Applicability of flux switching permanent magnet bearingless motors in present-day and future manufacturing and transportation

Rafal P. JASTRZEBSKI [ab], Sadjad MADANZADEH [a], Atte PUTKONEN [a], Leonid CHECHURIN [a], Wolfgang GRUBER [c], Akira CHIBA [d]

[a] *Lappeenranta-Lahti University of Technology LUT, 53850 Lappeenranta, Finland, rafal.jastrzebski@lut.fi;* [b] *University of Turku, 20014 Turku, Finland;* [c] *Johannes Kepler University Linz, 4040 Linz, Austria;* [d] *Tokyo Institute of Technology, 152-8550 Tokyo, Japan.*

Abstract

Flux switching permanent magnet (FSPM) motors in both rotating and linear applications have been gaining popularity because of high tangential stress, low cost, low amount of permanent magnets required, and robust construction. The scope of this work is present-day and future manufacturing and transportation applications in industry 4.0 that take advantage of FSPM rotating and linear bearingless motors (BMs). FSMP BMs provide contactless oil-free operation, positioning accuracy, and magnet placement leading to robust and affordable construction. We review design challenges, trends, and opportunities. Tangential stress, normal stress, torque, and force density per motor volume are benchmarked based on available published data in recent years. The main challenges in design optimization, implementation in applications, and control are analyzed. The work concludes with discussion on scaling for higher powers and wider airgaps.

Keywords: *Flux switching permanent magnet motor, Bearingless motor, Linear levitated motor, Magnetic levitation.*

1. Introduction

Arguably the 1st industrial revolution (IR) has started in the late XVIII century with the introduction of steam power enabling large-scale manufacturing, mechanization, and textile industry. The development of these ideas resulted in rapid urbanization with many new cities emerging and rapidly growing in that era, for example, Detroit in USA, Manchester in UK, Lodz in Poland, Edo (modern-day Tokyo) in Japan or Tampere in Finland. In the late XIX century, the 2nd IR with railroads development, electricity generation, internal combustion engines, moving assembly lines, and mass production flourished. The 3rd IR started in the middle of the XX century with the digitization of manufacturing enabling semiconductors, computing, and digital communication networks. The 4th IR in early XXI century leverages and fuses technology breakthroughs in fields such as robotics, autonomous systems, 3D printing, and additive manufacturing.

Industry 4.0 needs adaptation of manufacturing space to new methods. Faster, more efficient, reliable, clean, safe production of higher-quality goods at reduced cost requires new solutions for assembly and packaging transportation lines. Emerging fully automated smart factories require cleanness, precision, integration, modularity, and cyber-physical system compliance. Environmental and technological needs will demand oil-free clean solutions.

In the last decade, perhaps the most intensely investigated applications for electrical machines have been electric vehicles (EVs) and hybrid electric vehicles (HEVs). In general, permanent magnet (PM) motors offer higher torque and energy densities than induction motors (IMs) and switched reluctance motors (SRMs). Interior PM synchronous motors (IPMSMs) when benchmarked for HEVs as presented by Kiyota et al. (2014) offered 71% higher maximum energy and maximum torque densities than SRMs. Short operation peak densities computed for current densities as high as 50 A/mm^2 and per volume measured by the iron core external dimensions without end windings reached 76 Nm/L and 22kW/L. Densities and efficiencies significantly are affected by operating conditions and design constraints. Yang et al. (2015) compared IPMSMs SRM, and IM drives for EV and HEV applications. In that study, peak power densities per kg for IPMSMs SRM, and IM have been 50 kW/30 kg, 50 kW/42 kg, and 50 kW/48 kg, and per volume 10.5 kW/L, 8.4 kW/L, and 8.1 kW/L.

