding and development of novel high-performance AFPM motors, the research progress of topological structures, design and optimization methods and control techniques of AFPM motors are extensively reviewed in this paper. Specifically, the main contributions of this paper include: (i) a comprehensive summary of the progress of AFPM motors (especially topological structures, design and optimization methods and control techniques) over the past 5 years and (ii) a presentation of the important highlights and prospects regarding the optimization and innovation of AFPM motors. This review can provide better insight into current progress and future directions and provide some reference value for related studies on the optimization and innovation of AFPM motors.

2. Topological Structures of Axial-Flux Permanent-Magnet Motors

Many different topological structures of axial-flux permanent-magnet motors have been proposed. According to the number of stators and rotors in the AFPM motor structure, AFPM motors can be classified as four typical-types [19,21]: single-stator/single-rotor (SSSR), double-stator/single-rotor (DSSR), single-stator/double-rotor (SSDR) and multi-stator/multi-rotor (MSMR), as shown in Figure 3. The SSSR-type AFPM motors are widely used in the servo drive and transportation industry due to their compact structure and high torque capacity. However, the unbalanced axial force between stator and rotor can easily distort the structure and produce vibration noise and reduce the life of the motors [22]. For the DSSR-type AFPM motors, the rotor is located between two stators, and the permanent magnet (PM) can be located on the surface or inside of the rotor, and compared with the structure where the PM is located on the surface, embedding the PM inside the rotor can better protect the PM from impact and corrosion [23]. The SSDR-type AFPM motors with the stator located between two rotors have good symmetry to eliminate the unbalanced axial forces and can improve the vibration and life of the motor during the life cycle [24]. With N stators and (N+1) rotors, the MSMR-type AFPM motors can improve the torque density and power density without increasing the motor diameter and are very suitable for large torque occasions such as ship propulsion [25].

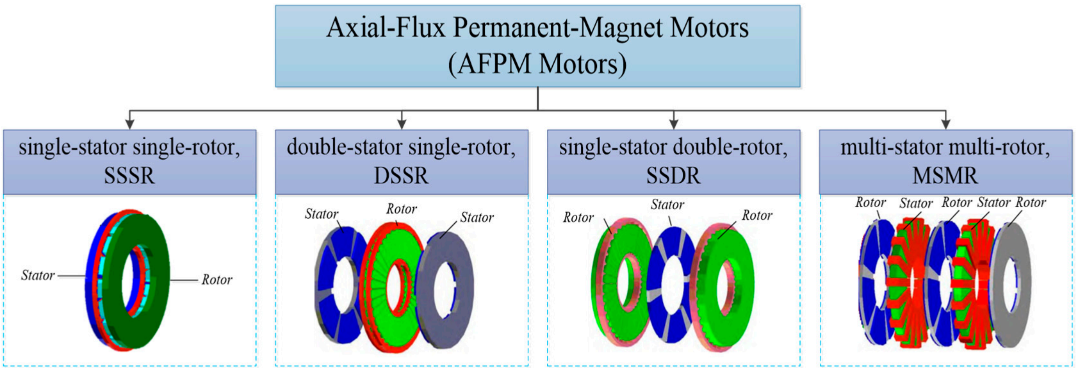


Figure 3. Four typical types of topological structures of AFPM motors.

AFPM motors have gradually become the application hotspot in the field of new energy vehicles due to their excellent characteristics [26,27]. Many studies have studied the new topological structures of AFPM motors for new energy vehicles. AFPM motors of external stator/internal rotor (axial flux internal rotor, AFIR)-type and external rotor/internal stator (toroidally wound internal stator, TORUS)-type can be designed to be suitable for the drive system of electric vehicles [28,29]. The topological structures of AFIR- and TORUS-type AFPM motors are shown in Figure 4 [30,31]. References [32–34] designed and analyzed the topology of AFIR-type AFPM motors and made some progress in reducing cost and improving efficiency and service life, and references [35–37] designed TORUS-type AFPM motors for the drive systems of electric vehicles, hybrid electric vehicles and fuel cell vehicles. Most of the designed AFPM motors used soft magnetic composite (SMC) cores to improve the weak magnetic capacity and reduce the magnetic flux loss.

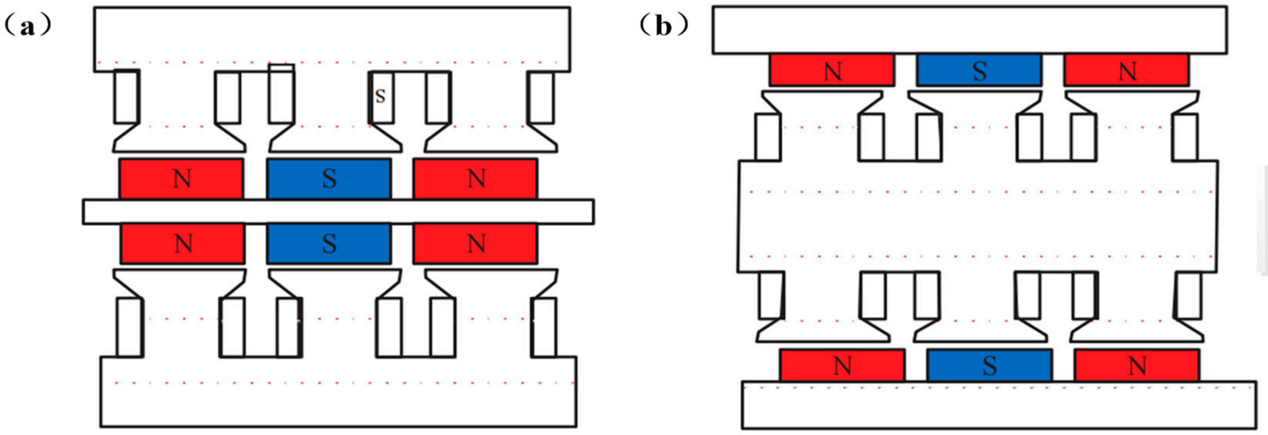


Figure 4. The topological structures of AFIR and TORUS: (**a**) AFIR type; (**b**) TORUS type. Adapted from Ref. [31]. Copyright 2018 MDPI.

