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A Comprehensive Review of Prior Art in Bearingless Induction Machine - Part II: Topology

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Abstract

This paper seeks to present a comprehensive review of the state of the art in the topology of bearingless induction machines, aiming to equip researchers in this field with a clear and thorough understanding of the topic. Such an overview is needed, as the last reviews of bearingless induction machine research, which were published in 2014 and 2019, were more control themed. Since then, significant improvements in the design of bearingless induction machines have been reported. The current review is part of a two-part series: the first part [1] focuses on the control of bearingless induction machines, while this second part reviews all publications that primarily address topology. This review begins with a categorization of the relevant papers, followed by a discussion of key technologies. Additionally, comparative metrics such as rotor surface velocities, shear stress, and thrust stress are introduced to systematically evaluate and benchmark different designs. Using these parameters, the designs are compared and conclusions drawn. The paper concludes with a brief outlook on potential directions for future research.

Keywords : bearingless, induction machine, bearingless induction machine, rotor topology, winding topology

1. Introduction

The concept of magnetic bearings, first introduced by Hermann in 1973 [2], laid the foundation for the development of bearingless machines, which were initially proposed by Bosch in 1988 [3]. Since then, various machine topologies have been implemented in bearingless configurations. In 1991, Chiba published the seminal paper on bearingless induction machines (BIMs) [4], where he first described the operating principles thereof. This and subsequent papers identified several general advantages of BIMs over permanent magnet excited synchronous machines (PMSMs), including:

Robustness: BIMs are more robust due to their simpler construction.

Lower Maintenance: BIMs require less maintenance because they lack mechanical bearings.

Lower Cost: Manufacturing is less expensive due to the absence of permanent magnets (PMs).

However, BIMs also have certain disadvantages compared to PMSMs, such as:

Efficiency: BIMs exhibit lower efficiency, particularly at lower speeds, because the air-gap field must be excited by induced rotor currents rather than PMs.

Control Complexity: A BIM with a standard squirrel cage rotor presents challenges when generating a suspension force. Assume that an additional suspension force-generating winding, with a pole-pair count of p_s, is used. If a change in the suspension force is desired, a corresponding change in the $2 \cdot p_s$-pole stator flux is required. This leads to an induced voltage in the rotor circuits, which produces rotor currents that prohibit an instantaneous change in rotor flux. As a result, the interaction between the stator (primary) and rotor (secondary) circuits introduces a delay in the $2 \cdot p_s$-pole flux, which subsequently delays the suspension force response. Furthermore, the rotor current complicates the alignment of the flux, making suspension force orientation more difficult to achieve.

This paper is based on a literature review conducted using the *IEEE Xplore*® [5] and the *magneticbearings.org* [6] database. A total of 115 papers were reviewed during the preparation of this work, of which 65 were directly related to the control of BIMs. These control-related papers are the topic of the first part [1] of this study, while the remaining 50 papers focusing on topology will be analyzed in this part of the paper series.