The Flux switching permanent magnet (FSPM) motor offers similarly high energy density per volume as IPMSMs. The main advantages of FSPM over SPM and IPM technology are better mechanical integrity and high reliability for high-speed operation, better thermal dissipation, and smaller copper loss with concentrated windings. However, the main drawbacks include smaller PM utilization ratio, smaller output torque per kg of PMs (Cao et al., 2012). Performance metrics greatly can vary depending on the design and operating conditions. Cao et al., 2012 compared a FSPM with the IPM used in 2004 Prius HEV, which is nearly the same IPM as used by Yang et al. (2015) in his comparison. The peak-to-peak value of cogging torque was a little bigger than that of the Prius IPM. For FSPM, the average *d* and *q* axes inductances (0.343 mH and 0.48 mH) do not differ significantly and therefore, the reluctance torque of FSPM is small. The FSPM compared to IPM motor has been of slightly lower power density (9.2 kW/L vs. 10.1 kW/L). However, FSPM had lower weight (34 kg vs 39 kg). Hua et al. (2017) studied an outer rotor FSPM machine for in-wheel traction. For outer rotor configuration, FSPM has been reported to reach 40% (and 61.5% with wedge shaped magnets) more torque than SPM machine with the same rated current density (5 A/mm^2).

Manufacturing in Industry 4.0 and Smart Factory concepts develop at such a pace that the past conceptual solutions become the key drivers for success today. Magnetic levitation in rotating and linear motion systems is one of the examples. The basic solutions for factory logistics and manufacturing have been using mechanical chassis. The use of mechanical bearings and rollers creates harmful dust particles, which must be laboriously filtered out by centrifugal air compressors in the cleanrooms. Mechanical bearings and transmission also cause maintenance and reliability issues.

This paper discusses growing potential and technological advancement of levitated linear as well as rotating FSPM bearingless motors (BMs) especially in expanding industry 4.0 manufacturing sector. The FSPM BMs potential applications include efficient blowers, mixers, pumps and compressors with ultra-purity or vacuum requirements. The linear FSPM (LFSPM) BMs can be applied to transportation without mechanical conversion such as horizontal (production lines) and vertical (elevators) transporters, warehouses, and storage facilities. LFSPM motors require PMs only in the mover offering huge cost reduction per length of constructed track over SPM and IPM motor solutions. Installing contactless manufacturing space management and precise transportation as well as leveraging oil-free blowers, mixers, and pumps can affect how the factories are planned and designed to improve production efficiency, quality, time to market, and reduce cost and resources usage.

2. Potential markets for levitated FSPM machines

We generalize potential market estimates as of 2023 in this chapter. However, the practical implementation and commercial share and viability of levitated FSPM machines in various sectors is difficult to estimate and will vary depending on cost, scalability, regulatory considerations, and technological integration.

In terms of interest for levitated FSPM motors we can estimate the main global market values of the applications as

- semiconductors and silicon foundries $523 billion
- smart factories $97 billion
- elevators and transporters $82 billion
- warehouse automation $15.7 billion
- linear motion products $12.3 billion
- cleanroom technology $3.6 billion

In c. 2000, most of the World's chip production has been moved to Asia with a handful of producers. Twenty years later, sales of semiconductors reached $523.1 billion according to Semiconductor Industry Association (SIA) (2023), which was a 29.7% increase year to year. Electronic key component shortages brought discussion on the need to reestablish and diversify the semiconductor industry. Advanced manufacturing such as semiconductor manufacturing requires absolute cleanness.

Smart factories market size was valued at $79.41 billion in 2021 and is expected to grow at a CAGR of 10.46 % till 2023 and beyond according to Polaris Market Research (2022).

Elevators and transporters global market size was valued at $72.39 billion in 2022 and is expected to expand at CAGR of 6.4% from 2023 to 2030 (Grand View Research, 2021). Still, we should point out that entry markets might be much smaller, for example, the high-rise buildings elevator market size is only about $40 million.

Warehouse automation global market size was valued at $13.6 billion in 2021 and is projected to grow at a CAGR of 15.3% from 2022 (Allied Market Research, 2022).