In order to further improve the efficiency and power density of the AFPM motors, the stator yoke of the TORUS-type AFPM motor is removed, and the stator structure is partitioned by the centralized windings, obtaining a new-type of AFPM motor, the yokeless and segment armature (YASA) topology (see Figure 5, [31,38]). Compared with the TORUS-type AFPM motors, the YASA-type AFPM motors not only reduce the core loss but also reduce the winding copper consumption so that the efficiency and power density of the AFPM motors are improved. Studies on YASA-type AFPM motor mainly focus on improving power and efficiency. Di Gerlando et al. studied and optimized the size of YASA-type AFPM motor to further reduce the additional power loss and improve the working efficiency of the motor [39]. Xu et al. investigated and optimized the cogging torque of the YASA motor with SMC core [40]. Concretely, the structure of YASA motor was with 10 poles and 12 slots, and the stator cores were made of SMC material, while the rotors were made of solid magnetic material. Fard et al. proposed a novel yokeless and segmented armature axial field flux-switching sandwiched permanent-magnet (YASA-AFFSSPM) motor [41]. The YASA-AFFSSPM motor with three-phase 12/19-pole was composed of a single stator and two rotors, which could exhibit higher torque density and lower cogging torque. Reference [42] innovatively designed the 65 kW 18-slot/20-pole YASA-type AFPM motor. The stator and rotor of the AFPM motor were manufactured with SMC to reduce the core loss at high frequency, and the PM was divided into three segments to reduce the magnet loss, and reference [43] studied and compared a double-rotor/single-stator YASA and a single-stator/single-rotor configuration, and the studies showed that YASA configuration exhibited higher efficiencies at higher speeds, while the single-stator/single-rotor was more efficient in high torque cycles. Currently, many motor manufacturers have developed more mature YASA-type AFPM motor products, such as Magnax AXF290 [44], YASA 750 [45], Magelec motor [46] and other motor products, and the peak power is higher than 200 kW and the efficiency is more than 95%, which can be used in the drive systems of new energy vehicles.

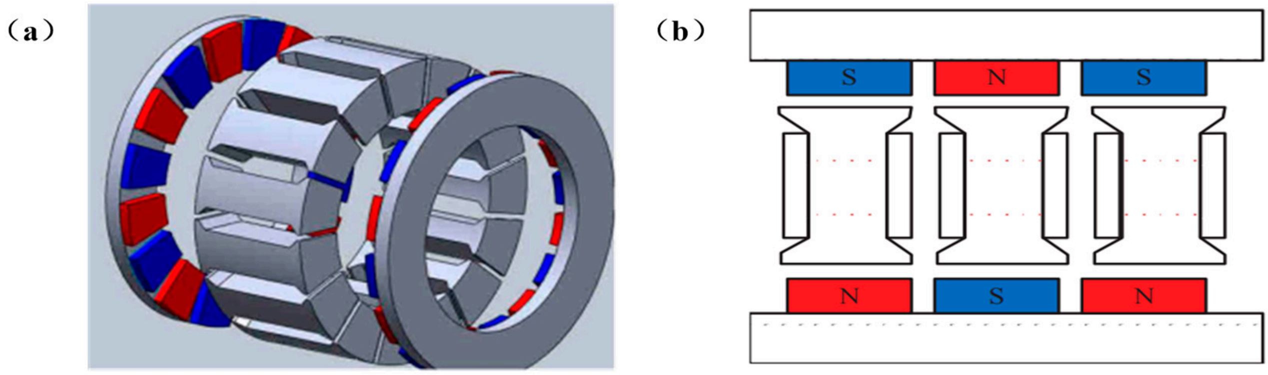


Figure 5. The YASA-type AFPM motors: (**a**) exploded view. Adapted with permission from Ref. [38]. Copyright 2018 John Wiley and Sons. (**b**) Profile view. Adapted from Ref. [31]. Copyright 2018 MDPI.

3. Design and Optimization of Axial-Flux Permanent-Magnet Motors

The design and analysis of AFPM motors usually starts from performance requirements and size constraints, followed by the matching design and optimization design of parameters and finally the evaluation of the mechanical performance of the overall structure [7,47]. After years of exploration in academia and industry, the unique design and analysis methods of AFPM motors have been established. This section focuses on analyzing and summarizing the recent advances in sizing equation, electromagnetic modeling and optimization design of AFPM motors.

3.1. Sizing Equation

The design starts with estimating the external size of the AFPM motors to meet the power/torque requirements under the given constraints (such as maximum allowable geometric size, rated/peak torque, rated/peak speed, peak voltage/current, etc.) [48,49]. If the stator resistance and leakage inductance of the AFPM motors are negligible, the output power P_{out} of the AFPM motors can be calculated by Equation (1) [21,50]:

$$P_{out} = \eta \frac{n_p}{T} \int_0^T e(t)i(t)dt = \eta n_p K_p E_{pk} I_{pk} \tag{1}$$

where η is the motor efficiency; n_p is the number of motor phases; T is the periodic cycle of the motor electromotive force (EMF); $e(t)$ is the phase air-gap EMF; $i(t)$ is the phase current; K_p is the electrical power waveform factor; E_{pk} and I_{pk} are the peak values of phase air-gap EMF and phase current, respectively, and K_p, E_{pk} can be defined from reference [51].

$$K_p = \int_0^T \frac{e(t)i(t)}{E_{pk} I_{pk}} dt \tag{2}$$

$$E_{pk} = K_e N_{ph} B_g \frac{f}{p} (1 - \lambda^2) {D_o}^2 \tag{3}$$

where K_e is the EMF factor per unit air-gap area; N_{ph} is the number of winding turns per phase; B_g is the flux density in air-gap; f is the converter frequency; p is motor pole pairs; λ is the ratio of the inner diameter D_i to the outer diameter D_o of the motor.

Based on the above equations, a general-purpose sizing equation for AFPM motors can be obtained, as expressed in Equation (4) [52]:

$$P_{out} = \frac{1}{1 + K_\phi} \frac{n_p}{n_1} \frac{\pi}{2} K_e K_i K_p K_L \eta B_g A \times \frac{f}{p} (1 - \lambda^2) (\frac{1 + \lambda}{2}) {D_o}^2 L_e \tag{4}$$

where K_ϕ is the ratio of electrical load on rotor and stator; n_1 is the number of phases of each stator; K_i is the current waveform factor; K_L is the aspect ratio coefficient related to the motor structure considering such factors as energy consumption loss, temperature rise and demand efficiency; A is the total electrical load; L_e is the effective axial length of the motor; and $K_L = D_o/L_e$.

