A Review of Optimization Methods for Pole-shoe Structures in Large-scale Salient Pole Synchronous Motors

Pengcheng Ma, Jinxiu Chen, *Member*, *CES*, and Yiwei Ding

***Abstract*—Optimizing the rotor pole-shoe structure of large salient pole synchronous motors is critical for improving their performance and efficiency, allowing for enhanced responsiveness to grid demands and adjustments in operating conditions. This paper provides a comprehensive review of various pole-shoe structures for salient pole synchronous motor rotors and their associated optimization techniques. First, it outlines the role of the pole-shoe structure and examines the theoretical theories of key electromagnetic parameters, including the pole-arc coefficient, voltage waveform coefficient, and armature reaction coefficient. Regarding structural design, this paper explores several configurations, including the three-segment arc, five-segment arc, single eccentric pole-arc combined with two chordal surface sections, and asymmetric poles. The effects of these designs on the air-gap magnetic field distribution and voltage waveform are evaluated. In terms of methodology, this paper reviews the application of numerical solutions to electromagnetic field inverse problems and the use of optimization algorithms for electrical machine structural optimization. This study illustrates the application of improved simulated annealing algorithms, tabu search algorithms, and particle swarm optimization algorithms for single-objective optimization of five-segment arc pole-shoe structures. Additionally, this paper discusses the use of vector tabu search and multi-objective quantum evolutionary algorithms for the multi-objective optimization of five-segment arc pole-shoe structures. The study concludes that multi-objective optimization algorithms are underutilized for pole-shoe structure optimization and suggests that multi-objective particle swarm optimization could be more extensively employed for this purpose. Furthermore, the potential application of topology optimization methods for the design of salient-pole synchronous motor rotor magnetic poles is proposed.**

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***Index Terms*—Electromagnetic field inverse problem, Five-segment arc pole-shoe, Multi-objective optimization, Particle swarm optimization, Rotor pole-shoe, Structural optimization.**

I. Introduction

As a clean energy source, hydropower provides numerous advantages: It is non-polluting, renewable, cost-effective, operationally flexible, and highly efficient. China's hydropower resources rank first globally. The orderly, rapid, and high-quality development of hydropower is indispensable for establishing a modern energy system and will serve as a cornerstone of the new-type power system [1]-[4]. Most hydropower generators are salient-pole synchronous motors. The salient pole structure inherently produces a non-sinusoidal air-gap magnetic field. As intermittent renewable energy sources and power electronic devices are increasingly integrated at large scale into power grids, conventional hydropower units bear significant responsibilities for peak shaving, frequency regulation, and reactive power support [5]-[7]. During these operating modes, the amplitude and waveform of the air-gap magnetic field deviate significantly from the rated operating conditions. Frequency regulation requires maintaining constant terminal voltage, which may necessitate increasing the main air-gap flux [8]. Excessive flux can cause local saturation of the iron core, leading to magnetic waveform distortion and increased harmonic content. Harmonics and magnetic saturation not only elevate the stator and rotor winding temperatures but also alter the motor's reactance parameters, affecting both steady-state and transient stability. Reactive power support requires the motor to reliably absorb or generate reactive power. Heavy reactive power compensation requires an extended stable operating range and imposes higher demands on the heat dissipation capability of stator and rotor windings, as well as on rotor oscillation damping [6].

Through the refined design of rotor pole structures—specifically the pole-shoe shape, damper winding configuration, and field windings—it is possible to improve the air-gap flux density distribution, mitigate waveform distortion, enhance motor stability, and boost rotor cooling performance. Consequently, these improvements better equip large salient pole synchronous motors to support China's new-type energy system [9]-[12].

This paper focuses on the optimization of the rotor pole-shoe shape, systematically reviewing various pole-shoe structures for salient pole synchronous motors and their associated optimization methods. Structurally, this paper analyzes the geometrical relationships of various pole-shoe configurations, including three-segment arc, five-segment arc, single eccentric pole arc with two chordal sections, and asymmetric pole structures. This paper focuses on the impact of these structures on the no-load voltage waveform and other key electromagnetic parameters. From a methodological perspective, the paper reviews optimization methods for rotor pole-shoe structures from two main standpoints: parameter optimization and topology optimization, both commonly employed in motor design. The essence of parameter optimization is framed as solving the inverse problem in electromagnetic fields (EMFs). This paper discusses the application of numerical analysis and optimization algorithms to solve inverse problems in motor structure optimization. A case study on the five-segment arc rotor pole-shoe is used to detail the application of both single- and multi-objective optimization algorithms. Finally, the paper summarizes the characteristics of various pole-shoe structures and the outcomes of applying optimization algorithms to their design. The paper concludes with an outlook on the potential application of improved particle swarm algorithm for multi-objective optimization of multi-segmented pole structures and the use of topology optimization for innovating motor pole designs.

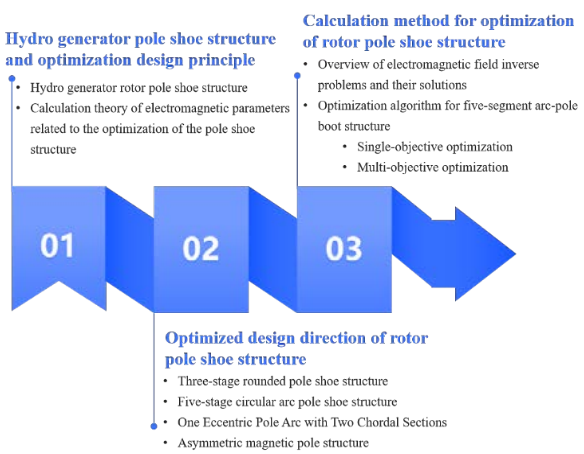

Fig. 1. The framework of this review article.

II. Salient Pole Synchronous Motor Pole-shoe Structure and Optimization Design Principles

A. Salient Pole Synchronous Motor Rotor Pole-shoe Structure

The rotor of a salient pole synchronous motor is the primary component responsible for energy conversion and torque transmission, and it typically consists of the main shaft, rotor bracket, yoke, poles, and other elements [13]-[16]. The rotor pole-shoe, a critical component of the salient pole synchronous motor rotor, serves to guide and uniformly distribute magnetic flux. This improves the homogeneity of the magnetic flux density in the air-gap and reduces the impact of flux density fluctuations on the operational stability of the generator [17]-[18]. Additionally, the pole-shoes are designed to transfer magnetic force while withstanding centrifugal forces and mechanical vibrations, thereby enhancing the mechanical strength of the rotor [14].

Salient-pole synchronous motors typically employ a salient-pole rotor design, where the magnetic poles are attached to the rotor yoke through a combination of the pole body and the pole-shoe. The pole-shoe, located at the outer end of the poles, primarily serves to extend the pole face and optimize the magnetic flux distribution. It is typically designed with a curved shape and a specific curvature to match the air-gap ensuring a uniform magnetic flux density distribution [9], [19]. Several studies have focused on optimizing pole-shoes to improve salient pole synchronous motor performance [20]. These optimizations include dividing the pole-shoes into multiple segments to enhance the flux path and air-gap flux distribution, and creating skewed slots on the surface of the pole-shoes to reduce harmonic components in the air-gap flux, which in turn mitigates electromagnetic vibrations and noise [21]-[26]. Additionally, some studies have explored using composite materials to reduce the weight of the pole-shoes while maintaining their desirable magnetic properties and mechanical strengths [27]-[28]. Collectively, these design optimizations improve the generator's electromagnetic performance and operational efficiency.

