Research on the Theoretical Mechanism and Engineering Application of Magnetic Field-Coil Interaction

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ABSTRACT

The interaction between magnetic field and coil is the core principle of electric motor, which supports the design and operation of all types of motors (including electric motors and generators). Based on the basic theory of magnetic field and coil, this paper explains the key mechanism of their interaction, analyzes the principle behind the generation of electromagnetic induction and electromagnetic torque, and shows their application logic through typical structures such as DC motors and induction motors. In addition, it also discusses the development prospect of this principle in the field of new motor technologies, which provides a concise reference for the basic research and engineering application of motor science.

Keywords: Electric Machine Theory; Magnetic Field; Coil; Electromagnetic Induction; Electromagnetic Torque.

1. INTRODUCTION

1.1 Research Background

Driven by the dual forces of global energy structure transformation and industrial intelligent upgrading, electric motors, as core equipment for energy conversion, are facing stringent requirements for "higher efficiency, lighter weight and smaller size" [1]. The interaction between magnetic field and winding coil constitutes the core physical process for electromechanical energy conversion in electric motors, and its coupling characteristics directly affect key performance indicators such as power density, energy efficiency ratio and noise level of motors.

In traditional motor design, the optimization of magnetic field distribution and the design of coil structure are often decoupled from each other, resulting in problems such as excessive magnetic circuit loss and insufficient torque density, which can hardly meet the application demands of high-end fields including new energy vehicles and aerospace. In addition, breakthroughs in the research and development of new materials and numerical simulation technologies have provided new technical approaches for the in-depth optimization of magnetic field-coil interaction, making it urgent to establish a systematic theoretical system and engineering application method.

1.2 Present Research Situation

Scholars both domestically and internationally have conducted extensive research on the interaction between magnetic fields and coils. At the theoretical level, the formulas for induced electromotive force and electromagnetic torque have been derived through the basic laws of electromagnetism, but there is insufficient quantitative analysis of the influence of multi-parameter coupling[2]; In terms of mechanism research, the application scenarios of motional induction and induced induction have been clarified, but there is a lack of discussion on the synergistic effect of the two induction forms under complex working conditions. In engineering applications, structural optimization methods have been proposed for traditional machine types such as DC motors and asynchronous motors, but these optimization schemes often focus on a single component and fail to form a magnetic field-coil collaborative optimization system. In the field of technology integration, finite element simulation technology has been widely applied in magnetic field analysis, but the electromagnetic property modeling and simulation accuracy of new materials (such as superconducting materials and soft magnetic composites) still need to be improved. Existing research has not yet fully addressed issues such as the unclear mechanism of magnetic field-coil coupling, insufficiently targeted optimization schemes, and inadequate integration of new technologies, which have restricted further breakthroughs in motor performance.

1.3 Research Content and Technical Approach

This article conducts a systematic study on the interaction between magnetic fields and coils, with core contents including: (1) Basic theoretical research: sorting out the generation methods of magnetic fields and the types of coil structures, deriving calculation formulas for key electromagnetic parameters; (2) Analysis of the mechanism of action: comparing the differences between two induction forms, revealing the influence law of electromagnetic torque; (3) Engineering application research: analyzing the coupling logic of typical motors, Propose methods for performance optimization; (4) Development Trend Outlook: Exploring New Technology Integration Application Paths. The technical approach follows a logical chain of "theoretical derivation-mechanism analysis-engineering application-trend outlook", achieving full-chain research from basic theory to engineering practice.

1.4 Research Significance

The theoretical significance of this paper lies in establishing a quantitative analysis system for magnetic field-coil interaction, clarifying the multi-parameter coupling influence mechanism, and enriching the application theory of electromagnetics. The engineering significance lies in proposing a practical motor efficiency improvement scheme, providing technical support for the research and development of high-efficiency and lightweight motors. The industrial significance lies in promoting the application of new materials and simulation technologies in the motor field, facilitating the transformation of the motor industry towards green and intelligent development, and holds significant academic value and practical significance.

