Structure principle and classification of Hybrid Excitation Motor

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Abstract. Hybrid excitation motor has two excitation sources: electric excitation and permanent magnet excitation. It has the advantages of convenient air gap magnetic field adjustment, high power density, wide voltage and speed adjustment range, etc. It has broad application prospects in industrial drive, new energy power generation and aerospace fields. Based on the magnetic adjustment principle of hybrid excitation motor, this paper summarizes the existing main classification methods and gives the equivalent magnetic circuit diagram. According to that coupling relationship between the permanent magnet magnetic circuit and the electric excitation magnetic circuit, the hybrid excitation motor is divided into series type, parallel type and parallel type, and further classified into stator main body type, rotor main body type and average type according to the placement position of the permanent magnet and the excitation winding. The typical motor structure and magnetic circuit characteristics are introduced.

1. Introduction
The motor is an electromechanical energy conversion device based on electromagnetic induction law and taking the magnetic field as a coupling field. There are two ways to establish an air gap magnetic field between the stator and rotor of the motor. One is to introduce current into the winding to form a magnetic field, that is, electrical excitation; the other is to use permanent magnets to generate magnetic fields, namely permanent magnet excitation[1]. Different excitation methods will lead to great differences in output characteristics, power density and efficiency of motors. The magnetic field of the electrically excited motor is easy to adjust, the power factor is controllable, and it can adjust the voltage and speed in a wide range. However, there is a large excitation loss in the motor, which reduces the efficiency of the motor and reduces the power density. The magnetic field of the permanent magnet motor is generated by the permanent magnet, and the excitation winding, brush and other structures are eliminated, which makes the permanent magnet motor simple in structure and high in reliability. At the same time, there is no excitation loss in the motor, the efficiency and power density are relatively large, and the structure is flexible[2]. Benefiting from the development of rare earth permanent magnets, the power density and efficiency of rare earth permanent magnet motors are continuously improved, and the dynamic response is fast. Widely used in aerospace, wind power generation, industrial and agricultural production and various fields of life[3]. However, the difficulty in adjusting the magnetic field has become an important technical bottleneck that limits its application and popularization. Therefore, the hybrid excitation motor which integrates the advantages of electric excitation and permanent magnet motor and overcomes their respective defects to the greatest extent has become a hot topic for experts and scholars from all over the world.
American scholars put forward the idea of hybrid excitation earlier in the patent published in 1985. After that, scholars from all over the world have made in-depth research and exploration on it, but there is still a lack of a relatively unified definition. At present, it is generally believed that hybrid excitation, also known as combined excitation or compound excitation, is the interaction between permanent magnet excitation and electric excitation. Excitation mode for realizing electromagnetic energy conversion together. Hybrid excitation motor is a new type of motor[4][5], which can adjust and control the main magnetic field of the motor by changing the topological structure of the motor and improving the speed regulation, driving performance, or voltage regulation characteristics of the motor.

This paper introduces the principle of magnetic adjustment of hybrid excitation motor and the existing main classification standards, and on this basis puts forward a more in-depth classification method. That is to say, based on traditional dividing hybrid excitation motors into parallel hybrid excitation motors, series hybrid excitation motors, and parallel hybrid excitation motors according to the coupling relationship between permanent magnet magnetic circuit and electric excitation magnetic circuit, According to the placement positions of permanent magnets and excitation windings on the stator and rotor of the motor, they are further classified, and their respective structural characteristics and application status are illustrated with examples.

2. Principle of magnetic adjustment of hybrid excitation motor

Taking the three-phase hybrid excitation synchronous motor as an example, the magnetic adjustment principle of the hybrid excitation motor will be explained below.

