A REVIEW OF DEVELOPMENTS IN BEARINGLESS MOTORS

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ABSTRACT

In the last decade, extensive works have been done in developments in bearingless motors. This paper reviews the published papers written in English in the points of view of motor types, winding types, mechanical structures, test results and applications. More than 90 papers are reviewed and are cited in the references.

INTRODUCTION

In the middle of 1970's, a primitive electro magnet with stator windings having pole numbers of p and (p+2) was proposed by Hermann [1,2]. This electro magnet was proposed as a motor having a possible function of a radial magnetic bearing. Moreover, a split winding motor was proposed by Meinke [3]. However, there was little idea to apply inverters, digital signal processors and field oriented control theories at that time.

In 1985 a stepping motor, which is magnetically combined with a magnetic bearing, was proposed by Higuchi [4]. It includes a decoupling structure of torque and radial force while taking an advantage of motor exciting current.

In 1988, a disc type motor with axial force generation adjusting exciting motor current was proposed [5]. To the author’s best knowledge, a word “bearingless motor” was used for the first time.

From the late 1980’s to early 1990’s, some important concepts had been proposed. A general theory of bearingless drives has been introduced taking an advantage of field oriented control theories [8,9]. The basic structure is having 4-pole and 2-pole windings in the stator core. The motor and radial positioning windings are connected to inverters regulated by a digital controller with an application of vector control theory.

It is also noted that radial force generation using split motor windings is investigated [3, 30~40]. The basic pole combination is also investigated [6, 11~12]. Some of the proposed concepts have been studied in several university-oriented researchers.

Since the middle of 1990’s the bearingless machine developments are widely spreading. Some application specific developments can be seen.

In this paper, extensive worldwide developments in bearingless drives are reviewed especially in the points of view of motor types, winding types, mechanical structures, test results and applications. In addition, a technical term and its definition are proposed. The references are cited in categories as (a) general, (b) induction, (c) permanent magnet, (d) homopolar, (e) synchronous reluctance, (f) switched reluctance bearingless motors. In the (b) through (f), papers are listed by research groups and publication year.

DEFINITION

Fig.1 shows some related technologies to bearingless drives. The fast digital signal processing technology with low cost is available in these days. Low cost static power converters, ex., IGBT inverters are widely used in industries thank to the integration of power devices. With these technologies, field oriented control theories of electrical machines are realized. The instantaneous flux rotational position and amplitude are regulated. With exact steering of the flux, bearingless machines are possible taking an advantage of the motor flux distribution. In addition, magnetic levitation technology developed in magnetic bearings and maglev trains is also noted.

Table 1 shows the proposed definitions of bearingless motors. The first definition is that “A bearingless motor is a motor with a magnetically integrated bearing function”, which is easily understood by electrical engineers. The second definition may be familiar to mechanical engineers, i.e., “A bearingless motor is a magnetic bearing with a magnetically integrated motor function”. The integrated magnetic bearing function may indicate radial or thrust magnetic bearings depending upon radial or axial flux motors, respectively. It is well known that a motor can be

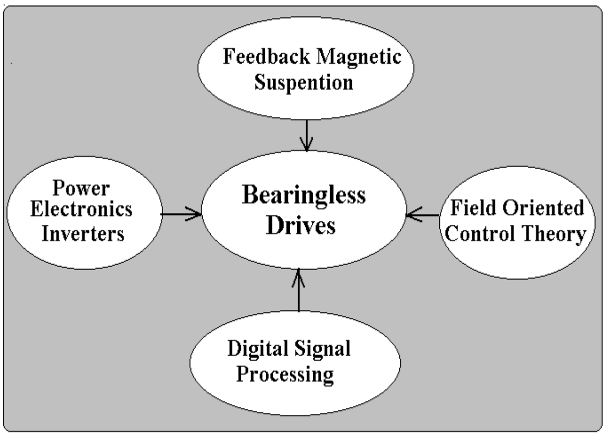

Fig.1 Technology bases

operated as a generator. In this case, a definition can be "A bearingless generator is a generator with magnetically integrated bearing function", in the case of the first definition.

Table 2 indicates a summary of technical term variations of bearingless motors. Some authors have some ideas. However, most authors use "bearingless motor". In our survey, 10 research groups use "bearingless motor", 4 groups use "motor magnetic bearing", less than 2 groups for the other terms. Thus, "bearingless motor" is recommended as a suitable technical term.

ELECTROMAGNETIC STRUCTURES

Table 3 segregates papers in motor types. The most papers are about induction motors and permanent magnet (PM) motors. The PM motors are divided into three categories based on the rotor structures. One is a surface mounted permanent magnet (SPM) rotor another is an interior permanent magnet (IPM) rotor, and the last is a buried permanent magnet (BPM) rotor. The SPM motors have PMs on the surface of a rotor iron. The PMs are glued or bound by a metallic can or other materials. Inset PM motors are similar except magnetic poles between PMs. The IPM motors have square-shaped holes in laminated silicon steel. The PMs are inserted and fixed in the holes. Some IPM motors need nonmagnetic shaft. The BPM rotor have PMs near the rotor surface like SPM motors, however, the PMs are inserted in holes in laminated silicon steel. The IPM and BPM motor are salient-pole motor, thus, control strategies require experiences.