B. Calculation Theory of Key Electromagnetic Parameters for Pole-shoe Structure Optimization

1) Pole-arc coefficient

The pole-arc coefficient is defined as the ratio of the pole-shoe width to the pole pitch. Its calculation and optimization significantly affect the generator's electromagnetic performance, mechanical structure, thermal management, and overall efficiency [29]-[31]. An appropriate pole-arc coefficient ensures that the generator operates under efficient, stable, and reliable conditions while optimizing manufacturing costs and material utilization. If the coefficient is too large, the leakage flux between the poles increases, resulting in excessive magnetic flux density in the pole body [31]. Conversely, if the coefficient is too small, the extended portion of the pole-shoe may not adequately support the field coil. Therefore, the value of the pole-arc coefficient typically falls within the range of 0.66 to 0.76 [32].

2) Voltage waveform coefficient

$$f_{\mathrm{B}} = \frac{B_1}{\alpha_i \cdot \sqrt{2} B_{\delta\max}} \tag{1}$$

where B_1 is the fundamental wave maximum of the air-gap flux density [33]; α_i denotes the pole arc coefficient; $B_{\delta\max}$ represents the maximum air-gap magnetic flux density.

The voltage waveform coefficient is a measure of the harmonic content or distortion in the voltage waveform. Controlling and optimizing the voltage waveform coefficient can improve power quality, reduce equipment losses, extend equipment lifespan, and meet power system standards, thereby ensuring the efficient and reliable operation of the salient-pole synchronous motor. The voltage waveform coefficient is 1.11 when the air-gap magnetic field is sinusoidally distributed [34].

3) Direct-axis and quadrature-axis armature reaction coefficients

The direct-axis and quadrature-axis armature reaction coefficients describe the impact of the armature magnetomotive force (MMF) on the main magnetic flux. The direct-axis armature reaction can either strengthen or weaken the main magnetic field, thereby influencing the main flux and magnetomotive force. The quadrature-axis armature reaction, on the other hand, generates electromagnetic torque, facilitating the transfer of energy between the electrical and mechanical systems [13], [35]-[36].

Table I lists the electromagnetic parameters of several hydropower plants [31], [34], [37]-[39]

TABLE I
POWER STATION PARAMETERS OF HYDROPOWER STATIONS

Power station	Pole-arc coefficient	Voltage waveform factor	Direct-axis armature reaction factor	Quadrature-axis armature reaction factor
ALQUEVA [31]	0.619	1.098	0.759	0.463
Bailianhe Pumped Storage Power Station [34]	0.716	1.108	0.758	0.435
Baoquan Pumped Storage Power Station [37]	0.753	1.085	0.749	0.475
Guangzhou Pumped Storage Power Station [38]	0.737	1.092	0.753	0.465
Huilong Hydrogenerator [39]	0.74	1.019	0.6249	0.5313

III. OPTIMIZED DESIGN OF ROTOR POLE-SHOE STRUCTURES

As the electrical and mechanical performance requirements for salient pole synchronous motors continue to increase, traditional rotor pole-shoe structures often fail to meet technical standards, particularly concerning parameters like the voltage harmonic distortion rate. Harmonics in the air-gap magnetic field induce harmonic currents, which in turn increase copper losses in the stator and rotor windings and amplify core harmonic losses. This ultimately reduces the generator's operating efficiency [12], [22], [31]. To address these challenges, researchers have proposed various topological designs to optimize the rotor pole-shoe structure, aiming to enhancing the overall generator performance to meet modern operational demands [10], [17], [23], [40].

A. Three-segment Rounded Pole-shoe Structure

In the 1980s and 1990s, researchers developed a non-uniform air-gap, three-segment arc magnetic pole, as shown on the right side of Fig. 2. Based on the uniform air-gap, three-segment arc design, this new structure involved offsetting the arc center of the pole-shoe's middle section from the stator's center of curvature, as depicted on the left side of Fig. 2 [41].

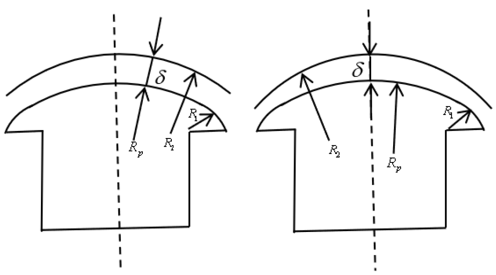

Fig. 2. Uniform and non-uniform air-gap three-segment arc magnetic poles.

In the three-segment arc pole-shoe, the central angle of the middle section is typically set to a specific electrical angle, and its chord length is equal to the width of the pole body. The left and right ends consist of two tangent arcs, the radii of which can be refined through harmonic analysis to optimize the air-gap magnetic field distribution [42].

The uniform air-gap three-segment arc magnetic pole structure offers the advantages of design simplicity and manufacturing economy, whereas the non-uniform air-gap design can reduce pole-shoe weight and decrease windage losses [5], [43]-[44]. However, both of these pole structures exhibit higher harmonic content in the air-gap magnetic field and relatively significant interpolar leakage flux [45]-[47]. The resulting harmonic losses are concentrated at the stator end, leading to rapid heat accumulation at high speeds and thus limiting the application of these designs in high-speed hydrogenerators [12].

B. Five-segment Arc Pole-shoe Structure

To address the limited applicability of the three-section pole-shoe structure in high-speed hydrogenerators, researchers have proposed a five-segment arc pole-shoe structure. In this design, the surface of each rotor pole-shoe is formed by a smooth transition between five arc segments, improving the air-gap magnetic field waveform [43], [47].

The five-segment arc pole-shoe structure inspired by the design concept of the three-segment arc structure, is shown in Fig. 3 [12].

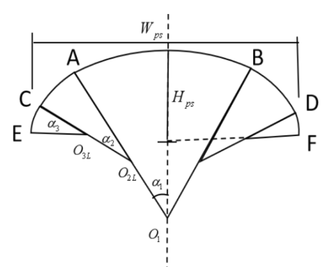

Fig. 3. Design schematic of five-segment arc structure for magnetic pole-shoes.

The five-segment arc pole-shoe structure of the salient pole synchronous motor rotor consists of five circular arcs connected by a smooth transition. This structure is typically designed symmetrically to ensure balance during operation, thereby reducing vibration and noise [12]. The total span angle of the five arcs is 180°, with the span angle of the central arc (AB), the maximum height of the pole-shoe, and the span angles of the outer arcs (CE and DF) being adjustable as needed [22].