When the motor is unloaded, the flux linkage of symmetrical three-phase winding is:

$$\begin{bmatrix}
\psi_a \\
\psi_b \\
\psi_c
\end{bmatrix} = \begin{bmatrix}
\psi_{ap} \\
\psi_{bp} \\
\psi_{cp}
\end{bmatrix} + \begin{bmatrix}
M_{af} & M_{bf} & M_{cf} \\
M_{bf} & M_{bf} & M_{cf} \\
M_{cf} & M_{cf} & M_{cf}
\end{bmatrix}$$

(1)

In which,
- $\psi_a$, $\psi_b$, $\psi_c$ the flux linkage of phase a, phase b, and phase c windings;
- $\psi_{ap}$, $\psi_{bp}$, $\psi_{cp}$ is a phase, b phase, and c phase permanent magnet flux linkage;
- $M_{af}$, $M_{bf}$, $M_{cf}$ is the mutual inductance between armature winding and excitation winding of phase a, phase b, and phase c;
- $i_F$ is the excitation winding current.

When the motor works in the power generation state, the induced electromotive force of the armature (taking phase A as an example) is:

$$E_a = \frac{\partial \phi_a}{\partial t} = \frac{\partial (\psi_{ap} + M_{af} i_F)}{\partial t}$$

(2)

According to formula (2), when the excitation current $i_F = 0$, the permanent magnet flux linkage establishes the initial output voltage of the motor. Adjusting the excitation current $i_F$, the armature induced potential changes accordingly.

When the motor works in the electric state, the motor terminal voltage $U_a$ induced electromotive force with armature $E_a$ (taking phase a as an example) satisfy:

$$|U_a| \geq |E_a| = \frac{\partial \psi_a}{\partial t} = N\omega_r \frac{\partial \phi}{\partial t} = N\phi \omega_r$$

(3)

In which:
- $N$ is the number of turns of armature winding;
- $\omega_r$ is the angular velocity of the motor rotor;
- $\phi$ is the total magnetic flux per pole.

According to formula (3), it can be known that the motor speed satisfies

$$\omega_r \leq \frac{|U_a|}{N\phi}$$

(4)
Adjusting the excitation current $i_F$, the total magnetic flux per pole can be adjusted according to formula (4). Adjusting the excitation current $i_F$, the working speed range of the motor can be adjusted to meet the needs of different actual working conditions.

To sum up, the air gap flux can be adjusted by adjusting the excitation current when the motor works in the power generation state and the electric state.

3. Classification and equivalent magnetic circuit diagram of hybrid excitation motor

3.1. Classification of hybrid excitation motors

After more than 30 years' development, the hybrid excitation motor has formed a variety of topological structures based on the existing motor.

According to the coupling degree of electric excitation magnetic potential and permanent magnet magnetic potential, hybrid excitation motor can be divided into strong coupling structure and weak coupling structure. According to the coupling form of electric excitation magnetic potential and permanent magnet magnetic potential in the motor, it can be further divided into series hybrid excitation motor, parallel hybrid excitation motor, and series-parallel hybrid excitation motor. Series-parallel hybrid excitation motor is a form of magnetic circuit combination based on series and parallel. The weak coupling structure shows parallel magnetic potential[6]. It can be divided into two types according to the permanent magnet placement position or motor prototype. One is the rotor permanent magnet hybrid excitation motor with permanent magnets placed in the rotor, which takes the permanent magnet synchronous motor as the prototype; the other is the stator permanent magnet hybrid excitation motor with permanent magnets in the stator, which is based on the reluctance doubly salient motor. According to the action mechanism of excitation magnetic potential and armature magnetic potential, hybrid excitation motors can also be divided into hybrid excitation synchronous motors and hybrid excitation magnetic field modulation motors.

To facilitate classification and analysis, hybrid excitation motors are divided into series hybrid excitation motors, parallel hybrid excitation motors, and parallel hybrid excitation motors. On this basis, permanent magnets and excitation windings are further classified according to their positions. Series hybrid excitation motors are divided into series rotor main body type with permanent magnets and DC excitation windings placed on the rotor, series stator main body type with permanent magnets and excitation windings placed on the stator, and series average type with permanent magnets placed on the rotor and excitation windings placed on the stator. The structure type of the parallel hybrid excitation motor can be classified according to the series structure, it can be divided into three types: parallel stator main body type, parallel rotor main body type, and parallel average type. Parallel hybrid excitation motor mainly analyzes two typical structures: axial flux switching type and magnetic field modulation type.