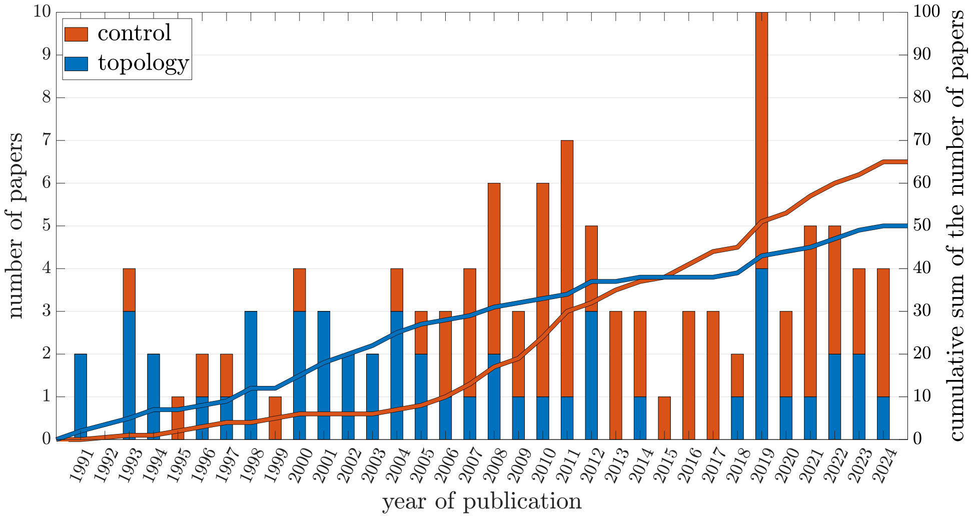
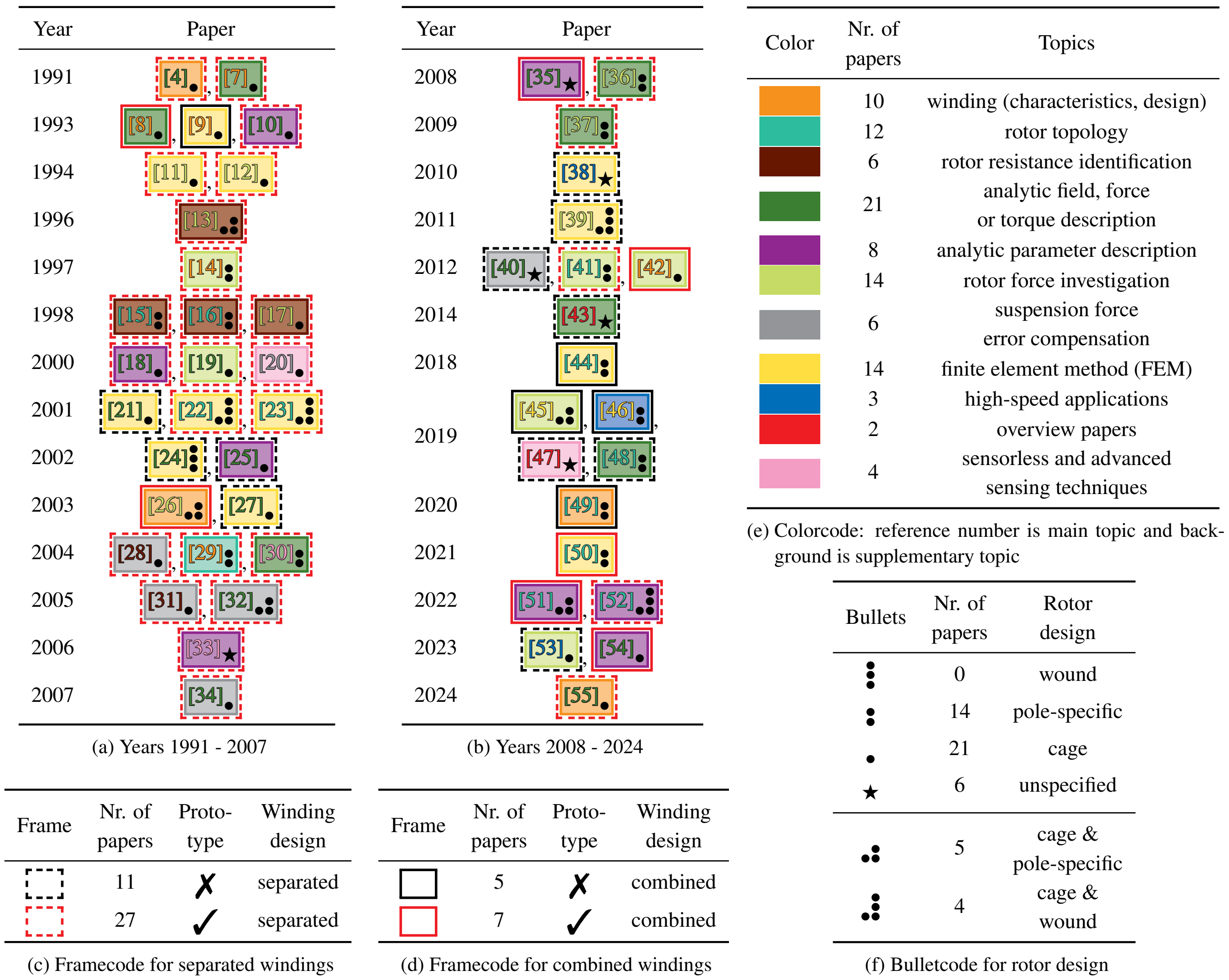


