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REVIEW ARTICLE

Concentric magnetic gears: A review of topological advances, the persistent rare-earth magnet dilemma, and a hybrid excitation pathway

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Abstract – Concentric magnetic gears (CMGs) offer significant advantages for electric vehicle drivetrains, including contactless torque transmission, high efficiency, and built-in overload protection. Despite these benefits, commercial viability is stalled by a heavy dependence on rare-earth permanent magnets (REPMs), which raises serious concerns about cost, supply chain security, and sustainability. This review critically examines strategies to mitigate this reliance. Analysis of recent topological innovations shows that while torque density has improved, the fundamental dependence on REPMs remains unchanged. Furthermore, direct reduction strategies, including system integration, material substitution, topological optimization, passive conductors, and complete electrification, often result in considerable performance trade-offs. Consequently, hybrid excitation is identified as a key paradigm shift. The core contribution of this review is the development of a clear taxonomy distinguishing "auxiliary electromagnetic integrations" for added functionality and "true hybrid excitation," where windings act as a co-primary source of magnetic flux. The study concludes that true hybrid excitation is the most strategic yet underexplored research area, uniquely enabling features such as variable gear ratios, overload resilience, and the capability to directly replace REPM volume. Therefore, focused research on true hybrid-excited CMGs is presented as the essential path toward developing sustainable, high-performance, next-generation magnetic gearing systems.

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1. Introduction

The global transition to electric vehicles (EVs) has intensified the demand for drivetrain solutions that are not only efficient and powerful but also highly reliable and sustainable. Mechanical gears, the cornerstone of conventional powertrains, are pivotal for power transmission, providing stable gear ratios for consistent performance [1]. Their high efficiency and proven operational safety have cemented their use across a broad spectrum of applications, from industrial machinery to automotive systems [1, 2]. However, the fundamental principles of mechanical gearing introduce inherent limitations. These systems require precision manufacturing and assembly, which increases complexity and cost [2]. The small contact areas between teeth result in high specific loads, necessitating enhanced surface hardness and advanced treatments, such as electrochemical-mechanical running-in (ECMR), to improve durability [2].

Furthermore, gears are subjected to complex mechanical stresses [1], demanding sophisticated design optimization to minimize weight and material usage [3]. Ongoing problems, such as frictional losses, acoustic noise, and the need for regular lubrication and maintenance, make their operation more challenging [4, 5]. This highlights the crucial role of early defect detection to avoid catastrophic failures [6]. The critical importance of overcoming these challenges is highlighted by a substantial and sustained body of research focused on mechanical gear failures, as evidenced by the high volume of related articles published from 2019 to 2024, as shown in Figure 1. This trend highlights the ongoing and escalating struggle to ensure the absolute reliability of mechanical gear systems, reinforcing the need for alternative technologies.

In this context, magnetic gears (MGs) present a promising alternative by enabling contactless torque transmission. This technology eliminates physical wear, drastically reduces noise and vibration, and offers maintenance-free operation with an extended lifespan [7-11]. Specific MG designs have demonstrated efficiencies of up to 99% [8], with continued advancements pushing the boundaries of torque density [9, 12, 13]. A key safety feature is their inherent overload protection, which prevents damage without requiring additional components, such as slip clutches [9, 14, 15]. Their quiet operation is particularly advantageous for noise-sensitive environments [10, 11], while their capability for high speed-reduction ratios makes them ideal for applications requiring significant speed conversion [7, 9]. The compact and energy-efficient nature of MGs is highly beneficial for modern applications, including electric vehicles and automated conveyor systems [14, 16]. The rising research interest in MG technology is quantitatively captured in Figure 2, which illustrates the average annual contributions over the past century. The sharp increase in the 2021-2024 period signals an accelerating viability for commercial deployment.

Concentric magnetic gears (CMGs), also known as coaxial magnetic gears, are the most extensively researched among different magnetic gear types due to their efficient utilization of magnetic fields and high torque density [11, 17]. However, they still face notable challenges. CMGs have traditionally relied heavily on expensive, REPMs raising substantial concerns regarding cost, supply chain security, and sustainability. Moreover, their high-speed performance can be compromised by eddy currents and iron losses, which can reduce efficiency in demanding applications [17]. While optimization strategies have mitigated some issues, the critical challenge of significantly reducing rare-earth content remains a primary research frontier.

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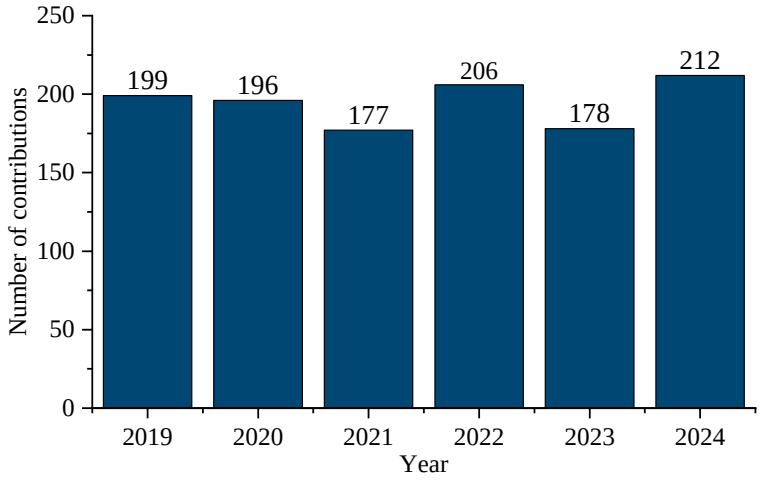


Figure 1. Annual number of publications on mechanical gear failures from 2019 to 2024. The sustained high publication count reflects persistent challenges in the reliability of mechanical gearing. Source: Scopus (Keywords = "mechanical" AND "gear" AND "failures"). Data updated December 2024

Several review articles provide insights into MG and CMG technology, highlighting their evolution, benefits, and challenges. [18] examines MG development with an emphasis on CMG industrial readiness. At the same time, [19] explores their potential as mechanical gear replacements in wind power, citing benefits such as reduced downtime but noting structural complexity and cost issues. Similarly, [20] assesses MGs in marine energy converters, highlighting operational cost reductions, while [21] focuses on torque density and reliability, identifying gaps in scalability. In the transportation section, [22] discusses the environmental benefits of MG. A comprehensive overview in [23] details MG designs and optimization strategies. Concurrently, [24] reviews rotary MG torque density, noting that radial coaxial types reach 239 Nm/L, a figure still below the torque density of mechanical gearboxes, which exceed 300 Nm/L. Computational modelling for high-torque applications is explored in [25], with [26] introducing new ripple factors and pole pair optimization. Further distinguishing applications, [11] reviews the advantages of MGs in wind and EV applications, while [27] analyzes field-modulated MGs, acknowledging their high torque density but citing implementation challenges. [28] classified CMGs into rotor-PM, reluctance, and emerging types, emphasizing their efficiency in the automotive, wind, and aerospace sectors. Crucially, a recent study [17] suggests that hybrid-excited CMGs could enhance performance, but it does not elaborate on the implementation or taxonomy of hybrid excitation.