3.2. Equivalent magnetic circuit diagram of hybrid excitation motor

Series connection means that the permanent magnet magnetic potential and the electric excitation magnetic potential are connected in series on the magnetic circuit[7] [8], and Figure 1-(a) is its equivalent magnetic circuit diagram. In figure1(a), $F_P$, the magnetic potential provided for the permanent magnet,$F_e$, the excitation magnetic potential provided for the electric excitation winding, $\Phi_b$The magnetic flux provided for the permanent magnet,$\Phi_e$The magnetic flux provided for the electric excitation winding,$R_g$Is air gap reluctance,$R_p$Is permanent magnet reluctance, $R_{i1}$, $R_{i2}$Is ferromagnetic reluctance.

Keywords series hybrid excitation motor, electric excitation magnetic potential$F_e$And that magnetic potential of permanent magnet$F_p$In a series relationship, they act together on the magnetic resistance of the magnetic circuit$R_g$, $R_p$, $R_{i1}$, $R_{i2}$The magnetic flux (air gap magnetic flux) of the main magnetic circuit is generated. The material characteristics of permanent magnets determine that the magnetic resistance of permanent magnets is very large. If the magnetic flux of the main magnetic
circuit is to be adjusted, a large magnetomotive force of electric excitation is needed, which leads to a large increase in electric excitation capacity. The hybrid excitation motor of this structural type has large excitation loss, low magnetic adjustment efficiency, high motor temperature, and easy to cause irreversible demagnetization of permanent magnets. The reliability is low, and it is seldom used in engineering practice.

A parallel connection means that the permanent magnetic potential and the electric excitation magnetic potential are in a parallel relationship on the magnetic circuit[9]. Figure 1(b) is the equivalent magnetic circuit diagram.

Keywords parallel hybrid excitation motor, electric excitation magnetic potential

In a parallel relationship, the magnetic flux generated by the electric excitation magnetic potential does not need to pass through the permanent magnet but is coupled with the magnetic flux generated by the permanent magnet magnetic potential in the air gap to form the main magnetic circuit flux of the motor together. At this time, the air gap magnetic flux of the motor can be adjusted only by adjusting the excitation current, the magnetic adjustment efficiency is high, and the influence on the magnetization of the permanent magnet is small. The phenomenon of demagnetization is effectively avoided. Compared with the series hybrid excitation motor, the working reliability of the permanent magnet is greatly improved, and the weakening ability is generally better than that of the series hybrid excitation motor. In addition, the structural design of the parallel hybrid excitation motor is flexible, and the permanent magnets can be placed on both the stator and the rotor, so the structural design of the motor is flexible and diverse.

The main magnetic poles of the parallel hybrid excitation motor are composed of permanent magnet parts and electric excitation parts, which are independent of each other on the magnetic circuit. Figure 1(c) is the equivalent magnetic circuit diagram.

In the parallel hybrid excitation motor, the permanent magnet field and the electric excitation field are separated and not coupled in the magnetic circuit. The air gap magnetic density is divided into two parts in space, the electric excitation part, and the permanent magnet part. However, the isolation in the magnetic circuit does not affect the superposition of the armature winding potentials of the permanent magnet and the electric excitation part, thus achieving the equivalent characteristics of air gap magnetic field adjustment. This kind of motor spatially separates the electric excitation part from the permanent magnet part, effectively blocks the influence of the change of the electric excitation magnetic potential on the working point of the permanent magnet, and improves the excitation and magnetic adjustment efficiency of the electric excitation part. In addition, the electric excitation part and the permanent magnet part of the axially parallel hybrid excitation motor are independent of each other, The design of the air gap and core length is flexible and free. However, the structure and
process of the parallel hybrid excitation motor are relatively complex, and the weight and cost of the motor are relatively high[10]. Table 1 gives the typical combination scheme of parallel hybrid excitation motor.

| Literature | Electric excitation part | Permanent magnet part |
|------------|--------------------------|-----------------------|
| [11,12,13,14] | Electrically excited synchronous motor (brushed and brushless) | Permanent magnet synchronous motor |
| [15,16] | Claw machine synchronous motor | Permanent magnet synchronous motor |
| [10,17,18] | Double salient pole motor | Tangential permanent magnet synchronous motor |
| [19,20] | Double salient pole motor | Double salient pole motor |
| [21,22] | Flux switching motor | Flux switching motor |
| [36,37] | Magnetic field modulation type motor | Magnetic field modulation type motor |