Figure 1: Reviewed papers about bearingless asynchronous machines, categorized by publication year and main subject area: motor control (red) or topology (blue).



Year	Paper
1991	[4]•, [7]•
1993	[8]•, [9]•, [10]•
1994	[11]•, [12]•
1996	[13]•⋮
1997	[14]:
1998	[15]:, [16]:, [17]•
2000	[18]•, [19]•, [20]•
2001	[21]•, [22]•⋮, [23]•⋮
2002	[24]⋮, [25]•
2003	[26]•:, [27]•
2004	[28]•, [29]:, [30]:
2005	[31]•, [32]•:
2006	[33]★
2007	[34]•

(a) Years 1991 - 2007

Year	Paper
2008	[35]★, [36]:
2009	[37]:
2010	[38]★
2011	[39]•⋮
2012	[40]★, [41]:, [42]•
2014	[43]★
2018	[44]:
2019	[45]•:, [46]:, [47]★, [48]:
2020	[49]:
2021	[50]:
2022	[51]•:, [52]•⋮
2023	[53]•, [54]•
2024	[55]•

(b) Years 2008 - 2024

Color	Nr. of papers	Topics
🟧	10	winding (characteristics, design)
🟩	12	rotor topology
🟫	6	rotor resistance identification
🟩	21	analytic field, force or torque description
🟪	8	analytic parameter description
🟩	14	rotor force investigation
⬜	6	suspension force error compensation
🟨	14	finite element method (FEM)
🟦	3	high-speed applications
🟥	2	overview papers
🟪	4	sensorless and advanced sensing techniques

(e) Colorcode: reference number is main topic and background is supplementary topic

Bullets	Nr. of papers	Rotor design
⋮	0	wound
:	14	pole-specific
•	21	cage
★	6	unspecified
•:	5	cage & pole-specific
•⋮	4	cage & wound

(f) Bulletcode for rotor design

Frame	Nr. of papers	Proto-type	Winding design
⬚	11	✗	separated
⬚	27	✓	separated

(c) Framecode for separated windings

Frame	Nr. of papers	Proto-type	Winding design
☐	5	✗	combined
☐	7	✓	combined

(d) Framecode for combined windings

Table 1: Considered papers about topology organized by their year of publication, color coded regarding their main topics, and marked for their winding design, if a prototype was built, as well as the rotor design.

The chronological sequence of the analyzed papers is presented in Fig. 1. The papers related to topology are indicated by the blue color. The data also indicates that, over the past two decades, there has been a marked increase in the number of papers related to control, while the number of publications concerning topology has undergone a substantial decline. Furthermore, the papers that address the subject of topology are organized in both a chronological and thematic manner in Table 1, more specifically in Tables 1a and 1b.

Table 1 is divided into sub-tables. The color-coding scheme for marking the main topics (indicated by the color of the reference number) and supplementary topics (indicated by the background color) is detailed in Table 1e. Additionally, a distinction is made in the bounding frames to indicate whether a paper involved the construction of a prototype and to specify the type of winding system used. The categories illustrated in Tables 1c and 1d encompass combined windings, including split, multiphase, and dual-purpose no-voltage (DPNV) windings, as well as separated windings, where the torque- and suspension force-generating windings are physically distinct. Similarly, an index of different rotor types is provided in Table 1f. The rotors are categorized as either unspecified, cage, pole-specific, wound, or combinations thereof.

2. Main topics

In this section, selected topics, which are outlined in Table 1e, are explored in detail.

