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# Milestones, hotspots and trends in the development of electric machines

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## ABSTRACT

As one of the greatest inventions of human beings, the electric machine (EM) has realized the mutual conversion between electrical energy and mechanical energy, which has essentially led humanity into the age of electrification and greatly promoted the progress and development of human society. This paper will briefly review the development of EMs in the past two centuries, highlighting the historical milestones and investigating the driving force behind it. With the innovation of theory, the progress of materials and the breakthrough of computer science and power electronic devices, the mainstream EM types has been continuously changing since its appearance. This paper will not only summarize the basic operation principle and performance characteristics of traditional EMs, but also that of the emerging types of EMs. Meanwhile, control and drive system, as a non-negligible part of EM system, will be complementarily introduced. Finally, due to the background of global emission reduction, industrial intelligentization and transportation electrification, EM industry will usher again in a golden period of development. Accordingly, several foreseeable future developing trends will be analyzed and summarized.

## KEYWORDS

Electric machine (EM), historical review, industrial applications, research hotspot, technology development, topology.

Electric machine (EM) is an electromagnetic device that converts mechanical energy and electric energy into each other through the medium of magnetic field. Since the first man-made EM was invented in 1821[1], it has been around for two centuries. In modern society, the EM is the core equipment for the production, transmission, utilization and characteristic transformation of electricity. EMs are widely used in all areas of human society, including electric power[2], metallurgy, manufacturing[3,4], transportation[5,6], construction, medicine, food processing, aerospace[7–9], household electrical appliances[10], and so on. It can be concluded that the EM has become one of the main carriers for human beings to improve production efficiency, scientific and technological level and life quality[11].

In today's era of climate change, the whole world is calling for the reduction of carbon emissions, development of green energy, industrial upgrading, transportation electrification, and so on. As the core driving equipment of various kinds of areas[12–14], EMs once again present the opportunity for further development. Consequently, in order to better develop EM technology and upgrade the EM product, it is time to summarize the evolution of EM from historical milestones, find new problems from current research hotspots, and finally discover the foreseeable developing trends for EMs.

Based on the fact above, this paper will firstly review the development of EMs in the past two centuries, highlighting the historical milestones and investigating the driving force behind it. These contents are in Sections 1 and 2, respectively. Second, in Section 3, several types of EMs, including the traditional mainstream types and the emerging ones, will be introduced, along with their basic operation principle and performance characteristics. Meanwhile, control and drive system, as a non-negligible part of EM systems, will be complementarily introduced including their pros and cons in Section 4. Finally, several foreseeable future developing trends will be analyzed and summarized in Section 5.

## 1 General development process of EM

### 1.1 Brief history of EM

### *A Theoretical preparation*

Although the first prototype of a modern EM appeared in the early 19th century, the necessary theories and techniques were already developed in the 18th century. Several notable historical milestones are listed below:

1) In 1785 , Coulomb's law, which describes the electrostatic force, was discovered and published independently by the French physicist, Charles-Augustin de Coulomb.
2) In 1799 , the invention of the electrochemical battery by Alessandro Volta made possible the production of persistent electric currents[15].
3) In 1820, Danish physicist and chemist, Hans Christian Ørsted, discovered that an electric current creates a magnetic field, which can exert a force on a magnet[16].
4) In 1820, French physicist and mathematician, André-Marie Ampère, developed the first formulation of the electromagnetic interaction and presented the Ampère's force law, which described the production of mechanical force by the interaction of an electric current and a magnetic field[17].
5) In 1821, after the publication of Ampère's force law, English

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scientist, Michael Faraday, demonstrated the effect of the law with rotary motion, which is regarded as the world's first electric motor, as shown in Figure 1(a).

6) In 1827, Hungarian physicist, Ányos Jedlik, started experimenting with electromagnetic coils, and demonstrated the first device to contain the three main components of practical direct-current (DC) motors: the stator, rotor and commutator, in the next year[18].

### B From experiment to application

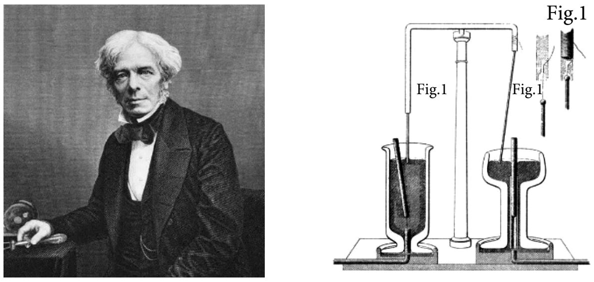
The evolution of the EMs in the 1830s began to accelerate as theories and technologies continued to develop.

DC motor was firstly developed due to the electricity form at that time.

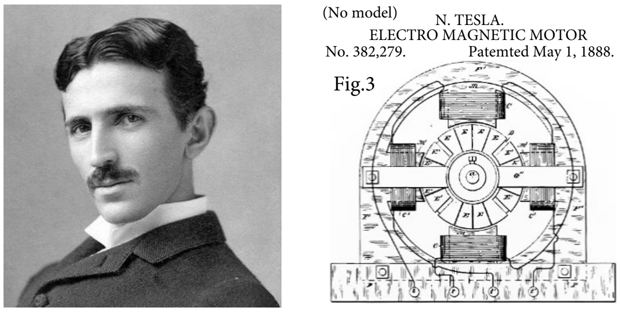
1) The first commutator DC-EM capable of turning machinery was invented by British scientist William Sturgeon in 1832.
2) In 1886, Frank Julian Sprague invented the first practical DC motor, a non-sparking device that maintained relatively constant speed under variable loads.

In the 1880s, many inventors were trying to develop workable alternating-current (AC) motors[19] because of AC's advantages in long-distance high-voltage transmission.

1) American electrical engineer, Nikola Tesla, invented independently his induction motor (IM) in 1887 and obtained a patent in May 1888, as shown in Figure 1(b).
2) Polish-Russian electric engineer, Mikhail Dolivo-Dobrovolsky, claimed that Tesla's motor was not practical because of the inherent vibration of two-phase, which prompted himself to persist in the three-phase work[20]. In 1889, he invented the three-phase induction motor of squirrel rotor and wound rotor with a starting rheostat.
3) In 1902, Swedish engineer, Danielson, invented the synchronous motor based on the rotating magnetic field concept from Tesla's IM.



(a)



(b)

**Fig. 1 Pioneers of electric motors and their achievements.** (**a**) Michael Faraday and his electromagnetic experiment device. (**b**) Tesla and his IM patent.

4) In 1923, Scottish James Weir French invented the variable reluctance stepper motor.
5) In 1962, with the help of the Hall element, a practical DC brushless motor was invented.

### C Age of permanent magnet machine

In the middle of the 20th century, with the emergence of high performance permanent magnet (PM) materials such as aluminum-nickel-cobalt (AlNiCo) and ferrite, PM machines (PMMs) were well developed[21]. In 1983, neodymium-iron-boron (NdFeB) rare-earth PMs with better magnetic properties and lower prices were introduced.

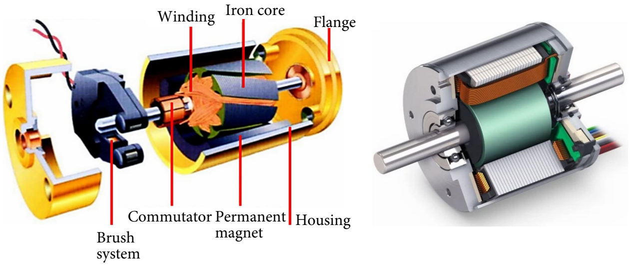
Due to the advent of rare-earth PM materials, PMMs achieve high power density and high efficiency under the same conditions compared with electric-excited machine (EEM)[22]. At the same time, because of the inherent characteristics of its simple structure, PMM began to replace the traditional EEM in small and medium power applications. In recent years, the market of emerging industries is growing rapidly, such as new energy vehicles, rail transit, wind power generation, more-electric airplanes and marine electric propulsion. PMMs have rapidly occupied the market and become the mainstream machine type of electric drive systems due to their high-performance advantages[23].

## 1.2 Feature of the developing procedure

### A From brush to brushless

In the early stage of EM development, the power supply mode was relatively single due to the lack of modern power electronic devices (PELDs). In variable-speed applications, brush DC motor has outstanding advantages. This is because the brush DC motor can realize the separate control of the excitation magnetic field and the motor current via the brush-commutator structure (as shown in Figure 2(a))[24]. Only by changing the voltage can achieve a wide range of speed regulation. Therefore, brush DC motors once had a huge market share. However, the brush-commutator structure also has obvious disadvantages, such as inherent voltage drop, inability to withstand excessive current, inability to meet high speed operation, frequent replacement of carbon brushes, and so on. Such demerits prevent brush DC motors from meeting the industry demand of higher power level, rotating speed, and output torque.

These problems hadn't been solved until the breakthrough of PELDs and the emergence of brushless technology. Brushless DC motor (as shown in Figure 2(b)) realizes electronic commutation through power electronic components. As a result, the fixed windings on the stator side can also produce alternating current, and generate rotating magnetic field, which will couple with the rotor magnetic field to rotate the rotor[25]. At present, brushless technology has been extended to most of EMs, only in a small



(a) (b)

**Fig. 2** (**a**) Brush DC motor. (**b**) Brushless DC motor.

amount of applications requiring small power, low speed, or considering the cost, will brush motor still be used.

### *B From fixed-speed to adjustable-speed*

Most early EMs had little complex controllers but only a single switch. When the motor was started, it could only rotate with a small range of speed according to the design of the power supply, motor body and the loading torque. Before the development of PELDs, the speed regulation of AC motors was even more difficult than that of a DC motor, which depended almost entirely on the power frequency and the pole-pair number. Even for the IM, it can only be regulated within a small range of speed by connecting a resistance in series.

After the 1970s, PELDs were rapidly developed. Due to the performance improvement of high current thyristor, DC power supplies with large capacity, easy control, small volume and small noise, were produced. This kind of DC power further intensified the inherent good speed regulation characteristic of DC motors. When it comes to AC motors, thanks to the higher-performance power electronic converter, both IM and SynM were able to smoothly adjust the rotating speed within a broad range, as well as to obtain a high efficiency. Meanwhile, various sensors helped the driving system know more about the real-time operation condition of the EM. As a result, complex and accurate control strategies could be realized, and the adjustable-speed intelligent EM could be manufactured.