To satisfy the requirements for frequency regulation and reactive power support in new-type power systems, the five-segment arc pole-shoe structure provides enhanced operational stability through its flexible geometric variations [34]. From the perspective of electromagnetic physics, this structure physically modulates the magnetic reluctance distribution by optimizing curvature radii, which smooths the flux density profile and suppresses local saturation-induced field distortion under the high excitation levels required for frequency regulation [48]. Additionally, its non-uniform air-gap design offsets the distorting effects of the armature reaction MMF during reactive power regulation, ensuring high sinusoidality of the magnetic field and reducing harmonic-induced temperature rise in the stator and rotor [49]. Numerical modeling typically utilizes a two-dimensional (2D) time-step finite element method based on a unitary motor model, transforming the three-dimensional (3D) field problem into a 2D analysis by neglecting end effects and employing stationary and rotating subdomains to ensure computational accuracy [12], [22]. Compared to traditional three-segment arc configurations, the five-segment arc design yields superior air-gap magnetic field and voltage waveforms, thereby enhancing power quality, reducing torque pulsation, and boosting overall generator efficiency [33], [50]. Nevertheless, existing research has primarily focused on the relationship between electromagnetic coefficients and geometric variables, leaving a notable gap in providing unified guidelines for optimal parameter selection.

C. One Eccentric Pole Arc with Two Chordal Sections

To address the complex machining process of the three-segment circular arc pole-shoe, the design was improved by replacing the two side arcs with a chordal structure. This modification reduces machining difficulty and material costs, while also allowing for a more rationalized selection of structural parameters to optimize the air-gap magnetic field distribution waveforms [50]-[51].

The structure, comprising one segment of an eccentric pole arc plus two segments of a chord surface, is shown in Fig. 4 [10].

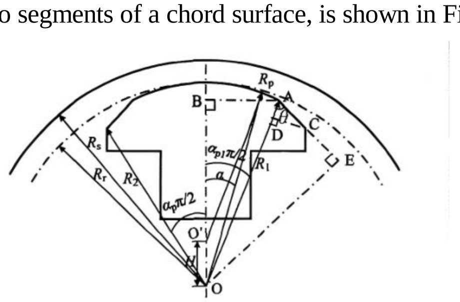

Fig. 4. Eccentric pole arc with two chord surface salient pole rotor structure.

During the design process, the stator and rotor radii, minimum air-gap length, pole-arc coefficient, and pole-shoe height are predetermined. The eccentric pole-arc radius and the pole-arc coefficient of the first section of the eccentric polar-arc surface are selected as design variables, with the fundamental amplitude and harmonic distortion rate of the air-gap magnetization as the optimization objectives. The results indicate that the fundamental wave amplitude and harmonic distortion rate of the air-gap magnetization are primarily influenced by the eccentric pole-arc radius and the pole-arc coefficient of the first eccentric pole-arc surface. Reducing these two parameters can decrease not only the fundamental wave amplitude but also the harmonic distortion rate within a specific parameter range [50].

D. Asymmetric Magnetic Pole Structure

To enhance the electromagnetic performance of cross-flow hydrogenerators, engineers typically employ skewed slots in the stator core or specialized magnetic poles to mitigate tooth harmonics. However, the former approach increases design and manufacturing complexity, whereas the latter requires precise calculation of the damping winding distribution and center offset. Dongfang Motor adopted four distinct magnetic pole designs and analyzed their effects on reducing tooth harmonics and improving the no-load voltage waveform [10].

The study utilized the SFWG45-44/5835 generator model; the four magnetic pole designs are illustrated in Fig. 5 [50].

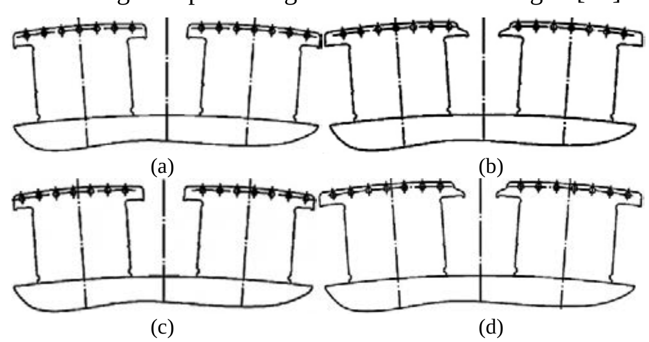

Fig. 5. Schematic diagram of asymmetric magnetic pole structure. (a) Symmetrical magnetic poles. (b) Polar shoe center offset. (c) Damping bar center offset. (d) Simultaneous shift of the pole-shoe and the center of the damping strip.

The study evaluated the harmonic flux density components for the four pole designs and performed harmonic analysis of the no-load voltage waveform and line voltage waveforms using the fast Fourier transform (FFT) method. The results indicate that the symmetric pole scheme exhibited higher tooth harmonic content in the no-load voltage, resulting in a pronounced sawtooth waveform. The sinusoidal quality of the no-load voltage waveform improved significantly when the centers of both the pole-shoe and the damping strips were offset simultaneously. This dual-offset strategy yielded more pronounced enhancements compared to shifting only a single component [52]-[53].

Researchers have investigated the influence of pole offset structures on damping winding losses, finding that such configurations can effectively reduce these losses [54]-[55]. However, under short-circuit conditions, pole offset adversely affects the maximum temperature of the damping windings. Additionally, other studies have shown that pole-shoe offset structures deteriorate the waveform quality and exacerbate damping winding losses in fractional-slot machines [56]. Conversely, these structures have a beneficial effect on the waveform quality of integral-slot machines [57]. Furthermore, the study showed that in pole-shoe offset configurations, progressively increasing the depth of the right-side pole-shoe corresponded to decreases in magnetic saturation, magnetic reluctance, and interpolar leakage flux. These phenomena collectively contribute to enhancing the fundamental amplitude of the air-gap flux density [58].

TABLE II
COMPARATIVE ANALYSIS OF DIFFERENT ROTOR POLE-SHOE TOPOLOGIES FOR SALIENT POLE SYNCHRONOUS MOTORS

Pole-shoe structure type	Principal physical mechanism	Dynamic robustness evaluation	Recommended application scenarios	Principal advantages	Major disadvantages/limitations
Three-segment arc	Step-like reluctance distribution.	General; rapid waveform distortion under over-excitation	Medium and low-speed units with stable operating conditions	Simple design and low manufacturing cost; non-uniform air-gap reduces weight and windage loss	High harmonic content in air-gap flux density and significant interpolar leakage flux
Five-segment arc	Quasi-continuous non-uniform air-gap	Extremely high; maintains low harmonic loss across a wide operating range	Core units in new power systems requiring frequent frequency and voltage regulation	Significantly improves sinusoidality of air-gap flux density; reduces voltage distortion and damping loss	Numerous design parameters with heavy coupling; lacks a unified guide for optimal parameter selection
Single eccentric pole arc with two chordal sections	Edge magnetic field weakening	Moderate; balances performance with manufacturing feasibility	Large-scale power generation units sensitive to cost	Greatly reduces machining difficulty and material cost; provides good basic correction of field waveforms	Lower precision in edge field regulation compared to multi-segment arc designs
Asymmetric structure	Phase shift cancellation	Good; extremely strong suppression of specific tooth harmonics	Bulb tubular units or specific models experiencing severe rotor surface scorching	Physically breaks harmonic superposition; effectively inhibits tooth harmonics and damping losses	May cause waveform deterioration in fractional-slot motors; uneven temperature distribution under short-circuits