2.1. Analytic field, force or torque description

Chiba's seminal paper [4] on the characteristics of BIM was the first to describe how to generate the necessary bearing forces to make an induction machine (IM) bearingless. Subsequently, Baoguo provided the first analytical description of air-gap flux densities and rotor forces depending on rotor eccentricities in [21]. Building on this work, Ding presented a comprehensive analytical description of the air-gap flux density in [55], derived suspension forces for different p and p_s combinations, and analyzed the harmonic impact of BIMs with concentrated windings on suspension forces. Ding also introduced a novel stator geometry for separated windings that allows for the independent adjustment of the stator slot number for the torque and suspension windings. Furthermore, Khamitov proposed a complete design procedure for multiphase windings for bearingless motors in [54] and demonstrated how to verify DPNV-equivalence, making the multiphase winding suitable for operation in a DPNV configuration. He also validated his design procedure on a BIM.

2.2. Rotor topology

In [16], Chiba first described a method for completely physically decoupling the drive torque and bearing force generation in BIMs. This was achieved through a pole-specific rotor as shown in Fig. 2, with a single cage depicted in Fig. 2a. Building upon pole-specific rotors Chen refined the concept in [51] by reducing the additional axial length of the rotor caused by the isolated end rings. This was accomplished by short-circuiting all parallel cages on one side of the rotor, as illustrated in Fig. 2b. The rotor topology in question permits the realization of higher speeds without entering the overcritical operational region. An alternative method for physically decoupling the drive torque and bearing force generation involves the use of a wound rotor. Essentially, this is a pole-specific rotor without a cage, where the winding is designed to couple only with the p-pole-pair field that generates torque. The concept was initially introduced by Cai in a series of papers [22], [23], [24]. An alternative drive design of interest was presented by Yang in [52], which also utilized a wound rotor. In this work, Yang applied the pole-switching principle to both the electrical and mechanical domains, integrating it into the stator and rotor, respectively. This approach facilitates enhanced start-up behavior and steady-state performance by enabling the motor to adapt to various use cases. The standard configuration of a BIM comprises a singular BIM unit in conjunction with an active magnetic bearing or two adjacent BIMs. If the rotor bars are skewed, this results in significant oscillating axial forces. Chiba described this phenomenon in [41] and proposed a solution consisting of two tandem BIMs with rotors that are equally but inversely skewed.

2.3. Rotor resistance identification

For the pole-specific rotors previously described, Chiba derived an analytical expression for the rotor resistance in [16]. This expression was then used to optimize the bar and end-ring dimensions. In addition, the findings in [17] led Chiba to conclude that there is an optimal reference value for the secondary resistance that enables the decoupling of the radial force and its control using a field-oriented controller in BIMs with a cage rotor. Subsequently, this concept was employed in [28], [31] to develop a stable field-oriented controller with online rotor resistance identification.

2.4. Suspension force error compensation

As previously stated in the introduction section, the control of a BIM with a cage rotor is challenging due to the fluctuations in the driving and suspension fluxes. These fluctuations are based on load torque or bearing force changes that induce rotor currents, which in turn alter the air-gap flux. In [20], Ohsawa conducted a study of this problem and developed a solution by adjusting the control loop. The subject of this study employs a flux-based feedback loop as

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opposed to a current-based one. The following publications sought to address this issue through a more analytical lens. In [32], [34], Hiromi undertakes a comprehensive analytical investigation into the influence of rotor current on the generation of suspension forces. Consequently, the construction of the inverse is feasible, thereby facilitating the calculation of the requisite stator currents from the desired bearing forces or air-gap fluxes.

2.5. Finite element method (FEM)

The majority of publications that utilize FEM employ this technique to validate or optimize their designs. Only the pair of papers [45] and [46] by Chen use the FEM to make a detailed design study of a BIM, as well as its characteristics. In [45] different FEM models are compared against each other, and [46] uses the results of the FEM comparison to optimize a BIM for high speed and high power density.