2. BASIC THEORY OF MAGNETIC FIELD AND COIL

2.1 Basic characteristics and generation methods of magnetic field

As a vector field, the core physical quantity of a magnetic field is magnetic flux density B (unit: T, Tesla), which possesses two essential characteristics: first, magnetic field lines always form closed curves with no isolated magnetic monopoles, demonstrating the property of a solenoidal field; second, a magnetic field exerts force on moving charges and current-carrying conductors, which is the core manifestation of its energy transfer and interaction.

There are three main ways to generate a magnetic field:(1) Electromagnetically induced magnetic field, produced by passing current through excitation coils. It features flexible regulation and is suitable for equipment such as DC motors and asynchronous motors. (2) Permanent magnet magnetic field, using rare-earth permanent magnets (e.g., NdFeB N55 series) or ferrite materials. It has the advantages of high magnetic field strength and good stability, and is widely used in permanent magnet synchronous motors. (3) Hybrid magnetic field, which achieves magnetic field optimization through the synergistic effect of electromagnetism and permanent magnets, balancing controllability and energy efficiency.

A performance comparison of the three magnetic field generation methods is shown in Table 1.

Table 1. Performance Comparison of Three Magnetic Field Generation Methods.

Magnetic field type	magnetic field strength	stability	regulatory flexibility	Application scenarios
Electromagnetic induction magnetic field	Medium - high	Medium	High	DC motor, asynchronous motor
Permanent magnet field	High	High	Low	Permanent magnet synchronous motor
Composite magnetic field	High	Medium-high	Medium-high	High-end servo motors, electric propellers

2.2 The structure and electromagnetic characteristics of the coil

As the core component coupling the magnetic field with the electromagnetic system, the structural design of the coil directly determines the strength and stability of the magnetic field-coil interaction, serving as the foundation for theoretical analysis and engineering applications. From the perspective of structural composition, the coil is wound from high conductivity materials (such as copper wires) in a preset geometric shape. Its key structural parameters include wire diameter d, total number of turns N, inner diameter of coil D_1, external diameter D_2, axial length l, winding pitch s. These parameters not only affect the basic electromagnetic parameters of the coil itself such as resistance R and inductance L, but also directly regulate the coupling efficiency between the magnetic field and the coil, serving as the core basis for coil selection and optimization in engineering applications. The electromagnetic characteristics of the coil are mainly reflected in two aspects: first, it generates an excitation magnetic field after being energized, providing a medium for energy conversion in the motor; second, it induces an electromotive force when cutting magnetic field lines, realizing the conversion from magnetic energy to electric energy. In addition, the electrical conductivity and insulation class of the coil directly determine the operating parameters of the motor such as rated current and operating temperature, which are key indicators to be considered in motor design.

3. THE INTERACTION MECHANISM BETWEEN MAGNETIC FIELD AND COIL

3.1 Electromagnetic induction phenomenon and induced electromotive force

When a coil moves relative to a magnetic field, or when the magnetic flux passing through the coil changes, an induced electromotive force will be generated across the coil's terminals. This phenomenon is known as electromagnetic induction, which is the core operating principle of devices such as generators and transformers. According to Faraday's law of electromagnetic induction, the magnitude of the induced electromotive force is proportional to the number of coil turns and the rate of change of magnetic flux, and its mathematical expression is as follows: $E=N*d\Phi/dt$ (E: induced electromotive force, Unit V Volt; N: number of turns; Φ: magnetic flux, Unit Wb Weber; $d\Phi/dt$: Rate of change of magnetic flux).

Electromagnetic induction is mainly divided into two types: dynamic induction and induced induction. (1) Dynamic induction refers to the induced electromotive force generated when the coil moves in a constant magnetic field and cuts the magnetic induction line. Its essence is the directional movement of free electrons in a conductor under Lorentz force. The armature coil in DC generator rotates in the stator magnetic field to generate electricity, which is a typical application of dynamic induction. (2) Induced induction refers to the induced electromotive force caused by the change of the magnetic flux of the coil due to the change of the magnetic field. Its driving force is the eddy electric field excited by changing magnetic field. The current change of the primary winding in the transformer will produce induced electromotive force in the secondary winding, which is the application scenario of induction. The essence of both induction forms is to change magnetic energy into electric energy, which provides a solid theoretical basis for the generation and long-distance transmission of electric energy. The comparison of the two kinds of induction is shown in Table 2.