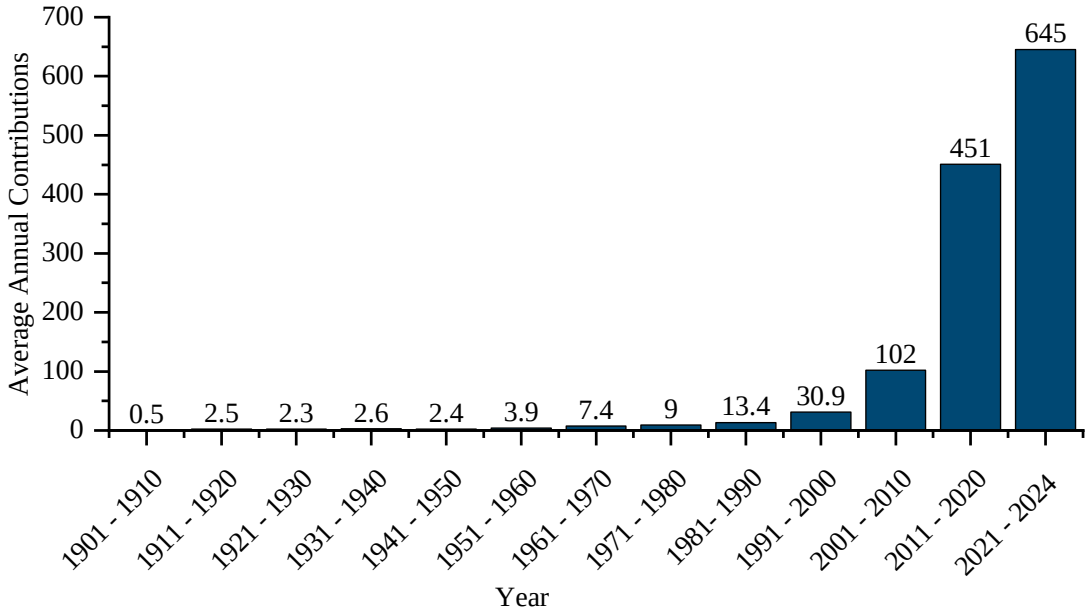


Figure 2. Historical growth of magnetic gear research expressed as average annual contributions (publications and patents). Data is normalized to correct for unequal time periods, revealing a significant acceleration in research output during the recent period from 2021 to 2024. Source: Google Scholar (Keyword = "magnetic gear")

This review bridges that gap in the literature by providing a focused analysis of recent concentric magnetic gear (CMG) developments, with a particular emphasis on strategies to mitigate dependency on REPMs. Section 2 systematically examines advances in CMG topologies, revealing that despite significant design innovations, a pervasive reliance on NdFeB magnets remains. Section 3 critically assesses strategies explicitly aimed at reducing REPM usage,

concluding that their impact, while promising, has been limited or accompanied by performance trade-offs. Section 4 presents the core contribution of this work: a clarified taxonomy and in-depth exploration of electromagnetic integration, distinguishing between auxiliary components for enhanced functionality and true hybrid excitation as a co-primary source of magnetic flux. This analysis identifies true hybrid excitation as the most strategic avenue for directly reducing REPM volume and enabling advanced capabilities, such as variable gear ratios, mitigation of PM demagnetization, and suppression of eddy current losses during high speed. Section 5 provides a quantitative synthesis of the design specifications from the reviewed studies, offering a data-driven consolidation of the research landscape. Finally, Section 6 summarizes the key findings and outlines a roadmap for future research, positioning the focused development of true hybrid-excited CMG topologies as the most promising pathway toward sustainable, high-performance magnetic gearing for next-generation EV drivetrains.

1.1 Literature Survey Methodology

This review is based on a systematic analysis of the literature concerning CMGs, with a specific focus on innovations from the last decade. The literature search was conducted using major academic databases, including those from publishers such as Elsevier, IEEE, and MDPI. A comprehensive set of keywords was employed, including "coaxial magnetic gear," "concentric magnetic gear," "hybrid excitation," and "field excitation windings," to ensure thorough coverage of the topic. The search strategy, detailed in Table 1, ultimately yielded a corpus of 144 sources. This final set consists primarily of peer-reviewed journal and conference articles (139), supplemented by patents (3) and relevant technical reports (2) to provide a complete technological overview.

Table 1. Systematic literature search strategy and results

Scope	Keywords	Results
Publisher: MDPI, Elsevier, IEEE, etc.	Coaxial magnetic gear Concentric magnetic gear Hybrid excitation Hybrid excited Electrical machine DC windings Finite element Auxiliary excitation windings Field excitation windings	Journal and conference articles (139) Patents (3) Website reports (2)

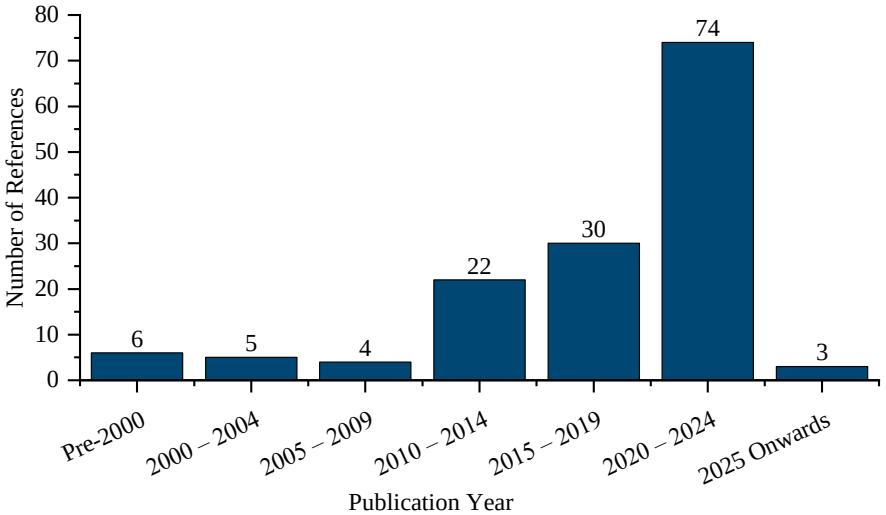


Figure 3. Chronological distribution of the literature referenced in this review. The data is grouped to highlight the rapid recent development of the field, with over 50% of the cited references published in the last five years (2020–2024)

The chronological distribution of these references is detailed in Figure 3. The data reveal a sharp increase in relevant publications, particularly over the last 15 years. The periods of 2010-2014, 2015-2019, and 2020-2024 account for 15.28%, 20.83%, and 51.39% of the total references, respectively. Crucially, articles published in the last five years (2020-2024) constitute the majority of the corpus, ensuring that the review's analysis is grounded in the most current research trends and technological advancements. The article selection process, detailed in Figure 4, was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure comprehensiveness, transparency, and reproducibility. To logically frame the findings from this literature search, the core analytical narrative of this review is structured around three central themes, as visualized in the conceptual map of Figure 5. The literature analysis is structured around three central themes: (i) recent innovations in topological

structures and configurations; (ii) design methodologies and optimization techniques to reduce rare-earth permanent magnet usage; and (iii) the application and benefits of hybrid excitation. A schematic overview of these focus areas is presented in Figure 5.

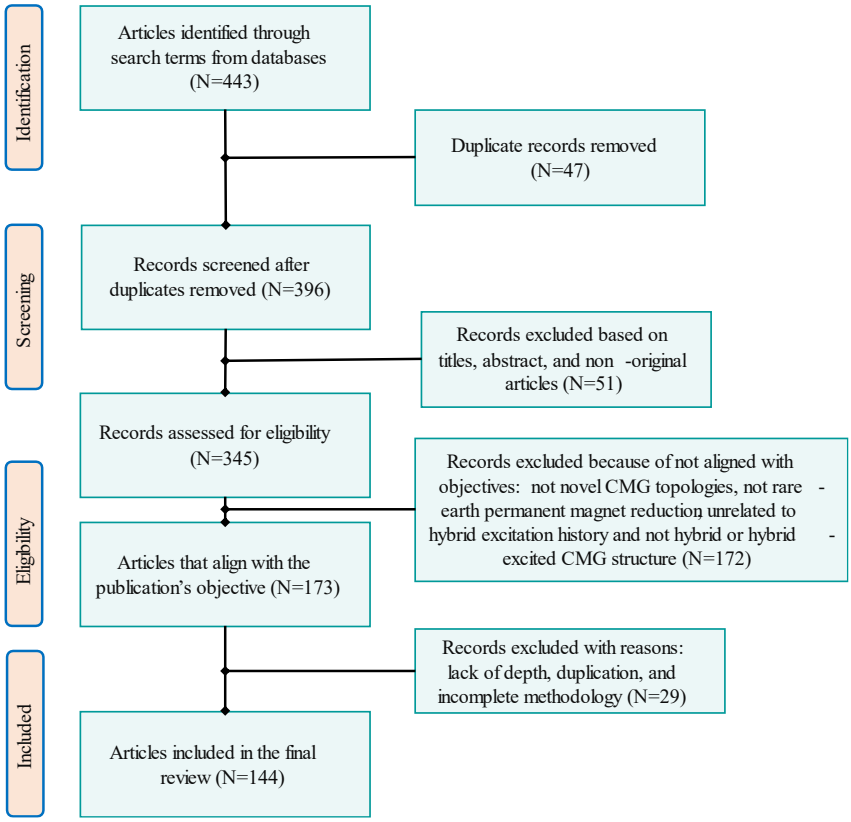


Figure 4. PRISMA flow diagram illustrating the systematic literature search and selection process, resulting in a final corpus of 144 relevant studies