The global linear motion products market is projected to grow from $11.5 billion in 2022 to $12.3 billion by 2023 (Fortune Business Insights, 2022). Examples of large companies in motion controller market include ABB Ltd., YASKAWA, Siemens, and Toshiba.

Similarly high cleanness levels are required by growing production segment of the pharmaceutical industry. For example, sterile drugs and biologics often require cleanroom production. New drug products, particularly biologics and cell therapies, require sterile manufacturing to ensure safety and efficacy. Additionally, the COVID pandemic has increased the demand for sterile drugs and vaccines. IQVIA Institute for Human Data Science (2022) forecasted spending on medication to reach $1.6 Trillion by 2025, which excludes spending on COVID-19 vaccines. The global cleanroom technology market size was estimated at $3.6 billion in 2022 and is expected to reach $3.8 billion in 2023 (Grand View Research, 2023).

Potential market sizes are large for levitated FSPM machines, but entry points are limited to special equipment primarily in silicon foundries and in cleanrooms.

3. Design considerations for bearingless operation

Applicability of BMs is broadening with performance improvements and rising realizable power levels (Chen et al. 2020). Rotors with active magnetic bearings (AMBs) and a separate motor unit have been easier to realize. They have been in industrial use with reported powers up to 29 MW. The constructed BMs reached 160 kW (Jastrzebski et al. 2021).

3.1 Rotating Applications

Motors with permanent magnets inserted in the stator core are rarer (Cheng et al., 2011). Those machines possess better rotor integrity and thermal dissipation advantage because of no PMs in the rotor. FSPM motors show torque densities on the same level as conventional PM motors. However, a standard FSPM machine suffers from high saturation. Evans and Zhu (2015) proposed the partitioned stator FSPM machine to relax the magnetic saturation. The stator partitioning separates the PM and copper and place PM within the rotor on a separate stationary body (inner stator). A second air gap is introduced between the salient rotor poles and the inner PM stator. Inherent saturation of FSPM technology contributes to cogging ripples. Pu et al. (2022) investigated and proposes a method to improve the electromagnetic torque of the FSPM motor considering the flux density harmonic reduction ratio.

Recent examples and technical evolution of rotating FSPM BMs have been introduced by Gruber and Radman (2017), Ding and Sarlioglu (2019) and Madanzadeh et al. (2022, 2023). Madanzadeh et al. (2022) introduced double stator concept to FSPM BMs. Fig. 1 shows example of high energy density per rotor volume geometry of such FSPM BM. The structure has discreate rotor poles and similarities to the magnetic geared motor (Kumashiro, 2022).

In the case of FSPM BMs in addition to torque also levitation force amplitude variations and foremost angle variations must be minimized. Good candidates for design optimization are maximizing mean torque, suspension force, and efficiency, when minimizing torque ripple, suspension force amplitude and angle variations.