The diameter ratio λ of AFPM motors is an important design parameter, which has a significant influence on the characteristics of the AFPM motors [53]. Yesilbag et al. pointed out that for a specific number of pole pairs, the power density of AFPM motors only depended on λ and its maximum value is a proper optimum λ value [54]. In practice, the optimal value of diameter ratio λ depends on the optimization objective. Although the optimization criteria are the same for a given electrical load and magnetic flux density, the optimal value of λ varies depending on the rated power demand, pole pairs and motor structure [55,56]. Additionally, reference [57–60] pointed out that the reasonable definition of parameters such as magnetic flux density, electrical load and current density could achieve a good estimation of the main geometric dimensions of AFPM motor, which was helpful for the parameter matching and design optimization of subsequent design and analysis of AFPM motors.

3.2. Electromagnetic Modeling

The electromagnetic modeling of AFPM motors is the next step of motor analysis after the sizing equation is determined, and the electromagnetic modeling is the basis of AFPM motor optimization design and performance evaluation. The electromagnetic model establishment and electromagnetic performance analysis methods of AFPM motors mainly include two mainstream methods: finite element analysis (FEA) [61] and magnetic equivalent circuit (MEC) [62]. Due to the inherent three-dimensional (3-D) structure and magnetic flux path, the magnetic flux density distributions along the radial and axial directions of AFPM motors show curvature effects and edge effects independently [63]. The 3-D FEA is generally recognized as the most accurate numerical tool for solving Maxwell equations of each volume element under boundary conditions, so the electromagnetic modeling based on FEA are widely used [64–66]. Some references [67–69] compared the solutions of the proposed new model with the results of 3-D FEA analysis to verify the rationality as well. However, the 3-D FEA method takes a long computational time, which is difficult to adapt to the modeling and analysis of complex AFPM motors' topological structure. To overcome the drawback of 3-D FEA, several studies have proposed two-dimensional finite element analysis (2-D FEA) modeling and analysis techniques. Gulec and Aydin converted the 3D AFPM motor models into 2D radial flux motor models with inner and outer rotors and 2D linear motor models for several 2D cut planes [70], as shown in Figure 6a. Concretely, the 2D inner rotor modeling approach (IRMA), 2D outer rotor modeling approach (ORMA) and 2D linear motor modeling approach (LMMA) were used to slice a 3D AFPM motor problem into a number of 2D problems considering the topology and motor symmetry. Kim and Woo developed a novel quasi-3-D model for the fast and accurate design of AFPM machines [71], as shown in Figure 6b. In the conventional quasi-3-D FEA, the cylindrical plane is represented as the 2-D analysis plane. However, enough 2-D analysis planes are required to achieve high accuracy. The novel quasi-3-D model used spatial interpolation to obtain the magnetic flux distribution on virtual air-gap sections between 2-D analysis planes, which could simplify the iteration of the optimization process, reducing the overall time cost and provide a reduction of 98.87% compared to 3-D FEA.

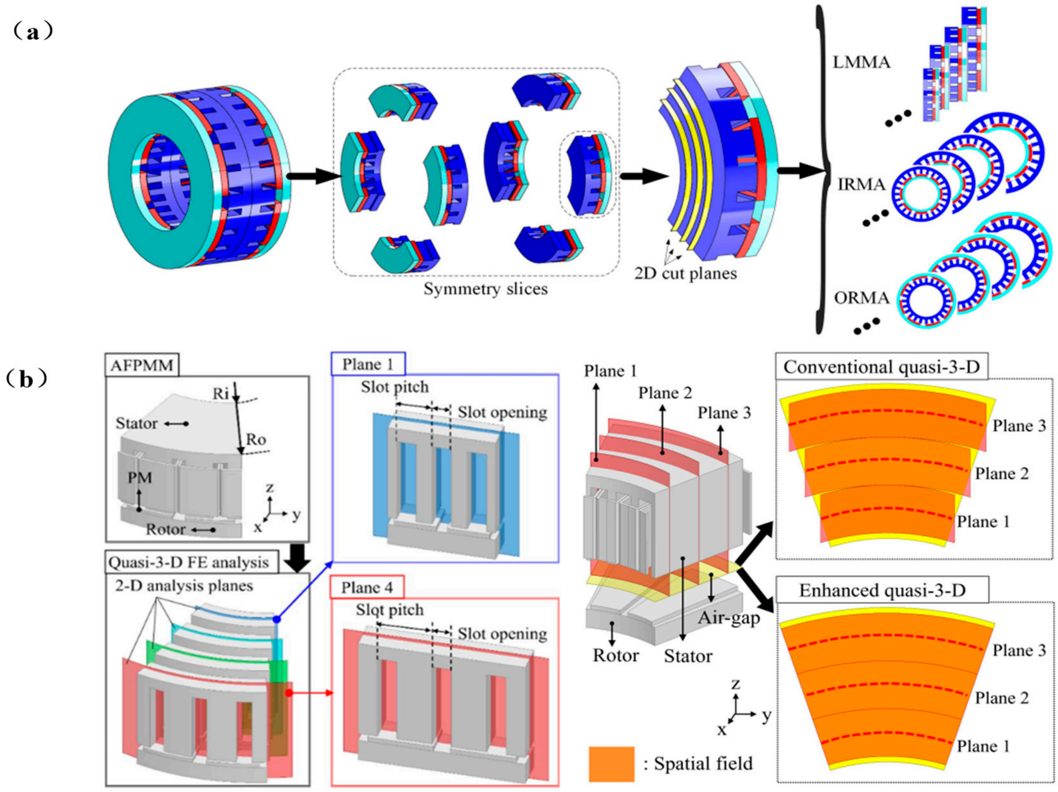


Figure 6. Electromagnetic modeling of FEA. (**a**) Diagram of converting 3D model to 2D model. Adapted with permission from Ref. [70]. Copyright 2017 John Wiley and Sons. (**b**) Diagram of novel quasi-3-D model. Adapted from Ref. [71].

