



Research paper

# Trends and Challenges in Linear Synchronous Motor Technology: A Detailed Review of Design and Optimization Approaches

Seyede Delaram Sadr , Hamid Reza Izadfar\* 

Faculty of Electrical and Computer Engineering, Semnan University, Semnan, Iran.

## Article Info

### Article History:

Received 20 December 2025  
Reviewed 15 January 2026  
Revised 26 February 2026  
Accepted 06 April 2026

### Keywords:

Advanced materials  
Coreless motor  
Linear synchronous motor  
Magnetic modeling  
Multi-objective optimization

\*Corresponding Author's  
Email Address:

[hrizadfar@semnan.ac.ir](mailto:hrizadfar@semnan.ac.ir)

## Abstract

**Background and Objectives:** Linear Synchronous Motors (LSMs) provide high precision, fast response, and reduced mechanical complexity, making them attractive for applications such as transportation, automation, robotics, and medical systems. Although numerous studies have investigated their structures, modeling, and optimization, challenges such as end effects, thermal management, and cost reduction remain unresolved. This review aims to synthesize recent advancements and highlight future directions for LSM design and optimization.

**Methods:** The study systematically reviews 54 high-quality research papers covering structural configurations, electromagnetic and thermal modeling approaches, optimization techniques, and application domains of LSMs. Comparative analysis includes flat, tubular, coreless, and superconducting designs, along with analytical, magnetic equivalent circuit (MEC), and finite element method (FEM) modeling. Multi-objective optimization strategies, intelligent algorithms, and material innovations such as Halbach arrays and grain-oriented steels are also examined.

**Results:** Recent research demonstrates that transverse flux and tubular structures enhance thrust density by 20–35% and up to 25%, respectively, while coreless and superconducting designs reduce cogging and enable threefold thrust improvements. Advanced FEM-based multiphysics modeling enables accurate prediction of coupled electromagnetic, thermal, and mechanical behaviors. Optimization strategies based on evolutionary algorithms have achieved up to 12.5% improvement in thrust, an 8.7% reduction in losses, and significant thermal performance enhancements through innovative cooling designs.

**Conclusion:** LSMs are advancing through structural innovations and intelligent optimization. Despite recent progress, challenges such as cooling, scalability, and material costs persist. Future developments will rely on adaptive control, machine-learning-based design, and novel materials, strengthening the role of LSMs in industry and emerging technologies.

This work is distributed under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>)



### How to cite this paper:

S. D. Sadr, H. R. Izadfar, "Trends and challenges in linear synchronous motor technology: A detailed review of design and optimization approaches," J. Electr. Comput. Eng. Innovations, 14(2): 295-310, 2026.

DOI: [10.22061/jecei.2026.12398.876](https://doi.org/10.22061/jecei.2026.12398.876)

URL: [https://jecei.sru.ac.ir/article\\_12555.html](https://jecei.sru.ac.ir/article_12555.html)



## Introduction

Linear Synchronous Motors (LSMs) have emerged as one of the most advanced technologies for achieving precise linear motion, attracting growing attention in recent years. Due to their simple structure, high accuracy, and capability to generate substantial traction force, LSMs are widely utilized in fields such as magnetic transportation (e.g., Maglev trains), electromagnetic launchers, and precision industrial equipment [1], [2]. These motors generate direct linear motion, eliminating the need for rotary-to-linear conversion. This makes them particularly suitable for applications demanding high precision and controllability [3]. The advantages of LSMs include high energy efficiency, accurate positioning, and reduced noise and vibration [4]. Moreover, the use of permanent magnets and superconducting materials in their construction has led to improved performance and reduced size and weight [5].

Nevertheless, challenges including end effects, thrust ripple, and thermal management, particularly under high-load operational conditions, persist and require further research [6], [7]. Beyond their well-established applications in transportation and industrial automation, recent research has increasingly investigated the potential of Linear Synchronous Motors (LSMs) in emerging domains such as defense systems, aerospace engineering, and advanced medical technologies [8], [9]. Thanks to their flexible design capabilities and reliable performance, LSMs play a critical role in advancing cutting-edge technologies [10].

Recent years have witnessed extensive research aimed at improving the electromagnetic, thermal, and structural performance of linear synchronous motors (LSMs). Notable advancements, such as double-sided configurations with novel track designs, have achieved higher force density while reducing magnet consumption [11]. Segmented winding topologies employing two-phase concentric distributed windings [12], along with double-layer Halbach arrays optimized for coreless structures [13], have demonstrated significant improvements in thrust linearity and harmonic suppression.

Further developments include secondary designs with width-modulated magnets to mitigate thrust ripple [14], particle swarm optimization (PSO)-based transient enhancements to improve line-start performance [15], and homopolar configurations capable of reducing vibration and facilitating fault detection [16]. Additionally, design optimization through semi-analytical modeling to improve efficiency in tubular linear permanent magnet synchronous motors [17], and asymmetric V-shaped magnet arrangements for detent force reduction [18] collectively enhance the operational

suitability and reliability of LSMs for demanding engineering applications. A broad body of recent literature [19]-[54] has investigated various structural, electromagnetic, and thermal aspects of Linear Synchronous Motors, including force generation, loss minimization, and advanced modeling techniques.

The various configurations of LSMs are presented, and their impacts on magnetic flux distribution, physical topology, symmetry, core utilization, and material selection are analyzed. Next, modeling and analysis methods are reviewed, with particular emphasis on electromagnetic, thermal, and multiphysics simulations. Subsequently, optimization strategies, including geometric, thermal, and multi-objective approaches, are examined. Major application areas of LSMs are then highlighted, ranging from transportation systems and electromagnetic launchers to industrial automation and emerging medical applications. Finally, the review concludes by summarizing the key findings and identifying potential directions for future research.

## Structural Configurations of Linear Synchronous Motors

The structural configuration of Linear Synchronous Motors (LSMs) significantly affects their performance, cost, complexity, and suitability for specific applications. This section provides a detailed overview of significant design variations, focusing on magnetic flux direction, physical topology, structural symmetry, core utilization, material choices, and excitation methods.

### A. Based on Magnetic Flux Direction: Longitudinal vs. Transverse

The direction of magnetic flux relative to the linear motion path is a key parameter for classifying Linear Synchronous Motors (LSMs) and significantly affects thrust. LSMs are primarily categorized into longitudinal flux and transverse flux configurations.

In longitudinal flux LSMs, illustrated in Fig. 1, the magnetic field lines are oriented parallel to the direction of motion. These motors are the most common in industrial and transportation applications due to their straightforward structure and ease of manufacturing [1], [5]. Typically, the stator includes linear arrays of windings or magnets, and the magnetic circuit is confined within a 2D planar layout. Despite their simplicity and ease of integration, longitudinal flux designs are limited in achievable thrust density and tend to exhibit more pronounced end effects, which can reduce overall performance under high dynamic loads [5].

On the other hand, transverse flux LSMs generate magnetic flux perpendicular to the direction of motion. This unique structure, illustrated in Fig. 2, allows the magnetic path to loop around the motion axis, increasing

the effective magnetic area and enabling higher thrust per unit volume. Studies [30] and [31] indicate that transverse-flux motors can achieve thrust densities 20%–35% higher than those of longitudinal-flux counterparts, primarily owing to extended flux paths and efficient utilization of three-dimensional magnetic fields.

However, the benefits of transverse flux configurations come with challenges. The complex winding arrangements, typically U-shaped or L-shaped, require advanced manufacturing techniques, and 3D finite element analysis (FEM) is often necessary for accurate modeling and optimization [30], [31]. Moreover, torque ripple and magnetic cross-coupling can be more challenging to manage due to the spatial distribution of magnetic forces.

Despite their increased complexity, transverse flux motors are highly suited for high-performance applications such as magnetic levitation (Maglev) trains, where high thrust density and compact volume are critical [1], [31]. Their ability to produce large linear forces in compact spaces makes them ideal candidates for heavy-duty transportation and precision electromechanical systems.

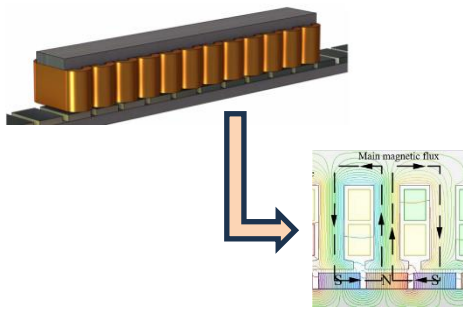


Fig. 1: Longitudinal flux LSM with magnetic paths [8].

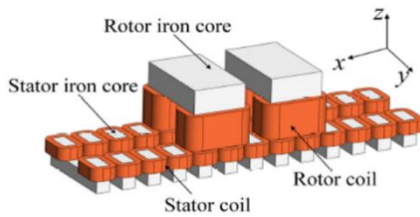


Fig. 2: Transverse flux LSM with orthogonal magnetic paths and segmented cores [31].

### B. Physical Topology: Flat vs. Tubular Structures

The physical topology of Linear Synchronous Motors (LSMs) strongly affects their electromagnetic behavior, mechanical layout, thermal characteristics, and application compatibility. Among the widely used machine topologies, the flat-type and tubular-type configurations are the most common, each exhibiting specific performance advantages and drawbacks.

In flat-type structures, the open magnetic path increases the sensitivity to end effects. This reduces the effective flux density, whereas the closed-loop magnetic circuit employed in tubular designs improves magnetic coupling, resulting in more uniform and stable force generation [3], [29], [40].