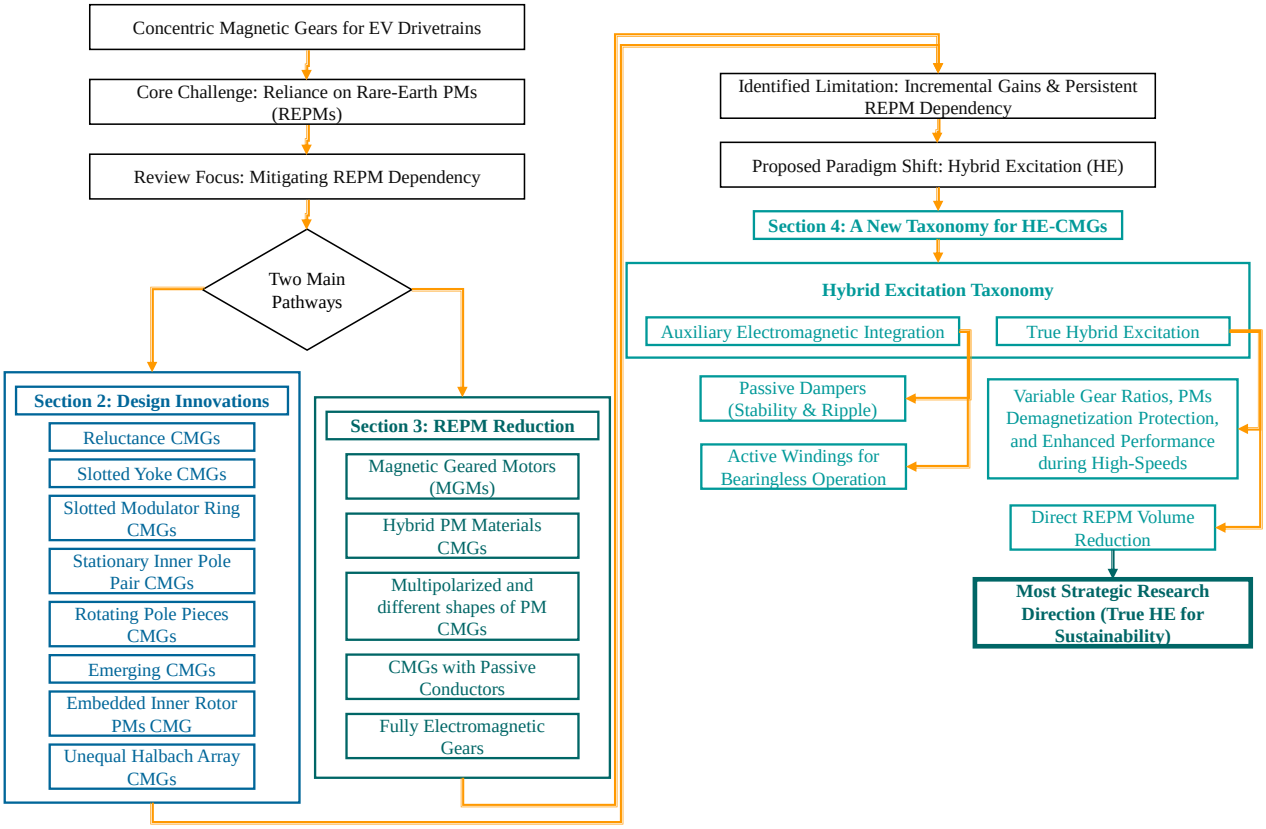


Figure 5. The analytical framework of the review paper

2. Recent Advances in Concentric Magnetic Gear Designs

This section provides a critical review of recent innovations in CMG topologies. The primary objective is to move beyond a mere catalogue of designs and instead evaluate their contributions and limitations through the lens of performance, manufacturability, and, crucially, their inherent dependency on REPMs. A central theme that emerges is the persistent trade-off between achieving high torque density and managing complexity, torque ripple, and REPM usage. Furthermore, this analysis highlights a significant gap between simulation-based studies and experimental validation, underscoring an area requiring urgent research attention.

To ensure clarity and allow for direct visual comparison across the diverse topologies discussed in this review, this paper adopts a unified "linearized 2D" visualization framework. Instead of full circular cross-sections, which can obscure component details, the gear structures are represented as stacked planar layers. This unified visualization strategy highlights the specific structural modifications introduced by each novel topology compared to the baseline Conventional CMG. Figure 6(a) establishes the baseline conventional CMG in this linearized form, showing the standard arrangement of the inner rotor, ferromagnetic pole pieces, and outer rotor. All subsequent structural innovations reviewed in this paper are presented using this standardized format to highlight their specific deviations from this baseline.

2.1 Reluctance Concentric Magnetic Gears

The concentric reluctance magnetic gear (CRMG) structure eliminates PMs from the inner rotor structure, thereby reducing cost and simplifying mechanical design [29]. This magnet-free rotor makes CRMG particularly suitable for high-speed and harsh environment applications [30-34]. Figures 6(b) to 6(g) present a comparative overview of the key reluctance rotor topologies developed to optimize this concept. Research has primarily focused on the salient pole (SP-CRMG) and flux barrier (FB-CRMG) topologies, shown in the linearized stacks of Figure 6(b) and 6(c), respectively [32]. While the SP-CRMG offers manufacturing simplicity, it is prone to higher acoustic noise and torque ripple [35, 36]. In contrast, the FB-CRMG can be optimized to reduce torque ripple despite a more complex design process [37-39].

Further optimization of SP rotors has been explored through variable geometry. Figures 6(d), 6(e), and 6(f) illustrate the variable tooth arc with inner centre point (VTIC-SP), variable tooth arc with middle centre point (VTMC-SP), and fixed tooth arc with arcuate groove (FTAG-SP), respectively [32]. Despite these innovations, the FB-CRMG consistently outperforms them. A distinct topology, shown in Figure 6(g), utilizes a non-ferromagnetic high-speed rotor core to reduce inertia, solidifying the potential of reluctance-based designs for high-dynamic applications [33]. A key advantage of this topology is its reduced REPM dependency, as magnets are confined to only one rotor.