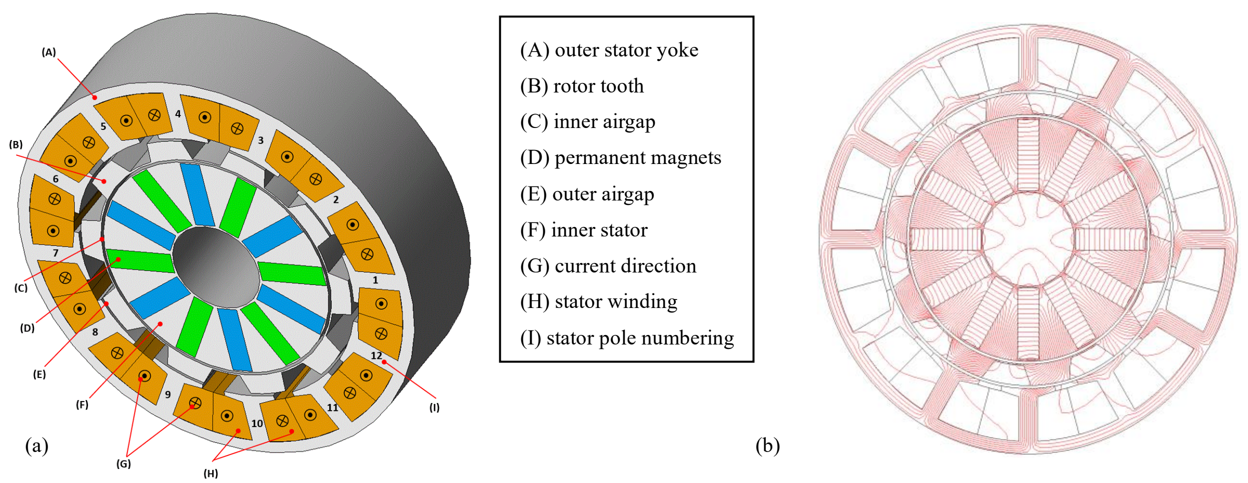

Figure 1 Double stator concept as in Madanzadeh et al. (2022): (a) 2D model of the FSPM BM with the magnets in the inner stator section. 12/10 (stator slot / rotor poles), configuration. (b) flux lines across 2D cross section when operating.

3.2 Linear Applications

The design structures from the rotating applications can be utilized also in the linear motion applications. Taking silicon foundries and smart factories as a potentially biggest market share for ultra-clean, precise, reliable but high-cost equipment demand for linear motion is rising. Substrate cassettes in the semiconductor manufacturing cleanroom or platform manipulators are traveling on wheels or rollers on the floor or as monorail transporter (with rollers) on the ceilings. This is also true for smaller range (within 1-2 meters) mechanical movement required for stationary manufacturing units (e.g., UV exposure process in mask-based etching, high-precision mechanical turning, high-speed packaging, and assembly stations), where the precision motion platforms can be used.

Technological advantages of linear LFSPM BMs over other functionally similar technologies are listed as follows. LFSPM BMs have PMs in the track making them significantly more affordable over linear levitated motors (LLMs) with PMs. At the same time, against reluctance linear motors, LFSPM BMs provide higher efficiency, higher energy density from the same volume, and smaller footprint. Against motors with mechanical rollers, they provide precision of movement, no maintenance needs, built-in monitoring and diagnostics, early warning, built-in weight estimate, and cleanness. Compared to rotating machines with transmission, no transmission, no gears, higher efficiency, no wires, no belts, no ropes are needed.

The well-studied configurations from the non-levitated machines include 12/10 and 12/14 (stator poles / rotor poles or mover slots / rail poles) (Cao et al., 2014). For rotating machine 12/14 configuration provides a higher torque with smaller ripple compared with the 12/10 configuration (Chen and Zhu, 2010). LFSPM motors produce thrust force without a need for conversion. Two additional teeth at the mover ends balance the magnetic circuit. For the levitated machine their width and distance can be varied to minimize the thrust and normal levitation force ripples (Fig. 2).

For FSPM machines significant number of geometry variants have been proposed in recent years to further enhance performance. For example, Tan et al. (2021) used discrete rail poles to increase thrust force density per volume. Metro lines have been one of possible applications where linear induction motors are in use in subways of, for example, Okamoto Green Line of Osaka Metro and Line 12 of Tokyo Metro in Japan. For railway transportation alternatives such as linear switched reluctance motors have been compared to FSPM motors when large 10 mm airgap is used (Cao et al. 2020). Specifically, the thrust, ripple, and efficiency of LFSPM motor was 2.13, 0.23, and 1.06 times that of switched reluctance counterpart, respectively.