Flat-type LSMs, as illustrated in Fig. 3, feature a planar configuration in which the stator and mover are arranged linearly on a flat surface. This structure is commonly used in industrial pick-and-place systems and linear actuators due to its simplicity in construction and ease of integration into planar systems [7], [27], [48]. In this design, the stator typically consists of laminated cores and distributed windings, while the mover comprises a row of permanent magnets. The open magnetic path, however, leads to increased end effects and lower magnetic flux density, which can limit performance in applications requiring high thrust and compactness. As a result, flat configurations typically exhibit higher leakage flux and experience greater variations in normal force, which may reduce motion smoothness in high-precision systems [27], [48].

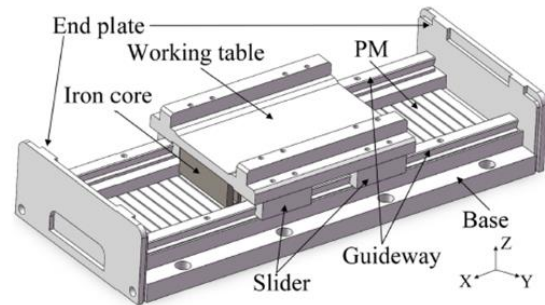


Fig. 3: Flat-type LSM with surface-mounted magnets and planar stator windings [7].

In contrast, the tubular-type LSM, shown in Fig. 4, offers a coaxial cylindrical geometry where the mover is enclosed by a circular stator. This configuration creates a closed-loop magnetic circuit, improving magnetic coupling and symmetry [3], [29], [40]. Tubular structures exhibit higher magnetic flux density (reported increases up to 25%) and significantly reduced end effects, enabling more efficient force production and improved dynamic stability [3], [29]. Furthermore, the radial symmetry of tubular motors enhances thermal dissipation and makes them better suited for vertical Z-axis motion, making them ideal for robotics and high-precision manufacturing. Moreover, the cylindrical enclosure also minimizes mechanical misalignment during motion, which can be beneficial in applications requiring consistent radial positioning [29], [40].

However, tubular LSMs tend to be more complex and expensive to manufacture due to their three-dimensional winding arrangements and tighter

mechanical tolerances [40]. Their structural form also demands more space in the radial direction, which may limit their use in systems with constrained volume.

Overall, the choice between flat and tubular LSM structures must balance factors such as thrust density, efficiency, manufacturability, and spatial constraints, with application-specific requirements guiding the final topology selection.

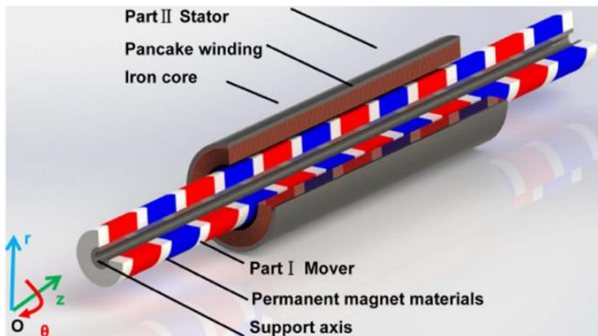


Fig. 4: Tubular LSM with coaxial structure enabling closed magnetic circuit [29].

### C. Structural Symmetry: Single-sided vs. Double-sided

The structural symmetry of Linear Synchronous Motors (LSMs), whether single-sided or double-sided, plays a critical role in determining their electromagnetic performance, mechanical balance, and application feasibility. The configuration choice directly influences force generation capability, magnetic field uniformity, cogging behavior, and system complexity.

In single-sided LSMs, the active components, typically either the stator windings or permanent magnets are mounted on only one side of the air-gap. In contrast, the opposite side consists of a passive back iron or non-magnetic support. This configuration simplifies construction and reduces weight and cost, making it attractive for applications with strict mass or dimensional constraints, such as planar transport systems and low-power automation [26], [41]. However, the asymmetric field distribution in single-sided designs often leads to uneven magnetic attraction, which can cause undesirable normal forces and limit stability, particularly at high speeds or under varying loads [26], [42].

To overcome these limitations, double-sided LSMs incorporate active components on both sides of the air-gap, either symmetrical windings or permanent magnet arrays, creating a balanced magnetic structure. As discussed in [2], [4] and [20], double-sided configurations significantly enhance the magnetic field uniformity, reduce leakage, and improve thrust force generation. For instance, [20] showed that double-sided motors using Halbach arrays achieved an 18% increase in thrust and efficiency, and a 30% reduction in leakage, compared to equivalent single-sided counterparts. In

addition to improved electromagnetic performance, double-sided designs offer better dynamic stability and reduced cogging effects in flux.

Study [44] demonstrated that thrust ripple was reduced by 12% in a double-sided modular LSM with hybrid excitation, resulting in smoother motion during high-acceleration operations. Similarly, [4] reported that double-sided structures exhibited more consistent force production in long-stator high-speed systems, where maintaining magnetic continuity is critical.

Nonetheless, the advantages of double-sided configurations come at the cost of increased volume, manufacturing complexity, and system integration challenges. The need for precise alignment of both stator sides and synchronized excitation can increase the control system's design burden. Therefore, while double-sided LSMs are highly suitable for high-thrust, precision-demanding applications such as Maglev, electromagnetic launchers, and high-end industrial drives, single-sided designs remain competitive in compact, low-cost systems where simplicity is paramount.

### D. Core-Based vs. Coreless Designs

The presence or absence of a ferromagnetic core in Linear Synchronous Motors (LSMs) critically impacts magnetic flux control, thrust ripple, dynamic response, and thermal behavior. Designs are generally classified as either core-based or coreless, with each offering distinct performance trade-offs.

Core-based LSMs employ laminated ferromagnetic cores, usually silicon steel, in both stator and mover sections to guide and intensify magnetic flux. These motors benefit from enhanced magnetic coupling and higher thrust force due to increased magnetic permeability [9], [42]. However, they also suffer from drawbacks such as hysteresis and eddy current losses, cogging effects, and increased overall weight. Studies in [26] and [42] showed that in core-based designs, cogging force amplitudes could exceed 10–15% of the average thrust force in mid-power applications, negatively impacting smooth operation and precision.

To address these limitations, coreless LSMs eliminate magnetic cores in one or both of the active components. As depicted in Fig. 5, coreless structures rely on air-cored windings, often using PCB-based coils or racetrack-shaped superconducting windings [10], [33], [36], [38], [49]. The absence of ferromagnetic material in the flux path significantly reduces cogging and thrust ripple. For instance, [36] reported a 15% reduction in thrust ripple and a 10% improvement in average thrust force in a coreless High-Temperature Superconducting (HTS) LSM compared to its iron-core counterpart.

In addition to smoother operation, coreless motors exhibit superior dynamic response, as the lack of core

mass reduces inertia. They are especially suited for applications requiring fast linear acceleration and deceleration, such as electromagnetic launchers and surgical robotics [10], [20].

Nevertheless, the advantages of coreless LSMs come with engineering challenges. Without core materials, the magnetic circuit becomes weaker, requiring stronger magnets or denser winding configurations. Moreover, thermal management is more difficult because PCB-based windings are thermally insulated by the surrounding air. To address this, [24] and [33] have proposed advanced cooling techniques, including embedded dual-channel structures and forced convection paths, achieving temperature reductions of up to 20% during continuous operation. Coreless designs continue to gain traction in high-performance and compact systems, offering lightweight, low-vibration, and precision-friendly alternatives to traditional cored motors.

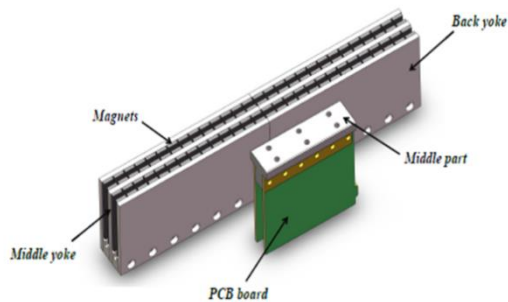


Fig. 5: Coreless LSM with air-cored windings for reduced cogging [10].

#### E. Use of Specialized Magnetic Materials

The selection of magnetic materials in Linear Synchronous Motors (LSMs) significantly influences performance factors such as magnetic flux density, efficiency, losses, and thermal behavior. In recent years, the adoption of advanced magnetic materials, particularly grain-oriented silicon steel (GO steel), has attracted considerable attention for improving magnetic performance and energy efficiency in high-precision LSMs.

Grain-oriented steels exhibit highly anisotropic magnetic properties, resulting in much lower core losses when the magnetic field is aligned with the rolling direction. This material choice enhances magnetic flux concentration, reduces eddy current and hysteresis losses, and improves system efficiency. According to [50], using GO steel instead of non-oriented electrical steel in stator laminations can increase magnetic flux density by 7–10% while simultaneously reducing total core losses by approximately 15% under sinusoidal excitation.

Moreover, [8] demonstrated that implementing GO steel in transverse flux LSMs resulted in 15% lower iron

losses and smoother magnetic-saturation characteristics compared to conventional laminated core materials. These improvements are particularly beneficial in high-speed, high-frequency applications, where reduced core loss directly translates into improved thermal stability and reliability.

However, the benefits of GO steel come with fabrication challenges. The anisotropic nature of GO steel requires precise alignment of the magnetic field with the material's grain orientation. As noted in [51], misalignment can significantly degrade performance, negate the benefits, and even introduce local hot spots. Additionally, laser cutting and punching operations must be carefully controlled to prevent magnetic damage along the edges, as highlighted in [28]. To optimize these materials in LSMs, researchers have proposed hybrid stator configurations combining GO steel in high-flux regions with conventional materials elsewhere, striking a balance between performance gains and cost [51]. In summary, specialized magnetic materials, such as grain-oriented silicon steel, offer measurable efficiency and performance enhancements in LSMs, particularly for applications that demand low losses, compact volume, and high magnetic saturation. Their integration, however, requires advanced design, accurate modeling, and careful manufacturing processes to realize their potential fully.