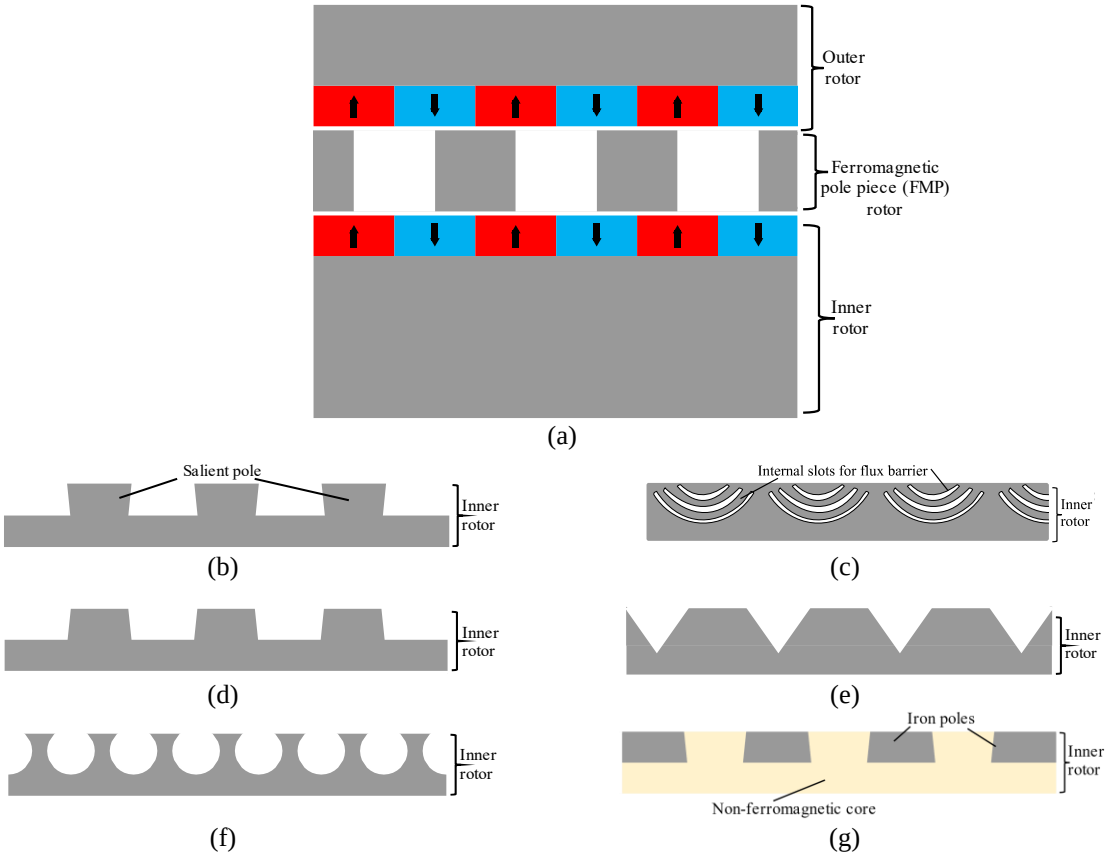


Figure 6. Linearized comparison of Reluctance CMG rotor topologies: (a) The baseline Conventional CMG; (b) Salient Pole (SP-CRMG); (c) Flux Barrier (FB-CRMG) [32]; (d) Variable tooth arc with inner centre point (VTIC-SP) [32]; (e) Variable tooth arc with middle centre point (VTMC-SP) [32]; (f) Fixed tooth arc with arcuate groove (FTAG-SP) [32]; and (g) Non-ferromagnetic inner rotor core [33]

2.2 Slotted Outer Rotor Yoke Concentric Magnetic Gears

To enhance torque density by reducing active mass, researchers have introduced slotted outer rotor yoke designs [40,41]. These designs strategically remove non-critical iron from the central portion of the yoke, which contributes minimally to torque transmission. Figure 7(a) illustrates this linearized outer yoke topology, where rectangular slots are introduced into the ferromagnetic back iron. This concept improves the mass-torque ratio but does not eliminate the fundamental reliance on REPMs. A secondary advantage is the creation of space within the yoke, enabling the potential integration of auxiliary components such as copper bars or field excitation windings [42].

2.3 Slotted Modulator Ring Concentric Magnetic Gears

The ferromagnetic pole pieces (FMPs) are the most critical component for flux modulation. Slotting the modulator ring significantly reduces silicon steel consumption and associated eddy current losses. A study in [43] demonstrated that a slotted FMP structure, shown in Figure 7(b), could reduce eddy current and iron losses by 66.57% and 8.9%, respectively. Building on this, the impact of bridge position on mechanical integrity and magnetic performance has been analyzed in [44]. Figures 7(c), 7(d), and 7(e) illustrate the linearized slotted modulator with inner, centre, and outer bridges, respectively. Analysis indicates that the inner bridge configuration with Halbach array magnetization delivers the maximum static torque. However, while the slotted modulator is superior for loss reduction, its performance is critically dependent on the trade-off between electromagnetic efficiency and the mechanical stress limits of the bridges. And it does not address REPM dependency.

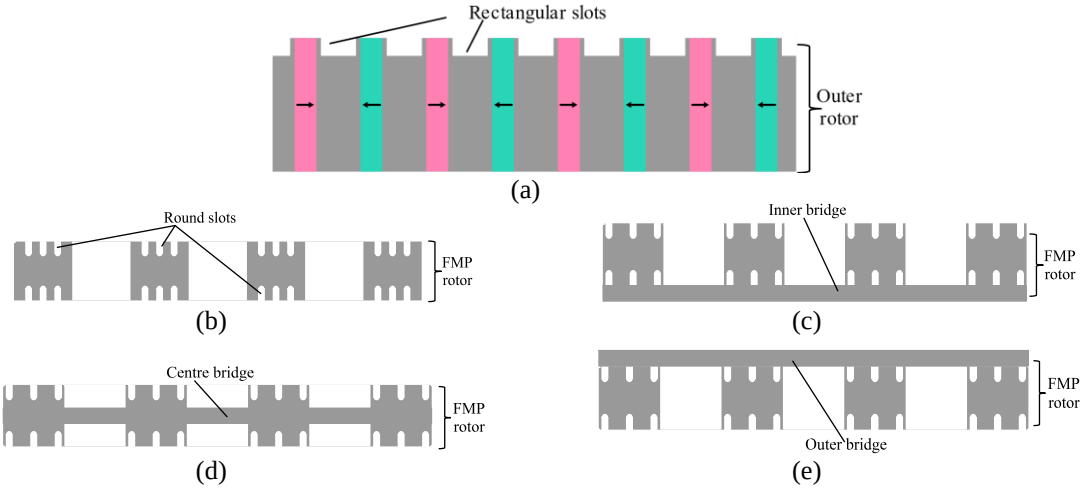


Figure 7. Linearized comparison of slotted and bridged ferromagnetic structures: (a) Slotted Outer Yoke CMG [40,41]; (b) Slotted Modulator Ring [43]; (c) Slotted Modulator with Inner Bridge; (d) Slotted Modulator with Centre Bridge; and (e) Slotted Modulator with Outer Bridge [44]

2.4 Stationary Inner Rotor Concentric Magnetic Gears

Conventional CMGs typically function as torque multipliers. However, an inverted topology proposed in [45] reconfigures the CMG as a speed multiplier. In this design, the inner PM assembly is held stationary, while the FMP ring acts as the high-speed inner rotor. This reconfiguration offers a 16% higher torque density and a 12% higher efficiency at high speeds compared to conventional fixed-FMP modes, while also improving mechanical robustness. However, this performance gain comes at the cost of a significantly higher torque ripple (65% vs. 25% in conventional designs) and does not reduce the system's REPM content.

2.5 Rotating Pole Piece Concentric Magnetic Gears

A key mechanical challenge in high-speed flux modulation machines is ensuring rotor integrity against centrifugal forces. The adhesive strength alone is often insufficient to withstand the centrifugal forces at high speeds, necessitating the use of a retaining sleeve to provide additional support. The Rotating Pole Piece CMG (RPMG) presents an innovative solution by reconfiguring the standard topology such that the FMPs rotor acts as the low-speed output rotor [46]. This configuration enables the outer permanent magnet array to remain stationary, thereby eliminating centrifugal forces on the outer component and eliminating the need for a retaining sleeve. This mechanical innovation also yields performance benefits, as the RPMG configuration inherently maximizes the gear ratio, leading to a higher transmitted torque capability. Initial studies demonstrated an 18% higher average torque than conventional CMGs.