Significant progress has been made in the research of rotor pole-shoe structures, leading to the proposal and application of various designs in operational generators. Building upon the design of three-segment arc poles with a uniform air-gap, researchers have introduced non-uniform air-gap variants that reduce both the pole-shoe weight and windage losses. However, these structures involve a more complex machining process and are unsuitable for high-speed hydrogenerators [12], [58]-[59]. To overcome these limitations, researchers have developed structures combining one eccentric arc with two chordal sections, as well as the five-segment arc pole-shoe design [60]. Furthermore, for cross-flow hydrogenerators with their unique structural constraints, offsetting the centers of the pole-shoe and the damping winding effectively attenuates tooth harmonics and improves the voltage waveform [46], [60]-[61]. To effectively guide the selection of these diverse configurations in practical engineering, Table II provides a systematic comparison of their physical mechanisms, dynamic robustness, and recommended application scenarios. Collectively, these studies provide a theoretical basis and practical guidelines for the optimal design of rotor pole-shoe structures.

IV. CALCULATION METHOD FOR OPTIMIZATION OF ROTOR POLE-SHOE STRUCTURE

Optimization methods for motor design can be broadly classified into two main paradigms: parameter optimization and topology optimization. The design process for parameter optimization typically involves three stages: a preliminary study, electromagnetic design, and structural design [61]. The preliminary study focuses on clarifying technical specifications and constraints. The electromagnetic design phase involves creating a parametric model and evaluating its performance across multiple scenarios, while the structural design phase includes finalizing the mechanical structure and performing the required mechanical analysis [62]-[66]. However, as the topological complexity of the motor increases, the number of design parameters grow exponentially, and these parameters exhibit strong nonlinear coupling [67]. If all parameters are treated as a high-dimensional matrix for global optimization, the computational complexity and time will increase significantly. To address this challenge, two primary solutions have been proposed: intelligent optimization algorithms and surrogate modeling techniques [68]. Nevertheless, the parametric optimization method has inherent limitations. The process is highly dependent on the initial topology, making it difficult to achieve innovative designs that transcend the established structural framework. Furthermore, this method requires extensive domain knowledge from designers and presents a bottleneck in parametric modeling when applied to novel motor topologies [69].

To overcome these limitations, topology optimization has been increasingly applied in recent years to the design of electromagnetic equipment. This approach achieves synergistic multi-physics field optimization by constructing material distribution functions. Compared to traditional structural topology optimization, the topology optimization of electromagnetic equipment requires additional consideration of multi-material interface effects, coupled electromagnetic-mechanical-thermal multi-field mechanisms, and dynamic operating conditions. Existing methodologies primarily include level set method, the variable density method, ON/OFF, and normalized Gaussian network [70]. The level set method describes the evolution of topological boundaries through the zero level set of an implicit function [71], while the solid isotropic material with penalization (SIMP) method introduces a continuous density variable and applies a cubic penalty factor to drive cell density toward the 0/1 poles. Cherrière et al. [72] developed a rotor topology optimization model based on partial differential equations to enhance electromagnetic torque, while imposing mechanical strength constraints, thereby achieving coupled electromagnetic-mechanical dual-field coupled optimization. He et al. [73] innovatively combined shape and topology optimization strategies to improve the optimization efficiency of synchronous reluctance motors, employing the finite element two-position sampling method. Pang et al. [74] employed the normalized Gaussian network to optimize the rotor structure of synchronous reluctance motors, selecting the optimal topology based on the objective function while simultaneously smoothing the optimized boundary. Li et al. [75] optimized the structure of a large bulb cross-flow rotor bracket using the variable density method, achieving lightweight design and a more uniform stress distribution. While these studies demonstrate the significant advantages of topology optimization in the design of electromagnetic equipment, its application to salient pole synchronous motors remains limited.

Although topology optimization has been extensively applied in small permanent magnet motors, its direct transplantation to large salient pole synchronous motors faces significant technical barriers. The massive scale of these machines results in 3D models with excessive mesh elements, making the iterative multi-physics simulations required for topology optimization extremely time-consuming and resource-intensive [63]. Manufacturing constraints represent a primary hurdle, as the laminated silicon steel or large forgings used in these motors are often incompatible with the complex irregular geometries, slender branches, or internal voids produced by topology optimization, leading to prohibitive costs or unproducibility [13], [69]. Additionally, structural safety remains a critical concern; discontinuous interfaces generated by topology optimization can cause severe local stress concentrations, making it difficult to withstand extreme centrifugal loads while meeting the rigorous fatigue life and safety factor standards required in hydropower engineering [76]. Furthermore, due to the high costs of testing and a lack of long-term operational data for validation, the associated design risks remain high, causing current practices to rely more on empirical formulas and traditional parametric optimization [72]. Consequently, at the current stage of large salient pole machine design, topology optimization is best utilized to explore non-traditional structural prototypes, which are then refined within traditional parametric design frameworks to achieve a necessary balance between electromagnetic innovation and engineering feasibility.

A. *Overview of EMF Inverse Problems and Their Solutions*

The EMF inverse problem aims to optimize the design of an electromagnetic device based on predefined parameters or material properties. It is typically considered a part of the integrated design process and relies primarily on numerical analysis and EMF computation [77]-[79]. Current solution methods generally decompose the EMF inverse problem into a series of forward problems, which are then solved iteratively through optimization. In each iteration, the target field is approximated by adjusting source parameters, such as boundary conditions, device geometry, and material properties [80]-[82]. Solving the inverse problem requires multiple numerical calculations of the EMF forward problem and other auxiliary operations, leading to a high computational load, significant memory and CPU resource consumption, and long computation time. Consequently, research on the EMF inverse problem focuses on developing optimization algorithms that offer high efficiency and stability [83]. The general solution process of the EMF inverse problem is shown in Fig. 6 [77].

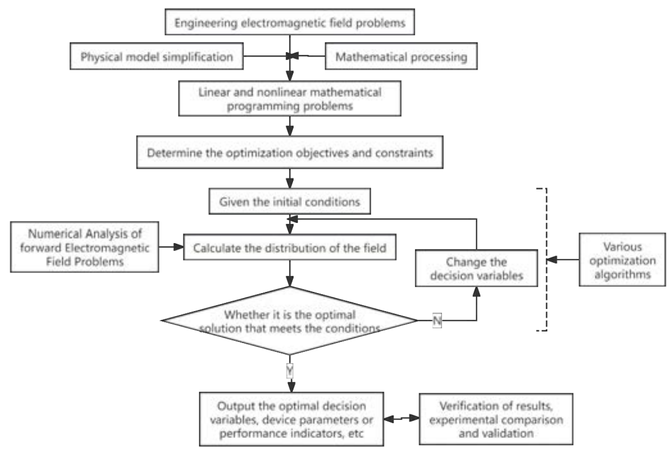

Fig. 6. General solution process for EMF inverse problems.