#### F. Magnetic Excitation Method: Permanent Magnets vs. Excited Windings

The magnetic excitation method in Linear Synchronous Motors (LSMs) not only determines the magnetic field generation mechanism but also affects controllability, force density, energy efficiency, and system cost. LSMs are generally classified into two excitation categories: Permanent Magnet (PM) excitation and electromagnetically excited windings, including superconducting windings.

Permanent magnet-excited LSMs are widely adopted in industrial and automation applications due to their compact design, high efficiency, and simple control. Rare-earth magnets such as NdFeB are commonly used due to their high remanence and coercivity, enabling dense magnetic flux without external excitation [23], [43]. Studies like [43] report that PM-LSMs achieve over 90% efficiency in steady-state operation with minimal maintenance requirements. However, PM-based systems lack flux controllability and are susceptible to demagnetization under high temperatures or fault conditions [23].

In contrast, electromagnetically excited LSMs use field windings energized by a DC source, allowing real-time control over the magnetic flux. While this approach increases the system's complexity and power consumption, it enables dynamic field tuning and fault-

tolerant control, especially in variable-load environments [39].

An exceptionally advanced form of excitation uses high-temperature superconducting (HTS) windings, which offer ultra-low resistance and extremely high current densities. As illustrated in Fig. 6, superconducting coils are arranged in racetrack geometries and cryogenically cooled to achieve efficient excitation without thermal losses. Research in [36] demonstrated that HTS-excited LSMs provide 2–3 times higher thrust density than PM counterparts, with significantly lower thermal losses. Similarly, [33] reported a 30% reduction in magnetic leakage and a 20% improvement in overall efficiency using racetrack HTS coil optimization.

Despite their promising performance, HTS systems require complex cryogenic infrastructure and face challenges such as minimizing AC loss, quench protection, and high material costs [39], [52]. To mitigate these issues, hybrid systems combining PM excitation with superconducting field assist have also been proposed, achieving improved performance with reduced cooling demand [52].

In conclusion, while PM-based LSMs are well-suited for conventional applications, electromagnetically excited and HTS-based systems offer significant advantages in high-performance domains such as Maglev transportation, aerospace, and defense. Their ability to dynamically control the magnetic field and deliver high thrust with minimal losses positions them as a key technology for next-generation LSMs.

### G. Winding Configurations

The winding configuration in Linear Synchronous Motors (LSMs) critically affects electromagnetic performance, thrust generation, thermal behavior, and overall system reliability. Appropriate selection and optimization of winding schemes can significantly reduce cogging force, improve magnetic field uniformity, and enhance thermal dissipation, all of which are vital for high-performance, compact applications.

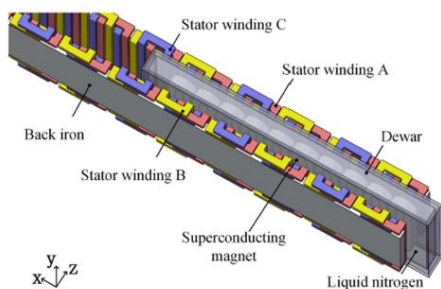


Fig. 6: HTS-excited LSM using racetrack coils and cryogenic cooling [36].

### G. 1. Distributed and Concentrated

Winding arrangements are broadly categorized into distributed and concentrated types. Distributed windings, typically employed in long-stator and industrial LSMs, span multiple slots per pole and phase, generating a smoother magnetomotive force (MMF) waveform and minimizing spatial harmonics. This configuration enhances thrust smoothness and reduces cogging, making it suitable for high-precision linear motion [4], [29].

Conversely, concentrated windings, which localize coils around individual poles or teeth, offer superior compactness and ease of manufacturing. They are particularly effective in modular, coreless, or PCB-based LSM designs. For instance, the PCB-based concentrated winding reported in [10] reduced cogging force by 15% and improved the thrust-to-weight ratio similarly, in [36], optimized racetrack-shaped high-temperature superconducting (HTS) windings achieved higher force density with enhanced thermal performance.

In addition to conventional distributed or concentrated windings, fractional-slot and fractional-pitch windings have received considerable attention in the development of linear synchronous motors (LSMs), as these configurations enable reduced force ripple, suppressed high-order harmonics, and improved MMF uniformity. In fractional-slot designs, as demonstrated by Lerch, the fractional division of slots disrupts the spatial periodicity between teeth and magnets, thereby preventing the overlap of undesirable harmonics. This arrangement, due to the non-periodic distribution of windings, significantly reduces cogging, improves the flux waveform, and enhances dynamic stability at low and medium speeds. Furthermore, the same study found that shortening the effective coil length relative to the pole pitch not only reduces fifth- and seventh-order spatial harmonics but also reduces the end-winding length, thereby lowering copper losses and improving thermal performance.

On the other hand, in modern linear configurations, the use of fractional windings in combination with a segmented stator yields even more favorable outcomes. For instance, in the design presented by Tariq *et al.* [54], the partitioned stator flux-switching linear machine with concentrated fractional windings achieves a notable reduction in force ripple and an improvement in flux density. FEM analyses in this study indicate that properly adjusting the slot-to-pole ratio and selecting a fractional coil pitch not only mitigate tooth forces but also reduce end effects in long-stroke linear machines, ensuring a continuous and uniform thrust force.

overall, recent studies [53], [54] emphasize that the combination of concentrated windings with fractional-slot and fractional-pitch configurations is a key strategy

for enhancing the electromagnetic performance of next-generation LSMs, particularly in motors that require high force density, modular construction, and low-ripple operation.

G. 2. Single-Layer vs. Double-Layer Configurations

Single-layer windings are mechanically simpler but may suffer from uneven MMF distribution and increased magnetic leakage.

Double-layer windings, especially those with asymmetrical arrangements, provide improved field symmetry and reduced core saturation. In [28], as shown in Fig. 7, an asymmetrical double-layer winding structure in an ironless LSM resulted in a 12% increase in thrust force and more uniform flux linkage. In thermal analysis, [44] reported that multilayer windings reduced local hot spots by more than 15%, improving overall thermal stability.

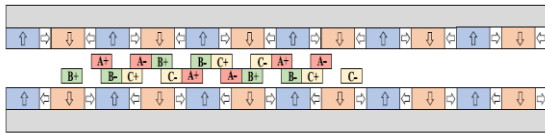


Fig. 7: Schematic of a Double-Layer PMLSM [28].

G. 3. Slot Skewing and Tooth Shaping

Advanced tooth-shaping and skewing techniques are widely employed to suppress detent force and cogging. The V-shaped tooth-slot design, shown in Fig. 8 and proposed in [26], reduced the detent force by approximately 38%, resulting in improved linear motion accuracy and a smoother dynamic response. In addition, the optimized slot-pole combination presented in [47] minimized the harmonic content of the magnetomotive force (MMF), which is particularly beneficial for high-speed applications.

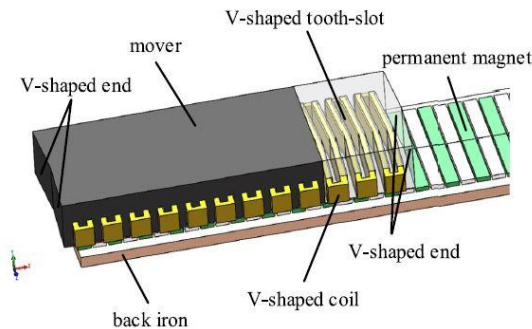


Fig. 8: V-shaped tooth-slot structure PMLSM [26].

G. 4. Modular and Segmented Winding Structures

Modular winding architectures offer scalable and reconfigurable design strategies for long-primary LSMs. In [27], modular segmentation of the primary part, shown in Fig. 9, reduced normal force ripple by 22% and

improved thrust linearity. Furthermore, [25] introduced a ring-shaped modular winding structure optimized via multi-objective algorithms, achieving over 10% efficiency enhancement with minimal increase in system volume.

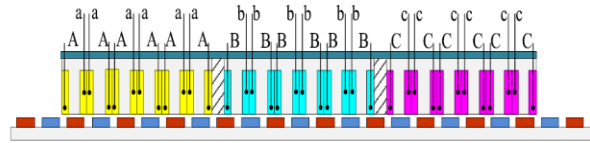


Fig. 9: Winding distribution of the PMLSM with segmental primary component [27].

Table 1: Structural configurations and characteristics of LSM

| Structure & Feature     | Type & Configuration     | Advantages & Benefits                     | Drawbacks & Challenges                |
|-------------------------|--------------------------|---|---------------------------------------|
| Magnetic Flux Direction | Longitudinal             | Simple design, commonly used              | Lower force density                   |
|                         | Transverse               | Higher thrust density, suited for maglev  | Complex modeling and structure        |
| Physical Topology       | Flat-type                | Easy to manufacture, compact              | High end-effect, lower efficiency     |
|                         | Tubular-type             | Symmetric flux, better cooling            | More complex to build                 |
| Structural Symmetry     | Single-sided             | Lightweight, low cost                     | Higher cogging and ripple             |
|                         | Double-sided             | High thrust, uniform flux                 | Bulkier and heavier                   |
| Magnetic Core           | With core                | Better flux guidance                      | Higher hysteresis losses, ripple      |
|                         | Coreless                 | No cogging, fast response                 | Complex design and cooling            |
| Magnetic Material       | GO Steel                 | Reduced eddy currents, better performance | High cost, difficult to process       |
| Excitation Method       | Permanent Magnets (PM)   | Simple, stable field                      | No controllability                    |
|                         | Superconducting Windings | Very high thrust density, adjustable      | Expensive and needs cryogenic cooling |

Modeling of Linear Synchronous Motors

Accurate and comprehensive modeling of Linear Synchronous Motors (LSMs) is crucial for predicting performance, optimizing design parameters, and ensuring stable, reliable operation. Recent research emphasizes not only the development of accurate

models but also balancing model complexity with computational efficiency. Modeling approaches typically cover three essential aspects: magnetic field analysis, thermal behavior, and coupled Multiphysics simulation.