Subsequent design optimization achieved exceptional torque densities of 364.5 kNm/m³ while successfully maintaining torque ripple below 15% [47]. This result underscores the significant performance potential of the RPMG structure, albeit with a continued high dependency on REPMs. The evolution of this topology also provided valuable insights for other MG architectures. The authors' early suggestion to introduce an auxiliary field to mitigate torque ripple in RPMGs [46] served as a direct precursor to the development of hybrid-excited CMGs, which are discussed in detail in Section 4 [48].

2.6 Emerging Concentric Magnetic Gears

This category encompasses novel CMGs that employ advanced materials and complex multi-component configurations to push performance limits. These MGs are referred to as emerging CMGs, as mentioned in [28]. A prominent example is the dual flux modulator CMG (DFM-CMG) with a double-layer permanent magnet (DLPM) inner rotor. As illustrated in the linearized topology of Figure 8(a), this design combines the benefits of multilayer PMs to reduce flux leakage and increase rotor saliency, resulting in superior torque characteristics compared to single-layer designs [49-51]. In the domain of advanced materials, research into CMGs utilising high-temperature superconducting (HTS) bulks continues to advance. Existing designs [52-56] exhibit high torque density but suffer from several drawbacks, including complex structures, significant torque ripple, and demanding technical processing requirements. To address the complexity of earlier designs, a model replacing the epoxy resin in the FMP ring with yttrium barium copper oxide (YBCO) HTS bulks was proposed [57].

Figure 8(b) illustrates this structure, where, upon cooling below 77 K, the superconducting material exhibits magnetic resistance, directing magnetic flux through the ferromagnetic segments while minimizing losses. Additionally, a carbon fibre frame reduces the mass of the FMP ring, and a circulating condensate cooling system, powered by an external HTS motor, maintains optimal operating temperatures. The vacuum chamber provides insulation, further reducing thermal leakage. Further innovations focus on guiding magnetic flux. Figure 8(c) shows an MG with an auxiliary silicon steel sheet placed outside the outer rotor, providing a low-reluctance return path to reduce flux leakage [58]. Another significant configuration is the Halbach Array Field Modulated Permanent Magnetic Gear (HFMPMG) [59]. Shown in Figure 8(d), this design features a dual-layer PM outer rotor, combining a Halbach array with conventional radial magnetization to optimize radial magnetic density. While these emerging CMGs push the boundaries of performance, they often increase complexity and cost and remain fundamentally reliant on REPMs for high torque density.

2.7 Embedded Inner Rotor Permanent Magnets Concentric Magnetic Gears

Embedding PMs within the rotor yoke enhances mechanical integrity at high speeds but often degrades electromagnetic performance. A study in [60] found that a standard buried PM configuration, illustrated in Figure 8(e), significantly reduced torque density. However, a strategically embedded design [61], shown in the linearized inner rotor of Figure 8(f), embedded the inner magnets flush with the rotor surface to preserve the active area. By pairing this radially magnetized inner rotor with an outer rotor Halbach array, the achieved topology resulted in a 16% increase in torque and a significant reduction in ripple. This stark contrast highlights that the success of embedded magnets is highly design-dependent, and like surface-mounted designs, they maintain a high REPM dependency.

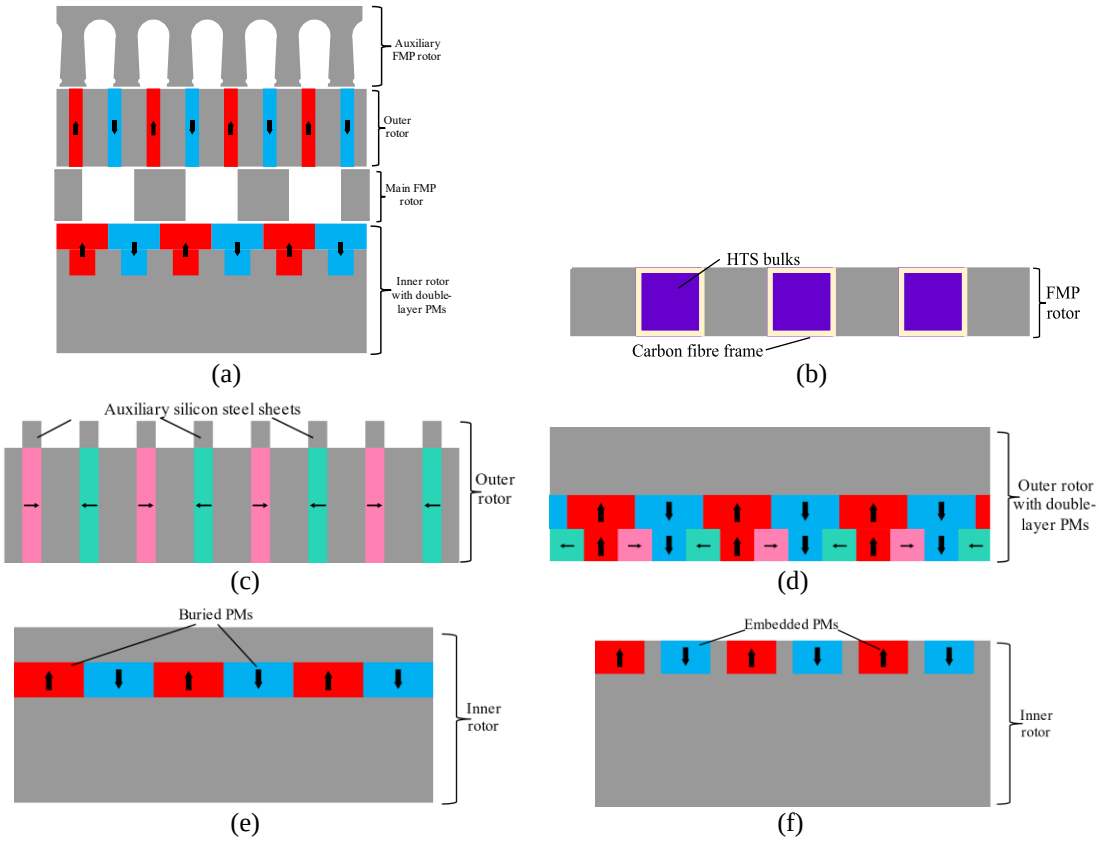


Figure 8. Linearized comparison of emerging and embedded rotor topologies: (a) Dual Flux Modulator CMG with double-layer PMs inner rotor [49]; (b) Modulator with HTS bulks [57]; (c) Outer rotor with auxiliary silicon steel sheets [58]; (d) HFMPMG dual-layer outer rotor [59]; (e) Inner rotor with buried PMs [60]; and (f) Inner rotor with embedded PMs [61]

2.8 Bridge and Non-Bridge Modulator Concentric Magnetic Gears

The FMPs are the primary source of loss in CMGs [62]. This is because the modulator receives two sources of flux density changes from the inner rotor PMs and outer rotor PMs, relative to the location of the part. Eddy current loss at the outer PM registered a higher value than the inner rotor because the PM size at the outer rotor is larger than that at the inner rotor. Therefore, their structural support presents a design dilemma.

A novel concept proposes eliminating separate modulators by using strength-modulated PM pole pieces on the outer PM rotor structure, thereby reducing part count at the cost of increased fabrication complexity [63]. Besides that, FMPs must be supported against strong magnetic forces; that's why a bridge is often employed to connect them, but this reduces the slip torque [64-66]. Furthermore, bridges are not universally employed [67,68]. This adds complexity to fabricating a CMG prototype. A crescent-shaped FMP ring, shown in Figure 9(a), was also proposed to enable bridgeless modulators using non-magnetic material [69]. A recent study [70] on bridged modulators and clamping rods, illustrated in Figure 9(b), found that reducing bridge thickness boosts torque but increases mechanical stress. Additionally, increasing the diameter and number of clamping rods enhances mechanical strength but may result in higher eddy current losses that must be managed. This ongoing dilemma illustrates that even optimizing passive components does not address the core issue of REPM dependency.

