2nd Review of Developments in Bearingless Motors

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Abstract

The present publication gives an overview about bearingless motor research by means of literature study, following the objective of enabling researchers in the field to develop a good overview. To that aim, the literature research methods offered by modern search engines and online repositories are not only applied but also explained. The actual overview about the technological developments is provided indirectly through the review of diverse overview publications with excerpts and references to especially noteworthy findings that contribute to a holistic understanding of the bearingless motor technology. From the more recent literature, observed trends are listed and described. The concluding discussion deals with the question on how to learn from the literature basis and reflects the author's opinions on rewarding future research questions.

Keywords: *Bearingless motors, development review, overview publications, terminology*

1. Introduction

The history of bearingless motors dates back to the 1970's and 1980's when the first ideas have been proposed and first research projects were started. An early publication titled "*A Review of Developments in Bearingless Motors*" (Salazar, et al., 2000) appeared at the International Symposium on Magnetic Bearings (ISMB) in the year 2000. That publication outlined the different types of bearingless motors, clarified technical notations and listed a substantial amount of citations on the – back then – relatively small total amount of bearingless motor literature. As such, the paper has proved to be very useful for many researchers in the field and was, thus, frequently referred to in following research works. With more than two decades having passed, it is not trivial to provide a renewed overview of the developments in the field, as the research activities have increased tremendously. Following the titling of the initial paper, the authors of this paper intend to present an updated review.

It would be scientifically improper to only review the actual publications on bearingless motors themselves, without also reviewing the numerous review and overview publications that have been published on diverse motor types, power ranges, or rotor topologies. After an initial reflection of the publication statistics and terminology in Section 2, Section 3 will, therefore, deal with existing review articles. Some trends that have been identified in the more recent literature are presented in Section 4. A discussion on the observed obstacles on the way to a broader industrial application of bearingless motors on the one hand and future chances and rewarding research questions conclude this article.

2. Literature review

Developments like online search engines and the collection of magnetic bearing related research papers at dedicated web portals, e.g. (magneticbearings.org, 2023) reduce the purpose of a review publication for just *finding* other research papers. However, the now available, powerful search methods can be used to determine interesting perspectives on the literature and its genesis, which will be described in the following paragraphs.

Terminology

Especially in the beginning of research activities, different terminologies have been used for the same idea:

Bearingless motors

The first documented usage of the term "bearingless" can be found in (Bosch, 1988). The genesis of the term can be attributed to the term "brushless motor", where the brushes in DC motors are replaced and their functionality is integrated by field oriented control. The same is true for a "bearingless motor", where the mechanical bearings are replaced and their functionality is integrated by suspension current control or combined current control in separated or combined winding systems, respectively. The same analogy can be drawn to the word "sensorless", where the physical motor angle sensors are replaced and their functionality is integrated by signal processing of the motor's winding currents. Publications using this term have first occurred in 1988 and continue to mark the largest share of publications.

Self-bearing motor

The second most widely used term is "*self-bearing*" motor. It is mostly used by several dedicated research groups with wide activities in the field of blood pumps. The term gained popularity around the turn of the millennium and continues to be used in a smaller amount of papers today. It can be observed that the term is often used by researchers with a strong background in mechanical engineering as there is bearing function provided by electromagnetic effects and control of the mechanical motor device *itself*.

(Combined) motor-bearing

Inversing the idea that a motor has an integrated bearing functionality leads to a bearing with integrated motor functionality which motivates the term "motor-bearing" or "combined motor bearing". Most scientific publications titled with these terms have been published between 1999 and 2006.