Given the significant influence of non-ideal electromagnetic phenomena on the accuracy and robustness of these modeling approaches, the end effect emerges as a critical factor that warrants a dedicated discussion in the next section.

#### A. End-Effect Phenomenon: Modeling, Impacts and Suppression Methods

The end effect is a critical design challenge in Linear Synchronous Motors (LSMs), arising from the inherent non-periodicity of the airgap magnetic field at the leading and trailing regions of the mover.

As demonstrated in flat-type LSMs in [27] and [48], the open magnetic circuit causes incomplete flux closure at the extremities, which in turn generates thrust drop, spatial force ripple, and significant distortion in the flux distribution. In contrast, tubular configurations inherently suppress this issue due to their enclosed magnetic flux path, leading to smoother field transitions and substantially lower end-effect severity, as reported in [29]. The impact of end effects extends beyond thrust reduction. According to the 3D electromagnetic analysis in [1], the discontinuity of the airgap field results in unbalanced inductance profiles, back-EMF harmonics, and transient force oscillations during the entry and exit of the mover. Neglecting these effects in analytical models leads to considerable performance prediction errors—up to 12% in thrust according to [31]. Moreover, end-region distortions are directly linked to thermal instabilities. As reported in [46], eddy current concentrations near end zones elevate local temperatures and introduce hotspots, emphasizing the need for coupled electromagnetic-thermal design strategies. Modeling approaches for capturing end effects vary in terms of complexity.

Analytical methods often require correction coefficients or modified MMF-permeance formulations, as implemented in the reluctance-based analytical model of [32], which compensates for flux imbalance and improves prediction accuracy. Nevertheless, FEM-based modeling remains the most reliable tool for quantifying end-effect-induced distortions, especially in long-stroke or modular structures.

Mitigation techniques include optimizing pole pitch and magnet width, adopting tubular magnetic structures [29], and refining stator or mover edge geometry to guide flux more uniformly. FEM-assisted compensation strategies, such as adjusting segment lengths or incorporating auxiliary end coils, can further reduce thrust roll-off and improve linearity. Collectively, these studies [1], [27], [29], [31], [32], [46], [48] highlight

that proper modeling and mitigation of end effects is essential for reliable design, accurate force prediction, and thermal stability in next-generation LSMs.

#### B. Magnetic Field Modeling

Accurate magnetic field modeling is pivotal for the analysis, design, and performance prediction of Linear Synchronous Motors (LSMs). It directly affects the calculation of thrust force, evaluation of end effects, flux leakage, and thermal interactions, and serves as the foundation for multiphysics simulations and system-level control.

The modeling techniques can be categorized into three primary groups: analytical formulations, magnetic equivalent circuit (MEC) representations, and full-scale numerical approaches such as finite element method (FEM) simulations. Each approach offers a different balance between complexity, computational cost, and modeling fidelity.

##### B. 1. Analytical Modeling

Analytical modeling methods provide fast, insightful estimates, especially during early-stage design optimization. These methods rely on simplified geometrical assumptions, linear magnetic behavior, and uniform field distributions.

A typical formulation of the electromagnetic thrust force generated by a surface-mounted LSM is given by:

$$F_x = (3/2) \cdot (P/\pi) \cdot \phi \cdot I \cdot \cos(\theta) \quad (1)$$

where  $P$  is the number of poles,  $\phi$  is the peak flux linkage per phase,  $I$  is the phase current (RMS), and  $\theta$  is the electrical load angle. These models, while computationally efficient, often overestimate performance due to non-linearities, complex flux paths, and end effects. As shown in [1], a 3D analytical model for LSMs required FEM validation to account for end effects, highlighting the challenge of capturing non-ideal magnetic behavior. Similarly, [32] addresses these issues, namely non-linear inductance variations, magnetic field distortions, and end effects in winding-segmented permanent magnet linear synchronous motors (WS-PMLSM) by proposing an analytical model that uses a reluctance-based approach to quantify inductance unbalance and a virtual winding technique with Fourier analysis to mitigate magnetic field distortions from partial excitation. Validated through FEM simulations, this model improves the accuracy of predicting transient inductance and thrust fluctuations, providing a robust tool for the design and optimization of segmented motors.

##### B. 2. Magnetic Equivalent Circuit (MEC) Modeling

MEC models provide a middle ground between purely analytical and fully numerical techniques. In this approach, the magnetic domain of the LSM is

represented by a lumped-element network of reluctances and magnetomotive force (MMF) sources, mimicking Ohm's law in magnetic systems:

$$\Phi = \mathcal{F}/\mathcal{R} \quad , \quad \mathcal{R} = l/(\mu A) \quad (2)$$

where  $\Phi$  is the magnetic flux,  $\mathcal{F}$  is the magnetomotive force,  $\mathcal{R}$  is the magnetic reluctance, and  $l$ ,  $A$ , and  $\mu$  denote the length, cross-sectional area, and permeability of the magnetic path.

A representative MEC diagram is shown in Fig. 10, extracted from [5], which demonstrates the main and leakage flux paths across the primary and secondary components of an LSM. The model includes individual reluctances ( $P_{ir1}$ ,  $P_{loss2}$ , etc.), flux paths through air gaps and iron cores, and considers leakage fluxes, which are often ignored in simplified models. The MMF sources ( $F_a$ ,  $F_b$ ,  $F_c$ ) represent the excitation inputs, while the branch structure allows accurate modeling of flux bifurcation and losses.

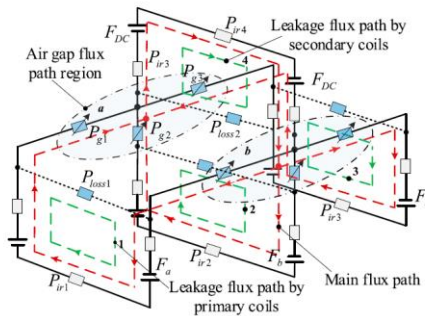


Fig. 10: 3-D magnetic circuit model of LSM [5].

Such detailed MEC models are especially beneficial in short-primary and modular LSM topologies, where end-effect compensation and leakage flux estimation become critical for thrust linearity and electromagnetic stability.

### B. 3. Finite Element Method (FEM) Modeling

FEM is the most comprehensive and accurate tool for analyzing LSMs, particularly when non-linear material characteristics, geometric asymmetries, and end effects are present. It solves the magnetostatic or time-harmonic Maxwell's equations numerically:

$$\nabla \times (1/\mu \nabla \times A) = J \quad (3)$$

where  $A$  is the magnetic vector potential, and  $J$  is the source current density.

FEM has been widely used to validate other modeling methods and to conduct parameter sweeps across geometry, excitation, and cooling configurations. In [31], it was shown that ignoring end effects in FEM models could lead to a thrust overestimation of up to 12%. In [51], a coupled electromagnetic-thermal FEM model highlighted the temperature-dependent demagnetization risk in high-power LSMs.

### C. Thermal Modelling

Thermal Modelling is essential for ensuring motor reliability, especially under high-speed or high-load conditions. Excessive heating can lead to insulation failure, magnet demagnetization, and accelerated wear. In many LSMs, localized heating near the end regions is observed due to asymmetric flux distribution caused by end effects. In [46], FEM-based thermal simulations revealed that eddy current losses near the stator ends can raise local temperatures by up to 30°C. This highlights the need to account for thermal hotspots caused by end effects during both the design phase and the implementation of cooling strategies.

Thermal Resistance Network (TRN) models, as applied in [3] and [24], provide quick estimations of temperature rise based on simplified thermal paths. In [24], the introduction of a staggered double-channel embedded cooling system reduced the hotspot temperature from 125°C to 96.5°C, thereby increasing motor lifetime by approximately 1.6 times, based on thermal degradation laws.

Finite element-based thermal simulations, discussed in [46], revealed that eddy current losses in coreless motors can elevate local temperatures by up to 30°C, highlighting the importance of integrated electromagnetic-thermal analysis for accurate prediction.

Furthermore, coupled electromagnetic-thermal models, such as those in [28], demonstrated that asymmetrical winding configurations could lead to uneven temperature distributions, resulting in performance degradation if not properly compensated during the design phase. While FEM provides high-resolution insight, it is computationally intensive. Therefore, simplified yet physically meaningful alternatives such as TRN models have gained significant attention for early-stage design evaluation.

These models represent the thermal behavior of various motor components using equivalent resistances and localized heat sources, enabling efficient estimation of temperature rise under different operating conditions.

A representative TRN model is shown in Fig. 11, adapted from [24], which captures the heat-conduction pathways across key regions of the motor, including windings, insulation, the iron core, the PLA casing, and embedded water-cooling channels.