2.6. High-speed applications

The only paper published that seriously attempts to design a high-speed BIM (defined as a rotor surface velocity of $\geq 100\,\mathrm{m/s}$) was published by Chen [46]. A variation of this design study was later implemented in [50] and [51].

2.7. Sensorless and advanced sensing techniques

A single publication, [33], employed sensorless techniques. The high-frequency carrier voltage and the mutual inductances are utilized in order to estimate the rotor displacement. Further, only some papers [20] and [30] employed flux-search coils to measure the air-gap flux and use this information to eliminate the error in the field oriented controller and stabilize a BIM with cage rotor.

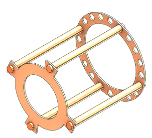
3. Comparison of characteristic data

The data presented in the studied papers allow for the assembly of diagrams that compare the characteristic drive parameters. The diagram presented in Fig. 3 showcases the surface velocities that have been achieved for both the assembled prototypes, indicated by the red crosses, and the simulation results, represented by the black crosses. The blue lines in the graph represent equivalent surface velocities. This indicates that the majority of published motors operate at surface velocities below $30\,\mathrm{m/s}$. A single prototype, which was published in [50] and[51], with slightly divergent values, has been shown to achieve a surface velocity of $100\,\mathrm{m/s}$. To provide a basis for comparison of the different motors, the torque T_z and the suspension force F_r are used to calculate the stress values shown in Fig. 4. The shear stress τ_{sh} is defined as

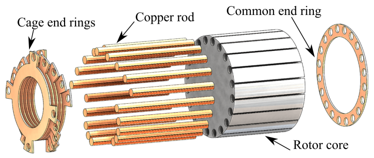
$$\tau_{sh} = \frac{F_t}{A_{surf,rot}} = \frac{T_z}{A_{surf,rot}\, r_{rot}} = \frac{T_z}{2\pi\, {r_{rot}}^2\, l_z}, \tag{1}$$

where F_t is the tangential force, $A_{surf,rot}$ is the rotor surface area, r_{rot} is the rotor radius, and l_z is the axial rotor length. Employing Eq. (1), the shear stress values depicted in Fig. 4a are derived. The examples from [19] and [37], with their constant tangential forces of $F_{t,[19]} = 1.3\,\mathrm{kN}$ and $F_{t,[37]} = 2\,\mathrm{kN}$, demonstrate that the remaining motors, which operate below $F_t = 500\,\mathrm{N}$, are not yet at the boundary of what is achievable. In order to compare the suspension force generation capability of BIMs, the thrust stress σ_{thr} is defined as

$$\sigma_{thr} = \frac{F_r}{A_{csa,rot}} = \frac{F_r}{2\, r_{rot}\, l_z}, \tag{2}$$



(a) Individual pole-specific rotor cage



(b) Assembly of the parallel cages into a rotor

Figure 2: Pole-specific rotor which does not link a suspension field with $p_s = 4$ pole-pairs that consists of five parallel cages. Source: [51]

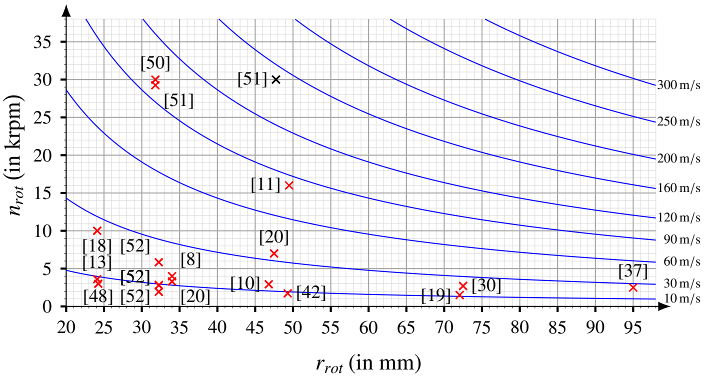


Figure 3: Rotor surface velocities of reviewed papers, in blue are lines of constant surface speed (red crosses are prototypes, black crosses are simulations)