Figure 1 shows the results of a literature search study using the Google scholar™ engine: The available database was searched for scientific publications (excluding patents) with the respective search term in the title. Several particularities during the search and the result analysis have been observed that may be helpful for other researchers:

- The term "bearingless" is frequently used, especially up to the year 2010, in publications on the mechanical construction of helicopter rotor hubs. In order not to distort the search results, relevant terms have been excluded and all results have been manually screened.
- The term "self-bearing" is also applied to describe self-supporting structures in the construction industry. It hence can be found on numerous publications on special construction technologies using steel, glass, or concrete. As with the term "bearingless", suitable measures have been taken to not distort the results.
- Publications using the term "motor bearing" have to be searched for with much care: Mostly, the meaning will relate to the (conventional) bearings of a motor, as, e.g., in "Lubrication failures in motor bearings".
- A certain amount of publications are not available online but can only be found as *citation*, i.e. the search result will indicate the citation but will not link an explicit document. On the one hand, this concerns many of the older publications, especially before the year 2000. On the other hand, certain repositories either do not explicitly hold the publication files or are not properly indexed by the used search engine. The most prominent ones are "Proceedings of the Chinese Society of Electrical Engineering", "Chinese Journal on Mechanical Engineering", "Advanced technology of electrical engineering and energy", or "Control Engineering of China". Beginning with 2010, a rising number of bearingless research papers appear with new open-access publishers, sharing the fate of the above-mentioned journals: "Dianli Dianzi Jishu / Power Electronics", "Control Theory & Applications", or "Wei-Te Dianji (Small & Special Electrical Machines). Also, some university journals have published substantial amounts of relevant publications that are not properly indexed, with the most prominent ones being: "Journal of Jiangsu University", "Journal of Sichuan University for Engineering Sciences", or "Dalian Jiaotong University".
- The frequent inability of non-Chinese editors to distinguish Chinese first names from last names leads to a certain confusion and to duplicate search results with identical publication title, e.g. once by authors "J. Gao and S. Huang", once by authors "G. Jian and H. Shoudao", each time referring to the same authors.
- As only the publication titles were searched, a number of publications may be missing in this Figure.

3. Previous review and overview work

Since the initial development review of (Salazar, et al., 2000), not only a lot of publications on bearingless motors themselves have been published but also several review and overview papers that have each selected specific sections of the available literature.

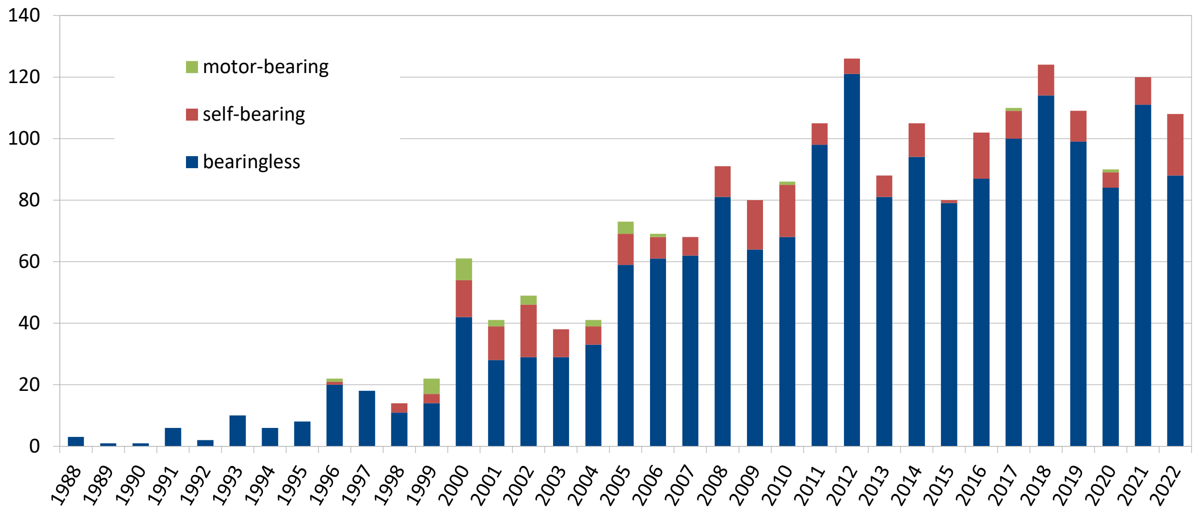

Figure 1 Number of scientific publications with a title holding "bearingless", "self-bearing", or "motor-bearing", respectively. The rising research activity and a certain dent in the Covid19-plagued year 2020 become clearly visible.

