Overview of Research and Development Status of Brushless Doubly-Fed Machine System

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Abstract: The brushless doubly-fed machine (BDFM) has been widely used due to its advantages of robustness, reliable operation, ease of maintenance, adjustable power factor, small converter capacity and low cost. BDFM is attractive for use in many applications such as variable frequency speed regulation systems and variable speed constant frequency generation systems. Hence, there is a rapidly growing interest in design and control of BDFM. In this paper, the origin and development of BDFM are reviewed, the structural characteristics of BDFM are discussed at length, the principles of operation and design are analyzed, and the different control methods used for BDFM are overviewed and compared in detail. Finally, challenges and opportunities of BDFM are concluded.

Keywords: Brushless doubly-fed machine, structure characteristics, rotor type, operation principle, design feature, control method.

1 Introduction

Brushless doubly-fed machines(BDFM) have been widely used in many applications such as variable frequency speed regulation systems and variable speed constant frequency generation systems, etc[1-4], due to its inherent advantages of robustness, reliable operation, ease of maintenance, adjustable power factor, small converter capacity and low cost. As a result, the design and control methods of BDFM have attracted research focus. Various types of BDFM topologies are emerging such as BDFM with cage rotor[5-7], BDFM with reluctance rotor[8-11], BDFM with wound rotor[12-14], BDFM with hybrid rotor[15-16], dual-stator BDFM[17-19], etc. Driving development in control methods such as scalar control[20-22], vector control[23-25], direct torque control[26-28], direct power control[29-30] and intelligent control[31-32], etc. However, due to the complexity of stator windings and the diversity of the rotor structure, BDFM is facing multiple problems. At present, the BDFM has not been widely used in application, but the study of BDFM has continued.

In recent decades, BDFM has been extensively studied and various topologies and control methods have been proposed. The purpose of this paper is to give an overview of related knowledge of BDFM for relevant researchers. The origin and course of development of BDFM are introduced and the winding types, rotor structures are reviewed and compared. The principles of operation and design are then discussed. Moreover, the more commonly used and newer developed control methods of BDFM are analyzed and compared in detail. Finally, the challenges and opportunities for the development and application of BDFM are presented.

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2 Origin and development of BDFM

The origin of BDFM can be traced back to 1902 when Lydall opened a patent related to the induction machine (IM)[33]. At that time, the IM was favored by people because of its simple structure and significant advantages. From advancements in industry, the speed requirement of the motor became higher and higher, and the cascade induction motor was introduced. The diagram of cascade induction machine(CIM) is shown in Fig.1. As shown in Fig.1, the pole number of the two IMs is different. The novel IM proposed in Lydall patent is similar to the CIM. The idea of Lydall was developed by Hunt in 1907. The slip ring can be cancelled by using Hunt idea. In addition, Hunt published papers to illustrate this new machine type[34-37]. Creedy further researched the design of rotor and stator based on Hunt[38] in 1921. It is more convenient to use the method of Creedy to choose combination of stator and rotor than the Hunt method, but the method is still not perfect. With the promotion of Hunt and Creedy, this new cascade machine has achieved some economic benefits, but there was no new development in the next twenty or thirty years. This can be regarded as the origin of the concept of the BDFM.

The next step in the development of CIM didn't occur until approximately 50 years later. Broadway and Burbridge proposed the real meaning BDFM on structure in 1970[39], and were considered to be the first to put forward the BDFM. The proposed machine in [39] was based on the prototype of Hunt. Because the prototype had some disadvantages, such as complex

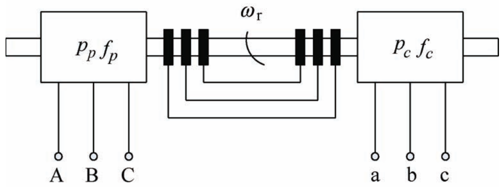


Fig.1 Diagram of cascade induction motor

process, low reliability and low efficiency, Broadway and Burbridge tried to design a BDFM with cage rotor. In [40], the BDFM with flux-barrier rotor was proposed by Broadway, and the effects of saturation and harmonics on machine behavior were discussed. Design and performance details of a prototype 400Hz, 3000r/min, 3-phase machine were discussed in [41]. In [41], the theoretical analysis was developed which had taken into account the effect of magnetic saturation both in the steady state and in the transient state. On the basis of the theory of Broadway and Burbridge, scholars from university of Oregon and university of Cambridge studied the BDFM further from the 1980s to the 1990s[42-47]. Based on their research, the design methodology of BDFM was obtained and optimized. Further research of BDFM of subsequent scholars was based on these machine models.

With the gradual maturity of BDFM design, the research on the control of BDFM had became a hot research topic[48]. The mature control theory of BDFM was presented until Brassfield and other scholars applied the direct torque control of IM to BDFM in 1992[49]. D. Zhouusing used a simplified PI algorithm to achieve the closed-loop control of BDFM in 1993[20], and became a milestone in the development of BDFM control theory. In subsequent years, D. Zhou proposed control methods based on flux oriented control to improve the control theory of BDFM[50-52]. By the end of 1990s, the control of BDFM was mainly focused on direct torque control algorithm. In recent decades, research of BDFM has continued, and many control methods have been applied in BDFM, such as vector control, rotor field oriented control, direct torque control, direct power control and so on[53-58]. The development of power electronics devices and microprocessors has promoted the development of BDFM. Because of BDFM is very suitable for variable speed constant frequency (VSCF) applications, it has became a research hotspot in recent decades.