The core concept of magnetic equivalent circuit is to simplify and assume the complex magnetic field to be equivalent to a simple circuit. And compared with FEA, MEC is considered as a simpler method to analyze the electromagnetic model and performance of AFPM motors [72]. Tong et al. proposed a quasi-3-D nonlinear MEC model for double-sided AFPM machines with 36 slots and 24 poles [73]. The proposed MEC model can be used to predict the performance of AFPM machines, including the 3-D distribution of air gap flux densities, flux linkage, no-load back EMF and electromagnetic torque, and the no-load magnetic field and armature magnetic field can be obtained as well. Zhao et al. presented an improved MEC model for a coreless AFPM synchronous machine with 16 poles and 12 slots, which was used to calculate the coreless AFPM synchronous machine's steady-state and transient performances [74]. Zhang et al. presented a 3-D MEC model for the magnetic field calculation in coreless AFPM synchronous generators by considering the magnetic leakage and fringing flux [75], as shown in Figure 7a. The presented 3-D MEC model was applied to a specific AFPM synchronous generators, and the magnetic field distribution, no-load back EMF and torque could be calculated. Due to the large reluctance of the main flux loop in the ironless stator motors, the end leakage fluxes of the ironless stator AFPM motors are serious. In the light of this, an MEC model considering end leakage fluxes was established in [76], and the MEC model diagram is shown in Figure 7b. The established MEC model could obtain the leakage coefficients representing the ratio of end leakage fluxes to main flux and radial coefficients representing effective radial lengths of end leakage fluxes. In order to implement the electromagnetic modeling and electromagnetic performance analysis of AFPM motors more quickly and accurately, some studies comprehensively use FEA and MEC methods. In addition, some studies combine FEA and MEC methods to implement electromagnetic modeling and the electromagnetic performance analysis of AFPM motors more quickly and accurately [77–79], which is the trend of modeling and analysis for AFPM motors in the future as well.

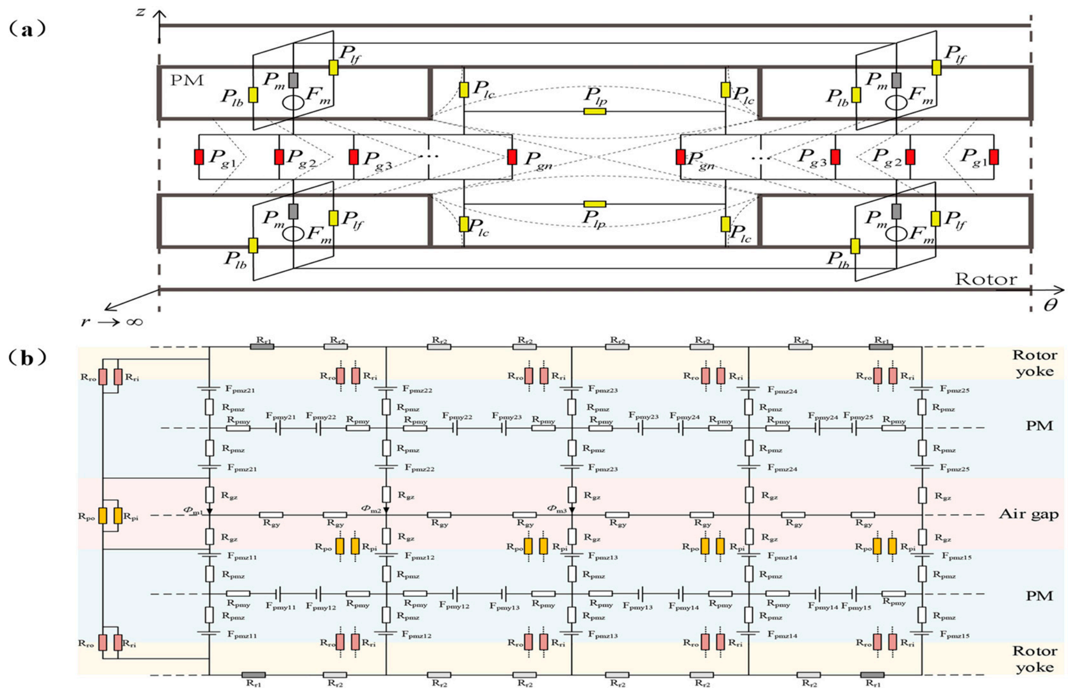


Figure 7. Electromagnetic modeling of MEC. (**a**) 3-D MEC model considering magnetic leakage and fringing flux. Adapted with permission from Ref. [75]. Copyright 2021 John Wiley and Sons. (**b**) MEC model considering end leakage fluxes. Adapted with permission from Ref. [76]. Copyright 2019 John Wiley and Sons.

3.3. Optimization Design

The design of AFPM motors must comprehensively consider the performance, cost and reliability. Therefore, the optimal design of the motor is a multi-variable and multi-mode problem [80]. For the optimization design of AFPM motors, studies mainly started with the key parameters and used the optimization algorithms to optimize the key parameters, and the common optimization algorithms include least square (LS) [81], genetic algorithms (GA) [82], neural networks (NN) [83], etc. Meo et al. proposed a new hybrid approach obtained combining a multi-objective particle swarm optimization and artificial neural network (ANN) [84]. In order to generate the training dataset and verification dataset of ANN, a preliminary design based on the sizing equations was developed, and then the FEA of the machine for different values was developed as well. As shown in Figure 8a, the numbers of neurons in the input layer, hidden layer and output layer of the ANN model are 5, 15 and 1, respectively. Fard et al. proposed a hybrid algorithm based on ANN and non-sorting genetic algorithm II (NSGA II) to obtain the maximum torque density and minimum cogging torque [85], and the scheme for the ANN is shown in Figure 8b. Patel et al. optimized the design of AFPM motors applied in electric vehicles and proposed using GA to optimize parameters such as diameter ratio, air-gap flux density and current density to obtain the best combination of parameters [86]. The optimization design combination was verified in the 3D-FEA model, and the results showed that the efficiency of AFPM motor was up to 91.5%. Additionally, some studies used hybrid algorithms with GA to optimize the design of AFPM motors, such as a hybrid genetic algorithm (HGA) combining simulated annealing and father-offspring selection [77], the elitist genetic algorithm (EGA) [87], the non-dominated sorting genetic algorithm (NSGA-II) [88], etc.