Review of bearingless induction motors (BLIM)

In 2014, the authors of (Sun, et al., 2014) describe the advantages and the most typical structures of BLIMs, e.g. the specific rotor short circuit rings which typically differ from induction motor rotors with conventional bearings. Multiple arrangement forms for the stabilization of different numbers of degrees of freedom (DOF) are summarized. The common mathematical models for torque and force calculation with separated winding systems and, subsequently, the most frequent control types such as vector control, direct torque control, and nonlinear decoupling control, are presented. The BLIM review paper closes by comparing the different control types and identifies advanced control for higher force dynamics, sensor integration, and generally increased reliability as the most important research trends.

Review of bearingless switched reluctance motors (BLSRM)

A first collection of BLSRM literature was presented and reviewed in 2012 by the authors of (Ahmed, et al., 2012). Besides a brief description of the working principle of a BLSRM, the authors review different design methods and published designs as well as control methods for BLSRM.

A very recent publication from 2023 (Xiang, et al., 2023) presents the typical coupling problem of standard 12/8 (denominating stator teeth / rotor teeth) BLSRM. In the following, the authors describe different decoupling – or rather, coupling-reduction – strategies. In order of appearance, these include hybrid stator topologies with dedicated windings on separated suspension force and torque teeth, different stator/rotor topologies e.g., 8/10 or 12/14 BLSRMs, asymmetric rotor pole shaping, permanent magnet bias flux injection in the stator, axially aligned dual stator BLSRMs, concentrically positioned dual stator BLSRMs (e.g., torque generation on the outside, force generation on the inside of the rotor) with or without permanent magnet bias flux excitation, wide tooth configurations for an increased angular window of force generation, and, ultimately, present a side-by-side arrangement of two radial active magnetic bearings (AMBs) with a BLSRM in the axial middle, whose motor winding extends onto the AMB stators. Comparisons of the behavior, the main characteristics in terms of torque/force decoupling and torque ripple, and general advantages and disadvantages are listed in an impressive appendix which can be recommended for a broad overview of the BLSRM state of the art. The concluding assessment on the industrial readiness of the BLSRM technology highlights the need for further research in topologies and control since the generically robust and potentially permanent magnet-free BLSRMs have not yet found their way into actual applications.

Review of bearingless synchronous motors (BLSM)

An early overview work on BLSM was presented in 2012 (Sun, et al., 2012) in Chinese language. A later, refined version was published in English (Sun, et al., 2013). Both papers give an overview about the force generation depict the different arrangement options of shafted bearingless motors in an electric machine assembly as shown in *Figure 2*.

The authors also give an overview about the state of the art of BLSM control methods including artificial intelligence-based methods, which seems remarkable, given the early publication year.

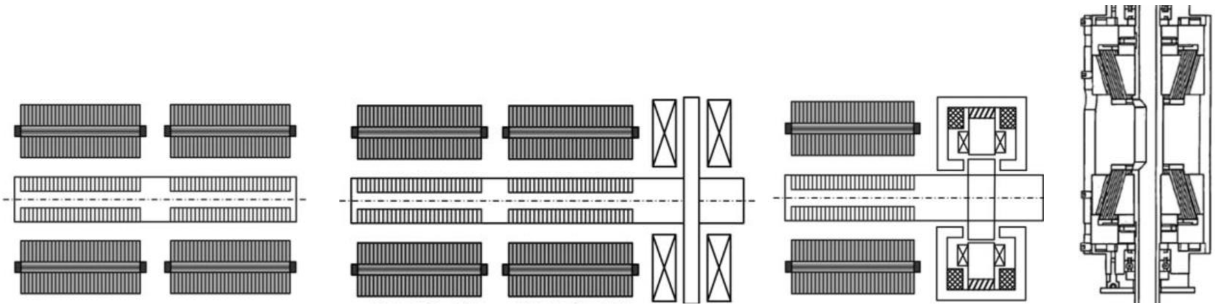

Figure 2 Bearingless motor arrangements from (Sun, et al., 2012) *including (left to right, with number of stabilized DOFs): dual side-by-side BLSM - 4DOF, dual side-by-side BLSM and active axial bearing - 5DOF, single BLSM with combined radial axial active bearing - 5DOF, dual conical BLSM - 5DOF. Copyright courtesy of original publication authors.*