3 Structural characteristics of BDFM

The BDFM is a new type of AC machine with characteristics of synchronous and asynchronous machines. The structure of BDFM is different from traditional AC machines. There are two windings with different pole-pair numbers in the same stator core, and the energy conversion is achieved by the magnetic field modulation of the special rotor. In this part, the stator and rotor are discussed in detail.

3.1 Stator core and winding type

The model of the BDFM can be derived from the models of two slip ring IMs connected back-to-back as shown in Fig.1. But BDFM with this structure type is not only large, but also inconvenient with regards to installation and debugging, so some researchers proposed that the stators and rotors of the two IMs be installed in the same frame as shown in Fig.2. As shown in Fig.2, this structure can reduce the size of machine, but the axial length of machine is still long, more materials are used, and the cost of machine is still high. Through the study, the BDFM used at present is a machine that has two stator windings with different pole numbers on the same stator. The conceptual diagram of BDFM is shown in Fig.3.

Although there is a big difference between the structure of BDFM and the traditional AC motor, the stator core of BDFM is basically the same as that of the traditional AC motor. However, the stator winding connection mode of BDFM and that of common AC machine are quite different.

According to the stator winding connection mode, the stator winding can be divided into single winding type and double winding type. The single winding structure is a structure that leads to two ports from a single stator winding, and the winding presents a different number of poles as seen from different ports. There are a variety of ways of single winding to achieve two kinds of poles, such as 4Y/3Y and 3Y/3Y. Fig.4 shows the connection types of 4Y/3Y and 3Y/3Y.

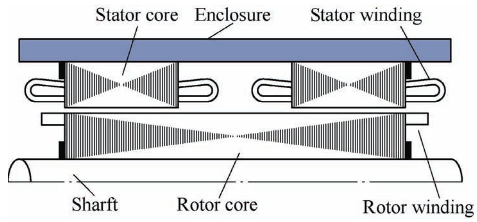


Fig.2 Diagram of BDFM with dual stator

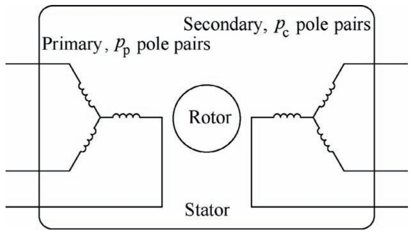


Fig.3 Conceptual diagram of BDFM

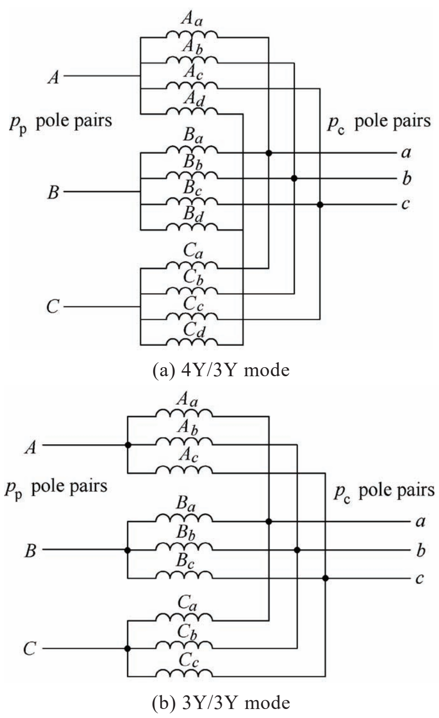


Fig.4 Single winding connection mode

Early on, Hunt, Greedy, Broadway, and others advocated using a single stator winding because it can improve the utilization rate of core material. However, single winding scheme should take into account the power winding and control winding functions together, so it can't ensure that both of the two sets of stator windings have a better winding coefficient. In addition, in order to eliminate the direct coupling between two sets of windings, the two windings should be orthogonal, limiting the flexibility of winding design. The connection mode of single stator winding where pole ratio of power winding and control winding is 3:1 was presented in [59] and [60], however, the connection mode mentioned in [59] and [60] will produce circular current. Design methods and connection modes are proposed in [61] to eliminate the circular current.

Double winding type is a mode in which two sets of windings are designed separately. Due to the coil pitch and arrangement mode of each winding being based on the principle of single winding, not only can it provide a higher winding coefficient for each winding, but it can also eliminate the influence of harmonics. Compared with single winding, the utilization rate of material is lower, but the flexibility of double winging mode is better, so BDFMs more commonly use double winding type at present. In [62], the stator winding design principle of BDFM was introduced. The stator windings were designed and analyzed by means of the double-pole and single-pole slot-number phase diagrams.

3.2 Rotor Structures and characteristics

As the magnetic field of the two stator windings can't be coupled directly, the electromechanical energy conversion between the stator and rotor must be modulated by the magnetic field modulation of the rotor. The BDFM rotor is a critical component, where the magnetic field modulation capability directly determines the efficiency and power index of BDFM. Similar to the conventional machine, the commonly used rotor can be divided into wound rotor, cage rotor and reluctance rotor. Table 1 shows some of the main universities that research BDFM.