1) *Algorithms for numerical analysis of EMFs*

Numerical analysis methods are crucial for solving EMF problems. Typical approaches include the finite difference method, boundary element method, methods of moments, finite volume method, finite element method, and meshless methods [79], [84]-[90]. The finite difference method converts differential equations into algebraic equations suitable for efficient computational solutions by discretizing space and time. The core principle involves using a difference format to approximate the partial derivatives at mesh nodes, forming large sparse linear systems. Although this method is straightforward to implement for regular geometries, its performance is limited for complex geometries [90]. The boundary element method is particularly suited for field problems involving boundary conditions. It discretizes only the boundaries of the solution domain, which significantly reduces the problem size [82]. The method of moments is based on integral equations, wherein the electric or magnetic field distribution is represented as a linear combination of basis functions. The continuous problem is discretized, and a system of algebraic equations is formed to solve the problem [91]. This method offers advantages such as high accuracy, stability, resistance to spurious solutions, and a straightforward solution process, particularly when dealing with EMFs in open domains and complex excitation source distributions [77]. The finite volume method divides the computational domain into several control volumes, ensuring the conservation of physical quantities such as electric fields, magnetic fields, and fluids by integrating over each cell and deriving numerical solutions based on conservation laws [87]. The meshless method avoids traditional meshing by directly selecting discrete points within the computational domain for numerical solutions of the EMF. It is particularly suited for complex geometrical, dynamic, and irregular boundary problems. Common methods include the Galyokin meshless method, regenerated nucleus-particle method, and collocation method based on radial basis functions [89].

The selection of an appropriate method must consider the specific characteristics of the problem, such as geometric complexity, material properties, and frequency range, as well as computational resource limitations. Meanwhile, with advancements in computational technology, hybrid methods and highly efficient parallel algorithms have emerged, offering new possibilities for solving complex electromagnetic problems [92]-[93]. In motor structure optimization, the primary method employed is the finite element method, which is based on discretization and the variational principle [14].

The finite element method transforms a continuous physical problem into a discrete algebraic problem. This is achieved by discretizing the domain into a finite number of elements, allowing the problem to be solved computationally [86]. The method is highly flexible and adaptable, capable of handling complex geometries and irregular boundaries, making it widely applicable in motor optimization [94]. Reference [95] details a mesh generation method for the finite element simulation of EMFs in electrical machines. This two-dimensional method features high mesh adaptability and fast computation speed [95]. An optimization scheme for the rotor structure of an automotive permanent magnet synchronous motor, based on the finite element method, was proposed in [30]. The scheme reduced eddy current loss by 90% and improved torque density. A multi-objective optimization design for a hybrid excitation switched reluctance motor using finite element analysis was proposed in [81], which increased motor torque and efficiency. However, the finite element method is computationally intensive for three-dimensional problems, necessitating its combination with EMF optimization algorithms to improve computational efficiency [79], [85].

2) Optimization Algorithm for the Inverse Problem of EMFs

Traditionally, multi-objective EMF inverse problems have been reduced to scalar optimization problems [96]-[100]. This is because the vector optimization algorithms have limitations concerning convergence speed and the performance of the final solution. After transformation, the EMF inverse problem typically becomes a nonconvex optimization problem with multiple extrema. To address such problems, traditional deterministic algorithms—such as the gradient method, Newton’s method, and the steepest descent method—are computationally fast. However, they do not guarantee convergence to the global optimum, and the final result is highly dependent on the initial point [79]. Therefore, stochastic search algorithms, including genetic algorithms (GAs), simulated annealing (SA), and particle swarm optimization (PSO) have emerged as important tools for solving these problems, achieving notable progress in motor structure optimization [5].

1) GA. GAs, by simulating natural selection and genetic inheritance mechanisms, are well-suited for addressing the common nonlinear and ill-posed characteristics common to EMF inverse problems. They are particularly effective for multi-modal, multi-variable, and complex optimization problems, as well as for handling inverse problems with high-dimensional parameter spaces [95].

Reference [96] explains the basic theory of the genetic algorithm, using the optimization of the pole shape of a salient-pole motor as an example to illustrate its application in optimal motor design. In [101], the genetic algorithm was applied to the optimal design of a permanent magnet motor. The study compared the performance of the genetic algorithm optimizer included in the Ansoft RMxprt software with a self-programmed algorithm, thereby demonstrating the method’s feasibility. A hybrid genetic algorithm, combining the genetic algorithm with the pattern search method, was proposed in [95]. Its reliability was verified by optimizing a brushless direct-current (DC) motor [99]. However, the convergence of the genetic algorithm is often slow, particularly for problems requiring high-precision solutions, which can be computationally expensive. Furthermore, parameter tuning is complex, requiring careful selection of the population size, crossover rate, and mutation rate [102].

2) SA algorithm. In EMF inverse problems, the SA algorithm optimizes electromagnetic source or medium parameters by simulating the physical annealing process. It can approximate the global optimum at a low computational cost and exhibits good convergence for continuous, bounded problems [103].

Reference [100] provides a detailed introduction to the principles and basic concepts of the SA algorithm and discusses its implementation using a permanent-magnet DC tacho-generator as an example [104]. An improved SA algorithm was proposed in [101] to avoid undirected exploration during the optimization search. This method was used to globally optimize the rotor pole geometry of a switched reluctance motor, significantly improving the static torque of the prototype [105]. However, the double-loop structure of the SA algorithm results in low computational efficiency, limiting its application in EMF inverse problems [87].

3) Tabu search (TS) algorithm. TS algorithm is a heuristic stochastic search method. Its core idea is to explore the neighborhood of the current solution, select the best candidate as the new current solution, and maintain a tabu list to record recently visited solutions, thereby preventing the algorithm from cycling. The algorithm can escape local optima and enhance global search capabilities, making it particularly suitable for complex multi-modal optimization problems [106].

Reference [74] presents an improved TS algorithm applicable to continuous variables. The feasibility of this method was verified through its application to the optimal design of a multi-segment circular-arc pole-shoe [78]. The TS algorithm was used in [103] to optimize a hub-type permanent magnet motor, significantly reducing the required amount of permanent magnet material without compromising electrical performance [107]. However, the algorithm's performance is highly sensitive to parameters such as the tabu list length and neighborhood structure, and parameter tuning is complex. To address these issues, researchers have proposed various improved TS algorithms that introduce dynamic adjustment mechanisms and hybrid strategies, thereby enhancing search efficiency and solution quality [108]-[109].

4) PSO. The PSO algorithm achieves an efficient evolutionary search by simulating the collaborative and competitive behaviors of individuals in a biological population. It leverages group intelligence, making it both efficient and flexible [110]. The particle swarm algorithm was applied to the design of electrical machines in [106]. Its effectiveness was demonstrated through optimization calculations on small three-phase asynchronous motors and medium-sized high-voltage motors [111]. In [107], after developing a model for a dual-rotor permanent magnet reluctance motor, the PSO algorithm was used to find the optimal structural dimensions. The optimization objectives were to increase the average torque and reduce torque ripple [112]-[113].

5) Quantum evolution algorithm. The quantum evolutionary algorithm integrates quantum computing concepts with evolutionary algorithms. In this approach, chromosomes are encoded using quantum bits (qubits), and their evolution is governed by quantum gate operations. Compared to traditional evolutionary algorithms, quantum evolutionary algorithms exhibit superior global search capabilities and faster convergence, making them particularly suitable for optimization problems with small populations [99].