Very recently, the authors of (Pei, et al., 2022) have released a renewed review of BLSM developments. As an interesting means of characterization, the authors divide the different BLSM types according to the nature of the magnetic excitation field (see *Figure 3*, reproducing the image contents presented in (Pei, et al., 2022)):

Passive BLSM do not refer to classic passive permanent magnetic bearings but to bearingless motors with additional electrodynamically stabilized DOFs, i.e. the stabilizing field is generated in a passive manner but still due to the operation of the motor.

Rotational heteropolar active BLSM denotes the major group of BLSM where the suspension force generating magnetic excitation field is heteropolar and rotating.

Stationary heteropolar or homopolar active BLSM includes the more exotic category of BLSM where the excitation field for force creation is non-rotating, either because it is homopolar or because the motor topology allows a stationary heteropolar field.

After introducing this categorization, an impressive literature overview is presented, including numerous figures from representative publications. It is especially these motor cross sections, drawings, and schematics that turn (Pei, et al., 2022) into an excellent summary and orientation point for the BLSM topologies to explain the differences and advantages of the individual concepts. A long list of prominent literature for deepened study is equally provided. The authors also give an interesting comparison of the different concepts, linking the number of stabilized DOFs and the output power and speed. It is noticeable that the 4DOF rotating heteropolar BLSM category (side-by-side BLSM) is dominant in both features.

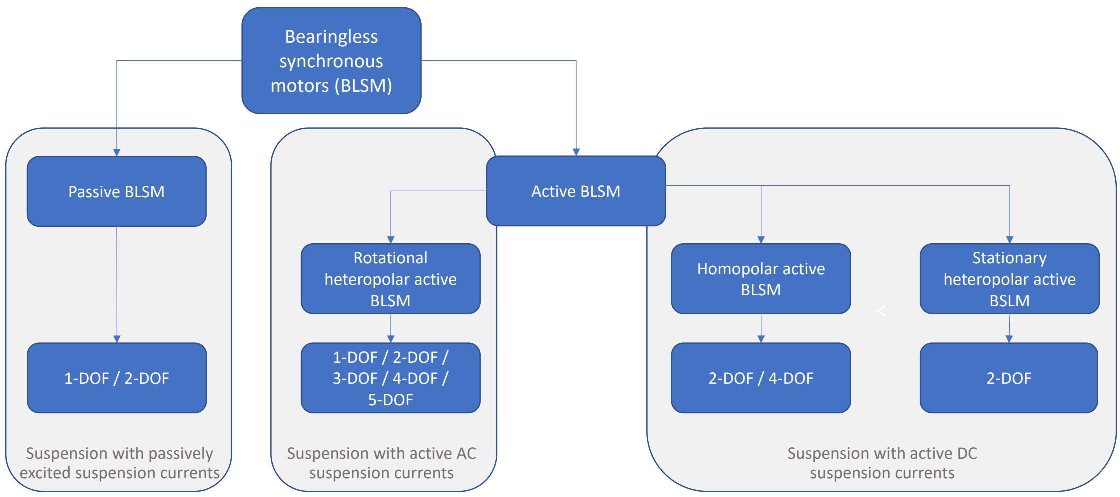

Figure 3 Topologic categorization of BLSM, reproduced from (Pei, et al., 2022)*. From left, three groups are used to classify the existing BLSMs: Passive BLSMs, rotational heteropolar active BLSMs, and homopolar active or stationary heteropolar BLSMs.*