4. Typical structure of hybrid excitation motor

4.1. Typical Structure of Series Hybrid Excitation Motor

There are three main structures of series hybrid excitation motor. First, the permanent magnet and excitation winding are placed on the stator, which is easy to realize brushless motor, simple structure, and reliable operation. It is called series stator main body hybrid excitation motor; Second, the hybrid excitation motor with permanent magnets and DC excitation windings placed on the rotor is difficult to brush. It is called series rotor main body hybrid excitation motor; Third, permanent magnets are placed in the rotor and excitation windings are placed in the stator, which is called series average hybrid excitation motor.

Series stator main body hybrid excitation motor. In 1995, Professor Lipo proposed a hybrid excitation motor[23] with stator main body doubly salient structure, as shown in Figure 2(a). The stator and rotor of the motor with this structure are all salient pole structures, and the annular permanent magnet is placed between the stator yoke and the stator inner core, and the permanent magnet is magnetized radially; The electric excitation winding divides the annular permanent magnet into two parts, The armature winding is wound on the salient pole of the stator. The magnetic potential of electric excitation is in series with that of the permanent magnet. In 2009, scholars from Southeast University proposed a C-type hybrid excitation flux switching motor[24]. The motor structure is shown in Figure 2(b). Stator parts of the flux switching motor are spliced together by C-shaped punching sheets, permanent magnets, and electric excitation windings are placed between adjacent C-shaped stator punching sheets, Permanent magnets are magnetized tangentially, and armature windings are wound in adjacent C-shaped punch cavities; The rotor part is of salient pole structure. Through the placement of permanent magnets, the same C-shaped punch is controlled to have the same polarity, and the magnetic flux generated by the electric excitation winding passes through the permanent magnets, and the electric excitation magnetic potential and the permanent magnet magnetic potential are in a series relationship. In 2019, based on the principle of magnetic flux modulation, Harbin university of science and technology scholars put forward a new type of magnetic circuit series hybrid excitation motor[25], whose structure is shown in Figure 2(c) below. The motor is mainly composed of an outer stator, a cup-shaped rotor, and an inner stator. Wherein the permanent magnet and the excitation winding are both located on the outer stator, and the permanent magnet is radially magnetized in a single direction, and forms a pair of magnetic poles with adjacent stator teeth; The electric excitation winding is wound on the stator teeth adjacent to the permanent magnet. The armature winding is placed in the inner stator. There is a series relationship between permanent
magnet magnetic potential and electric excitation magnetic potential. The motor with this structure realizes brushless by using the composite structure of double stators and magnetic gears. Compared with the traditional series magnetic circuit hybrid excitation motor, the amount of permanent magnets and electric excitation windings are reduced, and the magnetic modulation performance is improved.

![Typical structures of series hybrid excitation motor](image)

Series rotor main body hybrid excitation motor. Henneberger G proposed a series rotor type hybrid excitation motor[26] in 1994, as shown in figure 2(d). The permanent magnet and excitation winding are both installed on the rotor, the permanent magnet is magnetized radially, and the electric excitation magnetic potential and the permanent magnet magnetic potential are connected in series. Because the excitation winding is installed on the rotor, it is difficult to realize the brushless excitation of the motor.

Series average hybrid excitation motor. In 2020, scholars from Jiangsu University proposed the doubly-fed brushless hybrid excitation motor with magnetic field modulation[27], and its structure is shown in Figure 2(e). The motor adopts the structure of the inner stator and outer rotor, the permanent magnets magnetized radially are attached to the inner side of the rotor, and the magnetization directions of adjacent permanent magnets are opposite, so the rotor structure is simple. The stator has a salient pole structure and consists of six large teeth. Three-phase armature winding is placed in the slot, and each big tooth has three small teeth, which are used for magnetic field modulation and winding.
three-phase auxiliary windings, thus improving the utilization rate of the internal space of the motor. The magnetic potential of electric excitation and permanent magnet are in a series relationship.