In the field of motor structure optimization, various optimization algorithms have been validated and applied; specifically, the multi-segmented arc rotor pole-shoe structure has been extensively used in the design of large hydroelectric generators and cross-flow units [112]. This paper focuses on the optimization design of the multi-segmented circular arc pole-shoe, with an emphasis on applying both single-objective and multi-objective optimization algorithms to this structure.

B. Optimization Algorithm for Five-segment Arc pole-shoe Structure

The structure of the five-segment arc pole-shoe is depicted in Fig. 7. The optimization variables consist of the center coordinates and the radius of each arc segment, i.e., (x_i, y_i), $R_i (i = 1, 2, 3)$ in the figure. Based on the number of objective functions, the optimization can be categorized as either single-objective or multi-objective.

1) Single-objective optimization

For single-objective optimization, the objective function is

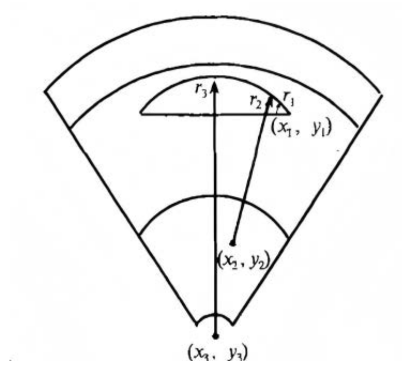

Fig. 7. Schematic diagram of multi-segment arc pole-shoes.

to maximize the fundamental component of the no-load air-gap magnetic flux density. The constraints include the no-load voltage waveform distortion rate (THD_v), the telephone harmonic factor (THF), the short-circuit ratio (SCR), and the direct-axis transient reactance. The optimization problem can be formulated as follows [59], all labeled values denote upper limits.

$$\begin{aligned} &\max B_{f1}(X) \\ &e_v - e_{v0} \le 0 \\ &\mathrm{THF} - \mathrm{THF}_0 \le 0 \\ &\mathrm{SCR} - \mathrm{SCR}_0 \ge 0 \\ &X_d^{'} - X_{d0}^{'} \le 0 \end{aligned} \tag{2}$$

where $B_{f1}(X)$: Fundamental component of the no-load air-gap magnetic flux density, the objective function to be maximized; e_v: No-load voltage waveform distortion rate; THF: Telephone harmonic factor, a metric evaluating harmonic interference with communication systems; SCR: Short-circuit ratio, a key index reflecting the motor's stability and reactive power capability; X'_d : Direct-axis transient reactance, characterizing the motor's transient performance under fault conditions.

The primary optimization algorithms that have been applied to the single-objective structural optimization of multi-segmented circular-arc pole-shoes include the following:

Yang et al. [113] developed an enhanced TS algorithm that improves both convergence speed and computational accuracy. This new algorithm removes the restriction that the objective function value of a new state must decrease; instead, it selects states based on the minimization of the objective function, which enables it to escape local optima. Additionally, it discards the traditional tabu list mechanism, introduces a dynamic termination criterion based on the characteristics of the objective function's changes, and incorporates an adaptive step-length vector adjustment strategy, thereby significantly reducing the number of invalid iterations [114]. When validated using engineering cases of multi-segment circular arc pole-shoes, the algorithm demonstrated considerable advantages over the traditional SA method. The number of searches and the computational time were reduced to 20% and 25%, respectively, of those required by the control algorithm [115].

The traditional SA algorithm can find the global optimum, but it often requires numerous iterations for large-scale or complex problems, leading to long computation time and high costs [116]. The performance and outcomes of the traditional algorithm are also sensitive to its control parameters; inappropriate settings can reduce its efficiency and accuracy. To address these limitations, an improved algorithm incorporates gradient information from the objective function to generate new points, which reduces unnecessary random exploration and conserves computational resources. This new algorithm also enhances stability by introducing a dynamic process stability criterion and geometric constraints, effectively minimizing redundant calculations. Validation on a multi-segment circular arc pole-shoe model shows that the improved SA algorithm requires approximately 50% fewer searches than the original algorithm [114].

The traditional region elimination method explores the global optimal solution by searching uniformly across the entire interval from multiple starting points and refining the search with a local optimization strategy. However, this method is hampered by slow convergence, low computational efficiency, and a lack of self-learning capability. To overcome these drawbacks, Ma et al. [115] enhanced the method by introducing a “memory” function via a typical set, which prevents repeated calculations in previously explored regions. Furthermore, search trajectories are represented by straight-line segments between neighboring sampling points, further reducing both computational and storage requirements. An optimization example of a multi-segment circular arc pole-shoe demonstrates that the number of iterations for the improved region elimination algorithm is approximately 84% of that required by the SA algorithm [116]

Traditional TS algorithms are inefficient with continuous variables, exhibit slow search processes in high-dimensional problems, and are prone to converging to local optima. To address these limitations, an improved approach refines the search process by incorporating a genetic algorithm to further optimize high-quality solutions [117]. New candidate solutions are generated through crossover and selection operations, which enhances local search capabilities. Additionally, the rules for generating new neighborhoods and the criteria for their absorption are adjusted, enabling the algorithm to explore more distant regions and avoid overlooking potentially superior solutions. Validation using multi-segment circular arc pole-shoe examples shows that the number of iterations for the improved TS algorithm is approximately 60% of that required by the SA algorithm [116].

Table III demonstrates that the improved TS algorithm achieves the fastest convergence with minimal iterations, making it suitable for time-critical engineering applications. The improved SA algorithm significantly enhances computational efficiency while maintaining global convergence, proving effective for complex multimodal optimization problems. Although the improved zone elimination method requires more iterations, it exhibits superior global search capabilities, making it appropriate for high-precision design scenarios. For practical implementation, the improved TS algorithm is recommended when computational resources are limited. The improved SA algorithm provides an optimal balance between computational efficiency and solution quality. For preliminary design phases, conventional SA, despite higher computational demands, ensures reliable solutions.

TABLE III
COMPARISON OF SINGLE-OBJECTIVE OPTIMIZATION ALGORITHMS

Arithmetic	Number of iterations
SA algorithm	10,347
Improved TS algorithm	2168
Improved SA algorithm	5198
Improvement of the area elimination method	8760
Improved tabu algorithm	3119

Wu et al. [114] noted that when using the PSO algorithm to search for the global optimum, the resulting solution was often located on a constraint boundary. This sensitivity to small perturbations in the design variables can compromise the algorithm’s stability in practical engineering applications. Therefore, considering solution robustness is crucial for practical applications, and it is typically assessed by calculating the expected fitness function. This process involves calculating the objective function for numerous additional sampling points. In EMF inverse problems, each sampling point requires complex finite element calculations, which significantly increases the computational cost. To address this issue, an expected fitness function has been proposed, wherein robustness is assessed by calculating the average performance of a solution at neighboring points, thereby reducing the need for extensive additional sampling. As presented in Table IV, the optimization results from a validation case involving multi-segment circular arc pole-shoes compare the performance of the general-purpose particle swarm optimization (GPSO), a new robust particle swarm algorithm, and a conventional robust particle swarm algorithm. The results show that the new robust algorithm and the conventional robust PSO algorithm converge to the same optimal solution. However, the new algorithm requires only one-fifth of the iterations of the conventional method while incurring a smaller computational increase compared to the general-purpose optimization algorithm [117]. The robust PSO algorithm achieves an effective balance between computational efficiency and solution stability, making it a preferred choice for engineering applications. For critical equipment designs that require maximum robustness, the conventional robust PSO may be selected to obtain the most stable solutions, albeit at a higher computational cost. A