3.2.1 Cage rotor

BDFM with cage rotor has better starting capacity and asynchronous operation capability [63]. In addition, the structure and manufacturing process of cage rotor is simple and it can be manufactured by using the same manufacturing process of traditional induction machine rotors. There are four main types of cage rotor structure as shown in Fig.5. In these four structures, rotor slots of Fig.5 (a) and Fig.5 (c) are more than the others at the same condition, and the structure of Fig.5 (d) is the simplest. In addition, use copper bar material can be economized and the technical difficulty reduced by using the structure in Fig.5 (d). In [5], the circuit mode of BDFM with cage rotor was established based on the electromagnetic relationship and the correctness of the mode verified experimentally. The BDFM with Fig.5(b) and Fig.5(c) rotor structure has the same effect of magnetic field modulation and the dynamic characteristics of torque-speed[96]. The energy transmission and power factor characteristics of BDFM with cage rotor were researched experimentally in [81]. In [6], magnetomotive force characteristics of cage rotor were analyzed and effect of rotor structure on magnetic field modulation was described in detail. The characteristics of asynchronous operation of brushless doubly fed machine with three kinds of cage rotor were analyzed and compared in [97]. The British scholars analyzed the influence of bar conductor number and span on impedance parameters of cage rotor based on equivalent circuit parameter methods. Beyond that, they designed and manufactured a 250kW BDFM with cage rotor, and the efficiency of BDFM can reach more

Table 1 Research on rotor type of BDFM

Country	University	Rotor type	Reference
USA	Oregon State University	Cage	[2],[45],[64],[65]
UK	University OF Cambridge	Cage	[66],[67]
UK	Durham University	Cage& Wound	[68],[69],[82],[83]
Australia	University of Technology	Wound	[29],[70],[86]
USA	University of Wisconsin-Madison	Reluctance	[48],[88],[89]
UK	Northumbria University at Newcastle	Reluctance	[3],[24],[71],[93]
Australia	University of Newcastle	Reluctance	[72],[73],[85]
USA	Ohio State University	Reluctance	[1],[74]
China	Shenyang University of Technology	Cage & Reluctance	[63],[75],[84]
China	Chongqing University	Cage	[59],[76],[91]
China	Zhejiang University	Cage	[77],[78]
China	China University of Mining and Technology	Cage	[5],[79],[90]
China	Huazhong University of Science and Technology	Wound	[13],[14],[87]
China	Hunan University	Cage	[55],[95]
China	South China University of Technology	Cage	[61],[80]
China	Taiyuan University of Technology	Cage	[81],[92],[94]
China	Southeast University	Wound	[17],[18]

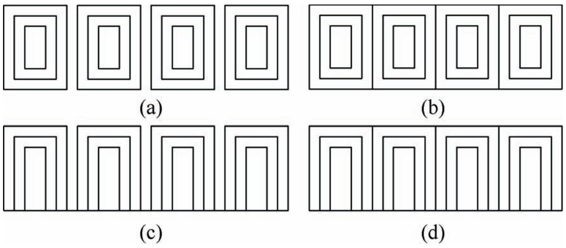


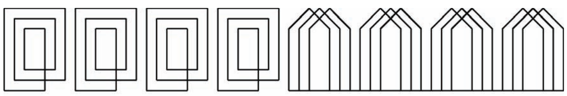
Fig.5 Common structures of BDFM with cage rotor

than 90%[82,83]. A 75kW BDFIG with wound cage rotor was proposed in [98]. Fig.6 shows the wound rotor. Iranian scholars proposed a novel rotor configuration to reduce spatial harmonic distortion of air-gap magnetic field as well as improving on some of the drawbacks of the conventional structure, including unequal magnitudes of rotor bar currents, teeth saturation at low average air gap magnetic fields, high core loss and inefficient magnetic material utilization[99]. The rotor loops are connected in series as shown in Fig.7(a). In [7], a new rotor structure——equidistant cage rotor was presented based on concentric cage rotor as shown in Fig.7(b).

3.2.2 Reluctance rotor

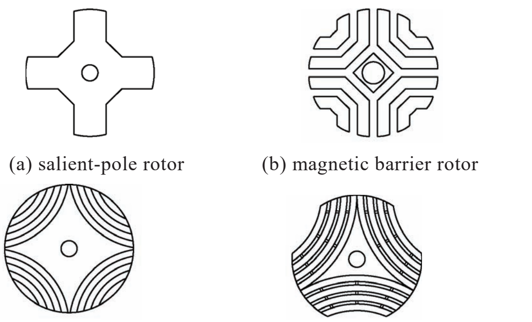
Because of the strong structure, low manufacturing cost, high system reliability and other advantages, the reluctance rotor has attracted much attention in the 1980s. The magnetic reluctance type rotor includes general salient-pole reluctance rotor, axially laminated magnetic barrier rotor and radial laminated magnetic barrier rotor[1,8-9,84]. The concrete structures of reluctance rotor are shown in Fig.8. The characteristics of these structures are compared in Table 2[9-10,100].