Thermal resistances such as  $R_{pit}$ ,  $R_{ptt}$ , and  $R_{ci}$  denote conduction paths through structural elements, while nodes  $Q_i$  represent localized thermal losses, including copper loss  $P_{cu}$ . This model offers a comprehensive yet tractable method for predicting temperature profiles and evaluating the effectiveness of advanced cooling strategies.

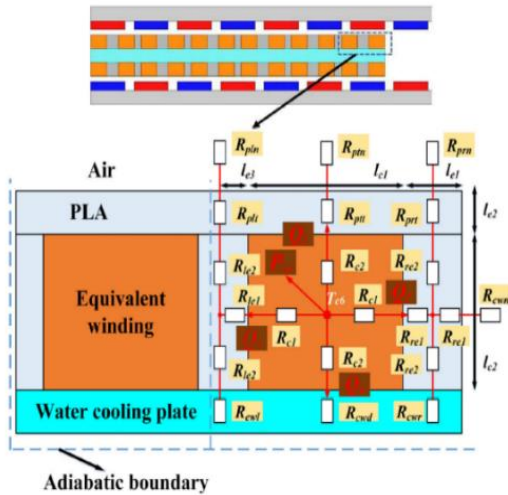


Fig. 11: Thermal network model of LSM [24].

D. Multiphysics and Hybrid Modelling

High-performance LSM applications, such as Maglev transportation and electromagnetic launchers, require multiphysics models that simultaneously consider electromagnetic, thermal, and mechanical phenomena. End effects play a significant role in multiphysics interactions, as they not only alter the boundary thrust force but also induce mechanical vibration and thermal nonuniformity.

In [22], integrating the Maxwell stress tensor and temperature-dependent material properties at the motor ends led to a more realistic prediction of the stress distribution during rapid acceleration.

Couple electromagnetic-thermal-mechanical models, presented in [22], achieved less than 3% deviation from experimental results when predicting motor behavior under dynamic loading conditions. Integration of Maxwell stress tensor computations with thermal and structural deformation models proved crucial in maintaining motor stability at high speeds. Hybrid modelling approaches, combining analytical field calculations with localized FEM, have also gained attention.

In [28], a hybrid 2D-3D model improved computational efficiency by 35% without sacrificing prediction accuracy, maintaining thrust force error below 5%. Hybrid modeling approaches combining analytical estimations with localized FEM refinement have proven especially useful in capturing edge-dominant electromagnetic and thermal behavior. As reported in [28] and [31], this approach improved accuracy in modeling LSMs with short secondary structures and non-periodic excitation, where end effect distortion becomes a dominant performance factor.

Overall, recent trends indicate that precise, multiphysics-based modelling is indispensable for the successful development of high-performance LSM systems, ensuring both superior operational efficiency and robust dynamic performance.

LSM Technology: Configurations, Modeling, and Applications

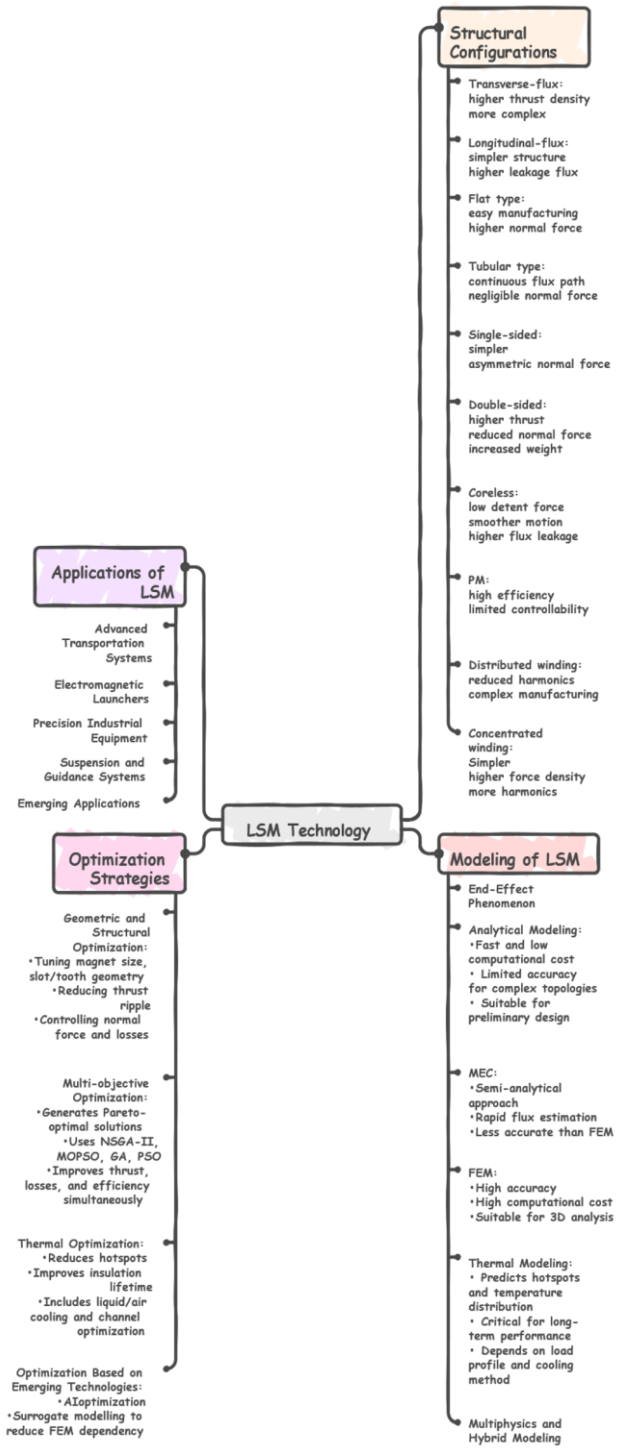


Fig. 12: The mind map for LSM technology.

Table 2: Comparison of LSM modelling methods by accuracy and computation time

| Modeling Domain       | Method                           | Accuracy    | Computational Time | Typical Applications   |
|-----------------------|----------------------------------|-------------|--------------------|--|
| Magnetic              | Analytical                       | Medium      | Very fast          | Preliminary magnetic design                                  |
| Magnetic              | MEC                              | High        | Fast               | Concept validation and end-effect estimation                 |
| Magnetic              | FEM                              | Very high   | Slow               | Final verification and non-linear flux analysis              |
| Magnetic              | Subdomain FEM                    | High        | Medium             | Dynamic response and partial saturation zones                |
| Thermal               | TRN (Thermal Resistance Network) | Medium High | Fast               | Approximate temperature prediction; cooling design [3], [24] |
| Thermal               | FEM                              | Very high   | Slow               | Detailed thermal distribution and hotspot analysis [46]      |
| Coupled Multi-physics | EM-Thermal FEM                   | Very high   | Very slow          | Integrated design of electromagnetic-thermal systems [28]    |

## Optimization Strategies for Linear Synchronous Motors

Optimization strategies are essential in the design of Linear Synchronous Motors (LSMs) to enhance thrust force, minimize losses, mitigate undesirable effects such as cogging, and improve overall system efficiency. Recent advancements integrate sophisticated computational tools, intelligent algorithms, and novel material applications to refine the performance of LSMs across various operating conditions.

### A. Geometric and Structural Optimization

Structural geometry directly affects magnetic flux distribution, force generation, and thermal dissipation in LSMs. Several optimization strategies have focused on improving the geometric configuration to suppress unwanted forces and enhance performance. Skewed pole and slot arrangements, as presented in [25]

and [26], effectively reduce detent and cogging forces. Specifically, [23] demonstrated that applying a V-shaped tooth-slot structure decreased detent force by approximately 38%, reducing peak force from 45 N to 28 N. This resulted in smoother operation, higher positioning precision and lower vibration levels during dynamic performance. Modular primary segmentation strategies in [27] showed a 22% reduction in normal force ripple, directly enhancing dynamic stability, particularly beneficial for high-speed linear actuators. Moreover, double-sided stator designs, as reported in [4] and [20], improved magnetic flux symmetry, resulting in an increase of 15–20% in effective thrust force compared to single-sided designs. This improvement, however, comes at the cost of increased system bulk and fabrication complexity. Tubular configurations, compared to flat designs, offer closed magnetic circuits that enhance flux density by up to 25%, as noted in [3] and [29], thereby providing higher thrust output and better thermal management.

### B. Multi-objective Optimization with Intelligent Algorithms

As modern LSM designs must simultaneously satisfy multiple performance requirements such as maximizing thrust density, improving efficiency, reducing copper and iron losses, ensuring thermal stability, and minimizing weight and material cost, multi-objective optimization (MOO) has become an essential design tool. Intelligent optimization algorithms, in particular evolutionary and swarm-based methods, have been increasingly adopted due to their capability to explore complex design spaces and address conflicting objectives without relying on explicit gradient information.

Evolutionary algorithms such as NSGA-II, MOPSO, and GA have demonstrated strong suitability for LSM optimization because they naturally generate Pareto-optimal solutions. In [28], the application of NSGA-II enabled simultaneous improvement of thrust (12.5%) and copper loss reduction (8.7%) while maintaining dimensional constraints, illustrating the advantage of Pareto-based search strategies for constrained electromagnetic designs. Similarly, the hierarchical multi-objective optimization framework introduced in [33] for long-primary LSMs achieved an approximately 15% improvement in overall efficiency with less than 5% growth in volume, a critical requirement for large-scale transportation and Maglev applications.