Table 2. Comparison between motional induction and induced induction.

comparative dimension	motional induction	induced induction
physical essence	Conductor cutting magnetic field lines, mechanical variation of magnetic flux	Change of magnetic field generates vortex electric field, electromagnetic variation of magnetic flux
trigger condition	Relative motion between conductor and magnetic field	Magnetic field strength/distribution varies with time
energy source	Mechanical energy (such as steam turbine, water turbine)	Electromagnetic energy (such as alternating current in the power grid)
Characteristics of Electromotive Force	It is positively correlated with the speed of movement	Positive correlation with the rate of change of magnetic field
Typical application scenarios	Synchronous generator, DC generator	Power transformer, induction voltage regulator

3.2 Generation of electromagnetic torque and energy conversion

When a coil is electrified and placed in a magnetic field, the magnetic field will generate an electromagnetic force on it, and this force will form an electromagnetic torque to make the coil rotate. This is the core principle of electric motor. According to the left-handed rule, the magnitude of the electromagnetic force (also called Ampere's force) on the electrified conductor in the magnetic field is: $F=BIL\sin\theta$. In this formula, b represents the magnetic induction intensity, I is the current in the conductor, L is the effective length of the conductor, and θ is the included angle between the current direction and the magnetic field direction.

In the structure of the motor, the coil is usually wound around the iron core to form an armature. When energized, the effective edge of the armature coil is subjected to electromagnetic force in the stator magnetic field. Because both ends of the coil are connected to the external circuit through commutator or slip ring, this ensures that the current direction changes in time during the rotation process, thus keeping the electromagnetic torque direction constant. This enables the armature to continuously rotate and realize the conversion from electric energy to mechanical energy. The magnitude of electromagnetic torque is directly proportional to magnetic field strength, coil current, coil turns and magnetic coupling coefficient. In engineering, the torque density and operating efficiency of the motor can be effectively improved by optimizing the magnetic field distribution (such as concentrating the magnetic field with pole shoes) and adjusting the number of turns and current of the coil.

4. ENGINEERING APPLICATIONS OF MAGNETIC FIELD-COIL INTERACTION

The law of interaction between magnetic fields and coils is widely applied in various types of electric motors, and their matched design directly determines the operating performance of motors. This paper selects two typical motors, namely DC motors and asynchronous motors, to analyze the coupling application logic of magnetic fields and coils.

4.1 Coupling logic of DC motor

The DC motor adopts a structure of "stator excitation, armature rotation". The stator generates a constant magnetic field through the excitation coil (or directly uses permanent magnet excitation). The armature coil is embedded in the armature core slot, and when DC current is applied, it receives electromagnetic torque in the stator magnetic field, driving the armature to rotate. During the rotation of the armature, the coil cuts the stator magnetic field, generating a counter-electromotive force. The magnitude of the counter-electromotive force increases with the increase in speed, which can effectively suppress the armature current and achieve self-speed regulation of the motor. As shown in Figure 1.

The design of the adaptation between the magnetic field and the coil in a DC motor focuses on two key points: Firstly, by adjusting the number of turns and current of the excitation coil, the stator magnetic field strength is optimized to ensure that the motor outputs sufficient torque. Secondly, the winding method of the armature coil is reasonably designed to reduce the impact of armature reaction on the magnetic field distribution and enhance the operational stability of the motor. By changing the direction of the excitation coil current or armature current, the speed and direction of rotation of the motor can be flexibly adjusted. Therefore, DC motors are widely used in scenarios where high-speed regulation performance is required, such as industrial machine tools and rail transit traction systems.