### *C From serialization to specialization*

It took around a century for EM to become a mature industrial product. To expand the scope of EM application on a large scale, the EM had to first undergo serialization and standardization. From the 20th century, most EMs were produced with specific power grades and sizes, meeting the requirements of standard documents, such as IEEE Std 112, 115, IEC 60034, 60072 , etc. Traditional DC motor, AC synchronous generator and AC induction motor were the mainstream of motor products. Meanwhile, their topologies were basically not much different. This kind of serialization and standardization contributes to the unified EM design, stable performance, wider applicability, accordingly, promoting the development of the EMs.

However, with the development of society and the trend of global electrification, there was a need for greater torque density, higher power density, faster rotation speed, special mode of movement and stronger environmental adaptability. Therefore, since the late 20th century, a variety of special motors has been proposed and produced. The advent of high-performance permanent magnets gives motor designers greater design freedom. Specialization of motor is the only way to adapt to the development of global electrification.

## 2 Key technology breakthrough promoting EM development

The EM is a kind of industrial products involving electromagnetic, mechanical, heat dissipation, control, fluid, material, manufacturing, management and other fields. The development of EM is inseparable from the technical breakthrough in these fields. This section will introduce the influence of key breakthroughs on performance improvement of EMs from three aspects, namely the theoretical research, the material performance and the computer technology.

### 2.1 Theoretical research

The invention of the very first prototype of a novel kind of EM may be accidental and experimental. However, theoretical research is indispensable to further develop the EM performance, to expand one type of EM into a large family or to promote a prototype into a practical product. The significance of theoretical research at least lies in the following aspects:

1) The emergence of a new theory promotes the invention of a new type of EM.
2) Numerical equation and analysis ensure that the design and calculation of EMs are more scientific, avoiding the experiential design resulting in huge performance differences.
3) Theoretical research strengthens the analytical ability of the motor designers, so as to determine a motor initial scheme more quickly.

Therefore, the theoretical research of the motor is an important part of the development of the motor, and researchers have never stopped making theoretical breakthroughs. In the 1890s, the theory of DC armature windings was established. At that time, DC motors already had the main structural characteristics of modern DC motors. Meanwhile, the theory of generating rotating magnetic field through alternating current was put forward, induction motor was then designed, and the era of alternating current motor began. In the late 19th century, calculation via complex numbers and phasor was introduced into the analysis of AC circuits. The theory of double rotating magnetic field, the theory of d-q axis magnetic field and the theory of two-reaction have been proposed successively. By the end of the 19th century, the basic types, theories and design methods of various AC and DC EMs were basically established. In 1920s and 1930s, symmetric component method, steady-state voltage equation of synchronous motor, d-q axis synchronous reactance, steady-state/transient power angle characteristics were deduced, which established the basis for the calculation of steady-state and transient parameters of synchronous motor. After that, with the generalized theory of electrical machinery and the use of tensor method to study rotary motor, the EM theory gradually tends to be unified. In the 1950s, the space vector method and frequency method were proposed, which contributed to the vector control of motor in terms of speed and torque and the transient analysis. On the other hand, many scholars have also done research on the generating mechanism electromotive force and electromagnetic torque. The problems in this area are now largely clear. Some major developments of EM theories mentioned above are shown in Table 1.

### 2.2 Material performance

The progress of material performance is another key driving force for EM development. Since EM is a kind of electromagnetic and mechanical device, three kinds of material essentially matter:

1) Magnetic material including soft magnetic material (SMM) and PM. The former one decides the flux path of EM, while the latter one is a perfect magnetic excitation with no need of fielding current.
2) Conductive material for armature winding as well as for excitation coil or induction motor squirrel cage.
3) Structural material for transferring torque (shaft) and necessary mechanical support (EM housing, etc.).

From the point of view of electromagnetic performance, only SMM, PM and conductive material will be discussed in this section.

### *A Soft magnetic material*

SMM is used to make stator/rotor core of EMs, building up the

**Table 1 Classical electrical theory**

| Year | Theory | Typical application | Proposer |
|---|---|---|---|
| 1894 | Graphical method for the prediction of power transformers and polyphase motors[26] | IM | Heyland, A. |
| 1913 | Two-reaction theory of synchronous machine[27, 28] | Salient-pole SynM, SynRM | Blondel, A. E. |
| 1925 | Rotating magnetic field theory[29] | Sinusoidal AC machine | Hansen, K. L. |
| 1926 | Cross-field theory[30] | Sinusoidal AC machine | West, H. R. |
| 1929 | Park transform[31] | Sinusoidal AC machine | Park, R. K. |
| 1930 | Generalized theory of electrical machinery[32] | Electromechanical converter | Kron, G. |
| 1954 | Transient analysis of AC machine by using the method of symmetrical components[33] | Sinusoidal AC machine | Lyon, W. V. |
| 1959 | Space vector theory[34] | IM & SynM | Kovacs, K. P. |
| 1973 | General theory of equivalent magnetic circuit[35] | IM & SynM & DC machine | Fienne, J. |
| 1975 | General theory of alternating current machine[36] | Sinusoidal AC machine | Adkins, B. |
| 1990 | Winding function theory[37, 38] | IM & SynM | Lipo, T. A. |
| 1992 | Spiral vector theory of AC circuits and machines[39] | AC machine | Yamamura, S. |
| 1994 | Unified theory of torque production[40] | All EM types | Staton, D. A. and Miller, T. J. E. |

**Table 2 Common soft magnetic materials and their characteristics**

| Alloy | Alloying element content | ● Pros<br>▪ Cons |
|---|---|---|
| Pure iron & mild steel | Carbon < 0.04% | ● High saturation magnetization, low price and good machining performance<br>▪ Low resistivity and high eddy current loss under alternating magnetic field |
| SiFe | Silicon 0.5%–4.8% | (with Si content↑)<br>▪ Thermal conductivity↓ brittleness↑ saturation magnetization↓<br>● Resistivity and permeability high coercivity and eddy current loss↓ |
| Cobalt iron (CoFe) | Cobalt 27%–50% | ● High saturation magnetization(> 2T)<br>● Low resistivity<br>▪ Much more expensive than SiFe |

magnetic circuit path as well as deciding the mechanical structure. Consequently, SMM should feature at least the following characteristics:

1) High initial permeability $\mu_i$ and maximum permeability $\mu_{max}$. This indicates that SMM has a high sensitivity to the external magnetic field, of which the purpose is to improve the functional efficiency.
2) Low coercivity $H_c$. This shows that SMM is easy to be both magnetized and demagnetized by the external magnetic field, and the hysteresis loop is narrow, reducing the magnetization power and hysteresis loss[41].
3) High saturation magnetization $M_s$ and low residual magnetic induction intensity $B_r$. This means the SMM consumption can be reduced, contributing to light, thin, short, small production, and the SMM can quickly respond to the polarity reversal (N-S) of the external magnetic field.
4) Low iron loss, high resistance, low hysteresis coefficient and other characteristics to save energy and reduce noise of SMM.
5) Sufficient mechanical strength. This prevents SMM from the deformation at high rotating speed or under strong electromagnetic force.

In order to constantly improve the aforementioned characteristics of SMM, material engineers have taken quite a few actions in two aspects, namely the chemical composition and molding technology.

Table 2 shows the characteristic of SMM with different chemical compositions. As we can see, the basic composition of all kinds of SMM is iron due to its naturally perfect permeability ability. According to their pros and cons, one can find that pure iron and mild steel are the only suitable candidates for static use, such as the manufacturing of electromagnetic iron cores, pole shoes, magnetic shield covers, etc. Silicon iron (SiFe) alloy is quite suitable for and is current widely used in AC machines. Moreover, the cobalt iron (CoFe) alloy offers best performance among the three kinds of alloy. However, its high price makes itself currently be used only in ultra-high speed and high-power density motors, as material mass per kW is intrinsically small.

Molding technology also plays an important role in the determination of material performance even for those with the same chemical component. One of the most important molding technologies is sheet lamination. The SiFe or CoFe alloys are produced into thin sheets (0.2–0.65 mm) by cold rolling. These sheets are stamped into the radial cross section of the iron core. Then, the plates are axial laminated to form the final iron core. Using sheet lamination instead of casting an iron core can dramatically reduce the eddy current loss and shorten the producing period. Sometimes, the sheets will be annealed, which may somehow scarify the magnetic performance, nevertheless significantly increase the mechanical strength of the sheets.

Gerada, et al., have compared the mechanical yield-strength and core loss characteristic at 1 T/400 Hz of commercially available grades of SiFe (♦) and CoFe (▪) under their respective tradenames as shown in Figure 3[42]. High frequency machines typically use thinner SiFe grades than 0.35 mm, such as NO20 and Arnon7 which are 0.2 mm, 0.17 mm thick, respectively. The core losses of the aforementioned thin grades are superior. However, this is at the cost of reduced yield strength, which is typically 300–380 MPa for such grades.

### *B Permanent magnet*

PM refers to a kind of material that can still retain strong magnetism after being magnetized by an external magnetic field and re-

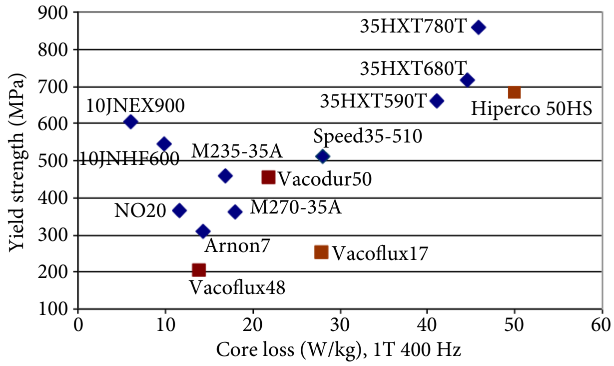


**Fig. 3** Comparison of core-losses and yield strength for different high-performance electrical steels (reprinted with permission from Ref. [42], © 2013 IEEE).

moving external magnetic field. Since no additional energy is required to provide the magnetomotive force (MMF), PM becomes an ideal excitation source of magnetic field for EMs. As a result, the basic requirements of PMs are:

1) High residual magnetic induction intensity $B_r$ and high residual magnetization $M_r$. They are a measure of the magnetic induction strength of a magnetic field that can be obtained by opening an air gap in a magnetic circuit.
2) High coercivity ${}_BH_c$ and high intrinsic coercivity ${}_MH_c$. ${}_BH_c$ and ${}_MH_c$ decide the PM's ability to maintain its permanent magnetic properties.
3) High maximum magnetic energy product $(BH)_{max}$. It is a measure of the maximum magnetic energy density per unit volume of PM that is stored and available
4) From the practical point of view, it is generally required that PMs have high stability, that is, the stability of external interference magnetic field, temperature and vibration and other environmental factors.

The first motor to appear in the world in 1831 was a PM one. However, the PM used at that time was natural magnetite ore ($Fe_3O_4$). The magnetic energy density was very low and thus soon replaced by electric excitation machines.