Review of bearingless motors for high output power

The authors of (Chen, et al., 2019) have performed an impressive literature review, identifying over 130 selected publications on bearingless motors. The focus for selecting the cited and reviewed publications was placed on presented experimental results, as the aim of the publication itself was to identify the most suitable bearingless designs for realizing increased output power. After listing the known applications of magnetic levitation in the fields of transportation and industry, the provided references for bearingless systems are categorized regarding several different aspects, which makes the paper a valuable piece of information for bearingless motor researchers:

The authors have screened and grouped previous works on all major bearingless motor categories, being: BLIM, BLSM, BLSRM, bearingless consequent pole, bearingless homopolar, bearingless flux switching, and bearingless hysteresis

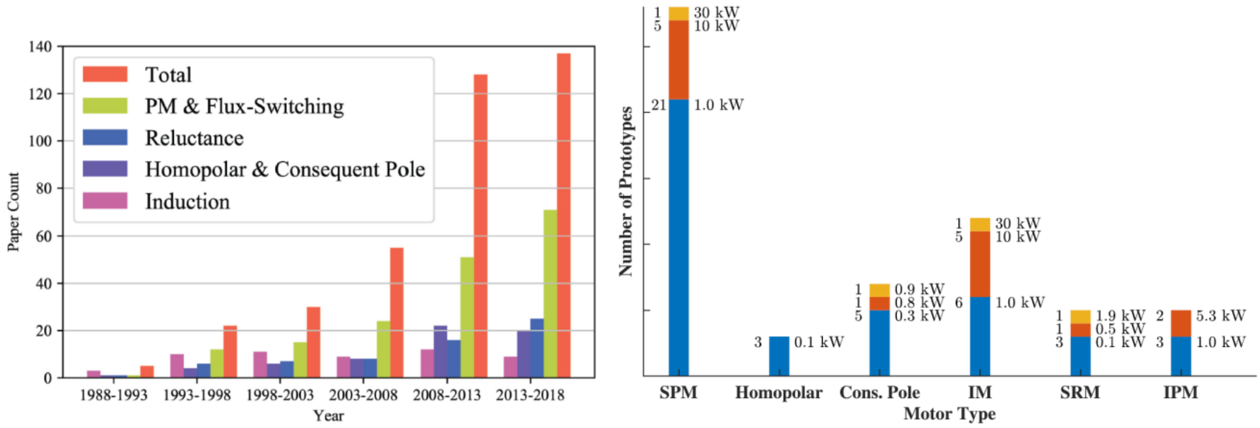

Figure 4 Categorization of existing literature on bearingless motor prototypes from (Chen, et al., 2019)*: Distribution to the main topologies (left), Numbers of realized prototypes including their demonstrated output power per topology (right). Copyright permission obtained from IEEE-CCC.*

motors and have provided an overview about the number of experimentally demonstrated designs for each motor topology (cf. *Figure 4*, left image). The figure clearly shows the dominance of the permanent magnet based BLSM both in absolute numbers as well as in growth rate over time. Lateron, the power of the prototypes found in the literature was also mapped onto the motor topologies, as shown in *Figure 4*, right image. Again, the BLSM dominates (especially when adding up the surface mounted (SPM) and interior permanent magnet (IPM) types), with the BLIM being second-ranked in this quantitative assessment for high-power suitability.

As in (Pei, et al., 2022), also the authors of (Chen, et al., 2019) investigate the number of actively controlled degrees of freedom; They describe the topologies used for 0-DOF (using electrodynamic forces) up to 5-DOF bearingless motors and reference the existing literature, again with a focus on experimentally supported publications. The 2-DOF topology with one bearingless motor and a combined radial-axial AMB and the 4-DOF topology with two bearingless motors and an axial AMB are again found to be the most promising ones for high output power. Consequently, the available data base was used for performance comparisons according to the found efficiencies, output power levels, attained speed regions, rotor diameters, and torque densities per rotor volume. The result of this impressive task again shows that the BLSM (in its SPM, IPM, sliced and shafted variants) is the most performant and hence, the most suitable topology for high output powers. A following parametric geometry optimization for BLSMs and BLIMs with either combined or separated winding systems with the optimization targets of efficiency and torque density per rotor volume confirms that the BLSM with combined windings is most suitable.