4.2. Typical structure of parallel hybrid excitation motor

The structural types of parallel hybrid excitation motors can be classified according to the structural classification of series hybrid excitation motors, which can be divided into parallel stator main hybrid excitation motors, parallel rotor main hybrid excitation motors, and parallel average hybrid excitation motors for classification analysis.

Parallel stator main body hybrid excitation motor. In 2007, Hoang, a French scholar, proposed a hybrid excitation motor[28] [29] with a parallel stator body based on a permanent magnet flux switching motor, as shown in Figure 3(a). The salient pole structure of the stator of the motor is Y-shaped, and a magnetic bridge is arranged outside. Permanent magnets are placed between the upper claws of two adjacent Y-shaped salient poles and magnetized tangentially; the excitation winding is wound at the root of the Y-shaped salient pole, so the magnetic resistance of the electric excitation magnetic circuit is relatively small, and the magnetic adjustment capability is improved. Permanent magnet magnetic potential and electric excitation magnetic potential are in a parallel relationship. In 2015, Professor Zhu Ziqiang proposed a new type of hybrid excitation motor[30] with a doubly salient pole structure. The structure is shown in Figure 3(b). For the motor of this kind of structure, an auxiliary permanent magnet is placed in the stator slot of the electroexcited double salient pole motor and tangentially magnetized; the electric excitation winding and the three-phase armature winding are both wounds on the stator teeth, and the electric excitation magnetic potential and the permanent magnet magnetic potential are in parallel relationship. The existence of the auxiliary permanent magnet improves the excitation efficiency and reduces the excitation loss. In 2018, Professor Qu Hairong of Huazhong University of Science and Technology proposed a magnetic flux reverse hybrid excitation motor[31]. The structure is shown in Figure 3(c). In the hybrid excitation motor with this structure, two permanent magnets with the same magnetization direction are placed on each stator tooth, and a space is left between the two permanent magnets to supply excitation magnetic flux, and the magnetization directions of the permanent magnets on adjacent stator teeth are opposite; The electric excitation winding is selectively wound on some stator teeth at equal intervals. The motor with this structure can improve the low-speed overload capability and high-speed flux weakening capability of the traditional flux reversal motor. Electric excitation magnetic potential and permanent magnet magnetic potential are connected in parallel.

(a) 12/10 pole flux switching motor  (b) doubly salient hybrid excitation motor  (c) flux reverse hybrid excitation motor

(d) hybrid excitation claw-pole motor
Parallel hybrid excitation motor with the main rotor. In 2014, Zhu Lisha of Shandong University proposed a rotor-type hybrid excitation claw-pole motor[32], whose structure is shown in Figure 3(d). In this hybrid excitation motor, the stator part is composed of three-phase AC winding and stator core, and the rotor part is composed of claw-pole rotor, permanent magnet, excitation bracket, an excitation winding. Permanent magnets magnetized tangentially are placed between the upper and lower claw poles and arranged alternately with the magnetic isolation welding blocks. The rotor excitation winding produces axial magnetic flux, which changes into radial magnetic flux after passing through the claw pole structure of the rotor and then closes after passing through the air gap and stator. The excitation winding produces the main magnetic flux of the motor, and the magnetic flux produced by the permanent magnet plays an auxiliary role in magnetizing. Electric excitation magnetic potential and permanent magnet magnetic potential are connected in parallel.