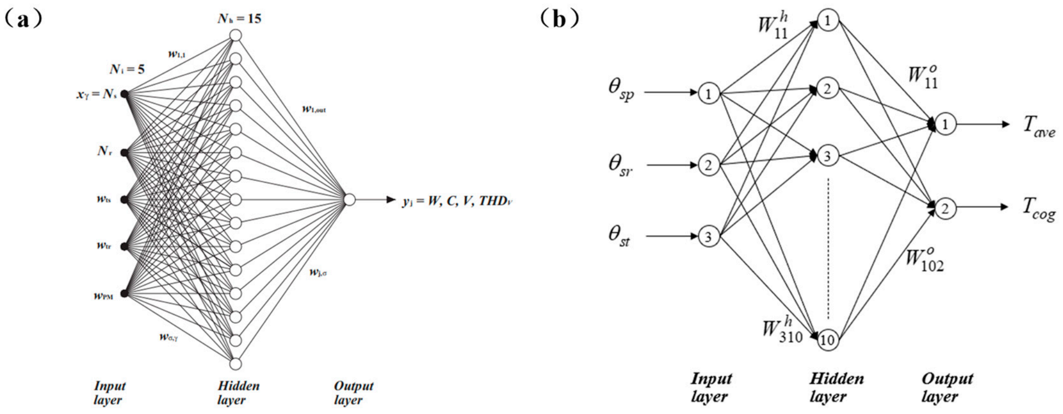


Figure 8. ANN models. (**a**) ANN model adapted with permission from Ref. [84]. Copyright 2016 Elsevier. (**b**) Multi-layered perceptron ANN model. Adapted with permission from Ref. [85]. Copyright 2018 Taylor & Francis.

With the further development of efficient computer system and optimization theory, new multi-objective optimization algorithms such as particle swarm optimization (PSO) [89,90], bat optimization (BO) [91] and the Taguchi algorithm [92] have also been applied to the optimization design of AFPM motors. Rostami optimized an AFPM motor applied in electric vehicles by using multi-objective optimization algorithms of the quasi-3D approach and PSO algorithm and evaluated the influence of the different driving cycles (NEDC and US06) on the obtained machine parameters [93]. Obviously, the AFPM motor design parameters optimized for different driving cycles would be quite different, and the optimized parameters were imported into the 3D finite element model to verify the accuracy. Chakkarapani et al. proposed multi-objective optimization techniques called the weighted sum method (WSM), multi-objective genetic algorithm (MOGA) and niched pareto genetic algorithm (NPGA) for the design optimization and analysis of slot-less permanent magnet brushless DC motor [94]. The rotor radius, stator/rotor axial length, magnet thickness and winding thickness were simultaneously accounted for in the proposed multi-objective optimization algorithms to maximize the output torque and to reduce the total volume and total power loss. A multi-objective design optimization technique using the response surface modeling and a novel multi-objective multi-verse optimization (MOMVO) algorithm was proposed for AFPM brushless DC micromotor in reference [95]. The two objectives of the optimization were to minimize the micromotor volume and improve the joules efficiency with the constraints of minimum required torque and maximum required back EMF. In the optimization design and analysis of AFPM motors applied in the new energy vehicles in addition to the basic design objectives, such as torque and power, limiting torque ripple, reducing power loss and reducing vibration and noise, were important considerations as well. In order to clearly describe the above optimization and design methods, the characteristics of above methods are compared and analyzed in Table 2.

Table 2. Summary of the optimization and design methods.

Methods	Optimization Objectives	Verification Methods	Ref
EGA	➢ weight of the permanent magnets, efficiency, sinusoidal voltage	✧ 3D-FEA	[87]
NSGA-II	➢ air-gap field, electromagnetic noise, 90 times rotation frequency	✧ 3D-FEA	[88]
PSO	➢ air gap magnetic density fundamental wave amplitude, waveform distortion rate, rotor moment of inertia	✧ 3D-FEA and experiment	[90]
MOMVO	➢ volume, joules efficiency	✧ against NSGA-II	[95]

4. Control Techniques of Axial-Flux Permanent-Magnet Motors

Despite the advantages of AFPM motors, the motors are required to provide sufficient torque and wide speed range for practical applications, which requires the motors to be controlled [96]. The main purpose of the AFPM motor control is to obtain the appropriate torque and speed to meet the requirements of the actual working environment and to obtain the efficiency, stability, reliability, speed range and other comprehensive performance improvement as well. In order to comprehensively reflect the control techniques progress of AFPM motors, this section classifies control techniques into traditional control techniques and novel control techniques.

4.1. Classical Control Techniques

4.1.1. Field Oriented Control (FOC)

The field-oriented control (FOC, also known as vector control, VC) is one of the most classical motor control techniques which is widely used in the control of AFPM motors [97,98]. FOC refers to use the frequency converter to control excitation current and torque current, respectively. Liu and Lee proposed a closed-loop field-oriented control realization method [99], and the closed-loop field-oriented control diagram is shown in Figure 9a. Among the outer feedback control loop of the FOC control diagram, the desired stator q-axis current command was calculated to satisfy the input speed command at various loading conditions. However, the FOC control algorithm is sensitive to rotor parameters, and the control network is more complex. Due to sliding mode control possess high performance robustness under parameter variation and load disturbances, Akhil et al. proposed a look-up table (LUT) based FOC with sliding mode control [100]. The inputs of LUT were reference torque and speed, and the outputs of LUT were reference currents i_d and i_q, and sliding mode control could modify the outputs of the LUT to enable an optimal control effect. The motor control system usually obtained high-precision rotor position and speed information through the position sensor to complete the closed-loop control of the control system [101]. In order to further improve the stability and reliability of the control system, some studies adopted the sensorless vector control algorithms for AFPM motors [102,103]. Luo et al. proposed the sensorless control strategy of the AFPM machine in electrical vehicles [104], including initial rotor position estimation and rotating position estimation, and the sensorless control strategy was convenient for in-wheel application of electric vehicles. Generally, FOC is easy to achieve, but the control effect is not good.