Due to the rapid development of various motors and the invention of current magnetizer, people carried out in-depth research on the mechanism, composition and manufacturing technology of PM materials, and discovered the steel-base PM, including carbon (C) steel, tungsten (W) steel, cobalt (Co) steel, etc. Then, the metal-base PM, i.e. iron-chromium-cobalt (FeCrCo), AlNiCo and the ferrite PM was discoveries in the 1930s and the 1950s. With further research, the magnetic properties of these two kinds of PMs were greatly improved, and all kinds of micro and small motors began to use PM excitation.

However, the ${}_BH_c$ of AlNiCo PM is low, and the $B_r$ of ferrite PM is low, which limits their wider application in EMs. When it came to the 1960s and 1980s, rare earth PM, including rare earth cobalt (RCo) PM and NdFeB PM, came out one after another. Their high $B_r$, high ${}_BH_c$, high $(BH)_{max}$ and excellent performance of the current demagnetization curve are especially suitable for manufacturing EMs, thus making the development of PM motors into a new historical period. Table 3 concludes the magnetic characteristics of the aforementioned PM materials.

### C Conductive material

**Table 3** Common permanent magnet materials and their characteristics

| Type | $(BH)_{max}$ (kJ/m³) | $B_r$ (T) | $H_c$ (kA/m) |
|---|---|---|---|
| Iron ore | — | — | — |
| C/W/Co steel | −/2.7/7.2 | 0.75−1.0 | 10−19 |
| AlNiCo | 85 | 1.35 | 36−160 |
| Ferrite | 40 | 0.2−0.44 | 128−320 |
| *$RCo_5$ | 199 | 0.85−1.15 | 480−800 |
| $R_2Co_{17}$ | 258.6 | | |
| NdFeB | 431.3 | 1.47 | 992 |

*R=Sm (samarium), Pr (praseodymium)

Conductive materials are indispensable for conducting current. They are used in the manufacture of armature windings, excitation windings, short-circuit rings of induction motors, etc. Obviously, such materials need to satisfy at least:

1) High conductivity $\sigma$. This can reduce the unwished Joule losses, so that the temperature raise can be reduced and efficiency will be guaranteed.
2) Sufficient mechanical strength (high yield strength). When conductive materials are located on the rotor, such as excitation windings, short-circuit windings and squirrel cages of induction motor, it needs to withstand the mechanical stress resulting from the rotation.

For traditional EMs, rotating speed and magnetic field strength are not so high. Therefore, common metals such as copper ($\sigma_{copper} \approx 6.0\times10^7$ S/m @ 20 °C), aluminum ($\sigma_{aluminum} \approx 3.8\times10^7$ S/m @ 20 °C), and silver ($\sigma_{silver} \approx 6.3\times10^7$ S/m @ 20 °C) can meet the application requirements. However, with the continuous higher requirement of EM power density, the rotating speed, air-gap flux density needs to be increased, which results in three research hotspots for EM conductor, namely, how to produce the high strength conductor located in rotor, how to reduce the AC loss due to high frequency, and how to produce extremely high magnetic field by coil.

Firstly, for conductor strength, replacing metals with alloys is the key. So far, several different types of high strength copper alloys have been developed for high-speed applications, such as copper-zirconium (CuZr), copper-beryllium (CuBe) and copper-aluminum-oxide ($CuAl_2O_3$). Figure 4 maps the characteristics of different materials in terms of electrical conductivity and yield strength. As can be seen, metal alloys can greatly improve the mechanical strength, but still sacrifice their electrical conductivity to some extent. Trade-off of strength and conductivity should be considered in the practical applications.

With the increase of EM frequency, AC copper loss becomes

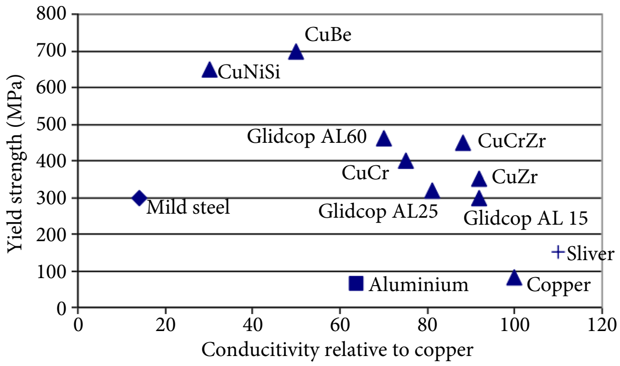


**Fig. 4** Characteristics of different conductive materials (reprinted with permission from Ref. [42], © 2013 IEEE).

severe, mainly due to skin effect and proximity effect, as shown in Figure 5. An effective solution can be adopted to reduce the AC loss cause by the skin effect, which is to use several strands of conductor with a small wire diameter instead of one strand with large-diameter conductor. It should be noted that, the more conductors that are used and located in the slot, the more likely will the EM suffer from a serious circulating current AC. Consequently, many techniques have been put forward, for instance, using a transposition method implemented within one coil (e.g., Litz wire)[43]. Some researchers also propose a suppression technique by transposing the coil connection in the same branch to balance the inductances of parallel strands, thus reducing the circulating current AC loss[44].

Field winding can theoretically produce a much stronger magnetic field than that of rare-earth PM, as long as more current is injected. The only problem is the unacceptable Joule loss. Superconductivity, which was discovered for the first time in 1911, then become a perfect solution for extreme high magnetic field production. Superconductivity arises in some elements and alloys, namely superconductors (SCs), which exhibit a near-zero DC resistivity when operated in their superconducting state. The use of SCs enables to achieve almost zero Joule losses in DC-operated windings for EMs. Consequently, electrical machines featuring a decreased volume, decreased mass and increased efficiency can be designed[45]. Early SCs are made of low temperature superconducting (LTS) materials, which required the use of liquid helium cooling at 4.2 K. The challenges related to the cooling system interrupted the widespread of LTS technology in EMs. Started from 1986, the discovery of high temperature superconducting (HTS) materials operating above 35 K allowed to overcome the challenges related to LTS technology[46]. The breakthrough occurred in 1987 when $YBa_2Cu_3O_7$ (YBCO), a new HTS compound operating above the boiling point of liquid nitrogen at 77 K, was announced[47]. The discovery of SCs operating well above 77 K brought superconductivity to a new era for electric power applications. To date, many demonstrators employ $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10}$ (BSCCO-2223 ) silver-sheathed HTS conductors exhibiting superconductivity up to ~ 110 K[45].

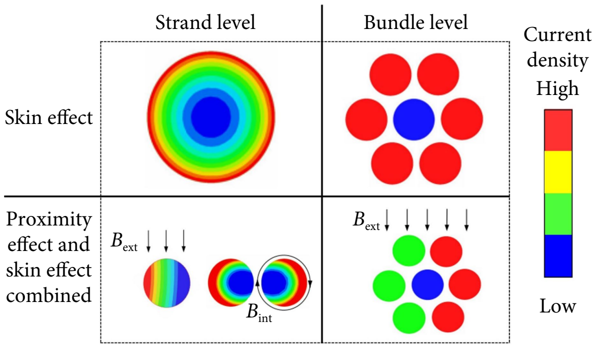


**Fig. 5** Strand-level copper loss and bundle-level copper loss caused by the skin and proximity effect (reprinted with permission from Ref. [44], © 2021 IEEE).

### 2.3 Computer technology

From 1965, computers were gradually introduced into all fields of EM engineering. Due to the rapid development of computer technology and the application of various numerical methods and software, many EM calculation problems can be numerically solved by computer, including the magnetic field distribution in various EMs, the unsaturated and saturation values of parameters, as well as the three-dimensional temperature field distribution inside the EMs, etc. Because of the introduction of state equation and numerical method, the nonlinear motion equation of EM in dynamic operation can be also solved by computer, so that the calculation and analysis of various dynamic problems can be realized.

Over the past few decades, a large number of computer-aided software (CAx) have appeared to overcome the complex path between the concept design and the final product of EMs[48]. Nowadays, designers of EMs can use different CAx tools on all the stages of product development, starting from the idea with sketching of the future EM through the manufacturing to using and recycling. The main steps in design flow and the corresponding required CAx tools is depicted in Figure 6. In the figure, each abbreviation represents the following meanings:

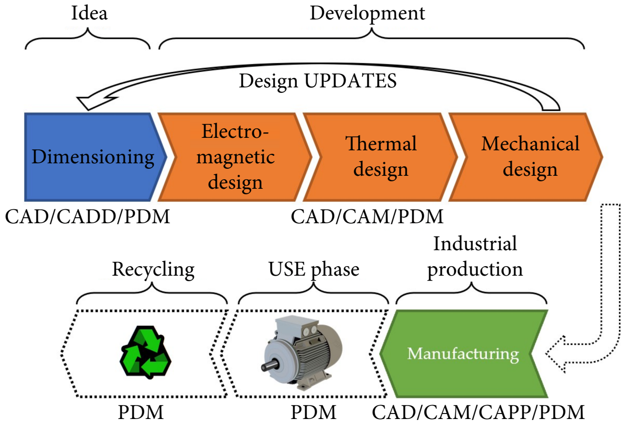


**Fig. 6** Lifecycle of electric machine.

1) Computer-aided drawing (CAD) and drafting (CADD) is for process planning and plots generation.
2) Computer-aided engineering (CAE) is used for the analysis, calculations and simulation, and has a goal to identify errors in construction design.
3) Computer-aided manufacturing (CAM) is the link between the final design and industrial production.
4) Computer-aided process planning (CAPP) is used as a link between CAD and CAM[49].
5) Product data management (PDM) systems have been integrated within product lifecycle management (PLM) especially for the design of complex products including EMs, which allows companies to find correct global teams as well as to adapt product legislations[50].

Table 4 shows several popular softwares for EM design, where the operational system platform and CAx subsystem are taken into account.

## 3 Classification and characteristics of EM

After years of development, a variety of motors have been invented. They have different structures, operating principles, performance characteristics, but are also suitable for different applications. This section will make a classification of existing motors, and then introduce some of the most popular conventional and emerging EMs in terms of their operation principle, performance feature as well as pros and cons.