FSPM levitated movers provide viable replacement for contact required motion platforms. For linear machines 12/14 configuration delivers commonly used thrust and normal force producing structure. For levitated platforms (Fig. 3a), with synchronous operated motors and at least 4DOF active control, eight three phase inverters are needed to supply opposite attractive force producing, e.g., 12/10 or 12/14 (Fig. 3b), configurations. Those can be replaced by joint or separated 6/5 (Fig.3b) or 6/7 configurations when short platforms are required. Side teeth of joint two modules can be eliminated but then normal force generation of each of joint modules is not magnetically independent. For example, when constructing simulation virtual prototype this means slightly more involved actuator modelling and more coupled control. Technology advancement has been presented in Jastrzebski et al. (2017), Sokolov et al. (2020), and Madanzadeh et al. (2023). Similarly, to the rotating BMs also linear BMs can have double stator (Madanzadeh and Jastrzebski, 2023).

Figure 4 illustrates 4DOF actively controlled (2DOF passively suspended) exemplary proof of concept. The commercial version would feature on board battery, and wireless energy transfer for self-powered untethered operation. Optimally, application integrated sensor technology that directly uses the rail poles as its target for gap and position detection should be installed (Jastrzebski and Tolsa, 2023). Similar platforms but using different levitation principles have been constructed in research labs (Meldrum et al., 2021, Zhou and Trumper, 2021). However, energy densities have been significantly lower limiting payload weight.

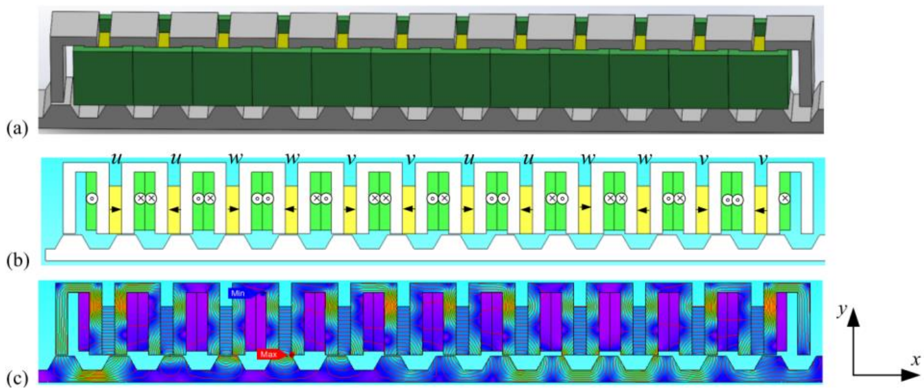

Figure 2 LFSPM BM as in Jastrzebski et al. (2017). (a) Isometric view of 12/14 LFSPM BM. (b) Coil and magnet arrangement. The laminations of the yoke are white, the 3-phase coils green, and the magnets yellow. (c) Flux lines and density distribution for the nominal normal load for i_d = 3.5 Arms and i_q = 0 A.

For BM operation, for example, in Jastrzebski et al. (2017) peak normal stress is 18.5 N/cm^2 and tangential stress (thrust force density) is 9.9 N/cm^2 with peak current densities reaching 13 A/mm^2 but for well saturated iron. The normal stress is about half of that corresponding to radial AMB. The normal force ripple is up to 7% at peak suspension current (and about 4% at lower currents) and nominal airgap. Mover to rail pole pitch ratio and structure optimization play significant roles in reducing normal and thrust force ripples without sacrificing normal and tangential stress values. In Madanzadeh et al. (2023) for 6/5 module at 5.2 A/mm^2 the peak normal stress is 11.8 N/cm^2 and the tangential stress is 5 N/cm^2. The stress values are slightly increased when two 6/5 modules are merged eliminating middle two side teeth, to 12.8 N/cm^2 and the tangential stress is 5.5 N/cm^2. Similar stress values should be possible for airgaps up to 1 cm with designs scaling based on results for non-levitated FSPM motors.