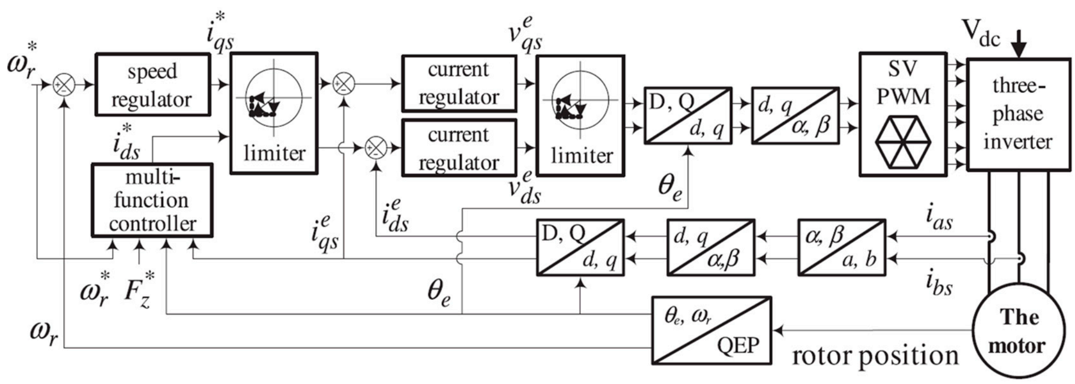


Figure 9. Closed-loop field-oriented control realization method. Adapted with permission from Ref. [99]. Copyright 2006 Elsevier.

4.1.2. Direct Torque Control (DTC)

Direct torque control (DTC) is another classic technology of AFPM motor control, and DTC refers to the technology of directly controlling the flux and torque obtained by predicting the measured voltage and current [105]. Siami et al. proposed a DTC method for AFPM machines [106], and the block diagram of proposed DTC is shown in Figure 10a. The torque and flux can be calculated by means of machine equations in stationary reference frames, and then the torque and flow were compared with the reference value in the hysteresis controllers to complete the control. However, only six active voltage vectors of inverters in the DTC method were used to control torque and flux. Aiming at the dynamic performance of axial-field flux-switching sandwiched permanent-magnet (AFFSSPM) motor, Fard et al. proposed a direct torque and flux control scheme [107]. The scheme in Figure 10b could improve the torque density and reduce the cogging torque but still needs to match the speed sensor. Nguyen et al. presented a motion sensorless direct torque and flux control algorithm and field-weakening algorithm for dual-airgap axial-flux permanent-magnet machines [108], which could accurately estimate flux and speed information. The proposed algorithm eliminated the rotary encoder, which in turn reduced the cost of the system. And in the above references [41,106], two sensorless DTC algorithms for AFPM motors were proposed to increase the space for windings and torque capability. Generally, DTC is simple to implement and can obtain fast torque response, but there are also the shortcomings of torque ripple and unstable system.

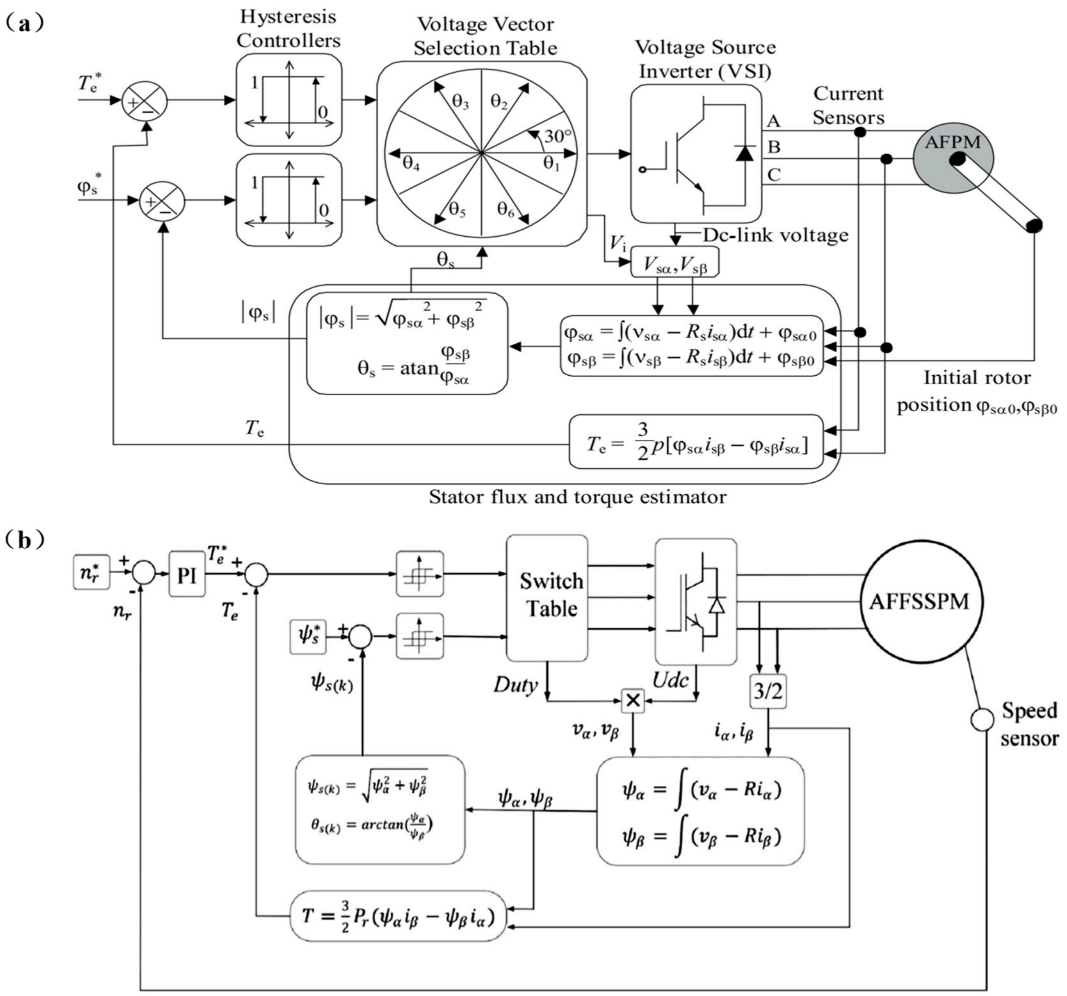


Figure 10. DTC algorithms. (**a**) DTC algorithm adapted from Ref. [106]. (**b**) DTFC algorithm adapted with permission from Ref. [107]. Copyright 2017 Emerald Publishing Limited.