### 3.1 Classification of EM

EMs can be classified from several aspects, including the power supply, operation principle, flux direction, direction of motion

**Table 4 CAx subsystems**[48]

| Software | Subsystem | | | |
|---|---|---|---|---|
| Moto-CAD | CAD | CAE | — | — |
| FEMM | — | CAE | — | — |
| Electric P8 | — | CAE | CAM | — |
| Mathcad | — | CAE | — | — |
| MATHLAB | CAD | CAE | — | — |
| ANSYS | CAD | CAE | CAM | — |
| Jmag Designer | CAD | CAE | — | — |
| QuickField | — | CAE | — | — |
| SAP | — | — | — | PDM |
| Wings 3D | CAD | — | — | — |
| Onshape | CAD | — | — | — |
| Maple | CAD | — | — | — |
| MS Excel | CAD | — | — | — |
| Simulink | — | CAE | — | — |
| COMSOL | — | — | CAM | — |
| FEMlab | — | CAE | — | — |
| GrabCAD | CAD | — | — | PDM |
| Tecnomatix | — | — | — | PDM |
| Fusion 360 | CAD | CAE | CAM | — |
| Soildworks | CAD | CAE | — | — |
| MotorSolvo | CAD | CAE | — | — |
| GstarCAD | CAD | — | — | — |
| ELCUT | — | CAE | — | PDM |
| Solid Edge | CAD | — | — | — |
| Emetor | CAD | CAE | — | — |
| Autodesk | CAD | CAE | CAM | PDM |
| Opera | CAD | CAE | CAM | — |
| Tracesoftware | CAD | — | CAM | — |

and so on. A general classification of EMs is presented in Figure 7.

According to the power supply type, EMs can be essentially classified into DC machines and AC machine. DC machine once dominated the EM market due to its simple structure and high controllability. With the development of electronic devices, the most critical drawback of traditional DC machine, the brush, is removed because of the brushless technique. Nowadays, the brushless DC machine (BLDC machine) is still welcome in many low-power-level applications. However, the development PELDs have even more impact on AC machines, PWM, SVPWM and other power supply technique make it possible to produce controllable polyphase sine-wave/square wave AC current. As a result, the AC machine family has been growing fast and become the mainstream in modern EM field.

In terms of operating principle, the conventional AC machine consists of induction machines (IMs), synchronous machines (SynMs) and reluctance machines (RMs). There are two main kinds of IM, which are the squirrel-cage type and the wound-rotor type. From the excitation source point of view, SynM can be further classified into the electrical-excited (EE) ones and the PM ones. Due to the high performance rare-earth PM material, PM-SynM now becomes the most popular machine type, widely used in various applications. PM-SynM has two main branches according to the way of PM installation: surface-mounted PM (SPM) type and interior PM (IPM) type. RM is a kind of EM without any excitation on the rotor. RM can be regard as a kind of special SynM operating on the magnetic circuit minimum principle. Based on different armature winding structure and control strategy, RMs consist of the switched reluctance machine (SRM) and synchronous reluctance machine (SynRM). It should be noted that by combining the PM-SynM with SynRM, an emerging type of EM, PM-assistant SynRM (PMA-SynRM) can be obtained. Moreover, as shown in the bottom right of Figure 7, there is another emerging kind of EM, the flux-modulation machine (FMM), which has become a research hotspot recently.

Besides the power supply and operation principle, EMs can be also classified according to the direction of motion and the flux path direction. From the former aspect, EM consists of the rotary type, linear type, planar type and so on, while from the latter one, EM includes the radial-flux ones, the axial-flux ones and the transverse flux ones.

In the following parts, several popular conventional EMs widely used in today's society and the emerging EMs with good performance potential will be introduced in terms the basic operation principle, performance feature and pros and cons.

## 3.2 Conventional EMs

### *A Induction machine*

An IM is an AC EM of which the stator windings are usually the

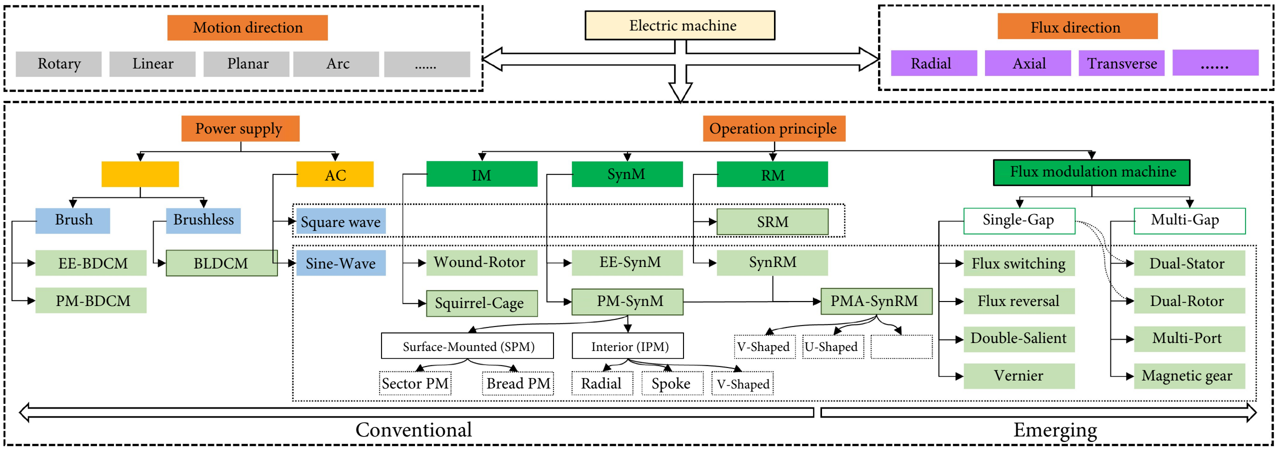


**Fig. 7 Classification of electric machines.**

traditional distributed overlapping winding. When excited by a symmetrical multiphase power supply, those windings will generate a magnetic field in the air gap that rotates at a synchronous speed. The electric current in the IM rotor needed to produce torque is obtained from the stator winding by electromagnetic induction or transformer principle. An IM can therefore be made without electrical connections to the rotor. When the load on the motor increases, the rotor speed decreases, so that the slip (ratio of the rotating speed difference between stator magnetic field and rotor) increases, the rotor induced current increases and the torque increases. Figure 8 is the classic torque-speed characteristic curve of induction motor. The distinct features of IMs are summarized as follows:

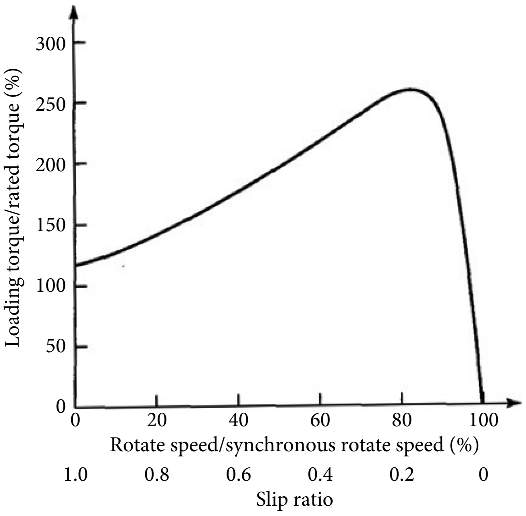


**Fig. 8 Operation characteristics of IM.**

1) IMs are cheap in construction cost and maintenance cost. In return, the whole IM drive system cost is largely reduced.
2) The absence of PMs improves robustness and reliability, which allows IMs to operate in a harsh operating conditions or environments including vehicular applications.
3) Three-phase IMs possess a starting torque that is unavailable in synchronous machines. A good starting performance is guaranteed for many traction applications.
4) IMs can reach high efficiency, though not higher than PMSM. This reduces the drive system losses and improves the efficiency of the whole system.
5) Highly precise speed control of the IM is difficult.

The rotor of an IM generally comes in two forms as shown in Figure 9(a). The wound rotor is composed of polyphase windings similar to the stator and has the same number of poles as the stator. At present, the application of wound rotor induction motor is relatively few, limited to some special applications, such as those with very strict starting requirements or the occasions needing to adjust rotate speed through rotor resistance. The other one is the squirrel cage rotor as shown in Figure 9(b). Its rotor consists of a series of conductor bars, embedded in slots in the rotor core and shorted at each end by conductive end rings. The simplicity and durability of the cage structure is the outstanding advantage of this IM and makes it one of the most common forms of machine used so far. Nowadays, three-phase squirrel-cage IMs are widely used as industrial drives because they are self-starting, reliable and economical. Single-phase IMs are used extensively for smaller loads, such as household appliances like fans. With variable-frequency drives (VFD), IMs are now used in variable-speed service, such as variable-torque centrifugal fan, pump and compressor load applications.

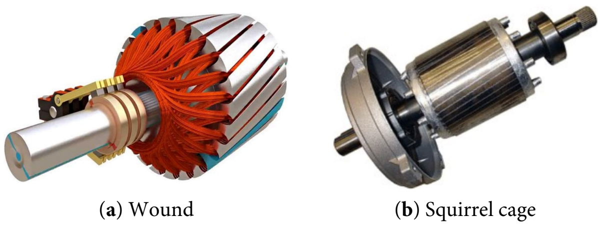

(**a**) Wound (**b**) Squirrel cage

**Fig. 9 Two types of IM rotor.**

### *B Permanent magnet synchronous machine*

PM-SynM is one kind of SynMs of which the excitation field is produced by the PMs located on the rotor. The operation principle of PM-SynM can be explained simply by the interaction between the stator armature field and rotor PM-excited field. The multiphase AC in the stator windings synthesizes a rotating magnetic field, and the rotor PM also generates a constant magnetic field relative to the rotor. A constant torque occurs only when the rotor and stator magnetic fields are rotating in synchronous. Meanwhile, there must also be a certain angular displacement between the two magnetic fields, which will determine the operation state and the torque of PM-SynMs. Such relationship is depicted in Figure 10.