Parallel average hybrid excitation motor. In 2002, American scholar T.A.Liop proposed a hybrid excitation motor with split poles[33] [34], whose structure is shown in Figure 3(e). The stator core of the motor consists of a laminated part and a solid part, within the laminated part is divided into two mutually independent parts by an excitation winding, and the solid part is made of magnetic conductive material and provides a path for electric excitation magnetic flux; The armature winding is a three-phase AC winding. The rotor is also divided into N-terminal and S-terminal. Each terminal is formed by alternately arranging permanent magnets and core poles with the same polarity, and the permanent magnets and core poles of the N-terminal and S-terminal are staggered with each other. Permanent magnetic potential and electric excitation magnetic potential are connected in parallel. In 2018, A new type of doubly-stator doubly-fed hybrid excitation motor[35] has been proposed by scholars from Southeast University. The two-dimensional and three-dimensional structural diagrams are shown in Figure 3(f). It can be seen from the figure that the motor structure is divided into three parts: inner stator, outer stator, and hollow cup rotor. The excitation winding adopts distributed AC winding and is embedded on the inner stator, to realize brushless excitation; The armature winding adopts fractional slot concentrated winding, winding on the outer stator teeth; The V-shaped NS permanent magnets and core poles are alternately arranged on the hollow cup rotor. This double stator structure reduces the coupling between armature winding and excitation winding and effectively improves the space utilization rate inside the motor. In addition, the AC excitation winding embedded in the inner stator can be used for both magnetic adjustment and AC armature. Used for magnetic adjustment, the brushless hybrid excitation of the motor can be realized, and the magnetic field adjustment is convenient; Used as AC armature, can be used as a hot backup of armature winding, and can contribute part of torque output when needed. Electric excitation and permanent magnet excitation are parallel.

4.3. Typical Structure of Parallel Hybrid Excitation Motor
The structure of axial flux switching parallel hybrid excitation motor[36] is shown in fig. 4(a). The motor rotor with this structure is a salient pole structure, which is formed by pressing silicon steel sheets. The stator is for by splicing stator core of H-shaped units, and is divided into an inner layer and an outer layer by a magnetic isolation ring; a permanent magnet with tangential magnetization is arranged between two H-shaped units of that inner stator; an excitation winding is wound on the
excitation bracket between two H-shaped units of the outer stator. The two magnetic circuits are independent of each other and completely juxtaposed. This kind of motor alleviates the stator space contradiction of hybrid excitation field modulation motor, reduces the risk of permanent magnet demagnetization, and has many advantages such as high torque power density, adjustable magnetic flux, and high efficiency.

(a) Axial flux switching parallel hybrid

(b) Magnetic field modulated parallel hybrid excitation motor

Figure 4. Typical structure of parallel hybrid excitation motor

In 2019, Harbin university of science and technology scholars proposed a magnetic field modulated parallel hybrid excitation motor[37]based on the principle of magnetic flux modulation and parallel hybrid excitation motor, and its structure is shown in Figure 4(b). In the motor with this structure, the outer stator is a permanent magnet part and an electric excitation part which are coaxially arranged in parallel, and the two parts must meet the principle of magnetic flux modulation at the same time. And share a set of armature windings on the inner stator structure. The motor is generally divided into three parts: the inner stator, the magnetic regulating ring, and the outer stator. The inner stator is embedded with the armature winding to generate a rotating magnetic field. After the magnetic field modulation of the magnetic regulating ring rotor, the optimal harmonic component equal to the polar logarithm of the outer stator's magnetic field is generated. The whole motor adopts the magnetic adjusting ring as the torque output port, so the whole motor is brushless and the structure of the motor is simplified.

5. Conclusion

There are two kinds of magnetic potential sources in hybrid excitation motor, which have the characteristics of the high power density of permanent magnet motor and convenient magnetic field adjustment of electric excitation motor. It is an important development direction of a new high-efficiency motor and has broad application prospects.
In this paper, the hybrid excitation motor is divided into series, parallel, and parallel according to the magnetic circuit coupling mode, and is further subdivided into stator main hybrid excitation motor, rotor main hybrid excitation motor, and average hybrid excitation motor. The stator and rotor of the main stator-type hybrid excitation motor are generally doubly salient, and both excitation sources are located in the stator. The rotor has a simple structure, low moment of inertia, and fast dynamic response. Rotor-based hybrid excitation motor is mainly based on permanent magnet synchronous motor, which introduces DC excitation winding to realize hybrid excitation, realize a wide range of speed adjustment, and effectively broaden the application fields of permanent magnet motor. The average hybrid excitation motor makes full use of the internal space of the motor. It is convenient to realize the miniaturization design of the motor, but the heat dissipation of the motor should be considered emphatically. In addition, two new structures of parallel hybrid excitation motor are introduced, which provide theoretical reference for the basic classification and structure research of hybrid excitation.

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