Fig.6 Wound cage rotor



(a) (b)

Fig.7 New types of cage rotor

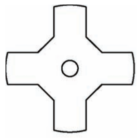
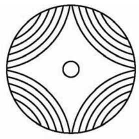
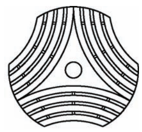


(a) salient-pole rotor (b) magnetic barrier rotor

(c) ALA rotor (d) radial laminated magnetic barrier rotor

Fig.8 Structure types of reluctance rotor

Table 2 Characteristics comparison of different reluctance rotor types

Types	Advantage	Disadvantage
	Simple and reliable structure, easy to manufacture	Air gap between stator and rotor is not uniform, magnetic conductivity is poor
	Enhance the quadrature-axis reluctance, magnetic field modulation is relatively good	Manufacturing process is relatively complex
	Magnetic field modulation is better	Large eddy-current loss, complex manufacturing
	Magnetic field modulation is better, low eddy-current loss, manufacturing is simple	Manufacturing process is complex, design is limited by connection reinforced

The design principles of BDFM with reluctance were presented and analyzed in [11,85,101]. In these papers, the relationships between choice of pole number combinations, power factor, and size are were explained and discussed. In [102], the effect of geometric parameter variations on global performance of BDFM with reluctance rotor was studied. The magnetic circuit modeling technique was proposed to calculate the flux density of BDFM with induction rotor and reluctance rotor in [103]. The parameter and performance of BDFM with cage and reluctance rotors were compared in [104].

3.2.3 Wound rotor

Compared with other rotor types, the wound rotor can improve the utilization ratio of conductor, reduce the harmonic content, and thus improve the performance of BDFM[12-14,105]. A “double-sine” wound rotor for the brushless doubly fed generator was presented to reduce the harmonic contents of the rotor winding in [12]. A new wound rotor was presented based on "changing-pole winding" idea in [13]. Fig.9 shows the 3Y/3Y different pole port negative phase sequence series connection method.

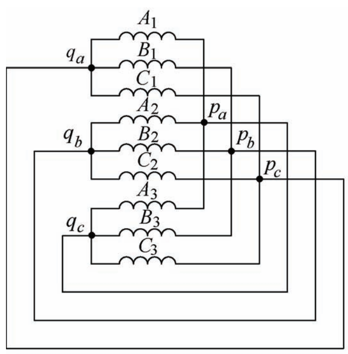
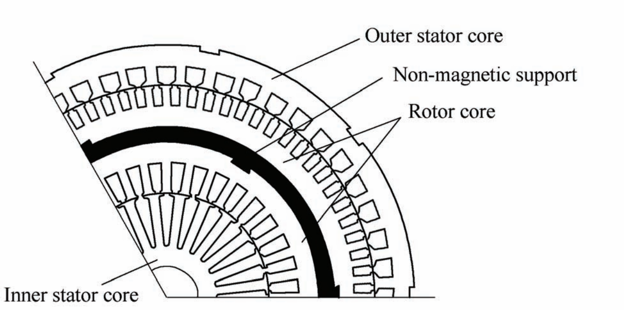


Fig.9 A wound rotor p/q-pole winding with 3Y/3Y different pole port negative phase sequence series connections

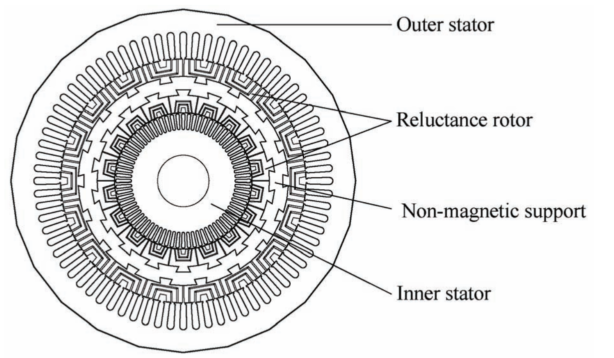
In order to reduce the rotor harmonic contents, the structure of the BDFM with the rotor designed by the unequal-turn coil was presented in [14]. The voltage amplitude fluctuation and compensation for wound rotor BDFM was studied in [105]. In [105], a better method of harmonic injection was introduced and applied. In [86], a preliminary investigation on developing a brushless doubly fed machine based on the theory of slot harmonics of magnetomotive force was presented to achieve high winding factor and power efficiency. The working principle, operation performance and equivalent circuit of BDFM with wound rotor was researched in detail by Prof. Xuefan Wang[87,106-107]. The magnetomotive force of BDFM with cage rotor and wound rotor was compared in [108]. According to the results, the efficiency of magnetomotive force of wound rotor is better than that of cage rotor. In [88], the dynamic model of BDFM with wound rotor was established.

3.3 New structures of BDFM

In order to improve the torque density and coupling capability of BDFM, new structures of BDFM were researched. Professor Ming Cheng and professor Fengge Zhang have developed the BDFM with dual-stator[17-19]. The schematic diagram of the BDFM proposed by Professor Ming Cheng is shown in Fig.10 (a). The detailed design and analysis procedure of the proposed BDFM was presented in [17]. Meanwhile, the detailed spiral vector model of the BDFM was developed in [18]. As shown in Fig.10(a), the BDFM consists of three parts: an outer stator with balanced three-phase power windings, an inner stator with balanced three-phase control windings, and a nonmagnetic support with dual-layer iron cores with balanced three-phase windings on each layer. The BDFM



(a) Wound rotor



(b) Reluctance rotor

Fig.10 The schematic diagram of BDFM with dual-stator

with dual-stator proposed by professor Fengge Zhang is shown in Fig.10(b). The electromagnetic design process of the dual-stator BDFM proposed by Professor Fengge Zhang and was illustrated in detail in [19].