Review of bearingless slice motors

A special geometric topology is under review in (Gruber, 2013) and (Gruber & Silber, 2016): Bearingless *disk* or *slice* motors which have been reported in the literature as early as 1995 (Barletta & Schoeb, 1995) with the principle of passively stabilized disk rotors even dating back to 1994 (Bleuler, et al., 1994). Due to their short axial length, these shaftless motors are stabilized passively in axial and tilting directions. With only two necessary DOF left to be stabilized actively, disk motors are amongst those bearingless motors that can be stabilized completely without a second bearingless motor or additional AMBs. The first review publication, (Gruber, 2013), presents an overview about the most common stator and rotor compositions, including a review of motors with separated and combined winding systems. After highlighting the different motor forms, e.g. segment motors for large diameter systems, compact slotless designs for high speed applications or high-pole count variants for torque motors, the industrial applications of bearingless slice motors – mainly in medical and semiconductor industries – are referenced. As the paper was published in 2013, high purity bearingless disk motor fans can be added as newly appeared product (Levitronix, 2023). The last chapter is dedicated to bearingless disk motors with permanent magnet-free rotors, enabling cheap disposables for sensitive applications.

The later review paper (Gruber & Silber, 2016) first presents an overview about the slice motor topologies and depicts a timeline of reported developments with experimental results, structured in designs with separated and combined winding sets. Then, a comprehensive overview is given in the form of comparison tables, listing 50 different prototypes, structured according to performance characteristics such as maximum speed or achieved force and torque coefficients, geometric or magnetic dimensions such as air gap width, rotor length and diameter, and pole count, and electric system parameters such as winding scheme, DC link voltage, or rated current. holds extensive tables, comparing test results presented in the literature. A graphic representation of the achieved surface speeds, suspension force densities, and shear stress densities (as a measure of torque density) conclude the paper.

4. Trends and novelties in bearingless machines

As shown in *Figure 1* and presented in the initial section, the research in bearingless machines has stabilized at a high level. The following Table 1 is dedicated to observed trends and topologic novelties from the past years in and around the bearingless motor research.

Table 1 Selection of trends in bearingless machine research

Observed trend	*Description*	*Literature references (exemplary)*
Non-conventional levitation technology	Permanent magnet Halbach arrays in one stator part, together with a pyrolytic graphite rotor, can be used to passively stabilize 5-DOFs using the diamagnetic effect and an axial flux stator is placed on the opposite rotor face to also provide torque onto the rotor.	(Sugimoto, et al., 2023), (Ozawa, et al., 2022)
Non-conventional torque generation technology	The hysteresis effect can be used for creating torques with very small amplitudes, yet in a synchronous, low torque-ripple affected manner. Selection of suitable suspension field pole number, the torque and radial force creation can be completely decoupled. The rotor structure is simple and motors can be operated without rotor angle sensors.	(Noh, et al., 2017), (Circosta, et al., 2018)
Integration of bearingless motors and magnetic gears	Many different forms of magnetic gears have been presented in the literature as they allow high torque density when high input speeds are provided by the attached motor. The integration of magnetic gears and bearingless motors allows eliminating the losses in the high-speed ball bearing stage and benefitting from all the advantages that magnetic levitation has to offer for high-speed motors.	(Kumashiro, et al., 2020), (Gruber, et al., 2022)
Trend towards higher motor output power	Diverse potential applications require significant output power of beyond 50kW, e.g. blowers for aeration of wastewater treatment facilities or compressors for diverse gaseous media. It becomes clear from published design studies or scaling investigations, that the race towards higher power bearingless motors is ongoing.	Realized prototypes: (Redemann, et al., 2000), (Munteanu, et al., 2011), (Liu, et al., 2020), Motor design targets: (Fu, et al., 2017): >50kW, 60krpm, (Kepsu, et al., 2019): 280kW, 25krpm

5. Discussion and Outlook

Obstacles on the way to broader application

The current state of the art shows a tremendous diversity of bearingless motors in theoretic works and academic prototypes. In the mid-term and long-term perspective however, increased industrial usage is the key factor to maintain and intensify the research interest amongst academics and the willingness to fund this research amongst technology companies and funding bodies. Up to the current point in time, bearingless motors were only able to conquer niche markets where the unique selling proposition of magnetic levitation (abrasion-free, lubrication-free, hermetically sealable operation) was beneficially combined with the more compact arrangement of a bearingless motor when compared to AMB-based solutions. It appears to the authors that there are two types of obstacles, that impede a broader application in industry.