4.1.3. Improved FOC and DTC

Aiming at the shortcomings of FOC and DTC, some studies proposed the improved FOC and DTC schemes to achieve a better control effect. For example, a sliding mode vector control system based on collaborative optimization of axial-flux permanent-magnet synchronous motors (AFPMSM) for electric vehicle was proposed in [109]. The proposed sliding mode vector control algorithm could improve the dynamic performance of electric vehicles, including torque tracking capability, speed limiting characteristics, and operating characteristics. For excitation copper loss and limited speed range, Yang et al. proposed a novel vector control based on three magnetization state (MS) manipulations for axial-field flux-switching memory machines (AFFSMM) [110], and the three MS manipulations and vector control diagram based on the three MS manipulations are illustrated in Figure 11a,b. Compared with the method based on proportional integral (PI) regulator, the improved FOC control algorithm could reduce the speed and torque overshoot and improve the dynamic performances of AFFSMM (see Figure 11c,d). In [111], Zhao et al. took the three-stator/double rotor AFPMSM as research object and proposed the deadbeat current predictive vector control system based on the efficiency optimal torque distribution method. The proposed deadbeat current predictive vector control system could effectively improve the torque tracking characteristics and achieved no torque overshoot and small torque ripple at steady state. Moreover, some studies also proposed the improved control techniques based on extended disturbance observer [112] and sliding mode observer [102,113,114] to further improve the control effect and accuracy of AFPM motors.

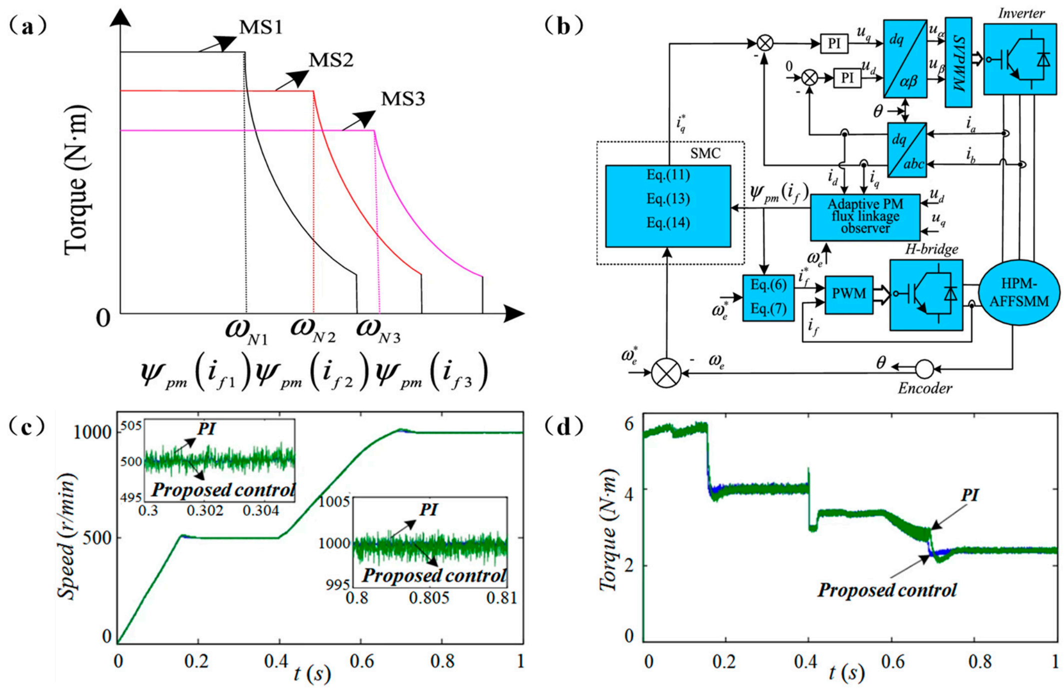
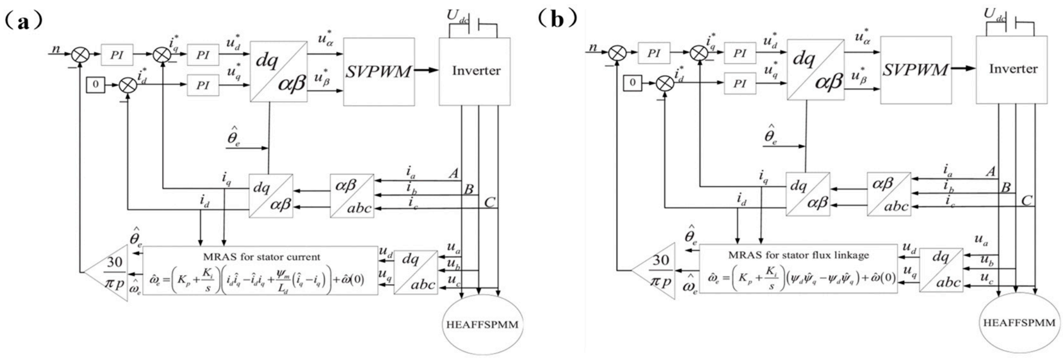


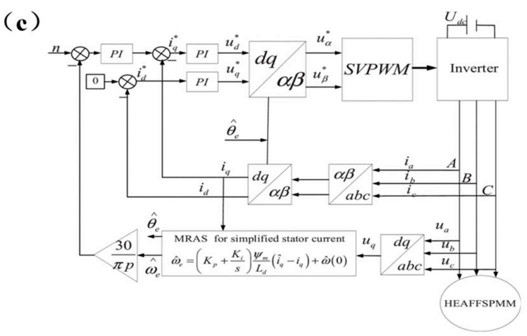
Figure 11. Improved vector control based on three MS manipulations. (**a**) Three MS manipulations. (**b**) Vector control diagram based on three MS manipulations. (**c**) Speed. (**d**) Torque. Adapted with permission from Ref. [110]. Copyright 2019 Springer Nature.