Genetic Algorithms (GA) have been widely used to optimize magnet geometry, slot dimensions, and winding configurations due to their robust global search capability. However, studies report that GA-based processes require a large number of FEM evaluations and therefore incur higher computational costs. Particle Swarm Optimization (PSO), by contrast, generally offers

faster convergence and has been applied effectively to tune dimensional parameters and magnetic topologies. However, PSO may suffer from premature stagnation when confronted with highly non-linear behavior such as magnetic saturation or strong end-effect interactions, as noted in [35]. To overcome the computational burden of repeated FEM simulations, recent studies have introduced surrogate-assisted and AI-supported optimization models. As reported in [28] and [32], response surface models and machine-learning-based predictors can significantly reduce optimization time by approximating electromagnetic outputs, enabling rapid evaluation of multi-objective criteria. However, these methods remain sensitive to the quality of the training data, and their reliability decreases when the design space involves strong multiphysics coupling or discontinuities. Overall, the literature shows that intelligent optimization algorithms play a crucial role in modern LSM development. Each technique offers specific benefits global exploration (GA), fast convergence (PSO), and high-quality Pareto fronts (NSGA-II/MOPSO) but none independently handles the full range of multiphysics constraints, fabrication limitations, and real-time adaptability requirements. Consequently, future research is expected to move toward hybrid optimization schemes that combine global search, surrogate modelling, and adaptive learning to support high-performance and computationally efficient LSM design.

### C. Thermal Optimization and Cooling System Design

Efficient thermal management is crucial to maintaining LSM performance and longevity, particularly under continuous high-load operation.

Thermal optimization strategies, such as the staggered double-channel water-cooling system presented in [24], reduced hotspot temperature from 125°C to 96.5°C, a 22.8% decrease, directly translating into an estimated 1.6-fold increase in motor operational lifespan.

Moreover, optimization of cooling structures for long-stator LSMs in [37] achieved a 17% reduction in hotspot temperatures and improved cooling uniformity by optimizing the coolant path design and embedding secondary flow channels.

Machine learning-based prediction models, as implemented in [3], further enhanced thermal optimization by forecasting thermal maps with less than 5% error compared to experimental results, allowing real-time thermal management strategies to be developed without expensive prototyping.

### D. Optimization based on Emerging Technologies

The application of superconducting materials and novel magnetic structures presents new frontiers in LSM optimization. In [33], racetrack-shaped superconducting

coils were optimized, achieving a 20% increase in force density and a 30% reduction in magnetic leakage compared to traditional circular coils.

Optimization of coreless high-temperature superconducting (HTS) LSMs, as discussed in [36], resulted in 15% lower thrust ripple and 10% higher average thrust, thereby offering better performance stability, particularly under dynamic high-load conditions.

Furthermore, the optimization of Halbach arrays in [20] increased thrust by up to 18% without significantly increasing the mover's weight, a critical advantage for high-acceleration applications such as electromagnetic launchers.

The integration of emerging technologies, combined with intelligent, multiphysics optimization frameworks, paves the way for the next generation of LSMs capable of meeting the increasing demands for precision, power density, and thermal resilience.

## Applications of Linear Synchronous Motors

Due to their inherent advantages, including direct linear thrust generation, high positioning accuracy, flexible structural configurations, and reduced mechanical complexity, Linear Synchronous Motors (LSMs) have found widespread adoption across diverse industrial, transportation, defense, and emerging technological sectors. This section outlines major application areas, highlighting key advantages, challenges, and specific examples supported by quantitative data.

### A. Advanced Transportation Systems (Maglev and High-Temperature Superconducting Systems)

One of the most prominent applications of LSMs is in magnetic levitation (Maglev) systems for high-speed transportation. LSMs provide direct thrust without mechanical contact, enabling silent, efficient, and high-speed operation.

High-Temperature Superconducting (HTS) LSMs, as explored in [36] and [39], have achieved thrust force densities exceeding 80 N/cm<sup>2</sup>, approximately 30% higher than conventional permanent magnet designs. Furthermore, the use of Halbach arrays in [20] increased propulsion efficiency by 18%, thereby reducing energy consumption in Maglev systems. Maglev trains, operating at speeds over 500 km/h, benefit from LSMs' smooth acceleration profiles, minimal maintenance requirements, and integrated propulsion and levitation forces. Advanced cooling strategies and lightweight coreless designs further enhance operational feasibility and cost-effectiveness.

### B. Electromagnetic Launchers

In the defense and aerospace sectors, electromagnetic launchers using LSMs are increasingly

avored for applications requiring rapid acceleration and high-precision trajectory control.

Coreless permanent magnet LSMs configured with Halbach arrays, as discussed in [20] and [21], have demonstrated acceleration capabilities exceeding 5000 m/s<sup>2</sup>. These systems offer mechanical simplicity, reduced mass, and real-time force control compared to traditional mechanical launch systems.

Electromagnetic launchers benefit from LSMs' ability to generate high instantaneous thrust without combustion, offering safer, quieter, and more controllable solutions for military and space applications.

### C. Precision Industrial Equipment and Production Lines

In industrial automation, LSMs are widely used for high-precision positioning and motion control across applications such as CNC machines, automated assembly lines, pick-and-place robotics, and semiconductor manufacturing. Studies such as [10], [27] and [48] have shown that replacing rotary-to-linear mechanical conversions with direct-drive LSMs can improve positioning accuracy by up to 25% and reduce maintenance costs by over 30%. Tubular LSM configurations are particularly favored for vertical Z-axis actuators, where high thrust density and minimal vibration are critical for maintaining micron-level precision during high-speed operations.

Moreover, reducing of backlash and mechanical compliance through direct linear actuation leads to faster cycle times and improved production throughput in modern smart factories.

### D. Suspension and Guidance Systems

In addition to thrust generation, specific LSM configurations can simultaneously provide suspension and lateral guidance forces, a feature critical for contactless high-speed applications.

Dual-sided homopolar LSM designs, introduced in [6] and [39], achieved integrated propulsion and suspension forces with improved stability margins. Suspension forces reaching up to 60 N/cm<sup>2</sup> have been reported, enhancing levitation robustness even under dynamic loading conditions. Such integrated solutions eliminate the need for additional mechanical components, such as air bearings or wheels, simplifying the system architecture and reducing overall system weight.

### E. Emerging Applications in Robotics, Medicine, and Renewable Energy

Due to their lightweight designs, high controllability, and non-contact operation, LSMs are increasingly explored in emerging fields such as:

- **Medical Robotics:** LSMs provide precise, vibration-free actuation for surgical tools and non-invasive magnetic stimulation devices. Early prototypes demonstrated force control accuracies within  $\pm 2\%$  of target profiles, as noted in [49].

- **Assistive Robotics:** Coreless tubular LSMs are being integrated into robotic exoskeletons and prosthetics, offering smooth, compliant motion with high torque-to-weight ratios.
- **Renewable Energy Systems:** Linear generators based on LSM principles are being developed for wave energy conversion, where direct-drive systems minimize energy loss associated with mechanical linkages.

While many of these applications are still under active research and experimental validation, the potential for widespread adoption is significant, given the unique advantages LSMs offer in precision, efficiency, and system simplification.

Table 3 :Application domains of LSMs

| Application Area                   | Required Features                              | Advantages of LSMs                       | Examples                   |
|------------------------------------|--|--|----------------------------|
| High-speed Transportation (Maglev) | High thrust, magnetic levitation, low friction | Quiet, high speed, contactless motion    | [1], [6], [36], [39], [49] |
| Electromagnetic Launchers          | Fast acceleration, high energy pulses          | Mechanical simplicity, real-time control | [20], [21], [49]           |
| Precision Industry                 | Positioning accuracy, high linear stability    | Gearless, precise, reliable              | [10], [27], [29], [48]     |
| Integrated Suspension & Guidance   | Mult axis force generation                     | Unified system, design simplification    | [6], [39], [44]            |
| Emerging Fields                    | Lightweight, soft actuation, non-invasive      | Innovation potential, experimental       |                            |

## Research Gaps and Future Challenges

Reviewing the recent literature on Linear Synchronous Motors (LSMs) reveals that, despite notable progress in structural configurations, modelling approaches, optimization techniques, and application-driven designs, several fundamental gaps remain. A consistent issue reported across studies is the persistence of end-effect distortion, which continues to degrade thrust, flux distribution, and back-EMF quality even in advanced designs such as transverse-flux motors, segmented stators, and coreless or tubular configurations [1], [27], [31], [48]. Likewise, while tubular structures offer improved flux continuity and reduced end effects, they introduce significant manufacturing complexity and sensitivity to mechanical tolerances, in contrast, flat structures remain more practical but suffer from leakage flux and normal-force variation [3], [29], [49]. Coreless and HTS-based architectures demonstrate reduced cogging and enhanced force density, yet studies indicate challenges

including flux leakage, structural fragility, and demanding thermal management requirements [10], [33], [36]. Even the adoption of grain-oriented steels, which improves flux density and reduces losses, is limited by material anisotropy, edge degradation, and fabrication constraints [8], [50].

Modelling approaches also exhibit clear limitations. Analytical and MEC-based models struggle to represent nonlinear and non-periodic end regions accurately, leading to thrust prediction errors of up to 12% relative to a full FEM analysis [1], [31]. Although multiphysics methods have been explored, most studies isolate electromagnetic, thermal, or mechanical domains, limiting predictive accuracy under dynamic or high-speed conditions. Thermal modelling gaps are particularly evident in coreless, tubular, and HTS systems, where hotspot formation and non-uniform temperature distributions remain difficult to predict and mitigate [24], [46]. Furthermore, reduced-order or hybrid models despite promising results in [28], [32] are not yet sufficiently mature for comprehensive design workflows.