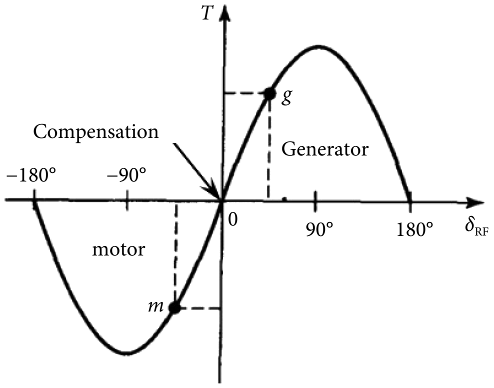
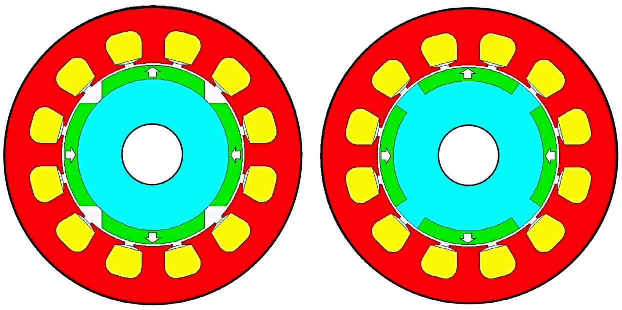


**Fig. 10 Torque-angle characteristics of SynM.**

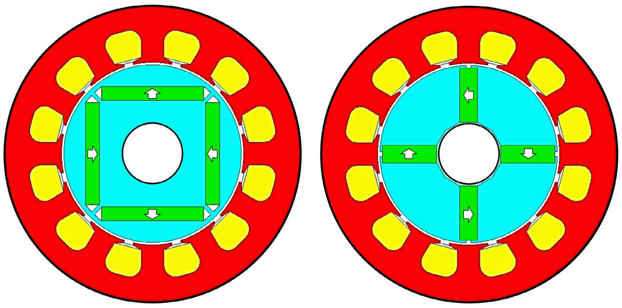
Compared to the traditional DC electric-excited (EE) SynM, PM-SynM has a much simpler structure simpler, reduces the cost of processing and assembly, and eliminates the collector ring and brush that are prone to problems, and improves the operation reliability. And because the excitation current is not needed, the excitation loss is omitted, and the efficiency and power density of PM-SynM are improved. As shown in Figure 11, according to the different arrangement of PM, the PM-SynMs can be divided into surface-mounted rotor, surface-inserted rotor, radial interior rotor, and spoke interior rotor, V-shaped interior rotor and so on. Nowadays, neodymium-rare-earth PMs are the most commonly used magnets in these machines. In the last few years, due to rapid fluctuation in the prices of neodymium PMs, a lot of research has been looking at ferrite PMs as an alternative[51].

The distinct features of PM-SynMs are summarized as follows:

1) Magnetically strong PMs provide a residual flux for the coils, which largely improves the overall machine performances.
2) It is known that PM-SynMs possess the high torque density, power density, and efficiency.
3) The flux-weakening technique is required under high-speed

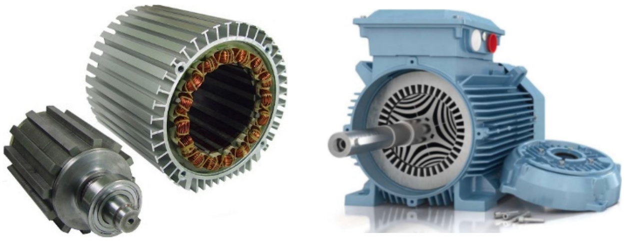


(**a**) Surface-mounted (**b**) Surface-inserted



(**c**) Radial interior (**d**) Spoke interior

**Fig. 11 Alternative PMSM topologies with different types of PM array.**



(**a**) SRM (**b**) SynRM

(**c**) PMA-SynRM

**Fig. 12 Different types of RMs.**

driving, increasing the risk of demagnetization. More complex control strategies should be involved in its controller.

4) Rare-earth PMs suffer from eddy current loss, demagnetization risk, and mechanical failure. Hence, the reliability and fault tolerance should be considered carefully.
5) Due to the PM-slot structure, PM-SynM suffers from the cogging torque, which may result in the vibration of PM-SynM.
6) Most PM-SynMs require a variable-frequency drive to start[52]. However, some incorporate a squirrel cage in the rotor for starting—these are known as line-start or self-starting PM-SynMs[53].

### C Reluctance machine

The RM is probably the simplest motor, consisting of a stator with excitation windings and a rotor with uneven circumferential reluctance. The rotor does not need any excitation source. When the stator is energized, the rotor pole always tends to be aligned with the flux wave generated by the stator, thus maximizing the stator flux for a given stator current. This tendency to "align" produces the so-called reluctance torque. Reluctance motors can produce high power densities at low cost and are quite attractive in many applications. The disadvantages of reluctance motors are the high torque ripple (difference between maximum and minimum torque after one turn of rotation) and the noise caused by torque ripple during low-speed operation.

The RMs can be subdivided into switched reluctance machine (SRM), and synchronous reluctance machine (SynRM), of which the typical topologies are given in Figure 12(a) and 12 (b). Although the two kinds of reluctance machines are both operated by reluctance torque, they are quite different in structure and control mode.

1) SRM has a double salient pole structure. Each tooth of the stator is wound by a concentrated winding, which makes the rotor align each tooth in sequence and finally rotate by providing electricity to different teeth in a regular way. This intermittent power-on mode makes the SRM inherently subject to large torque fluctuations, resulting in serious noise and vibration during operation, especially at low speeds[54]. At the same time, in order to accurately control each break time, it is necessary to accurately measure the position of the motor rotor. However, SRM is easy to achieve high frequency and high-power density due to its simple power mode and robust structure.
2) SynRM has the stator windings similar to those of a synchronous machine, where a multiphase current generates a rotating magnetic field and the rotor uses a reluctance torque to follow the field in synchronous[55]. Thus, the control of SynRM is closer to that of a synchronous motor. At the same time, because there is no discontinuous torque, the torque is smoother. In recent years, rare-earth permanent magnets have become popular due to their excellent characteristics. Applying rare-earth PMs to SynRMs can help to improve the overall performance. Namely, this emerges a type of machine called PM-assisted SynRMs (PMA-SynM), as shown in Figure 12(c).

### 3.3 Emerging EMs

Flux-modulation permanent magnet machines (FMPMMs), naturally featuring high torque density and suitable for direct-drive (DD) applications, have become one of the research hotspots in the field of EMs in recent years.

Actually, FMPMM is an EM family that consists of all the EMs that operate on the so-called flux-modulation effect or the magnetic gear effect)[56]. Figure 13 shows how the basic topology of FMPMM is formed from the "magnetic gear + regular PM machine" structure. As can be seen, the inner rotor of the magnetic gear and PM rotor of the machine can be designed to be with same pole number, and thus connected. Different from a traditional PM-SynM, FMPMM have three components, armature winding, PM array and flux modulator[57].

In a FMPMM, the pole number of the armature and the excitation fields are different, and the flux modulation is requisite to work as a pole number transformer through an air-gap permeance function. As shown in Figure 14, in the FMPMMs, the magnetic field with large pole number produced by PM array on

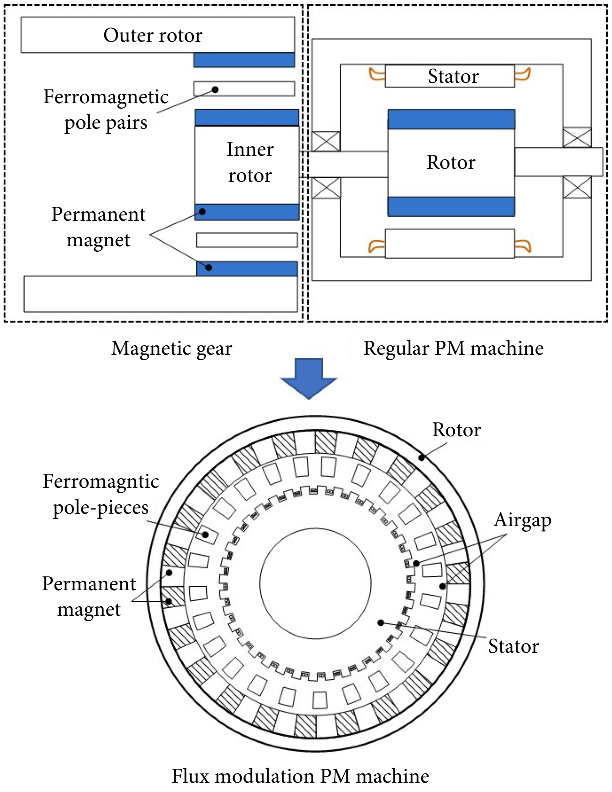


**Fig. 13** Topology transforming of FMPMM.

the rotor is modulated into the magnetic field with a small pole number on the armature side (stator) via the flux modulation block (FMB). Basically, the pole-pair number of PM array $P_{\mathrm{PM}}$, the number of FMBs $N_{\mathrm{FMB}}$ and the pole-pair number of armature winding $P_{\mathrm{a}}$ should obey the following equation:

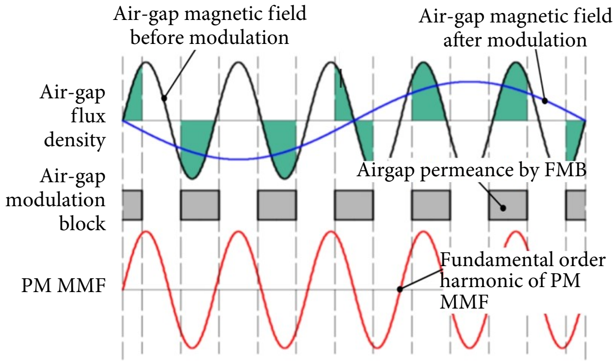


**Fig. 14** Diagram of flux modulation principle.

$$P_{\mathrm{a}} = |P_{\mathrm{PM}} \pm N_{\mathrm{FMB}}| \tag{1}$$

Correspondingly, the FMB also transforms the speed of flux from $\Omega$ (stator side) to $P_{\mathrm{a}}/P_{\mathrm{PM}} \times \Omega$ (rotor side), which means the speed of rotor is slowed down. Such "pole/speed change" phenomenon has a similar effect as mechanical gear, which can amplify the torque of EMs. Based on the above flux modulation principle, the torque $T$ of FMPMMs can be expressed as

$$T \propto \frac{P_{\mathrm{PM}}}{P_a} A B_{\mathrm{g}} \tag{2}$$

where $A$ is the electrical loading, $B_{\mathrm{g}}$ is the magnetic loading and $P_{\mathrm{PM}}/P_{\mathrm{a}}$ is defined as pole ratio. As a result, the torque density of FMPMM can be significantly higher than that of the traditional PM-SynM with a proper slot/pole-pair combination and pole ratio selection.

Although the generalized model of FMPMM shown in Figure 13 has a three-ring/two-airgap structure, the most widely studied topologies of FMPMM family are different. Due to the series character of magnetic circuit, the three components of FMPMM can be arbitrarily combined, as long as it is guaranteed that among flux modulator, armature and excitation fields, only one component can be, but not necessary, stationary. Therefore, FMPMM can be classified into the stationary flux modulator (SFM) type, stationary excitation field (SE) type, stationary armature field (SA) type and the all-rotary type as shown in Figure 15.