2.9 Unequal Halbach Array Concentric Magnetic Gears

The Halbach array is renowned for producing a highly sinusoidal magnetic field distribution, high torque density, enhanced magnetic field modulation, and reducing harmonic-related loss [71-75]. However, the design and manufacturing of Halbach arrays are complex and costly due to the precise arrangement of magnets required [76]. Specific configurations, such as the quasi-Halbach array, are susceptible to demagnetization under repeated overload, which can potentially degrade performance [77]. Recent work has focused on "unequal" Halbach arrays to optimize performance beyond standard sinusoidal distributions. Figure 9(c) illustrates the linearized inner rotor topology utilizing unequal Halbach arrays combined with non-uniform air gaps [78]. In contrast, Figure 9(d) depicts the linearized inner rotor structure featuring unequal Halbach arrays but integrated with uniform air gaps [79]. Distinct from standard unequal arrays, the inner rotor of a Non-uniform Air-gap Halbach CMG (NAH-CMG) featuring a modified PM shape is shown in Figure 9(e). This topology, although it utilizes a regular Halbach arrangement on the outer rotor, employs a unique, curved three-segment magnet structure on the inner rotor to create the non-uniform air gap [80]. While this design achieves a notable volumetric torque density of 172.8 kNm/m³, it exhibits higher torque ripple compared to conventional topologies. All three proposed designs represent the pinnacle of PM-focused topological optimization, delivering one of the highest reported torque densities; however, they also exemplify the most complex and REPM-intensive CMG architectures.

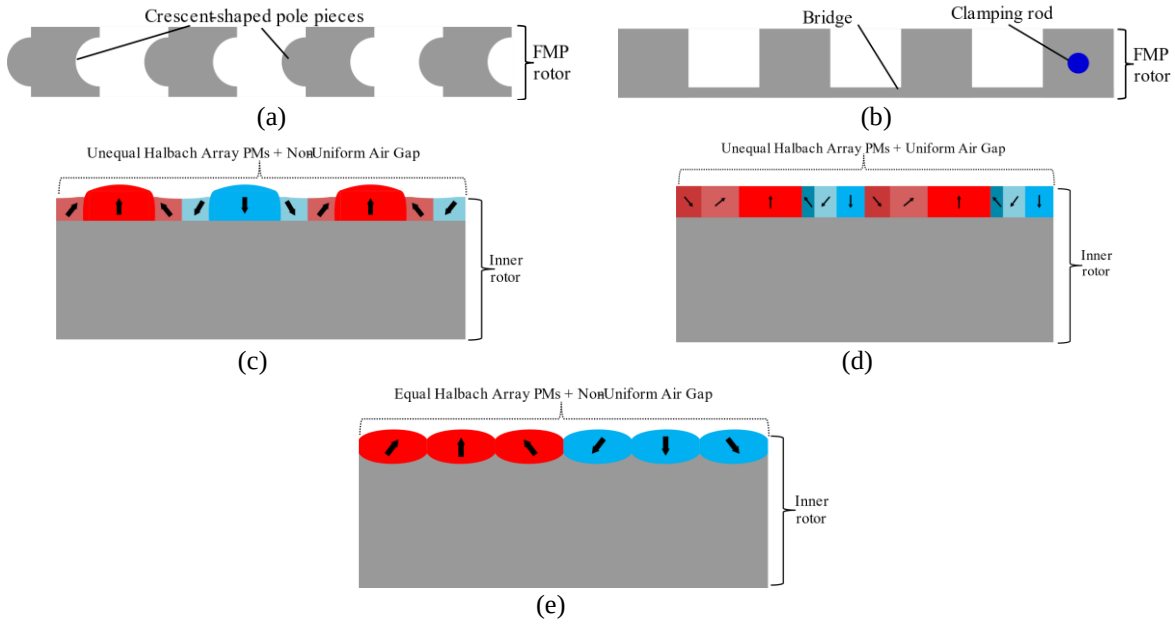


Figure 9. Linearized comparison of modulator supports and Halbach optimizations: (a) Bridgeless crescent shape FMP ring [69]; (b) Bridged Modulator with clamping rods [70]; (c) Unequal Halbach with non-uniform air gap [78]; (d) Unequal Halbach with uniform air gap [79]; and (e) Non-uniform Air-Gap Halbach (NAH-CMG) [80]

2.10 Synthesis of Design Trends and Rare-Earth Permanent Magnets Dependency

Table 2 provides a comparative summary of the CMG topologies discussed in this section. A critical analysis reveals a dominant and concerning trend: with the singular exception of reluctance-based designs, every high-performance CMG topology remains fundamentally dependent on NdFeB rare-earth magnets. The structural innovations detailed herein, from slotted components and rotated pole pieces to advanced Halbach arrays, have successfully advanced torque density and efficiency but have largely failed to address this core bottleneck. This pervasive reliance creates severe economic,

supply chain, and sustainability challenges. This observation necessitates a strategic pivot away from purely topological changes and towards fundamentally rethinking the excitation source itself, leading directly to the material-level strategies discussed in Section 3 and the paradigm-shifting hybrid excitation concepts in Section 4.

Table 2. Summary and critical analysis of CMG topologies in Section 2

Subsection & Topology	Primary Innovation	Key Advantages	Key Limitations & Research Gaps	REPM Dependency	Estimated Technology Readiness Level (TRL)
2.1 Reluctance CMGs	Eliminates inner rotor PMs.	Lower cost; high-speed capability; only PM demagnetization risk at the outer rotor	Lower torque density; high torque ripple/audio noise; structural fatigue of complex rotors not thoroughly analyzed.	Medium	6-7
2.2 Slotted Outer Rotor Yoke CMGs	Removes non-critical iron.	Reduced weight; improved mass torque density.	Does not reduce REPM use; weakens mechanical structure; lacks stress analysis.	High	3
2.3 Slotted Modulator Ring CMGs	Introduces slots in FMPs.	Reduced iron loss and consumption	Structural compromise: electromagnetic vs. mechanical performance of bridges; design complexity.	High	3
2.4 Stationary Inner Rotor CMGs	Inverted topology for speed multiplication.	Higher torque density and higher gear efficiency at high speeds.	Extremely high torque ripple (65%); non-standard operation.	High	3
2.5 Rotating Pole Piece CMG (RPMG)	Pole piece as outer rotor.	Eliminates the retaining sleeve in the outer rotor, achieving high torque density and simpler manufacturing.	High torque ripple and requires hybrid excitation for possible mitigation.	High	3
2.6 Emerging CMGs	Novel materials (HTS) / multi-component.	Very high potential performance.	High complexity and cost	High	3-4
2.7 Embedded Inner Rotor PMs CMG	Buried PMs for mechanical integrity.	Improved PM retention at high speed.	Conflicting findings on performance; often reduces torque and increases ripple; sensitive to design.	High	3
2.8 Bridge/ Non-Bridge Modulators CMGs	Novel structural support for FMPs.	Bridged and bridgeless: Manufacturable and can be optimized for maximum torque performance.	Bridged: Reduced torque capability if the bridge is thick. Non-bridged: Complex assembly and lower mechanical robustness.	High	3-4
2.9 Unequal Halbach CMGs	Optimized Halbach array segments.	Very high torque density; sinusoidal field.	High manufacturing cost/complexity	High	3

3. Design Strategies for Reducing Rare-Earth Permanent Magnet Usage in Concentric Magnetic Gears

The dependency on REPMs is a significant barrier to the sustainable and widespread adoption of CMGs. While CMGs share operational principles with permanent magnet synchronous motors (PMSMs) [81], their development faces a unique challenge: as a less mature technology than PMSMs, CMGs must compete for the same scarce REPMs despite their lower technology readiness level (TRL). This premature reliance, highlighted in Section 2, creates a significant bottleneck. Consequently, this section moves beyond structural innovations to review design strategies that directly target the mitigation of REPM usage. These strategies are evaluated on their potential for material reduction, performance,

complexity, and technological maturity. The persistent price volatility and supply chain risks associated with REPMs, as historically illustrated in Figure 10, underscore the critical nature of this research pursuit [82, 83], alongside projections of a three- to sevenfold increase in rare-earth demand by 2040 [84]. The ongoing development of reduced-rare-earth motor and MG technologies further emphasizes the urgency of this research [82,85].