Besides the structure of BDFM, the coupling capability of rotor is always a hotspot for researchers from all over the word[85,89,99,109,110]. In [15] and [16], a new hybrid rotor was presented and analyzed. The hybrid rotor is shown in Fig.11. As shown, the hybrid rotor is the combination of multi-layer magnetic barrier rotor and nested-loop cage rotor. In addition, the performance and coupling capability of hybrid rotor were analyzed in [15] and [16].

3.4 Comparison of different rotor structures

The magnetic torque comparison of different reluctance rotors is shown in Fig.12. Moreover, Prof. Zhang conducted an experimental study on the performance of hybrid rotor and magnetic barrier rotor[111]. The comparison results of air-gap flux density harmonics are shown in Fig.13(8/4 BDFM and

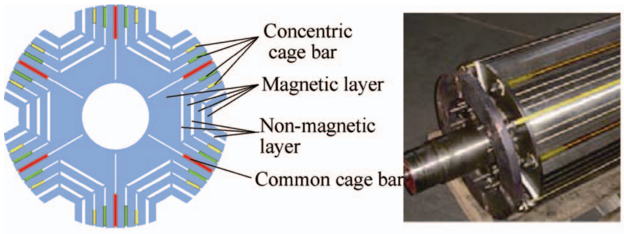


Fig.11 Hybrid rotor structure

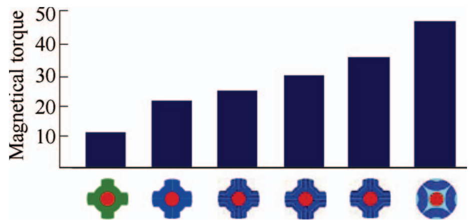
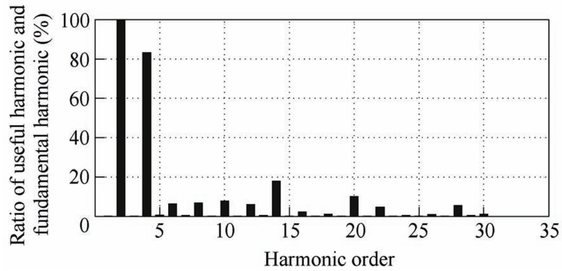
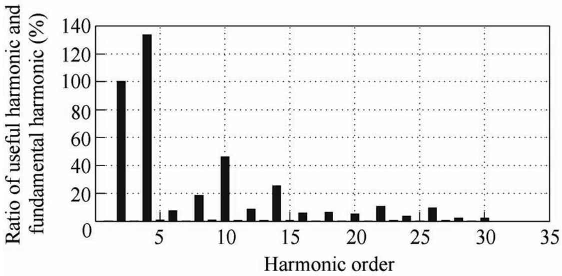


Fig.12 Magnetic torque of different reluctance rotors



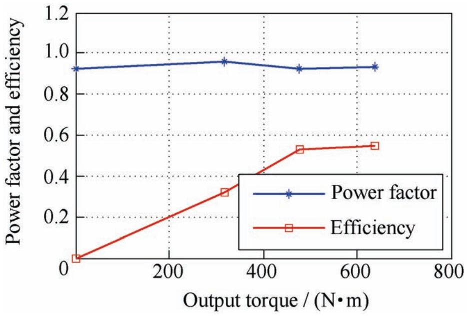
(a) Magnetic barrier rotor



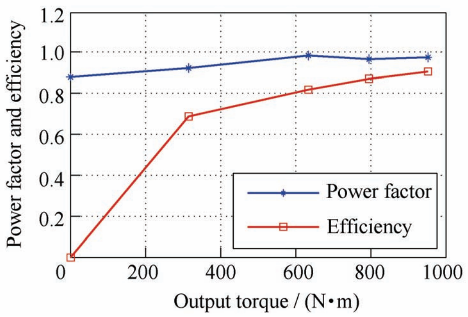
(b) Hybrid rotor

Fig.13 Air-gap flux density spectrum diagram of BDFM

4 pole winding is the exciting wingding). According to the results, the useful harmonic of hybrid rotor is higher than that of magnetic barrier rotor. In other words, the coupling capability and output capacity of hybrid rotor is better than that of magnetic barrier rotor. Fig.14 and Fig.15 show the experimental results of BDFMs with magnetic barrier rotor and hybrid rotor in doubly-fed operation mode. It can be seen from Fig.14 and Fig.15 that the load capacity and efficiency of BDFM with hybrid rotor are better than that of BDFM with magnetic rotor.