TABLE IV
COMPARISON OF RESULTS OF OPTIMIZATION ALGORITHMS CONSIDERING ROBUSTNESS

Arithmetic	Number of iterations	B_{f1}/T	$(B_{f1})_{esp}$/T
GPSO	1348	1.086	1.001
Robust particle swarm algorithm	1564	1.054	1.041
Conventional robust PSO	6840	1.055	1.041

Note: $(B_{f1})_{esp}$, the expected value of the fundamental component of no-load air-gap magnetic flux density, which is calculated under parameter uncertainties to evaluate the robust performance of the optimized pole-shoe structure.

staged approach is recommended: employing general algorithms for rapid concept screening in the preliminary design phase, followed by robust algorithms to ensure design reliability in detailed design phases.

It must be emphasized that the numerical performance recorded in Tables III and IV, specifically the iteration counts for various optimization algorithms, is inherently case-specific and highly sensitive to factors such as model complexity, initial variable settings, and search space dimensionality. Consequently, evaluating these algorithms for the multi-dimensional parameter optimization of motor pole-shoe structures requires a comprehensive focus on their applicability within complex, multi-modal solution spaces rather than a narrow reliance on convergence speed.

For the design of five-segment arc pole-shoe structures, the improved TS algorithm—enhanced with dynamic state-transfer mechanisms and adaptive step-size adjustments—exhibits exceptional local exploitation efficiency within ten-dimensional spaces, allowing it to rapidly lock onto optimal solutions. However, as the dimensionality increases, the definition of its neighborhood becomes prohibitively complex. In contrast, the improved SA algorithm leverages stochastic search and objective function gradient information to provide robust global optimization for multi-modal landscapes, although its inherent randomness can compromise stability in ultra-high-dimensional domains.

In the presence of highly non-linear multi-physics constraints—such as mechanical stress and rotor end winding temperature rise boundaries—robust PSO emerges as the preferred choice due to its superior parallel exploration and parameter linkage optimization capabilities. By incorporating expected fitness functions and dynamic neighborhood definitions, improved PSO variants effectively balance global traversal with local convergence while maintaining solution robustness against the small perturbations typical of practical engineering applications. Collectively, these technical advancements—alongside the development of region elimination methods featuring “memory” functions and hybrid TS-GA strategies for enhanced population diversity—demonstrate significant advantages over traditional methodologies, providing a more stable and efficient framework for the structural design of multi-segment arc pole-shoes.

2) Multi-objective optimization

The multi-objective optimization problem is formulated with three objective functions: maximizing the fundamental component of the no-load air-gap magnetic flux density, minimizing the no-load voltage waveform distortion rate, and minimizing the THF. The constraints include the SCR and the direct-axis transient reactance. The problem is defined as follows [54], all labeled values denote upper limits.

$$\begin{aligned} &\max B_{f1}\left(X\right) \\ &\min\left(e_v, \mathrm{THF}\right) \\ &\mathrm{SCR}-\mathrm{SCR}_0 \geq 0 \\ &X_d' - X_{d0}' \leq 0 \end{aligned} \tag{5}$$

Given the inherent conflicts between these multiple performance criteria, the optimization does not yield a single unique solution but rather identifies a set of Pareto optimal solutions—a collection of non-inferior candidates where no individual objective can be further improved without deteriorating at least one other metric [115]. This solution set forms a multidimensional hypersurface in the objective space, providing a rigorous mathematical framework for designers to evaluate the trade-offs across various performance indicators.

To effectively navigate the high-dimensional and non-linear search spaces of multi-segment arc pole-shoe structures, various intelligent optimization algorithms have been successfully deployed. Wu et al. [118] applied the vector TS algorithm to the EMF inverse problem for optimizing the pole-shoes of multi-segment arcs. This algorithm combines TS with multi-objective optimization techniques to address such problems. The algorithm accurately identifies the Pareto optimal front through mathematical conditions, ensuring the validity of the solution set. Additionally, it considers the solution density in both the objective function space and the decision variable space to guarantee a uniform distribution across the Pareto front. Validation examples demonstrate that the Pareto solutions found by this algorithm are uniformly distributed in the objective function space. Furthermore, a diverse set of optimal solutions can be obtained in a single run, indicating higher computational efficiency.

The standard quantum evolutionary algorithm faces several challenges, including optimal solution selection, the lack of an effective information-sharing mechanism, and the trade-off between convergence and computational efficiency. To address these limitations, an improved approach introduces an indicator vector that tracks the selection frequency of each individual’s optimal solution into an elite set [119]. This mechanism prevents the algorithm from converging prematurely on specific solutions, thereby preserving the diversity of the solution set and enhancing its global search capability. Furthermore, this new algorithm replaces the simplistic information-sharing method of the traditional approach by incorporating concepts from PSO. This allows individuals to more effectively share historical search experiences, which accelerates convergence while mitigating the rapid loss of population diversity [120]. As demonstrated in [120], the improved quantum evolutionary algorithm exhibits superior convergence performance and higher solution quality. In comparison with the traditional SA algorithm, the new algorithm not only identifies a single optimal solution but also generates a diverse set of Pareto-optimal solutions, which offers greater practical value for engineering decision-making [120].

In multi-objective optimization, population-based intelligent algorithms, particularly PSO, have become effective tools for solving complex engineering problems due to their robust global search capabilities and straightforward frameworks. However, standard PSO algorithms are susceptible to premature convergence to local optima, which has prompted researchers to develop various improved multi-objective PSO algorithms. For example, Lu et al. [121]

developed an optimization strategy integrating a multi-objective PSO algorithm with response surface methodology (RSM) to enhance the efficiency and reduce the cogging torque of interior permanent magnet synchronous generators, verifying its feasibility. Similarly, Xu et al. [121] proposed a strategy combining a Kriging model with an enhanced PSO algorithm to improve convergence speed and global optimization accuracy. This method integrates an environmental sensing mechanism with genetic algorithm operators to iteratively optimize parameters, proving effective for switched reluctance motors. Wang [98] combined a non-dominated sorting mechanism with a dynamic congestion evaluation strategy, developing a multi-dimensional solution set update criterion that incorporated elitism. This approach enhances search efficiency in high-dimensional objective spaces by controlling the density of the Pareto front. Furthermore, Fang et al. [97] integrated the crossover operator from the NSGA-II algorithm with the PSO velocity update equations, achieving a synergistic enhancement of both global exploration and local exploitation capabilities. Reference [121] proposes a novel stator structure for switched reluctance motors (SRMs) to mitigate operational vibration and acoustic noise. In this study, a multi-objective particle swarm optimization (MOPSO) algorithm, in conjunction with the technique for order of preference by similarity to ideal solution (TOPSIS) method, was employed to select the optimal design parameters. Subsequently, a multiphysics coupling approach was utilized to perform harmonic response and acoustic field simulation analyses on the motor stator. The results verified that the proposed structure was effective in reducing the vibration and noise of the SRM [122].