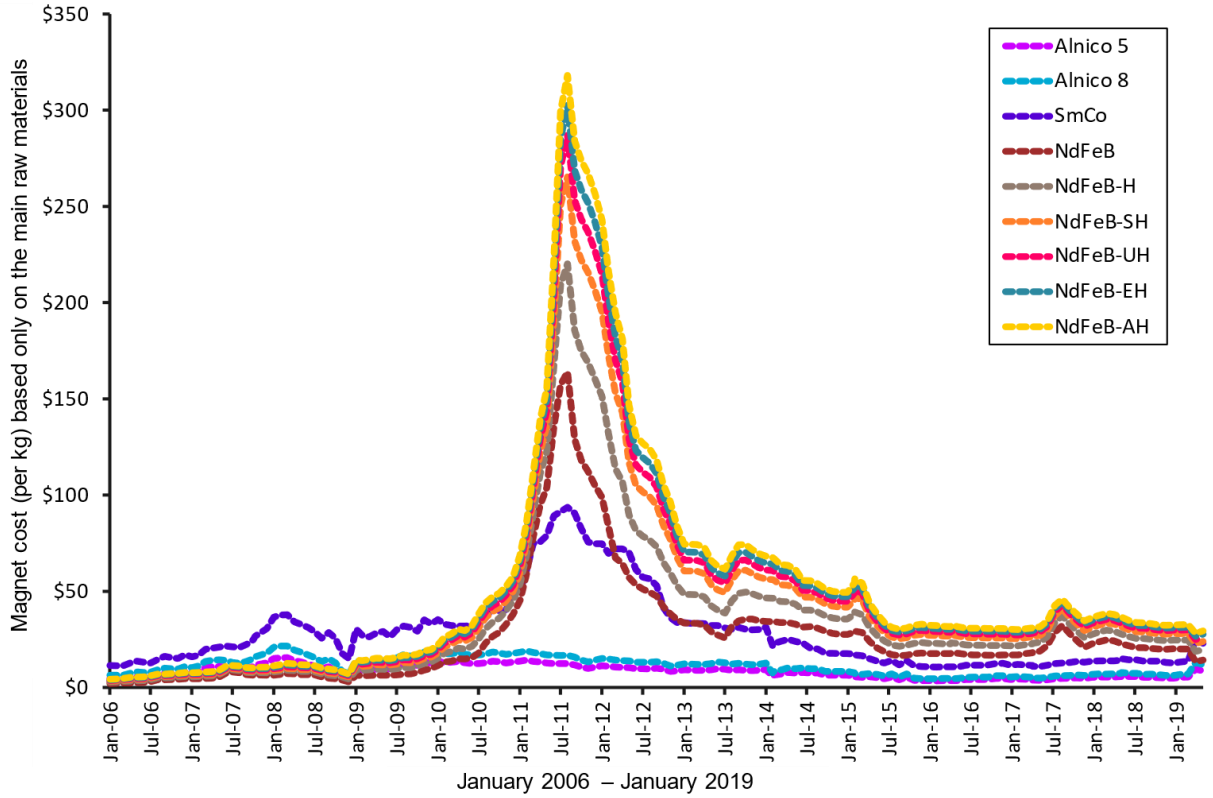


Figure 10. Historical cost trends for magnet (per kg) based on primary raw materials (2016-2019). Adapted from [85]

3.1 Concentric Magnetic Geared Motors

The integration of magnetic gears with motors into a single unit, known as a Magnetic Geared Motor (MGM), can lead to a reduction in the total PM volume of a system by sharing components and optimizing the magnetic circuit for dual functionality. This approach has gained recent attention, particularly with the integration of reluctance motors [86]. While reluctance motors generally exhibit lower torque density than fully PM motors [87], they are considered promising candidates for torque density enhancement through MG integration. A key challenge, however, is that integrating a conventional CMG with a reluctance motor reintroduces REPMs, negating a primary advantage. This limitation can be mitigated by adopting a fully reluctance-based magnetic gear (RMG), as illustrated in the linearized structure of Figure 11(a), or by utilizing an electromagnetic reluctance magnetic gear (ERMG) in combination with a segmented rotor–switched reluctance motor (SSRM) to reduce or eliminate PM usage [81]. This reflects an inherent trade-off: although complete removal of REPMs is achievable, it generally results in lower torque density compared to PM-based magnetic gear systems [86, 88].

In this regard, Dey et al. [81] proposed two configurations for achieving PM reduction: an electromagnetic reluctance magnetic gear integrated with an SSRM (ERMG-SSRM), shown in Figure 11(c), and a reluctance magnetic gear integrated with an SSRM (RMG-SSRM), shown in Figure 11(d). The ERMG-SSRM utilizes electromagnets for field excitation, resulting in a 100% reduction in PM material compared to a conventional PM-based MGM. In contrast, the RMG-SSRM employs a small amount of PM material for one field excitation while using salient poles for the other. The SSRM topology, depicted in Figure 11(b), was selected due to its approximately 40% higher torque density compared to conventional switched reluctance motors, which is attributed to its larger flux-conducting area per pole and its concentrated windings that reduce the end-winding length.

Furthermore, Byeon et al. [84] introduced an MGM with a shared rotor. The rotor core's width was strategically reduced to enhance the inner radius of a surface-mounted permanent magnet CMG motor (SPMGM), as shown in Figure 11(e). This design achieved the same torque density with a consistent diameter and stack height, allowing for a comparison with a similarly sized interior permanent magnet CMG motor (IPMGM), as shown in Figure 11(f). The improved SPMGM model achieved a 17.6% improvement in overall losses compared to the initial SPM model and demonstrated a 37.6% reduction in PM usage compared to the IPMGM model, establishing it as a more advantageous configuration for the shared rotor MGM [84]. This demonstrates that system-level integration can yield significant REPM savings without entirely abandoning the use of rare-earth materials.