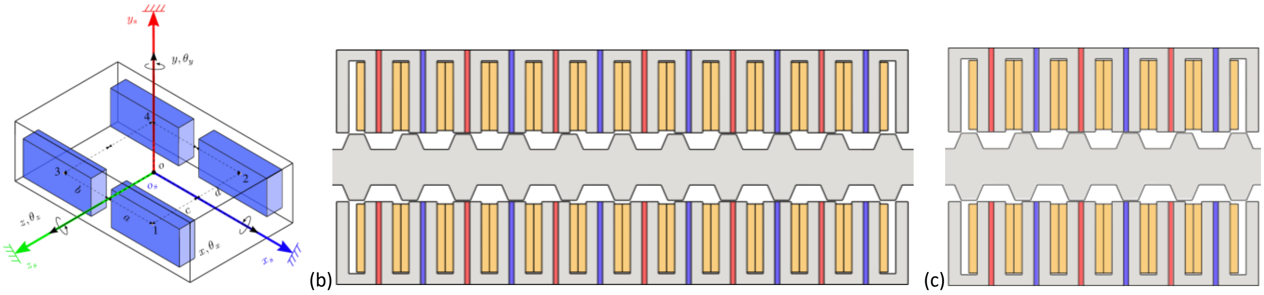

Figure 3 Levitated platform as in Madanzadeh et al. (2023): (a) Illustration of linear motion platform. (b) Exemplary cross section of 12/10 LFSPM BM module. 2DOF levitation is achieved using 2 3-phase inverters per armature. (c) Exemplary cross section of 6/5 LFSPM BM module. 1DOF levitation is achieved using 1 3-phase inverter per armature.

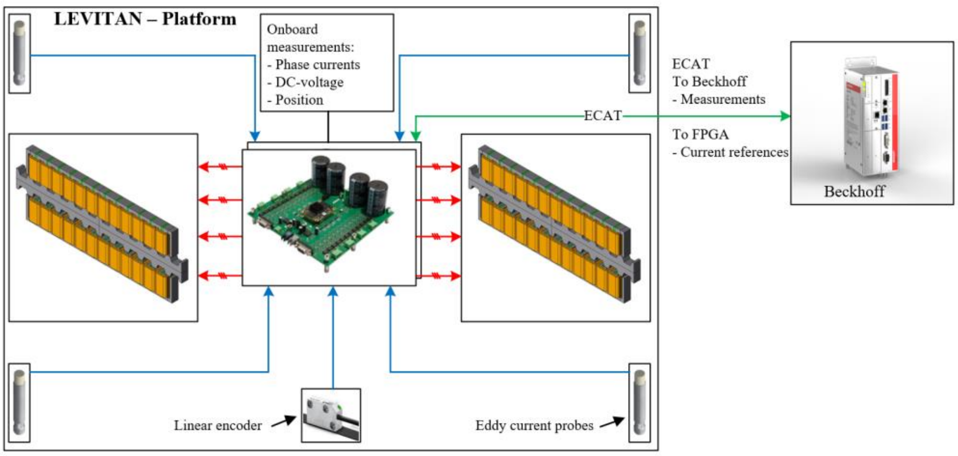

Figure 4 4DOF actively controlled (2DOF passively suspended) levitated linear motion platform with electronics similar to Mirić et al. (2021). The production version would feature integrated sensors, on board battery, and wireless energy transfer for self-powered untethered operation.

4. Conclusions

The FSPM BMs, levitated movers, and their virtual prototypes respond to demanding requirements in silicon foundries, smart factories, robotic assembly, additive manufacturing, pressing, forging, transporting, pharmaceuticals production, and other Industry 4.0 applications. High energy densities are achievable without need for PMs nor windings in the tracks. However, high number of inverters is required for active suspension.

The combination of magnetic levitation and vacuum technology offers improved performance, no friction, and enhanced stability, making it useful for high-speed or space exploration applications. Nevertheless, laboratory and industrial vacuum chambers for, for example, thin film deposition, vacuum drying, vacuum casting, vacuum packaging, composite material production are more likely early adopters.

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