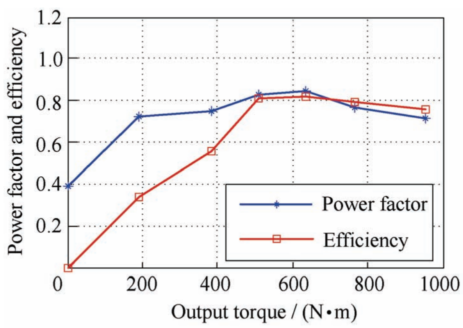


(a) Sub-synchronous mode (300 r/min)

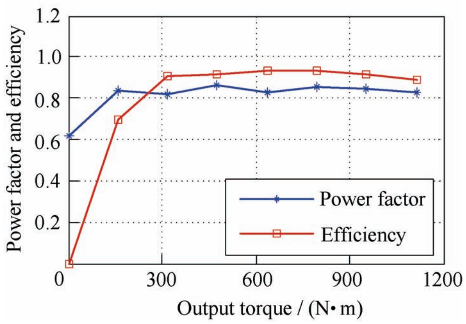


(b) Super-synchronous mode (600 r/min)

Fig.14 Experimental results of BDFM with magnetic barrier rotor



(a) Sub-synchronous mode (300r/min)



(b) Super-synchronous mode (600r/min)

Fig.15 Experimental results of BDFM with hybrid rotor

4 Principle of operation and design feature of BDFM

The principle of operation and design feature of BDFM is very different from traditional AC machines as a result of the complexity of stator windings and the diversity of the rotor structure determine. The principle of operation and the design feature of BDFM are analyzed in this part.

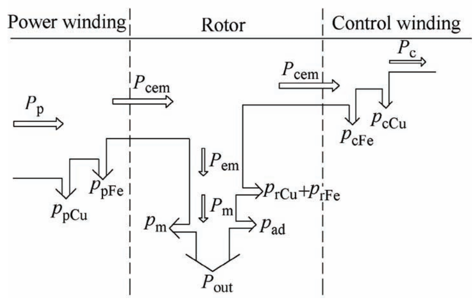
4.1 Principle of operation of BDFM

As shown in Fig.3, there are two windings with different pole-pair numbers in the stator core, and the BDFM can achieve multiple operational modes by changing the power supply mode of control winding. The BDFM will operate in synchronous mode when the control winding is supplied by DC power supply. The BDFM will operate in asynchronous mode when the three-phase control winding is shorted, and BDFM will operate in doubly-fed speed governor operation mode when the control winding is connected to the grid through a back-to-back converter [63,112]. The speed of BDFM can be expressed as:

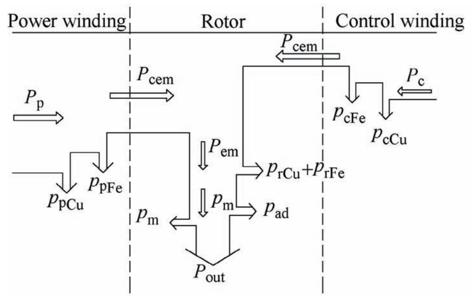
$$n_r = \frac{60\left(f_p + f_c\right)}{p_p + p_c} \tag{1}$$

where, n_r is speed, f_p and f_c is frequency of power winding and control winding, respectively. p_p and p_c is pole-pair of power winding and control winding, respectively.

The energy flow diagram of BDFM in doubly-fed mode is shown in Fig.16. In Fig.16, the capital letters P and lowercase letters p respectively represent power and loss, subscript p and c represent power winding and control winding, respectively, and the subscript em, m and ad represent electromagnetic, mechanical and additional, respectively. It can be seen that the output



(a) Sub-synchronous



(b) Super-synchronous

Fig.16 Energy flow diagram of BDFM in doubly-fed operation mode power is supplied by the power winding and control winding in super-synchronous operation mode, while the output power is only supplied by power winding in sub-synchronous operation mode.

4.2 Design feature of BDFM

The structure of BDFM is more complex than that of the common AC machine, so the design principle is different from traditional AC machines[90-91,113]. Paper [113] discusses the various stator and rotor structures and design principles of BDFM in detail. Due to the magnetic field modulation principle of BDFM, the pole-pair number of power winding can't be equal to the control winding, and the difference must be greater than 2 as shown in equation (2), so the minimum pole number of power winding and control winding is 6 and 2.

$$p_\mathrm{p} - p_\mathrm{c} \geqslant 2 \tag{2}$$

In principle, the largest number of BDFM poles is not restricted, but like other electric excitation AC machines, the excitation power increases with the increasing number of poles and the power factor decreases with increasing number of poles. From application point of view, the number of BDFM poles should not exceed 20. Therefore, according to equation (1), the synchronous speed of BDFM corresponds to 300~750r/min. Taking into account the doubly-fed operational mode of BDFM, the speed range is 150~1500r/min, and the economic speed range is from 200~1200r/min.

The rotor pole-pair number of BDFM should be selected according to equation (3) to maximize performance. In addition, Table 3 lists the mutual inductance between power winding and control winding of BDFM with different pole number combinations[114]. It can be seen that the absolute value of positive value and negative amplitude of mutual inductance are gradually approaching with the increasing number of poles. In other words, the coupling ability is enhanced with increasing number of poles.

$$p_r = p_\mathrm{p} + p_\mathrm{c} \tag{3}$$

In [90] and [91], the electromagnetic design features and principles were discussed in detail. A magnetic circuit model for the design of BDFM was proposed in [115]. A BDFM design procedure which is based on equations derived from a simplified equivalent circuit was presented in [116]. The method allows many variables in the BDFM design to be handled in a straightforward way. In [117], a BDFM with reluctance rotor was designed and analyzed. The calculation power and electromagnetic load selection principle were detailed and discussed in [118].