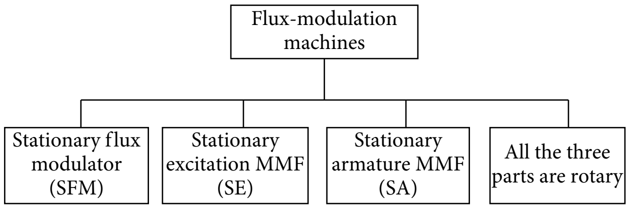


**Fig. 15** Classification of FMPMM (reprinted with permission from Ref. [57], © 2015 IEEE).

## A Vernier PM machine

When the number of the stator teeth is designed to be the same as the number of the FMB, i.e. $Z = N_{\mathrm{FMB}}$, the stator teeth can work as flux modulator to modulate the air-gap magnetic field, and the FMB could be completely eliminated as shown in Figure 16, and then the topology becomes vernier PM machines (VPMMs). Obviously, VPMM can be regarded as the simplest kind of SFM-FMPMM.

VPMM has the desirable feature of high torque at low speed and, therefore, is regarded as a suitable alternative for direct-drive applications such as robot arms or electric vehicles. However, due to the flux modulation effect, VPMM as well as other kind of FMPMM suffers from two problems:

1) The relationship between the dimensions and the magnetic flux distribution becomes significantly nonlinear, making design optimization a time-consuming process. A torque-maximizing design methodology for VPMM has been presented through quantitative analyses of the machine, which greatly reduces the design effort[58].
2) The serious PM and slot leakage results in the naturally low power factor feature of VPMM. To solving this problem, a dual-stator spoke-array (DSSA) VPMM topology has been proposed as shown in Figure 17, which is able to exhibit high power factor, viz., ~0.9, and significantly high torque capability[59].

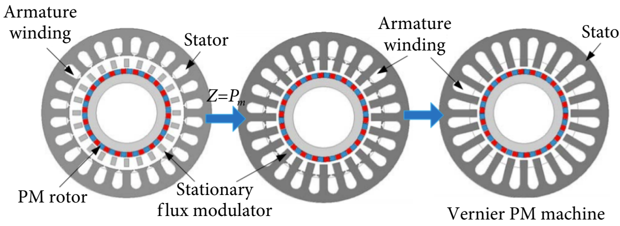


**Fig. 16** Topology transferring from basic model to vernier machine (reprinted with permission from Ref. [57], © 2015 IEEE).

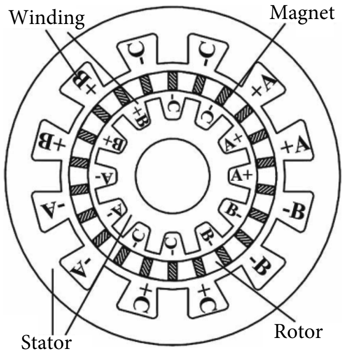


**Fig. 17 Topology of DSSA-VPMM (reprinted with permission from Ref. [59], © 2014 IEEE).**

### B Flux reversal and flux switching machine

For the SE-FMPMM, the PM array is stationary relative to the stator, therefore the magnets can be moved to the stator and a flux reversal PM machine (FRPMM) is obtained, as shown in Figure 18. FRPMM features the bipolar phase PM flux-linkage and the fault tolerance capability due to its natural isolation between phases, and the small variation of the inductances versus rotor position[60]. Moreover, its simple and robust rotor make itself suitable for tough operation environment. However, the magnet of FMPMM mounted on the gap side of stator tooth, which increases the effective air-gap length. Therefore, the magnet thickness, as well as rotor pole arc, air-gap length, etc., has significant effects on the electromagnetic performance of the FRPMM machine[61].

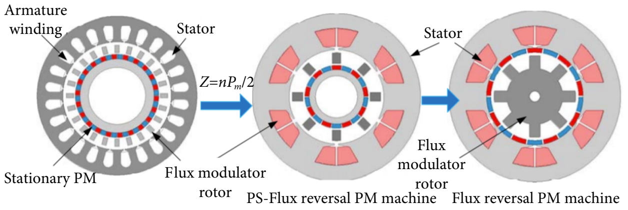


**Fig. 18 Topology transferring from basic model to flux reversal PM machines (reprinted with permission from Ref. [57], © 2015 IEEE).**

By replacing the tooth-top magnets with the sandwiched spoke PM array located in the middle of stator teeth, the flux switching PM machine (FSPMM) can be obtained as shown in Figure 19. It should be noted that the magnets of FSPMM are magnetized circumferentially in alternative opposite directions[62]. The concentrated coil is wound around the adjacent stator teeth with a magnet sandwiched. Hence, the polarity of the PM flux linkage in the coil reverses when the rotor pole aligns the alternative stator tooth that belongs to the same phase, i.e., realizing the "flux-switching" action. Compared with FRPMM, phase EMF waveforms of FSPMM are essentially sinusoidal without any additional measures due to the magnetic reluctance difference between the two pairs of coils composing a phase[63].

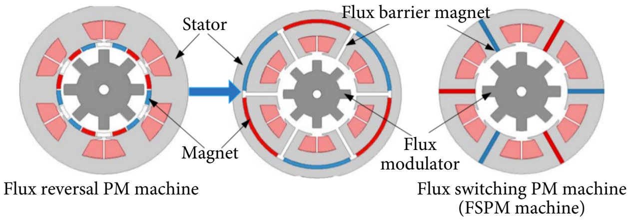


**Fig. 19 Topology transferring from flux reversal to flux switching PM machine (reprinted with permission from Ref. [57], © 2015 IEEE).**

It should be noted that, both FRPMM and FSPMM will suffer a serious end-effect due to the axial flux leakage of stator-PM configuration. Meanwhile, since the PM is near armature windings, the cooling issue of magnets should also be considered.

### C Multi-port flux modulation machine

Due to the three-component structure, FMPMM can easily own at least two rotors as the mechanical ports. And by setting over one sets of armature windings, multiple electric ports are obtained. These FMPMMs with multiple ports are called multi-port flux modulation machine (MP-FMM), which is a typical kind of all-rotary-type FMPMM. The application potentials of the MP-FMM are vast, from multi-source hybrid traction, integrated starter and generator, to variable gearboxes[64].

Figure 20 gives an example of MP-FMM proposed by Ren et al. in 2017, which is a dual-electric-port dual-mechanical port MP-FMM as shown in Figure 21. Multi-port flux modulation machine with integrated winding configuration[65]. This kind of MP-FMM can replace conventional power split system based on planetary gear of hybrid electrical vehicles (HEVs), which will greatly reduce the complex and mass of the dynamical system. Moreover, the proposed integrated winding configuration replaces the original two sets of windings, contributing to 40% higher available current under the same copper loss.

## 4 Modern control and drive system of electric machines

As shown in Figure 22, a modern control and drive system (CDS) calculates the collected signals via a certain algorithm, then gives

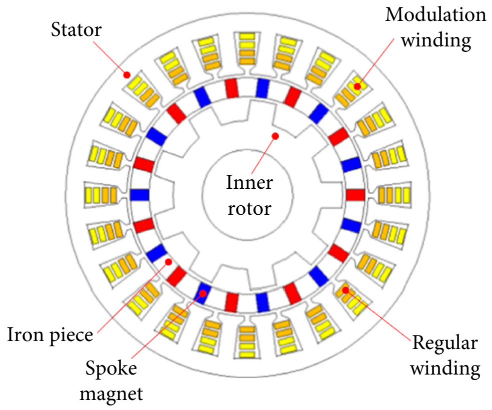
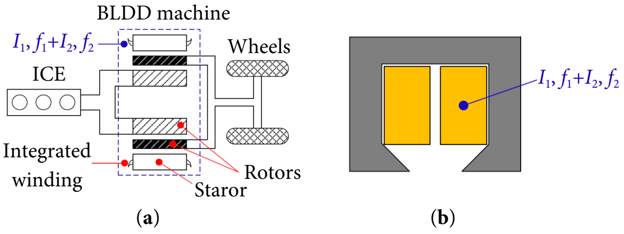


**Fig. 20 Structure of the presented MP-FMM (reprinted with permission from Ref. [65], © 2020 IEEE).**



(a)

(b)

**Fig. 21 Integrated winding design for the presented MP-FMM (reprinted with permission from Ref. [65], © 2020 IEEE). (a)** Machine system with integrated winding. **(b)** Coil displacement of integrated windings in slot.

orders to inverter based on PWM technology and finally outputs the necessary phase current to drive the EM for specific requirement. CDS is an inseparable part of EM system and can fully exert the potential of EMs[66]. Over the past century, CDS has gone through a dramatic progress, due to:

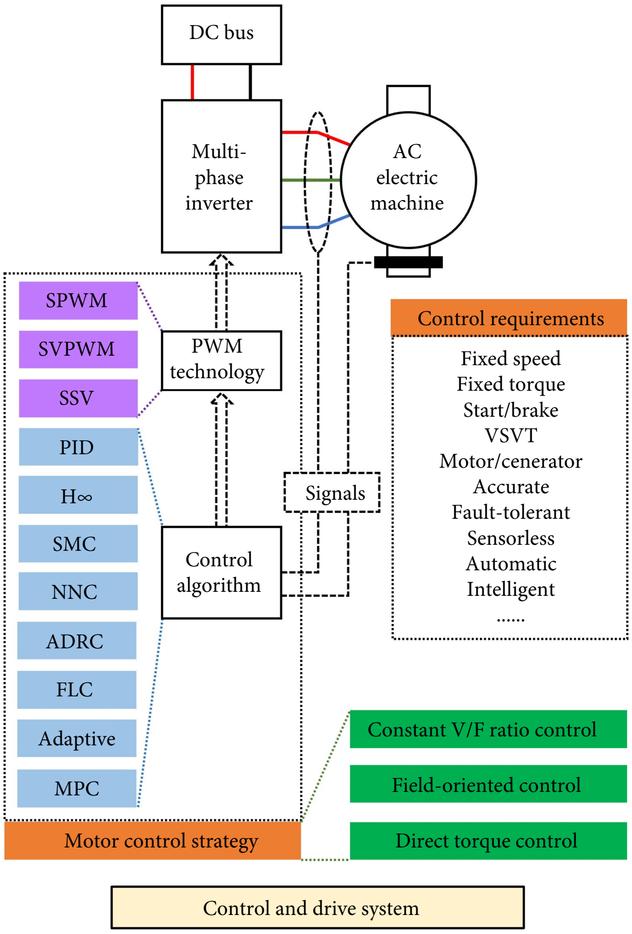


**Fig. 22 Diagram of control and drive system.**

1) The rise of AC machine, which is nonlinear; with strong coupling, time-varying parameters; multiple variables, and large disturbance compared to DC machine[67].

2) Thanks to the progress of PELD, high-accurate/ dynamic sensors and computer science, the complex control strategies can be realized.

3) More and stricter control requirements for EMs, including but not limited to the frequent start and stop, variable-speed/variable torque (VSVT), mode switch between motor and generator, fault tolerance, sensorless control and so on.