There is a trade off in the rotor design in torque and radial force generations. If thick PMs and wide air-gap length are designed, the torque performance is better. However, thin PMs with small air-gap length are preferred in radial force generation because magnetic resistances are low.

The magnetic resistance in radial force flux paths in homopolar, synchronous reluctance and switched reluctance motors are low, thanks to the small air-gap lengths. The rotors of these motors are made of only silicon iron like magnetic bearings, except salient poles.

TABLE 1. Definitions of Bearingless Motors.

No	Definitions
1	A motor with a magnetically integrated bearing function
2	A magnetic bearing with a magnetically integrated motor function

TABLE 2. Technical terms used in bearingless motors.

Technical terms	Reference
Bearingless motor	[5,8,17,32,41,46,62,73,77,88]
Motor-(magnetic) bearing	[60,63,69,77]
Combined motor bearing	[61,69]
Self-bearing motor	[58]
Lateral-force-motor	[12]
Levitated rotating motor	[55]

TABLE 3. Type of Motor.

Type		Reference
Induction		[18~46]
Synchronous PM	SPM, etc.	[47~51,53,55,56,58~68,70 ~77]
	IPM	[57,69]
	BPM	[52,54]
Homopolar		[78,79,80]
Synchronous Reluctance		[81~88]
Switched Reluctance		[89~92]

PM = Permanent Magnet, SPM =Surface Mounted Permanent Magnet, IPM = Interior Permanent Magnet, BPM = Buried Permanent Magnet.

Rotational variations of radial force should be compensated at low speeds in reluctance motors.

Table 4 shows stator-winding configuration. In "4-pole motor & 2-pole radial force", 4-pole windings are wound as motor windings in stator slots together with 2-pole windings as radial force windings. This stator configuration is valid for both cylindrical rotor and salient-pole rotors. It is also easy to exchange winding functions in cylindrical rotor. It is better idea to employ 2-pole windings as motor windings in squirrel cage induction motor. These 2-pole and 4-pole winding configurations have an advantage of decoupling magnetic field. Some reports on "p" pole and "p+2"

TABLE 4. Stator Winding Configuration.

Stator Winding Configuration	Reference
4 pole motor & 2 pole radial force	[8,10,13,41,47~54,62~67,81~88]
2 pole motor & 4 pole radial force	[11,42~46]
p pole & (p+2) pole	[1,2,6,11~13,55,56,57,59,68]
Split winding	[3,30~40]
Concentrated winding	[55,62,89~92]
Single phase drive, 2 phase radial force	[62~67]

TABLE 5. Special Mechanical Structure.

Special Mechanical Structure	Reference
Slice Motor	[14,59]
Disk Type Rotor	[60]
Outer Rotor	[61,65]
Ring Type Rotor	[70,71]

TABLE 6. Test Machines.

rpm	kW	Motor type	Ref.
3,000	30	Induction	[44,45]
3,000	2.2	Induction	[46]
3,000	1.5	Induction	[43]
6,000	0.3	Induction	[30~34]
11,000	4	PM	
10,000	1.65	PM	[53]
300	0.078	PM	[70,71]
11,000	0.01	PM	[77]
12,000	2.12	Reluctance	[87]

TABLE 7. Applications.

Type of Application	Reference
Blood pump	[14,59,61,76]
Computer spindle	[77]
Canned pump	[43,44,45,46]
Bio-pump	[70,71]

pole winding configuration are also seen. It is also good idea to have several terminals in original motor windings. The mid point of 3-phase windings can be connected as a neutral point; independent current regulators drive the other 6 terminals. The current values are adjusted to supply original motor current with slight variations to generate radial force. This is called as split winding. Similar concepts can be applied to motors with concentrated windings. These windings are practical in small power motors. It is also noted that a reduction of number of windings is reported in a single-phase motor with well-adjusted controllers.

Table 5 shows special mechanical structures of bearingless motors. The slice motor is a radial motor with a short axial length. Thus, the rotor is stable with only a 2-axis active controller. The disk type motor generates axial magnetic force basically.

The outer rotor has a rotating part outside saving space for blood pump application. The ring type rotor has a hole inside the rotor to accommodate water blades.

Table 6 summarizes speed and power ratings of bearingless motors. The 30 kW and 2.2 kW induction motors are for canned pump applications. The 1.65 kW PM motor has efficiency of 90.4% including magnetic suspension losses. The 4 kW PM motor is reported in this conference.

INDUSTRIAL APPLICATIONS

The bearingless ac motors are most suitable for highly specific applications. The bearingless motors offer many possible practical advantages as low energy loss, lack of vibration, extremely silent, contamination less and maintenance free operations. Table 7 contains the list of some bearingless ac motor applications.

CONCLUTIONS

It is noted that there are significant number of literature written in Japanese, Portuguese, Germany and other languages. It is important to check the foreign literature to see early developments. Only English documents are surveyed in this paper.

The study found out a great investment in the research and technological development of Bearingless motors. The new motor improvements are in continuous developments. Particularly, the well acknowledges of the bearingless motors and new strategies of control are still demanding efforts of the researchers.

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