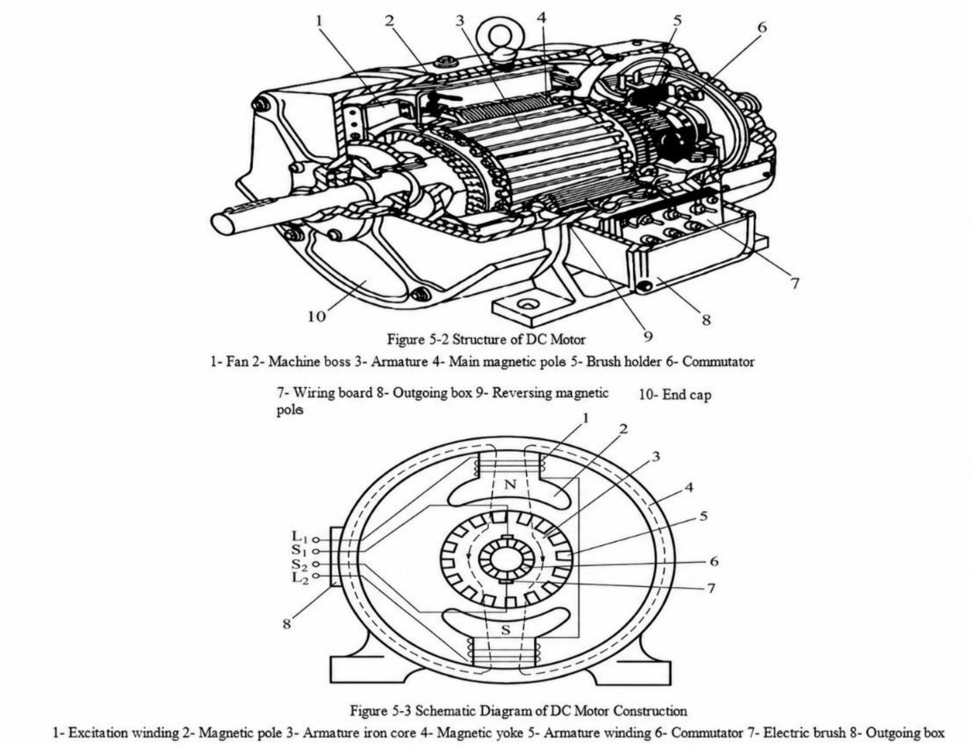

Figure 1. Basic structure of DC motor (stator excitation, armature rotation).

4.2 Coupling logic of asynchronous motor

The stator of a three-phase induction motor is made of three-phase winding coils, while the rotor is composed of closed conductive bars (end rings).The coupling logic is as follows: three-phase alternating current is supplied to the stator windings to generate a rotating magnetic field; the rotor bars cut the magnetic field to produce induced current (motional electromotive induction), which then interacts with the stator magnetic field to form electromagnetic torque. The core coupling points include: the speed difference between the stator rotating magnetic field and the rotor (slip ratio), the matching between coil impedance and power supply frequency, and the uniformity of air-gap magnetic flux density distribution. Efficient motor operation can be achieved when the slip ratio is controlled within the range of 2%-5%.

4.3 Motor performance optimization method

Based on the analysis of magnetic field-coil coupling logic, a three-dimensional optimization method is proposed, namely “magnetic field optimization-coil optimization-coupling optimization”.

4.3.1magnetic field optimization

(1) Arrange permanent magnets using the Halbach array to enhance the uniformity of the air gap magnetic field by over 15% while reducing magnetic flux leakage; (2) Optimize the stator core slot shape (such as pear-shaped slot, trapezoidal slot) to reduce hysteresis loss and eddy current loss; (3) Adopt a composite magnetic field design that combines the advantages of electromagnetic and permanent magnets to achieve precise control of magnetic field strength.

4.3.2 coil optimization

(1) Select copper alloy conductors with high conductivity to reduce copper loss in the coil; (2) Optimize the number of coil turns and conductor cross-sectional area to achieve a balance between “torque-loss” based on the electromagnetic torque formula; (3) Adopt fractional slot concentrated winding to shorten the end length and increase the winding utilization rate to over 80%.