In the practical design of large salient pole units, electromagnetic optimization must satisfy hard constraints regarding mechanical stress and thermal safety. Modern optimization workflows typically employ sequential or co-simulation coupling of electromagnetic, structural, and thermal fields. Regarding the maximum mechanical stress at the pole-shoe root, algorithms first calculate the centrifugal load based on rated and runaway speeds after generating a geometric model in each iteration, checking it against the allowable stress of the material. If the stress exceeds the limit, the individual's fitness is heavily penalized via a penalty function or directly discarded. For rotor end winding temperature rise, researchers often rapidly evaluate thermal conditions using analytical formulas or equivalent thermal circuit models based on the harmonic losses obtained from electromagnetic simulations, ensuring they remain within the limits defined by the insulation class. As mechanical and thermal constraints often render the feasible region extremely fragmented and discontinuous, PSO exhibits superior robustness in complex constrained spaces due to its strong global search capability and adaptability to non-linear boundaries. However, to mitigate the computational pressure of high-fidelity simulations, researchers are increasingly introducing RSM or Kriging surrogate models to construct approximate mathematical expressions of multi-physics constraints, significantly enhancing computational efficiency while maintaining optimization accuracy.

The ultimate goal of multi-objective optimization is not merely to obtain a Pareto solution set, but more crucially, to filter the final candidate that aligns with practical engineering requirements. To address the "selection dilemma" inherent in Pareto sets, researchers typically introduce multi-criteria decision-making (MCDM) methods for scheme evaluation. For instance, the weighted average method assigns weight coefficients to various objectives based on the priority of engineering tasks, reducing the multi-objective problem into a single-attribute score for ranking. The fuzzy comprehensive evaluation method employs membership functions to fuzzify the performance of different objectives, effectively handling the coexistence of qualitative and quantitative indicators in power systems. The technique for order of preference by similarity to ideal solution (TOPSIS) ranks alternatives by calculating their geometric distances to both the "ideal" and "negative-ideal" solutions; other methods include the rank-sum ratio (RSR) and the VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR). The integration of these decision mechanisms transforms multi-objective optimization from a purely mathematical search into a design process that comprehensively considers multiple engineering constraints.

Although these enhanced particle swarm and quantum algorithms have demonstrated superior performance across various multi-objective optimization domains, their specialized application specifically tailored for the optimization of multi-segmented circular arc pole-shoe structures remains an under-explored area with significant potential for future innovation.

V. Summary and Outlook

Significant progress has been made in rotor pole-shoe structural research, leading to the proposal and practical application of various multi-segment arc designs. The three-segment arc pole-shoe, which combines a large central arc with smaller arcs at the ends, optimizes the air-gap magnetic field distribution, reduces harmonic content, and minimizes interpolar leakage and windage losses. However, this design necessitates a trade-off between the excitation current and mechanical strength, making it unsuitable for high-speed hydrogenerators. The five-segment arc pole-shoe further refines the pole profile, which improves magnetic field uniformity, reduces voltage waveform distortion and harmonic content, and enhances generator efficiency and stability. These characteristics make it particularly suitable for high-speed hydrogenerators. The structure combining one eccentric pole arc with two chordal sections optimizes the magnetic field distribution while reducing machining complexity and material costs. For specialized applications, the asymmetric pole structure effectively mitigates tooth harmonics and optimizes the air-gap field distribution, which significantly improves the no-load voltage waveform quality and enhances dynamic performance. In summary, the optimized design of these pole-shoe structures improves the uniformity of air-gap magnetic field distribution and enhances the operating efficiency and electromagnetic performance of the generator. This work provides both a crucial theoretical basis and practical guidelines for salient pole synchronous motor design.

In most studies, the finite element method is employed for the numerical analysis of EMFs, while parameter optimization approaches are used to determine the optimal geometric parameters of multi-segment arc pole-shoes. These approaches focus on improving the efficiency and robustness of single-objective and multi-objective optimization algorithms in practical applications. For single-objective optimization, researchers have significantly enhanced the convergence speed and computational efficiency by refining traditional methods, such as TS, SA, and region elimination algorithms. These improved algorithms have demonstrated strong adaptability in optimizing the geometrical parameters of five-segment arc pole-shoes, effectively balancing key electromagnetic performance metrics like the fundamental amplitude of the air-gap magnetic flux and the voltage waveform distortion rate.

Although existing studies have explored single-objective optimization of the five-segment arc-pole-shoe structure, practical engineering applications require the simultaneous consideration of multiple performance metrics, including fundamental amplitude, harmonic distortion rate, and short-circuit ratio. This necessity underscores the value of multi-objective optimization algorithms. The vector TS algorithm and the improved quantum evolutionary algorithm have already demonstrated their effectiveness in the multi-objective optimization of these structures. Future research could focus on applying MOPSO to pole-shoe design. Such an approach can generate a set of Pareto-optimal solutions, allowing for a comprehensive analysis of the trade-offs between conflicting objectives under complex operating conditions. This would enhance not only the overall performance but also the practical viability of salient pole synchronous motor designs.

Current pole-shoe designs, typically exemplified by multi-segment arc structures, are inherently constrained by initial geometric assumptions, which may preclude the discovery of non-traditional structural forms with superior performance. Future research should focus on establishing a multi-stage optimization path tailored for large salient pole synchronous motors. Because these machines are massive and involve complex manufacturing processes, total reliance on free-form topology optimization may result in unmanufacturable designs. Therefore, in current design practices, topology optimization should first be utilized in 2D or simplified 3D models to explore non-traditional structural prototypes. Subsequently, these innovative configurations should be converted into parameterizable descriptions and refined within traditional parametric design frameworks for engineering correction. Finally, high-fidelity multi-physics simulations should be employed to precisely calibrate the electromagnetic, mechanical, and thermal characteristics of the synthesized structures. This synergistic optimization strategy can fully exploit the innovative potential of topology optimization while ensuring the engineering feasibility and reliability of the motor design.

The optimization of rotor pole structures in salient pole synchronous motors has matured into a comprehensive research system, representing a typical deeply coupled multi-physics design challenge. Building upon theoretical analysis and numerical computation, advancing this research framework through improved computing power and sophisticated algorithms has become the mainstream approach. This paper presents a systematic review of the pole-shoe structure optimization design framework, whose principles are universally applicable to other motor components. Notably, the field of motor design is undergoing a profound transformation driven by advances in computing power and optimization algorithms, making data-driven optimization strategies an inevitable trend. Motor design is evolving toward a modern scientific computing domain characterized by data-driven approaches, global optimization, and high automation. Establishing evaluation benchmarks by leveraging classical theoretical formulas and empirical design data, combined with developing high-dimensional and efficient global optimization algorithms, is key to enhancing the accuracy and cost-effectiveness of structural design for large electrical machines.

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