4.2. Novel Control Techniques

With the further development of control theory and optimization theory, some studies have proposed novel control techniques for the dynamic response performance of AFPM motors, mainly including model predictive control (MPC) [115] and adaptive robust control (ARC) [116]. MPC is widely used in the field of machine drive and control due to its simple implementation, fast dynamic response and high tracking accuracy [117,118]. Yuan et al. analyzed the topological structure of AFFSPM motor with 13 poles and 6 slots and proposed a model predictive torque control (MPTC) method for AFFSPM motor [119]. The torque reference value was obtained by the PI controller of the speed outer loop, and the reference flux-linkage amplitude is set to a fixed value, ψ_s^*. Compared with the VC and DTC, the proposed MPTC method could achieve quicker torque response speed and the smallest torque ripple, and the flux-linkage ripple of the MPTC was only about 1.5%, which was far less than the flux-linkage ripple of 15.3% under DTC. In addition, Zhao et al. proposed a continuous-control-set model predictive control (CCS-MPC) method for the AFSFPM machine drive system [120]. In the CCS-MPC method, the maximum torque per ampere and maximum output power flux-weakening strategies were presented in constant torque and constant power regions, respectively. The proposed CCS-MPC method could improve the anti-load disturbance capability and dynamic response.

The adaptive robust control can continuously obtain the input, state, output variables and performance parameters of the controlled system and update the structure of the controller [121,122]. Therefore, ARC can not only keep the system robust but can also achieve the optimal control effect. Wang et al. studied and proposed an adaptive robust drive control system for an AFPMSM of an electric medium-sized bus based on the optimal torque distribution method, focusing on anti-disturbance control [123]. The simulation and experimental results show that the proposed ARC method could improve the control accuracy of the drive system and could effectively suppress the disturbances, and in [124], Zhang et al. studied the speed sensorless control methods based on model reference adaptive system (MRAS) for hybrid excitation axial-field flux-switching permanent-magnet machine (HEAFFSPMM). The MRAS observer of speed was designed based on the FOC strategy, including three speed sensorless control algorithms: stator currents, stator flux linkages, and simplified stator currents. The control block diagrams of HEAFFSPMM with MRAS for stator current speed sensorless control, for stator flux linkage position sensorless control and for simplified stator current position sensorless control are respectively shown in Figure 12a–c. The simulation and experimental results shown that the MRAS algorithm based on simplified stator currents had good control performance and high control accuracy (see Figure 12d).





(d)

Control method	Speed error (r/min)	Position error (rad)	Torque ripple (%)
Stator current	3	0.8	53
Stator flux linkage	4	0.86	60
Simplified stator current	3	0.7	50

Figure 12. The diagrams of speed sensorless control methods based on MRAS. (**a**) MRAS for stator current. (**b**) MRAS for stator flux linkage. (**c**) MRAS for simplified stator current. (**d**) Simulation performances comparison. Adapted from Ref. [124].

In order to clearly describe the characteristics of the control techniques, this paper compares the well-established FOC and DTC algorithms with the novel control algorithms (see Table 3). As shown in Table 3, the complexity, response and robustness of algorithms are summarized.

Table 3. Summary of the improved and novel algorithms.

Algorithms	Complexity	Response	Robustness	Ref
improved FOC vs. PI	basically same	quicker response than PI	better robustness	[109]
improved FOC vs. PI	more complex control than PI	quicker response than PI	better robustness	[110]
MPTC vs. DTC	more complex control than DTC	quicker response than DTC	better robustness	[119]
ARC vs. PI	basically same	better response than PI	better anti-interference ability	[123]
MPC vs. FOC	more complex control than FOC	quicker response than FOC	better steady-state performance than FOC	[125]
FO-EMPC vs. FOC	more complex control than FOC	quicker response than FOC	better robustness	[126]

5. Conclusions

In order to improve the size and cost, torque density, dynamic response and other comprehensive performance factors of AFPM motors and expand their applications, it is urgent and meaningful to explore the key technologies of AFPM motors. This paper mainly reviewed the studies on AFPM motors in the past 5 years, which mainly included three categories: topological structures, design and optimization methods and control techniques. At present, some studies have made progress in the structural design and performance improvement of AFPM motors. Despite of this, there is still much room for improvement. The main findings of the review are the following:

1. **Topological structures:** There are many novel topological structures of AFPM motors, among which the YASA-type AFPM motors have great potential for development due to their advantages of high efficiency and high energy density. At the same time, new materials have also been applied to the design of novel topological structures of AFPM motors. For example, AFPM motors with printed circuit board (PCB) windings have larger air gap flux density and can effectively reduce magnetic flux leakage, which has broad application prospects. In the future, AFPM motor topological structures should be innovatively developed towards simple structures, with light weight and low cost.
2. **Design and optimization methods:** In the design of AFPM motors, the diameter ratio is regarded as the most important design parameter of AFPM motors, and power loss, torque ripple and vibration noise are important considerations in the design of AFPM motors as well. The three-dimensional model of AFPM motors can be transformed into a quasi-three-dimensional model by comprehensively using the FEA and MEC analysis, and on this basis, the multi-objective optimization design theories are integrated to optimize the design of AFPM motors, which can achieve accurate modeling and efficient analysis of AFPM motors.
3. **Control techniques:** The AFPM motors have high requirements for the control system, such as simplicity, stability and reliability. With the development of traditional control algorithms (FOC and DTC), the novel control algorithms (such as MPC and ARC) are design and proposed to optimize the control of AFPM motors, and the sensorless control algorithm can improve reliability and reduce cost. In the future, the control techniques of AFPM motors will be further explored and developed around comprehensive aspects such as robust performance, dynamic response ability and intelligence level.

The novel topological structures, the accurate electromagnetic models, the design and optimization methods and the excellent control techniques will promote the rapid development of the overall performance of AFPM motors. In the future, our work will focus on the optimization design and dynamic performance improvement of AFPM motors for new energy vehicles.

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