In order to make sure the fast system dynamic response, high dynamic/static precision and strong anti-interference ability[66], different kind technologies has been proposed and applied in EM products in terms of motor control strategy, control algorithm, pulse-width modulation (PWM) technology and as such.

## 4.1 Motor control strategy

Motor control strategies provide the general control framework for EM controlling. Among the various strategies, variable-voltage-variable-frequency (VVVF) control method has absolute advantages in performance. In the early years of this field, the constant voltages-per-frequency (V/F) ratio control, also known as constant flux control, was widely used due to its simplicity, effectiveness, and high robustness. However, it also suffers from the low control accuracy, slow dynamic response, and poor load capacity of the systems due to speed and flux drifts resulted from the V/F open-loop control. Afterwards, two modern VVVF control strategies with high efficiency based on either current or torque loop control methods were proposed, namely the field-oriented control (FOC, proposed in the 1970s), and direct torque control (DTC, proposed in the 1980s).

### *A Field oriented control*

The application of the FOC scheme can ensure the precise torque output of EMs[67]. The FOC for traditional three-phase motors usually employs an orthogonal transformation matrix to map the control variables in the a-b-c coordinates to those in the d-q-0 coordinates. Therefore, the flux and the torque can be decoupled by regulating current components on the d- or q- axis, respectively[68]. The total process of FOC is proposed in Figure 23. The complete FOC controller is a cascade control loop, composed of two internal PI-current controllers and an external speed PI controller. The internal PI controllers calculate the control voltage reference $u_d^*$ and $u_q^*$ based on the error between the current references, $i_d^*$ and $i_q^*$, and the real currents, $i_d(k)$ and $i_q(k)$, which are calculated by sampled stator current $i_s(k)$. The external PI controller calculates the current reference based on the error between rotor speed reference $\omega^*$ and real speed $\omega$. It means that tuning of PI controllers is difficult and should be returned according to different operating conditions.

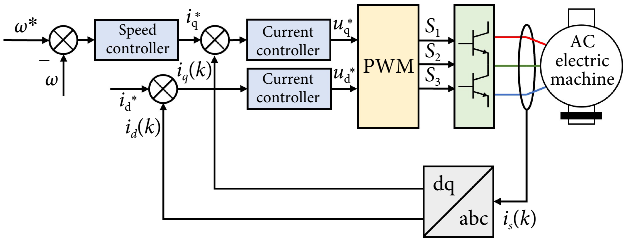


**Fig. 23 Control scheme diagrams of FOC.**

Nowadays, there are some modified FOC controllers to meet the special demand.

1) Maximum torque per ampere operation with FOC can enhance the acceleration ability[67].
2) FOC controller with flux weakening design can expand the speed range of electric motor, which can further increase the maximum speed[69,70].

It should be noted that, though the FOC control scheme can provide precise torque output, the higher switching frequency can cause additional energy cost.

### *B Direct torque control*

DTC has been attractive for the application that desires fast torque response. Moreover, DTC does not rely on current control and slightly depends on parameters[71]. The main idea of DTC is to use two hysteresis controllers for electromagnetic torque and stator flux separately. The torque hysteresis controller is a three-level comparator with a bandwidth, whereas the flux hysteresis controller is a two-level comparator with another bandwidth[66].

The total process of basic DTC is shown in Figure 24. The flux hysteresis bandwidth mainly affects the motor current distortion in terms of low-order harmonics. Switching frequency and switching losses are mainly affected by the torque hysteresis bandwidth. In this case, a careful choice of hysteresis bandwidths is necessary. The switching table can be determined according to the electrical position and hysteresis controllers. However, the total harmonic distortion (THD) performance of DTC can be worse because of the hysteresis controllers. Nowadays, the literature has given some improved solutions.

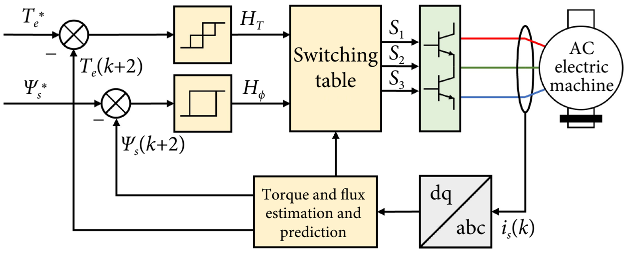


**Fig. 24 Control scheme diagrams of DTC.**

1) To improve the performance of DTC, the concept of PWM technology applied in FOC is combined in DTC to reduce its torque ripples[72–74].
2) Some controllers remain the structure of hysteresis controllers but subdivide the switching table to provide a precise voltage vector[75,76].
3) The deadbeat control concept can be combined with DTC to obtain faster transient performance and better steady-state performance[77,78].

DTC control scheme can provide stable performance of EMs. Moreover, the parameter independence characteristics of DTC are important advantages against FOC.

### 4.2 Control algorithm

Within a certain EM control strategy, the method of processing measured signal, namely the control algorithm, will have a great impact on the control performance in terms of the accuracy, robust, dynamic, intelligence and so on. Therefore, according to the different control requirements, various of control algorithm have been proposed.

#### *A Classic control algorithm*

A proportional–integral–derivative (PID) controller has become the most mature and widely used EM control method since it appeared in the late 1930s. PID controller is a control loop mechanism employing feedback. It calculates an error value as the difference between a desired setpoint and a measured process variable and applies a correction based on proportional, integral, and derivative terms[79,80]. Since only several parameters needs to be adjusted when using PID controller, it is welcomed by industrial applications. Conversely, its simplicity makes itself feature relatively long response time and poor static-state performance. Therefore, many advanced control algorithms are proposed to improve PID controller or be used exclusively.

#### *B Advanced control algorithm*

Benefit by the increasing computing power of processor and the sampling speed/accuracy of sensors, many complex but high-performance control algorithms are realized. The adaptive control algorithm handles system uncertainties by adjusting the controller parameters online, thus having strong robustness[81]. The H∞control algorithm is a typical robust control (RC) method, aiming at minimizing the sensitivity of the controller uncertainties to maintain the system control performance[82]. Active disturbance rejection control (ADRC) uses a disturbance observer to estimate the system uncertainties and then introduces the disturbance rejection into the control signals to compensate the uncertainties[83]. Model predictive control (MPC) is based on solving an optimal control problem of open loop in the finite-time domain at every sampling moment[84]. Neural network control (NNC) can achieve a smooth start, small torque ripple, wide speed range, and high robustness with a simple parameter setting, strong self-learning ability, and low motor parameter sensitivity[85]. Fuzzy logic control (FLC) has a simple structure, good robustness, and a small impact on the motor startup[86]. Sliding mode control (SMC) being invariable to external disturbances, has a simple structure, low sensitivity to the internal parameter perturbations, and high control accuracy[87].

### 4.3 Pulse-width modulation technology

PWM technology was proposed after the thyristors were invented and is getting mature with the development of power electronics technology and devices. PWM technology is a method of reducing the average power delivered by an electrical signal, by effectively chopping it up into discrete parts. The average value of voltage/current fed to the EM is controlled by turning the switch between supply and load on and off at a fast rate. The longer the switch is on compared to the off periods, the higher the total power supplied to the load. PWM technology makes it possible to easily vary voltage, frequency and suppression harmonic at the same time[88]. Among numerous PWM methods, space vector pulse width modulation (SVPWM)[89,90], and sinusoidal pulse width modulation (SPWM)[91] are the most common.

#### *A SVPWM*

By combining the different switching modes (space vectors shown in Figure 25 and controlling the switch-on time for each vector in a certain period, SVPWM enables the motor to be fed with a circular magnetic field with constant amplitude. The main features of SVPWM are as follow:

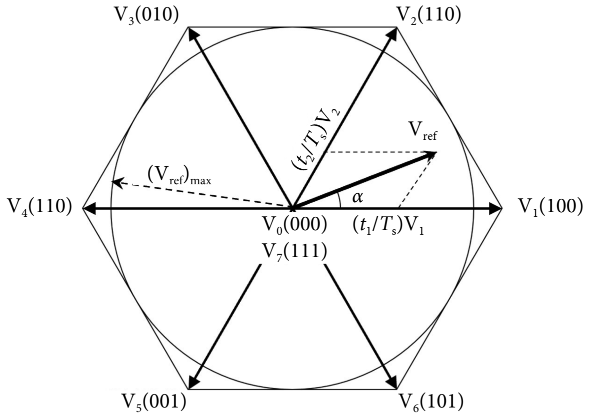


**Fig. 25 Diagram of SVPWM technology.**

1) Small switching loss since each switching involves only one device of inverter.

2) Simple calculation by using voltage space vector directly generate three-phase PWM wave.

3) Obtaining 15.47% higher output voltage than that of the general SPWM inverter, because the maximum value of the basic wave of the output line voltage of the inverter is the dc side voltage,

#### *B SPWM*

SPWM works on the physical principle that narrow pulses with equal impulse but different shape (here is voltage/current pulse will have basically the same effect on an inertial element (EM coils). According to the method of generating a modulated signal, there are many kinds of SPWM. Compared to SVPWM, SPWM is simpler but will have larger harmonic distortion and the amplitude of its fundamental phase voltage can only be 1/2 of the DC bus voltage.

## 5 Future development trend of electric machines

In the background of mitigating global warming and reducing carbon emissions, electrification has become mainstream worldwide. EMs, as the main equipment to utilize electric energy will also get new development opportunities. In general, the EM will at least have the following two development trends in the future:

1) To achieve higher power/torque density.
2) Special EMs for special applications or occasions.

### 5.1 High power/torque density

Increasing the power/torque density means that more power or torque can be obtained for the same volume or weight requirements. It is of great significance in the fields of new energy power generation, traffic traction, aerospace equipment and so on. On the other hand, the improvement of power/torque density is conducive to the realization of direct drive, miniaturization and weight-lightening of EM system, which greatly reduces the volume and weight of equipment and improves system efficiency and reliability to a certain extent.

According to the general expression of power/torque, in order to improve PD or TD, it will be an inevitable trend to design high-performance EM topology, develop high-speed/ultra-high-speed motors, and improve electromagnetic load.

$$P = T \times \Omega \propto AB_g\Omega \tag{3}$$

### *A High-performance topology*

When the motor speed and size are constant, the motor power density and torque density can be further improved only by increasing the torque output capacity of the motor. In order to improve the torque, the design of high-performance topology is the key. At present, thanks to the popularity of high-performance permanent magnets, permanent magnet motors have higher torque output capacity compared with induction motors and reluctance motors. In the future, permanent magnetization is still one of the main development trends in motor field. In this area, there are three types of motors that deserve further study:

1) Interior PM (IPM) SynM and PM-assisted (PMA) SRM. These two types of motors have essentially similar characteristics, that is, they make use of both reluctance torque and PM torque. The difference is that PM torque accounts for the main part in IPM-SynM, while reluctance torque is the primary component in PMA-SRM. For these two kinds of motors, how to arrange permanent magnets and design the magnetic circuit of rotor is the key to improve performance[55].