Technical issues

The control of bearingless motors is complex in theory and implementation. Some parts of the extensive literature on bearingless motor control may be too decoupled and not well available to those researchers actually designing, realizing, and testing prototypes for industrial applications. Abstractions in control theory and accessible tools and methods may help to enable better control for more bearingless drives.

Bearingless drives typically require non-conventional power electronics due to unusual switching frequencies, phase count, or programmability. Custom-built electronics negatively influence the bearingless motor development in two ways: First, the hardware costs may overturn potential business cases or prototyping budgets. Second, the person-power and knowledge to design or acquire and to program such custom-made devices may not be present in many research groups.

The necessary non-contact distance sensors in bearingless motors are not available as cheap, reliable mass market products. Additionally, knowledge on EMC issues and signal treatment are usually necessary to achieve the required high position signal quality.

Non-technical issues

Bearingless motor research publications often still present novel topologies or related control methods which is understandable given the huge variety of possibilities. Future research will also have to focus on increasing efficiency, power ratings, and improved designs for better industrialization in terms of winding technology, material usage, or required precisions in manufacturing.

High system complexity and the lack of widespread industrial use cases reduces the willingness of industry to invest in bearingless motor developments and, thus, creates a *chicken and egg* problem.

Bearingless motor R&D work requires thorough understanding of electric motors, mechanical design, manufacturing technology, and control theory, making them truly mechatronic components. Also, practical knowledge concerning prototyping, commissioning, and test bench measurement are necessary. On the academic research side, this may be the central explanation why most research results with experimental results are created in one of the established research groups. On the industrial side, this illustrates the costs and risks associated with bearingless motor product development.

Chances and opportunities in the future

Based on the mentioned shortcomings and on decades of bearingless motor research experience, the authors have identified chances and opportunities and want to express their opinions on possibly rewarding research questions.

- The need for global decarbonization of energy supplies results in a tremendous technological push. Many new needs for highly performant motors will arise in this context and, especially in the field of high power density, high rotational speed, and lubrication and abrasion free operation, bearingless machines can play an important role.
- The concepts of reusability, remanufacturability, and eventually recyclability as well as lifecycle assessment will play an increased role in future products and systems. This imposes new demands on the design of bearingless motors which must be answered in respective research activities.
- The availability of robust and cost-efficient components for, e.g., position sensors, touchdown bearings, or inverters will play an essential role. Research on assessing the suitability of existing off-the-shelf components to this aim and on best-practice on how to implement and – for the example of the position sensors – process the related data would be very rewarding and of high service to the community.
- The technologic development of electric motors has received a strong push due to the electrification trend in the mobility sector. Development methods such as the multi-physics simulations applied in e.g., automotive traction motor design can also be of high value when applied to bearingless motors.
- For low power, high volume applications: The combination active suspension force creation with cost-effective passive stabilization can reduce material costs and electronics needs and is, therefore, essential for cost reduction. Significant research has already been conducted but further activities will be necessary.
- For high power applications: Higher power motors in industrial applications often feature long on-times, which basically combines well with the reduced maintenance intervals and high expected lifetime offered by bearingless motors. However, focus on increased efficiency will be essential to be able to compete with conventional motors with both, conventional bearings or AMBs.
- Research on bearingless motors has come a long way. In contrast to the very first years of scientific activity, today’s researchers can rely on well-established terminologies, a wide range of investigated and classified

motor topologies, and a broad range of scientific conferences and journals that are known to host bearingless motor publications. The wide range of available information will help to avoid repeating errors and accelerate research towards a *more bearingless* future.

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