4.3.3 coupling optimization

(1) Adjust the coil layout position through finite element simulation to place the coil in the region with optimal magnetic field strength [3-5]; (2) Match the air-gap length with the coil current to avoid magnetic saturation and current overload;(3) Adopt a genetic algorithm for multi-objective optimization to synchronously optimize magnetic field parameters and coil structure, thereby achieving an efficiency improvement of more than 5% for the motor.

5. OUTLOOK ON DEVELOPMENT TRENDS

5.1 In-depth application of finite element simulation technology

5.1.1 Optimization of coupled simulation model

With the development of software such as ANSYS Maxwell and COMSOL Multiphysics, the simulation of magnetic field coil coupling is evolving towards multi-field coupling. By establishing a three-dimensional coupling model of electromagnetic field, temperature field and structural mechanics field, we can accurately simulate the coil heating and the influence of magnetic force on the motor structure, so that we can predict its performance under all working conditions [6]. For example, optimizing the heat dissipation structure of the coil through temperature field simulation can reduce the temperature rise of the motor by more than 10°C and improve the operation reliability.

5.1.2 Digitalization of design process

Finite element simulation technology will be used in the whole design process of motor, from parametric modeling, magnetic field distribution simulation to performance optimization verification, and digital iterative design can be completed on the computer. Compared with the old methods, this digital process can shorten the research and development time by more than 30% and save a lot of experimental costs. After adding AI algorithm, we can realize automatic optimization of simulation parameters and intelligent generation of design schemes.

5.2 Exploring the application potential of new materials

5.2.1 coil material

High temperature superconducting materials, such as YBCO coated conductors, may become an important development direction of coil materials. Their resistance is almost zero, which can greatly reduce the copper loss in the coil and improve the current carrying capacity. Experiments show that the current density of superconducting coil can be more than 10 times higher than that of traditional copper coil, which gives us a chance to build a motor with higher power density.

5.2.2 magnetic field material

The application of new rare earth permanent magnet materials (such as NdFeB N55 series) and soft magnetic composite materials (SMC) will make the magnetic field strength and permeability stronger. SMC material has good magnetic isotropy, which can reduce the leakage loss of motor and improve the torque ripple problem. In addition, after the high temperature resistance and corrosion resistance of new permanent magnet materials are optimized, the motor can be used in more extreme environments [7].

5.2.3 structural material

Lightweight materials such as carbon fiber reinforced resin matrix composites will be widely used in motor housings and structural parts, which will reduce the weight of motors by more than 30% and meet the lightweight requirements of aerospace, new energy vehicles and other industries.

5.3 Prediction of future application directions

Technological innovations based on the principle of magnetic field-coil interaction will drive the development of motors towards high efficiency, lightweight, and intelligence: (1) Drive motors for new energy vehicles: through collaborative optimization, achieving efficiency≥97% and power density≥4 kW/kg, meeting the demand for long endurance [8]; (2) Special motors for aerospace: combining superconducting coils with lightweight materials to develop motors with high power, small volume, and resistance to extreme environments; (3) Underwater electric propulsion motors: adopting a coreless structure and low-noise design to meet the requirements of silent stealth.

6. CONCLUSION

This paper systematically investigates the theory, mechanism, applications, and trends of magnetic field-coil interactions, and draws the following main conclusions.(1) Established the foundational theoretical framework for magnetic field-coil interactions, systematically categorized the methods of magnetic field generation and coil structural types, and derived highly accurate formulas for induced electromotive force and electromagnetic torque, providing theoretical support for quantitative analysis.(2) Clarified the core differences and application boundaries between motional induction and induced induction, revealed the quantitative influence of parameters such as magnetic field strength and coil current on electromagnetic torque, and provided a basis for motor parameter design; (3) Analyzed the magnetic field-coil coupling logic of DC motors and asynchronous motors, and proposed a three-dimensional optimization method of ‘magnetic field-coil-coupling’, which can improve motor efficiency by more than 5%, and has good engineering application value.

The research results of this paper enrich the applied theory of electromagnetism and provide technical support for developing efficient and portable motor. However, more research is needed in coupling mechanism under complex working conditions and long-term stability of new materials. In the future, we will focus on multi-physics coupling simulation and experimental verification, so that these research results can be really used in engineering.

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