♦ This involves a lot of combination and nonlinear factors, the traditional design method often can not get the optimal result, so it needs to develop computer aided optimization software.

2) FMPMM. Thanks to the principle of flux modulation, this type of EM is naturally capable of high torque output. However, as described in Section 3.3, its structure is complex and variable, and the air-gap magnetic field harmonics are abundant. How to better design and utilize these harmonics is the key to further improve the torque density of FM-LPMM[92]. There is one aspect worth studying as follow, namely the "quantitative construction method of air-gap topology":

♦ Air-gap permeability plays a key role in the FMPMM, which directly determines the distribution and amplitude of working harmonic components of the EMs. This method makes it possible to directly design the air-gap permeability to obtain the optimal topology. The proposed method is guided by general air gap topology constructing principle where air gap topology construction is to find optimal permeance function $\Lambda(\theta_s)$ that maximizes object function of torque $T = f(\Lambda(\theta_s))$. The proposed method can directly connect the air gap topology with torque while working permeance harmonics serve as bridge. Thus, when $f(\Lambda(\theta_s))$ achieves maximum, air gap topology is accordingly obtained. The proposed method could serve as a powerful tool in inventing high torque density EM with strong theoretical foundation. The design procedure of the quantitative construction method of air gap topology is shown in Figure 26.

### *B High-speed machines*

Increasing the rotating speed of the motor can effectively improve the power density of the motor. High-speed electric machine (HS-EM) usually refers to the EMs with over 10000 -rpm rotating speed. So far, high-speed IM, PM-SynM and SRM have been designed and manufactured. Table 5 shows the main feature and the notable products of these three kinds of HS-EMs (●, ●● , ●●● represent the low/poor, medium and high/good indices, respectively):

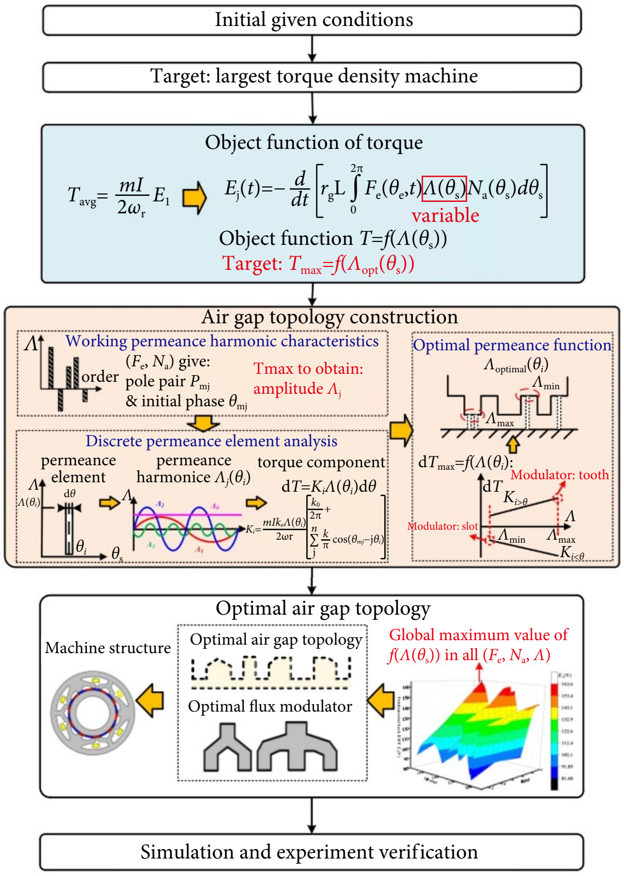


**Fig. 26 Flow of quantitative construction method of air gap topology.**

**Table 5 Main feature and notable products of three kinds of HS-EM**

| Type | IM | PM-SynM | SRM |
|---|---|---|---|
| Simple structure | ●●● | ●● | ●●● |
| Mechanical strength | ●●● | ●● | ●●● |
| Power density | ●● | ●●● | ● |
| Power factor | ● | ●●● | ● |
| Heat resistance | ●●● | ● | ●●● |
| Efficiency & loss | ● | ●●● | ●● |
| Controllability | ●● | ●●● | ● |
| Vibration & noise | ●●● | ●●● | ● |
| Manufacture & Cost | ●● | ● | ●●● |
| High-power product | 15 MW<br>@ 20 krpm | 8 MW<br>@15 krpm | 250 kW<br>@ 22 krpm |
| High-Speed Product | 0.2 kW<br>@ 300 krpm | 1 kW<br>@500 krpm | 1 kW<br>@ 200 krpm |

The main characteristics of high-speed motor are high rotor speed, high stator winding current, high magnetic flux frequency in the iron core, high power density and loss density. These characteristics determine that the high-speed motor has unique key technology and design method different from the regular-speed motor, which can be concluded but not limited to five aspects:

1) Loss calculation and cooling system design. With the increase of speed, the feature and mechanism of machine loss can be totally different. More accurate calculation model for HS-EM should be proposed, especially for stator iron loss, AC copper loss, and wind friction loss. Meanwhile, high loss density requires better cooling system, which has already become the research hotspot of many motor manufactures.
2) Machine type selection. As discussed above, different kind of EM has very distinctive feature. A proper selection of machine type is the initial key to guarantee the design requirement.
3) Rotor structure design. The rotor of HS-EM suffers the severe mechanical stress, poor cooling condition and strong wind friction. Therefore, rotor structure must be designed carefully to keep its strength. For high-speed surface-mount PM-SynM, rotor sheath is necessary. The material selection, processing and assembly of rotor sheath are also worthy of study.
4) Vibration and noise reduction. For the HS-EM, serious vibration and noise may result from abundant magnetic field harmonic, high-frequent switching of PELD, friction from the mechanical connection and many other aspects. Corresponding reduction methods should be proposed and applied to HS-EMs.
5) Bearing for high-speed application. Bearing is an indispensable part in HS-EM. However, with the continuous increase of rotating speed. Conventional mechanical bearing can no longer meet the requirement and the bearing loss will be too large to be endured. Therefore, magnetic bearing[93] and bearingless technology[94] are bound to be research hotspots.

### *C Improvement on electromagnetic load*

Increasing electromagnetic load is one of the important means to improve the power density and torque density of the motor which includes two main aspects of research:

1) Increase the source of the magnetic field, i.e. magnet and energized coil.

♦ Improving the performance of permanent magnet materials will be the focus of future material research.

♦ Hair-pin winding technology is a new development trend, which can help to improve the slot filling ration of EMs, so as to obtain more electrical load[95].

♦ Superconductivity technology will revolutionize the electromagnetic load class of future EMs. Taking advantage of the fact that superconductors have almost no DC resistance below critical temperatures, superconducting motors can achieve hundreds of times higher current and an air-gap flux density of several Tesla.

2) In order to maintain motor performance under high intensity magnetic field and high heat loss, future research needs to be focused on:

♦ Soft iron material with higher saturation magnetic density.

♦ Design a cooling structure with stronger cooling capacity.

## 5.2 Special electric machine

Driven by electrification, traditional mechanical, hydraulic and pneumatic structures are being replaced by electric motors in many fields. At the same time, due to the maturity of motor technology, motor has gained application prospect in many new fields. However, these applications often have very special design constraints and performance requirements, so it is an important trend to design special motors for special applications in the future. Below are the two examples of special motors for a certain application.

### *A Limited angle torque machine for valve*

Limited angle torque motor (LATM) is one kind of torque machines, which is mostly a rotary machine and can swing within a limited angular operation range usually smaller than 180° without any extra mechanical conversion device[96]. Due to the advantages such as simple structure, high reliability, and uncomplicated control mode, LATMs are widely applied as primary executive components in many servo systems that demand limited mechanical rotation, such as aerospace equipment, ON–OFF valve of fuel engines, and optical scanning system[97].

Many researchers have been done to investigate various LATM topologies for different performance requirements. These LATM can be mainly classified into the would field ones[98] and the permanent magnet (PM) ones[99]. Furthermore, the PM LATMs consist of the slotted PM ones and slot-less PM ones. Due to the larger magnetic load and slot-pole structure, slotted PM LATMs feature higher torque density but also larger cogging torque than the slot-less PM ones. For various application occasions, the performance focus and the design criteria of LATM are quite different from each other[100]. Thus, there is no universal topology or optimization method for LATMs.

### *B Linear motor for vehicle active suspension*

A linear motor (LM) is functionally the same as a rotary electric motor with the rotor and stator circular magnetic field components laid out in a straight line. Since the motor moves in a linear fashion, no lead screw is needed to convert rotary motion to linear, resulting in high efficiency and stability. With the utilization of high-performance PM and development of flux modulation theory, flux-modulation linear PM motor (FMLPMM) is proposed and features much higher thrust density than conventional LM.

In the vehicle suspension system, there is a trend to replace the traditional mechanical passive suspension system and the hydraulic or pneumatic active actuators by the high thrust density FMLPMM electromagnetic active suspension system (e.g., citroen, rolls-royce, mercedes-benzes, etc.). By using FMLPMM, it will significantly shorten the system response time, and improve the effect of the vibration absorption. At present, some western countries have developed the corresponding prototype system and made application test[101], while China is still in the stage of theoretical design.

## 6 Conclusions

This paper briefly reviews the important historical milestones of the EM since its birth 200 years ago. Three driving forces for the development of EMs are summarized, namely the theoretical research, the material performance breakthrough and the development of power electronics and computer science. These factors not only in the past, that is, are still playing a dominated role in EM development. Consequently, the current research hotspots in these areas are investigated in this paper.

Then, this paper introduces the classical and emerging types of EMs, and summarizes their principles, characteristics and applications. So far, the development of traditional motors has been very mature in terms of technology, but it also limits their greater development and application potential. As a result, several kinds of emerging EMs, represented by FMPMM, PM-assisted SRM, axial-flux EM and LM, with unique performance characteristics, are becoming the focus of current research. As an inseparable part of the EM system, some popular EM control strategies are also introduced in this paper.

Finally, combined with the current development trend of global economy, industry and society, some future trends of EM development are prospected.

By reviewing the development history, introducing the current hot spots and analyzing the future trends, this paper aims to outline the timeline of EM development, the EM research distribution map and the blueprint for the future EM development, providing some extensive, clear and constructive information for motor beginners, motor researchers and motor manufacturers.

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## Additional information

## Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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