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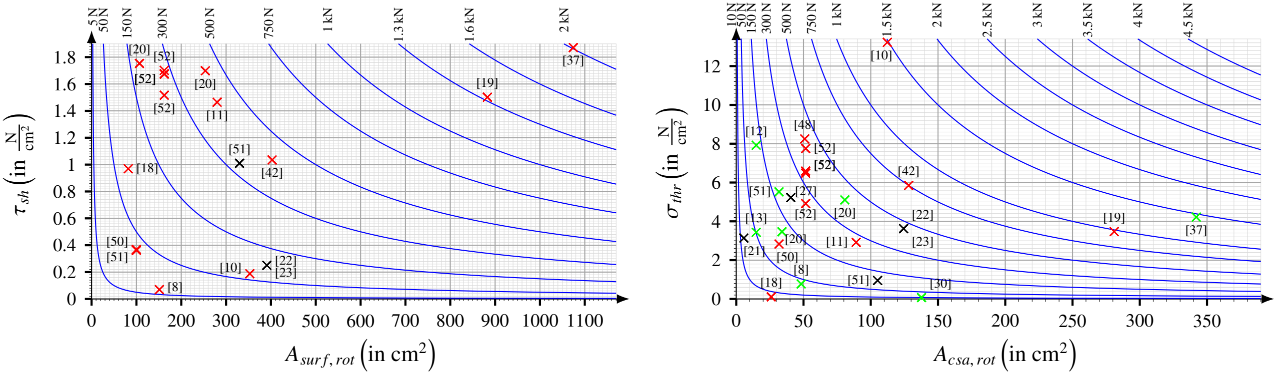
where $A_{csa,rot}$ is the rotor cross-sectional area. The majority of motors demonstrate a suspension force capability that is less than $F_r = 500\,\text{N}$. It is essential to note that for all motors designated with a green cross (which represent prototypes), the suspension force was calculated based on the rotor weight due to the absence of data regarding the maximum achievable suspension force.



(a) Shear stress τ_{sh} of reviewed papers, in blue are lines of constant tangential forces F_t acting on the lateral rotor surface area $A_{surf,rot}$

(b) Thrust stress σ_{thr} of reviewed papers, in blue are lines of constant radial suspension forces F_r acting on the rotor cross section area $A_{csa,rot}$

Figure 4: Rotor stresses of reviewed papers (red crosses are prototypes, black crosses are simulations, green crosses are bearing forces derived from rotor weight)

4. Conclusion

This paper provides an in-depth review of 50 publications focusing on the topology of BIMs. Key advancements include the development of pole-specific and wound rotor designs, which enable the physical decoupling of torque and suspension force generation. The review also highlights the challenges associated with achieving an instantaneous suspension force response due to rotor current dynamics. Additionally, this paper introduces parameters such as rotor surface velocities, shear stress, and thrust stress to systematically compare different BIMs. These parameters are used to evaluate and benchmark all published motors against one another. The analysis reveals that most currently published BIMs operate significantly below the performance limits imposed by the available materials. Furthermore, it is noted that the suspension capabilities of existing motors are difficult to compare. This is because nearly all prototypes with published data report only levitation and axial displacement, without providing the maximum suspension force their motors can generate. An analysis of rotor surface velocities shows that most BIMs achieve surface velocities below 30 m/s, with only one prototype reaching 100 m/s. These findings underscore the need for further optimization of rotor designs and winding configurations to fully exploit the potential of BIMs which lies in high-speed applications.

5. Outlook

Future research should prioritize addressing the challenges identified in this review. In particular, the lack of advancements in the integration of advanced sensing techniques and sensorless control methods, represents a significant opportunity to enhance the stability and control precision of BIMs. Additionally, the development of high-speed applications and the achievement of higher shear and thrust stress distributions as well as higher rotor surface velocities remain critical areas for further exploration. Finally, the construction of additional prototypes and the experimental validation of theoretical models will be essential for bridging the gap between simulation results and practical implementation, ultimately enabling BIMs to reach their full potential in industrial applications.

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