Table 3 Mutual inductance of BDFM with different pole number combination

Pole number combination	Mutual inductance between power winding and control winding / H	
	Positive amplitude	Negative amplitude
6+2	0.28479	−0.44453
8+4	0.18267	−0.18388
10+6	0.11961	−0.08841
12+8	0.06796	−0.06806
16+12	0.03895	−0.03919
20+16	0.02643	−0.02642

5 Control strategies of BDFM

Based on the establishment of the basic mathematical model, research of BDFM control algorithms began in 1990s[20,52,58,119]. The typical control methods of BDFM mainly include scalar control, vector control, direct torque control, direct power control and so on.

5.1 Scalar control method of BDFM

The scalar control (SC) strategy only needs to adjust the amplitude and frequency of controlling parameters, so the requirement for the controller is not high. However, the transient process isn't taken into account and many factors are ignored, so the dynamic performance of SC is not good and results differ from the actual value. The closed-loop SC of BDFM is proposed in [20]. The speed and power factor of power side were subjected to closed-loop control in this algorithm, and the control principle is shown in Fig.17. In [21], an open-loop SC strategy was presented. In order to control the speed of BDFM, the algorithm is used to calculate the voltage frequency of control winding according to the given speed value and then the voltage amplitude of control winding is adjusted. Paper [22] presents a stability analysis of the BDFM under closed-loop scalar current control.

5.2 Vector control method of BDFM

Compared with SC, the performance of vector control (VC) is superior [120], and is one of the most popular high performance control technologies[23-25,53-54,88,121]. The design of the VC algorithm is based on the mathematical model of machine. So according to the mathematical model used, the VC of BDFM can be divided into two types: one is based on dual synchronous frame model of Zhou[122], the other is based on unified reference frame model of Poza[123]. The VC block diagram of BDFM which is based on dual synchronous frame model is shown in Fig.18. In [53], a generalized VC system was proposed for BDFM with nested-loop rotor. The proposed VC system is liable to be employed for BDFM in wind power industry.

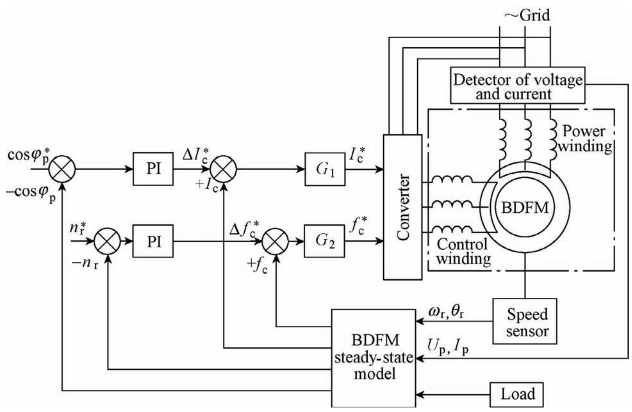


Fig.17 Closed-loop scalar control diagram of BDFM

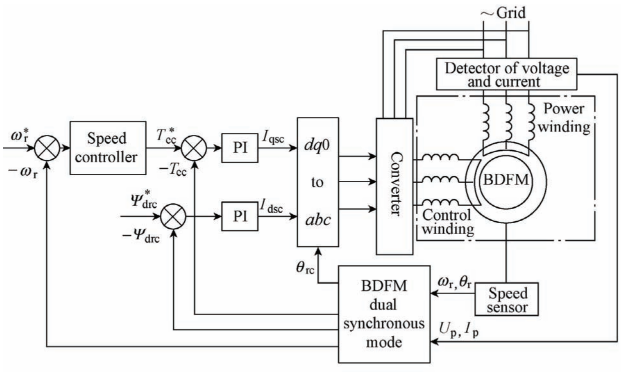


Fig.18 Vector control diagram of BDFM

Taking advantage of the relation between synchronous angle and torque, a simple and practical vector decoupled control strategy was proposed in [121]. The theoretical considerations for the VC design, control loops tuning and limits were shown in[54]. The unified reference frame model was used to develop the proposed VC strategy.

5.3 Direct torque control of BDFM

The direct torque control (DTC) calculates the value of flux and torque directly on the stator coordinates and realizes the PWM output of power converter by tracking the hysteresis of flux and torque[26-28,124,125]. The DTC block diagram of BDFM is shown in Fig.19. A maximal power tracking method through controlling torque and power factor of brushless doubly-fed wind power generator to regulate active power was proposed based on DTC in [57]. A novel-speed observer was designed by estimating the rotor flux synchronous rotating speed and slip speed. In [56], the DTC system of BDFM without speed sensor was developed by applying the stator flux observer value to the DTC algorithm. The principles and implementational aspects of DTC for BDFM were explored in [27]. A DTC strategy in static reference frame for BDFM was presented in [92]. The rotation coordinate transformation was prevented and parameters used in system were reduced by using the proposed method. A fuzzy Logic DTC based on stator flux- oriented and machine's relation and equations with voltage and current of both stators have been introduced in [28]. In [125], an improved DTC of BDFM for wind turbine was proposed. The space vector modulation method was used to reduce the ripple of torque and flux.