In the field of optimization, existing work demonstrates improvements through evolutionary and intelligent algorithms [30], [35], but key practical factors such as thermal degradation, magnetostriction, cost, manufacturability, and vibration highlighted independently in several studies [7], [46], [49] are rarely integrated into multi-objective frameworks. Optimization research on emerging structures such as HTS and segmented stators remains preliminary, and no studies address real-time or adaptive optimization under varying load and environmental conditions.

Application-oriented works in Maglev transportation, electromagnetic launchers, precision manufacturing, and medical systems show promising performance [1], [6], [20], [27], [49]. However, most reported results rely on simulations or short-duration testing, with limited long-term validation under thermal cycling, vibration, or high-speed operation. Integrated propulsion–levitation–guidance systems still present unresolved coupling effects and dynamic instabilities [6], [39], [44] and scalability remains a challenge for HTS-based and GO-steel-based designs.

Overall, the literature indicates that future progress in LSM technology depends on more accurate end-effect Modelling, fully integrated multiphysics simulation frameworks, advanced thermal management strategies, cost-effective manufacturing approaches for complex magnetic structures, intelligent and adaptive optimization techniques, and long-term reliability assessment. Furthermore, emerging architectures such as hybrid PM–HTS excitation, segmented coreless motors, and non-integer-pole structures [47], [54].

represent promising yet underexplored directions for next-generation high-performance LSM systems.

## Conclusion

This paper has presented a comprehensive review of 54 high-quality research articles covering the structural design, modeling approaches, optimization strategies, and diverse applications of Linear Synchronous Motors (LSMs). The key findings can be summarized as follows:

- **Structural Diversity:** LSMs exhibit a wide range of configurations from flat and tubular types to transverse-flux, coreless, and superconducting structures selected based on application demands, magnetic and thermal requirements, and manufacturing feasibility.
- **Advanced Modeling:** The use of multidimensional and hybrid modeling techniques, such as MEC, subdomain methods, thermal analysis, and machine learning, is increasing the precision of LSM simulation. FEM remains the most validated tool.
- **Optimization Trends:** Recent research emphasizes intelligent multi-objective algorithms, modular architecture, thermal optimization, and the application of advanced materials to improve efficiency and control.
- **Expanding Applications:** LSMs are now utilized in Maglev systems, electromagnetic launchers, precision manufacturing, medical devices, and robotic platforms, positioning them as a vital component of future technologies.

Despite these advances, challenges remain, including:

- Accurate control under variable load conditions
- Efficient cooling solutions for coreless and HTS designs
- Cost constraints of magnetic materials and HTS technologies

Future research is recommended to focus on:

- Fast and precise multiphysics modeling for coupled force, temperature, and vibration analysis.
- Machine learning algorithms for intelligent design and optimization.
- Integration of novel materials like graphene and nanocomposites.
- Development of adaptive structures with online parameter tuning.

Overall, this review contributes to the field by integrating recent advancements in LSM structural design, electromagnetic and thermal Modelling, and modern optimization strategies within a unified analytical framework. By consolidating findings across these domains, the study clarifies key design trade-offs, highlights persistent modelling and performance challenges, and outlines research directions that can

guide the development of more efficient and application-oriented LSM systems.

### Author Contributions

Conceptualization and supervision were carried out by Hamidreza Izadfar. The literature review and data collection were performed by Seyede Delaram Sadr. Analysis and interpretation of the reviewed studies were jointly conducted by Seyede Delaram Sadr and Hamidreza Izadfar. The initial manuscript was drafted by Seyede Delaram Sadr, while manuscript review and editing were undertaken by Hamidreza Izadfar.

### Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

### Acknowledgment

The authors declare that there is no acknowledgment for this study.

### Funding

This research received no external funding.

### Abbreviations

A list of abbreviations used in the manuscript is provided below:

|          |   |
|----------|---|
| PMLSM    | Permanent Magnet Linear Synchronous Motor                     |
| FEM      | Finite Element Method   |
| LSM      | Linear Synchronous Motors                                     |
| MEC      | Magnetic equivalent circuit                                   |
| PM       | Permanent Magnet  |
| WS-PMLSM | Winding Segmented- Permanent Magnet Linear Synchronous Motors |
| TRN      | Thermal Resistance Network                                    |
| MOO      | Multi-Objective Optimization                                  |
| GA       | Genetic Algorithms  |
| PSO      | Particle Swarm Optimization                                   |
| Maglev   | Magnetic Levitation   |
| HTS      | High-Temperature Superconducting                              |

### References

- [1] G. Lv, R. Zhi, L. Cui, B. Liu, "3-D analytical model of the end effect in the transverse flux linear synchronous motor for maglev vehicle with pitch angles," *IEEE Trans. Magn.*, 61(3): 1-8, 2024.
- [2] Y. Yang, Q. Wu, "A fast prediction method for thrust performance of axial array permanent magnet synchronous linear motor," *IEEE Access*, 12: 91242-91251, 2024.
- [3] T. Wu, P. Dai, G. Xue, Y. Guo, G. Lei, J. Zhu, Y. Wang, "A novel thermal analysis method for tubular pm linear motors based on transfer learning," *IEEE Trans. Trans. Electr.*, 11(3): 7379-7388, 2025.
- [4] Q. Wu, G. Yang, E. Tang, L. Wang, X. Wang, Z. Wang, "A slotted double-primaries permanent magnet synchronous linear motor with a low thrust ripple," *IEEE/ASME Trans. Mechatron.*, 29(5): 3786-3798, 2024.
- [5] G. Lv, L. Cui, "Analysis and calculation for a novel transverse flux linear synchronous motor with 3-D magnetic circuit method," *IEEE Trans. Ind. Electron.*, 71(11): 14683-14690, 2024.
- [6] G. Lv, Z. Zhang, Y. Liu, T. Zhou, "Analysis of forces in linear synchronous motor with propulsion, levitation and guidance for high-speed maglev," *IEEE J. Emerging Sel. Top. Power Electron.*, 10(3): 2903-2911, 2022.
- [7] T. Dong, W. Feng, B. Zhang, Z. Fu, R. Fu, G. Zhao, "Analysis of natural vibration characteristics of permanent magnet linear synchronous motor considering elastic contact," *IEEE Trans. Appl. Supercond.*, 34(8): 5203805, 2024.
- [8] T. Dong, R. Fu, B. Zhang, B. Peng, X. Wei, "Analysis of permanent magnet linear synchronous motor made by oriented silicon steel sheet," *IEEE Trans. Ind. Appl.*, 53(3): 3332-3340, 2023.
- [9] H. Shi, W. Yang, S. Fu, H. Liu, J. Yang, K. Li, "Characteristics analysis and dynamic test of air-cored permanent magnet linear synchronous motor for null-flux pmeds vehicle," *IEEE Trans. Instrum. Meas.*, 73: 3524115, 2024.
- [10] L. Li, J. Zhang, H. Qiao, S. Li, H. Lan, Z. Xu, "Design and optimization of a new structure PCB coreless-type linear motor," in *Proc. IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*: 674-678, 2024.
- [11] A. Boduroglu, Y. Demir, B. Cumhur, M. Aydin, "A novel track structure of double-sided linear PM synchronous motor for low cost and high force density applications," *IEEE Trans. Magn.*, 57(2): 8201305, 2021.
- [12] C. Wen, J. Liu, W. Wang, J. Liu, Z. Zhao, J. Liu, "Research on improved permanent magnet linear synchronous motor for direct-drive application," *IEEE Trans. Magn.*, 55(10): 8107007, 2019.
- [13] Z. Zhang, M. Luo, J. Duan, B. Kou, "Design and modeling of a novel permanent magnet width modulation secondary for permanent magnet linear synchronous motor," *IEEE Trans. Ind. Electron.*, 69(3): 2749-2758, 2022.
- [14] J. Di, H. Chen, H. Chen, J. E. Fletcher, L. Meng, "Design of line-start permanent magnet linear synchronous motors with transient optimization," *IEEE Trans. Ind. Appl.*, 61(1): 77-88, 2025.
- [15] F. Yue, Z. Sun, W. Xu, Md. R. Islam, "Electromagnetic design and vibration analysis of a homopolar linear synchronous motor," *IEEE Trans. Appl. Supercond.*, 31(8): 0602405, 2021.
- [16] N. N. L. Do, A. J. Taberner, B. P. Ruddy, "A linear permanent magnet synchronous motor for large volume needle-free jet injection," *IEEE Trans. Ind. Appl.*, 55(2): 1437-1446, 2019.
- [17] A. Boduroglu, M. Gulec, Y. Demir, E. Yolacan, M. Aydin, "A new asymmetric planar v-shaped magnet arrangement for a linear PM synchronous motor," *IEEE Trans. Magn.*, 55(7): 8105905, 2025.
- [18] L. Wu, Y. Li, Q. Lu, "Detent force fast optimization method of modular permanent-magnet linear synchronous motors," *IEEE Trans. Ind. Electron.*, 71(12): 16191-16199, 2024.
- [19] Y. Mao, Z. Sun, W. Zhou, Z. Zhuang, H. Qian, "Electromagnetic design of toroidal permanent magnet linear synchronous motor," *IEEE Access*, 9: 98005-98012, 2021.
- [20] L. Yu, S. Chang, J. He, H. Sun, J. Huang, H. Tian, "Electromagnetic design and analysis of permanent magnet linear synchronous motor," *Energies*, 15(15): 5441, 2022.
- [21] Z. Xiao, J. Fang, L. Nie, X. Wang, Y. Zan, C. Wang, "Excitation field analysis of cogging-free superconducting motors for electromagnetic catapult," *IEEE Trans. Appl. Supercond.*, 34(8): 5209504, 2024.
- [22] R. Xu, J. Zhao, J. Wang, Z. Yu, Z. Pan, L. Wang, S. Wang, X. Hu, M. Jiang, "Heat transfer performance improvement of permanent magnet synchronous linear motor based on embedded staggered double channel water cooling structure," *IEEE Trans. Transp. Electr.*, 10(4): 10158-10168, 2024.
- [23] K. Yang, L. Zhang, R. Wang, "Hierarchical multi objective optimization of a multi sided permanent magnet linear synchronous motor with ring structure winding for conveyor systems," *IEEE Access*, 12: 128833-128842, 2024.
- [24] Z. Lan, L. Chen, X. Xiao, Y. Luo, M. Deng, S. Zhu, "Detent force suppression of permanent magnet linear synchronous motor based on a V shaped tooth-slot structure," *IET Electr. Power Appl.*, 17(4): 535-546, 2023.
- [25] Q. Tan, B. Tian, X. Wang, X. Huang, L. Li, "Primary component segmental design to suppress the normal force ripple for the permanent magnet linear synchronous motor," *IET Electr. Power Appl.*, 18(7): 801-812, 2024.

- [26] Z. Xie, Q. Lu, W. Mei, Y. Li, "Improved analytical modeling of a novel ironless linear synchronous machine with asymmetrical double layer winding topology," *IEEE Trans. Ind. Appl.*, 57(2): 1411-1419, 2021.
- [27] Y. Zhao, Z. Liu, J. Gong, X. Yu, J. Qiu, J. J. Rodríguez-Andina, "Improved multiobjective optimization of tubular slotless permanent magnet linear synchronous motor for high performance Z Axis actuators," *IEEE/ASME Trans. Mechatron.*, 30(6): 1-12, 2025.
- [28] G. Lv, L. Cui, R. Zhi, "Inductance analysis of transverse flux linear synchronous motor for maglev trains considering three dimensional operating conditions," *IEEE Trans. Ind. Electron.*, 71(1): 769-776, 2024.
- [29] G. Lv, R. Zhi, L. Cui, B. Liu, "Magnetic field and force calculation of transverse flux linear synchronous motor with improved analysis model," *IEEE Trans. Transp. Electr.*, 10(3): 6361-6369, 2024.
- [30] Q. Sun, M. Wang, M. Liu, C. Zhang, L. Li, "Magnetic field distortion analysis and suppression for the minimum unit winding segmented moving magnet linear motor," *IEEE Trans. Ind. Electron.*, 71(4): 3452-3460, 2024.
- [31] Z. Zhao, W. Yang, Z. Yan, B. Jia, Y. Xu, J. Luo, "Mult objective optimization of superconducting linear motor considering general racetrack coils," *IEEE Trans. Appl. Supercon.*, 34(9): 3603209, 2024.
- [32] X. Hu, J. Zhao, Z. Pan, Z. Yu, X. Yang, "Optimal design of PMSLM based on extremum robust domain characteristic," *IEEE Trans. Ind. Electron.*, 71(6): 6063-6072, 2024.
- [33] F. Cui, Z. Sun, W. Xu, H. Qian, C. Cao, "Optimization analysis of long primary permanent magnet linear synchronous motor," *IEEE Trans. Appl. Supercon.*, 31(8): 0603504, 2021.
- [34] L. Nie, J. Fang, "Optimization of coreless high temperature superconducting linear synchronous motor," *IEEE Trans. Appl. Supercon.*, 34(8): 3603704, 2024.
- [35] A. Yingke Chen, B. Rong Wei, C. Zhigang Xue, "Optimization of long stator synchronous linear motors for high-speed maglev trains," in *Proc. IEEE 10th International Power Electronics and Motion Control Conference (IPEMC2024-ECCE Asia)*, 2024.
- [36] K. Liu, G. Ma, L. Jun, Z. Zhao, P. Zhou, J. Xu, "Performance improvement for superconducting linear synchronous motor with general racetrack coils," *IEEE Trans. Energy Conversion*, 39(2): 1436-1445, 2024.
- [37] J. Zheng, S. Nie, H. Jing, Y. He, M. Li, Y. Ma, Z. Ding, "Potential and electro mechanical coupling analysis of a novel HTS maglev system employing double sided homopolar linear synchronous motor," *IEEE Trans. Intell. Transp. Syst.*, 25(10): 13573-13583, 2024.
- [38] Q. Wu, L. Wang, G. Yang, E. Tang, X. Wang, "Ramming mechanism based on permanent magnet synchronous linear motor," *IEEE Trans. Transp. Electr.*, 10(1): 122-134, 2024.
- [39] Q. Tan, M. Wang, L. Li, J. Li, "Research on noninteger pole number for segmental permanent magnet linear synchronous motor," *IEEE Trans. Ind. Electron.*, 68(5): 4120-4130, 2021.
- [40] E. Shirzad, "Analytical model for double sided linear permanent magnet inner armature synchronous machine with slot-less stator at on-load in different patterns of magnetization," *Electr. Eng.*, 106: 1533-1547, 2024.
- [41] J. Di, J. E. Fletcher, W. Li, "Simplified piecewise model of line start permanent magnet linear synchronous motors," *IEEE Trans. Ind. Appl.*, 58(5): 6093-6104, 2022.
- [42] K. Mao, Y. Ji, X. Du, D. Hu, "Structural dynamics modeling of an on board hts magnet prototype cooled by solid nitrogen for high-speed maglev trains," *IEEE Trans. Transp. Electr.*, 10(4): 8298-8308, 2024.
- [43] J. Zhao, Q. Mou, C. Zhu, Z. Chen, J. Li, "Study on a double-sided permanent magnet linear synchronous motor with reversed slots," *IEEE/ASME Trans. Mechatron.*, 26(1): 3-12, 2021.
- [44] Q. Sun, M. Wang, M. Liu, L. Li, "Suppressing the eddy current damping of the permanent magnet linear synchronous motor by setting the toothed cooling plate," *IEEE Trans. Transp. Electr.*, 9(2): 3050-3059, 2023.
- [45] S. U. Chung, J. Y. Lee, "Teeth arrangement and pole slot combination design for PMSM detent force reduction," *Energies*, 14(23): 8141, 2021.
- [46] J. Di, J. E. Fletcher, W. Li, H. Xu, Y. Fan, "Transient analysis of line start permanent magnet linear synchronous motors," *IEEE Trans. Energy Convers.*, 36(4): 3365-3375, 2021.
- [47] X. Zhou, H. Li, L. Wang, C. Peng, S. Wang, L. Liang, Z. Deng, "Vertical dynamic response analysis of HTS maglev vehicle excited by a designed coreless typed PMSM," *IEEE Trans. Transp. Electr.*, 9(2): 3421-3433, 2023.
- [48] R. Fu, B. Zhang, T. Dong, W. Feng, F. Meng, "Vibration analysis of grain oriented silicon steel sheet PMSMs considering material anisotropy," *IEEE Trans. Appl. Supercon.*, 34(8): 5204405, 2024.
- [49] R. Fu, T. Dong, B. Zhang, G. Zhao, W. Feng, "Vibration analysis of pmsm considering magnetostriction under high intensity magnetic fields," *IEEE Trans. Magn.*, 60(10): 8102805, 2024.
- [50] G. Fuchs, A. Kugi, W. Kemmetmüller, "Magnetic equivalent circuit modeling of a permanent magnet linear synchronous motor composed of curved segments," *Mechatron.*, 104: 103256, 2024.
- [51] J. F. Gieras, Z. J. Piech, *Linear Synchronous Motors: Transportation and Automation Systems*. Boca Raton, FL, USA: CRC Press, 2000.
- [52] I. Boldea, *Linear Electric Machines, Drives, and MAGLEVs Handbook*. Boca Raton, FL, USA: CRC Press, 2013.
- [53] T. Lerch, "From transverse flux machine to fractional slot concentrated winding permanent magnet synchronous machine," *Arch. Elect. Eng.*, 73(2): 393-407, 2024.
- [54] S. Tariq, F. Khan, B. Ullah, N. Muhammad, B. Alghamdi, "Novel partitioned stator flux-switching permanent magnet linear machine: Design, analysis, and optimization," *Machines (MDPI)*, 11(3): 390, 2023.

## Biographies



**Seyede Delaram Sadr** was born in Dezful, Iran, in 1994. She received the B.Sc. degree in Power Electrical Engineering from Lorestan University in 2019 and the M.Sc. degree in Power Electronics and Electrical Machines Engineering from Iran University of Science and Technology in 2024. She is currently pursuing the Ph.D. degree in Power Electrical Engineering at Semnan University. Her research interests include the design and development of electrical machines and linear motors. She is particularly interested in the practical modeling and construction of electrical motors.

- Email: [S.Delaram\\_Sadr@semnan.ac.ir](mailto:S.Delaram_Sadr@semnan.ac.ir)
- ORCID: [0009-0005-3299-4833](https://orcid.org/0009-0005-3299-4833)
- Web of Science Researcher ID: NA
- Scopus Author ID: NA
- Homepage: NA



**Hamid Reza Izadfar** is currently an Associate Professor in the Electrical and Computer Engineering Department of Semnan University. His main research interests are the design and analysis of electric machines and drives.

- Email: [hrazadfar@semnan.ac.ir](mailto:hrazadfar@semnan.ac.ir)
- ORCID: [0002-0002-9685-0389](https://orcid.org/0002-0002-9685-0389)
- Web of Science Researcher ID: NA
- Scopus Author ID: NA
- Homepage: NA