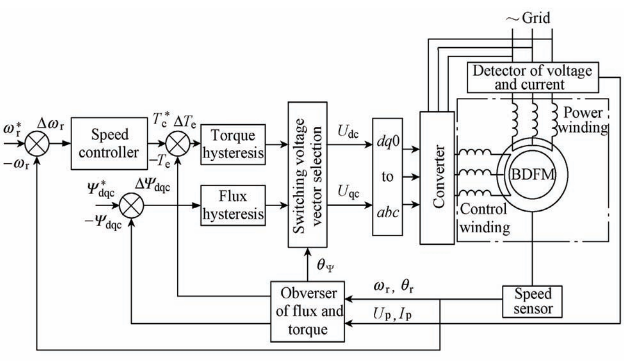


Fig.19 Direct torque control diagram of BDFM

5.4 Direct power control of BDFM

The direct power control (DPC) is proposed based on the idea of DTC and transient power theory[93,126-128]. The block diagram of DPC is shown in Fig.20. The excellent potential of the DPC scheme for generating operating mode of the custom designed BDFM at maximum power factor was demonstrated by simulation studies in [129]. A new control method of cascaded BDFM using DPC was proposed in [29]. The effects of voltage vectors on the output active and reactive power were investigated. The DPC for open-winding BDFM was studied by Jin[30,130]. A power error comparison DPC method was proposed to implement the power tracking for BDFM in [130].

5.5 New control methods for BDFM

Based on common control methods, some new control methods have been proposed to improve the performance of BDFM. In [94], an indirect stator-quantities control strategy for the BDFM was proposed. The proposed method provides the benefit of the simple structure. Furthermore, the controller structure is less dependent on the BDFM parameters, only the two winding resistances are used. The dynamic control of reactive power for the BDFM with indirect stator-quantities control scheme was developed in [131]. A new algorithm for shaft position sensor-less independent control of real and reactive power of the BDFM was proposed and experimentally verified in [132]. The algorithm is inspired by the fundamental operating principles of the machine and does not depend on any parameters. In [133], a sensorless maximum power point tracking control of BDFM based on extended Kalman filter for estimation of rotor speed was presented. In [134], a variable structure robust controller of BDFM for wind energy conversion system was proposed. Based on the active and reactive power mathematical model of BDFM, a new power control system scheme was proposed in [95]. The proposed method can realize the independent control of BDFM active power and reactive power. In [135], a direct voltage control method was proposed to optimize the output voltage of a dual-stator BDFM with wound rotor.

5.6 Comparison of common control methods

Table 4 gives a comprehensive comparison of the common control methods of BDFM.

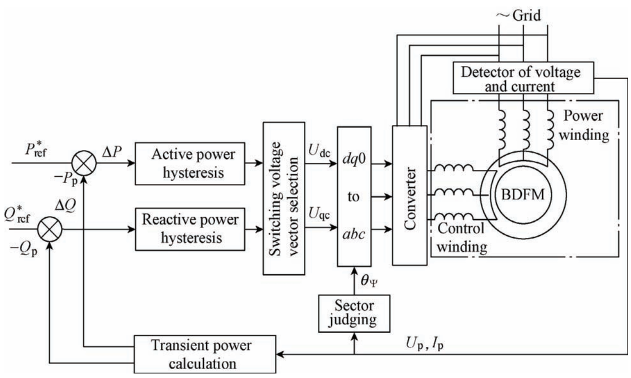


Fig.20 Direct power control diagram of BDFM

Table 4 Comparison of different control methods

Control method	Advantages	Disadvantage
SC	Algorithm is simple and easy to implement	Poor dynamic performance
VC	Good dynamic performance	Large calculation, easily affected by parameters
DTC	Simple implementation, fast response and little dependence on machine parameters	High torque and flux ripple, variable switching frequency problems
DPC	Simple implementation, fast response, easier calculation	High system cost, variable switching frequency

6 Conclusion

In this paper, an overview on BDFM is provided. Firstly, the origin and development course of BDFM are briefly reviewed. Secondly, the stator characteristics, winding types, rotor types and new structures of BDFM are indicated and compared. Thirdly, the operation principle and design features of BDFM are illustrated. After that, the commonly used and recent control methods are analyzed and compared in detail. Finally, the challenges and opportunities for promoting the technology development and the application of BDFM are addressed:

6.1 Challenges

- The electromagnetic design program with strong commonality and accurate calculation features of BDFM is eager to be developed.
- There is a wealth of harmonics in BDFM, and there is no way to accurately calculate the losses of BDFM.
- Most of the converters are still for traditional AC machines and as a result are lacking to use for BDFM.
- Improvement of efficiency and reduction of noise and torque ripple calls for optimizing design and development control strategies.

6.2 Opportunities

- As a asynchronous and synchronous universal machine, BDFM can achieve brushless and generalized, possessing not only the good self-starting performance of the asynchronous machine, but also the excellent performance of the synchronous machine.
- In common with the doubly fed induction machine, BDFM has the benefit of a low-cost converter but does not have brush gear, promising low maintenance costs and high robustness. The BDFM is attractive for wind power, especially offshore.

The converter only needs to provide a small part of the power, the variable frequency speed regulation (VFSR) system with BDFM can reduce the system cost. In addition, the power factor of BDFM can be adjusted, and the force-energy index of VFSR system can be improved.

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