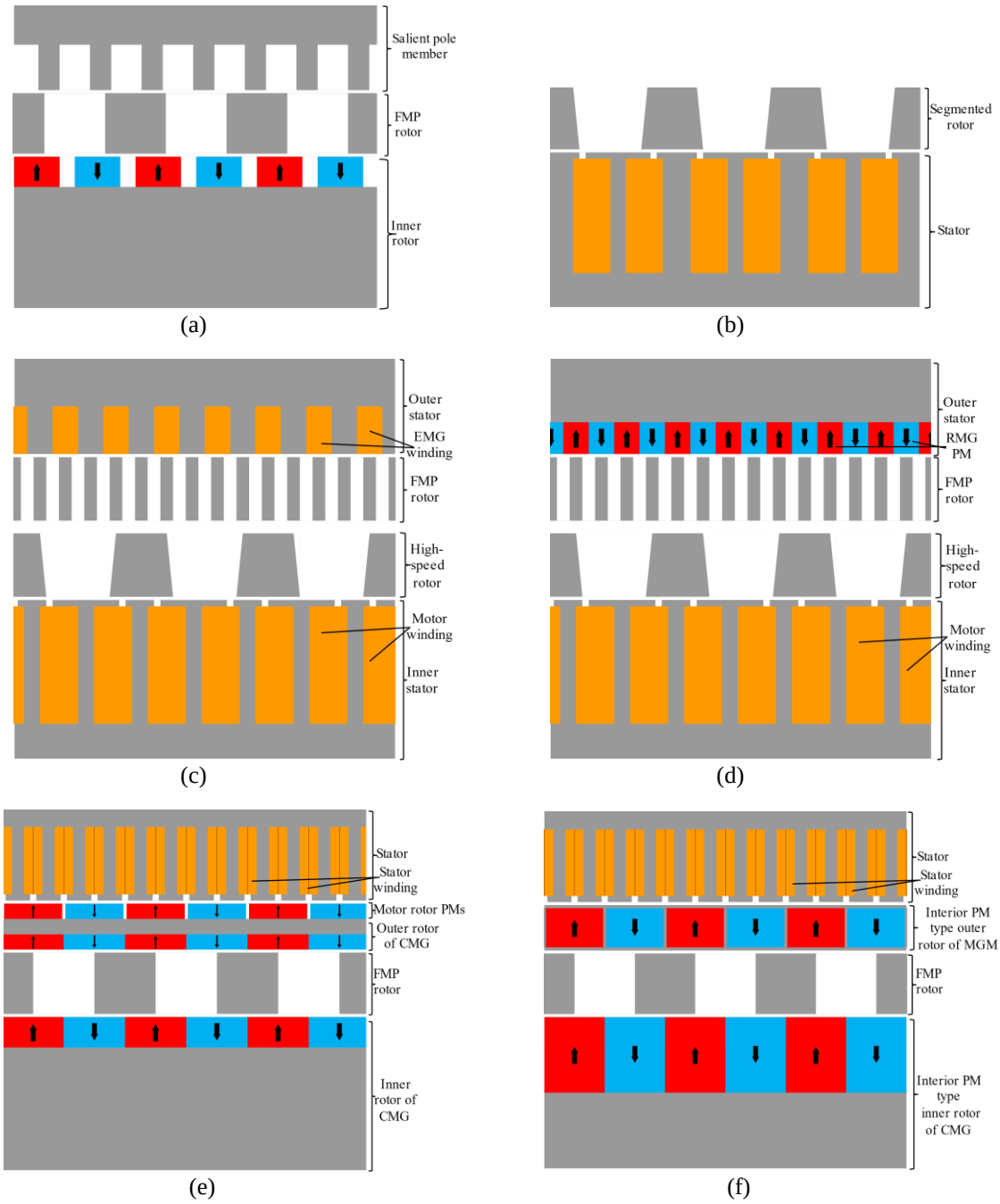


Figure 11. Linearized comparison of Integrated Magnetic Geared Motor (MGM) topologies: (a) Fully reluctance-based magnetic gear (RMG); (b) Segmented rotor–switched reluctance motor (SSRM) topology; (c) Electromagnetic reluctance magnetic gear integrated with SSRM (ERMG-SSRM) [81]; (d) Reluctance magnetic gear integrated with SSRM (RMG-SSRM) [81]; (e) Shared-rotor Surface-Mounted PMGM (SPMGM) [85]; and (f) Shared-rotor Interior PMGM (IPMGM) [85]

3.2 Hybrid PM Materials in Concentric Magnetic Gears

The use of hybrid PM materials, which combine high-performance rare-earth magnets (NdFeB) with lower-cost ferrite magnets, presents a direct strategy to mitigate cost and supply chain risks by displacing a portion of the REPM volume. Eddy current losses in conductive PMs pose a significant challenge for MGs, especially at high speeds where heat-induced demagnetisation is critical [89, 90]. Although NdFeB magnets are highly effective, their substantial eddy current losses at high speeds can render them unsuitable for such applications [91]. In contrast, ferrite magnets lack electrical conductivity and do not experience these losses.

Park et al. [91] analyzed CMGs using different PM materials, specifically comparing a ferrite model to an NdFeB model. Their study revealed a critical trade-off: while the ferrite model eliminates REPMs and associated eddy current losses, it requires a larger diameter to achieve a comparable output torque, which increases housing losses. Consequently, the efficiency of the two MGs reversed at a specific speed. Thus, while ferrite magnets can mitigate certain losses, they introduce new challenges related to size and efficiency at different operating points. Some literature advocates for ferrite magnets over NdFeB magnets due to their cost-effectiveness [91, 92, 93]. However, ferrite PM motors exhibit lower

torque density due to the low-energy product of ferrite magnets, resulting in lower magnetic loading [94, 95]. The price per volume of rare-earth PM materials is approximately 15 times that of ferrite PMs [96]. To balance cost and performance, recent rotor designs propose hybrid configurations that utilize both ferrite and rare-earth magnets [96, 97].

Malakooti and Afsari Kashani [98] developed a hybrid IPM inner rotor (HIPM) that strategically positions NdFeB and ferrite PMs, as illustrated in the linearized inner rotor topology of Figure 12(a). Through finite element method (FEM) and genetic algorithm (GA) optimization, they achieved a 70% reduction in NdFeB volume while maintaining nearly identical output torque, proving that ferrite magnets can effectively displace REPMs without compromising core performance. Similarly, Masoudi and Afsari [99] proposed a hybrid W-shaped IPM rotor (HWIPM) for CMG, as illustrated in Figure 12(b), which is explicitly optimized for cost. The resulting prototype achieved higher torque density and lower cogging torque than a conventional NdFeB design, with a minimal increase in total magnet volume, confirming a significant net reduction in expensive REPM content.

Furthermore, a comparative study on the NAH-CMG [80], as presented in Section 2.9, demonstrated that advanced topologies can enable the use of non-rare-earth alternatives. While NdFeB achieved the highest torque density, the Alnico-based CMG proved to be the most cost-effective. This confirms that a strategic trade-off, accepting lower torque density, can facilitate a complete transition to rare-earth-free systems using stable-supply magnets, such as Alnico, albeit with a higher risk of demagnetization.

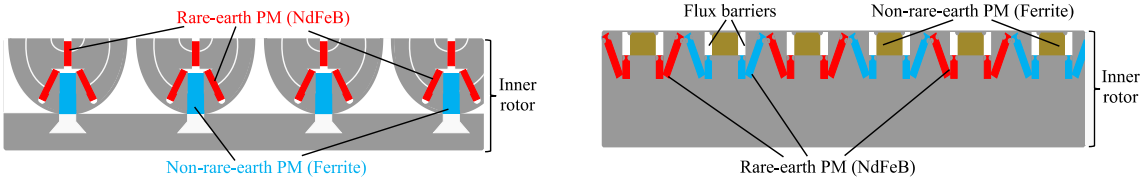


Figure 12. Linearized comparison of CMGs with Hybrid PM Inner Rotors: (a) Hybrid IPM (HIPM) rotor combining NdFeB and Ferrite [98]; and (b) Hybrid W-shaped IPM (HWIPM) rotor [99]

3.3 Multipolarized and Geometrically Optimized PMs

Optimizing the geometry and magnetization patterns of PMs is a highly effective pathway to improve magnetic flux utilization, thereby achieving higher torque per unit volume of magnet and reducing the required REPM mass. Sumi et al. [100] demonstrated this in a two-stage optimization for a large-scale CMG. Starting from a baseline with parallel magnets, introducing Halbach arrays and multipolarization increased the torque-to-weight ratio by a factor of 4.7. A subsequent re-optimization for PM reduction decreased the magnet weight by over 30% compared to the multi-polarized model, demonstrating that superior flux focusing directly enables material savings. In a different application, Song et al. [101] used rectangular PMs in a tool-changing CMG to minimize material waste and manufacturing complexity. This highlights that even simple geometric changes, such as moving away from custom arc-shaped magnets, can reduce costs and PM usage for specialized, lightweight applications.

3.4 3.4Concentric Magnetic Gears with Passive Conductors

A distinct strategy integrates passive conductive elements, such as copper bars, to enhance performance, which can indirectly permit a reduction in PM material. Unlike electromagnetic coils, these elements function reactively, improving stability without providing primary field excitation. Sun et al. [102] introduced a CMG where copper bars are embedded in the outer rotor for damping and, crucially, in the inner rotor to physically replace PM material at pole junctions, as illustrated in the linearized structure of Figure 13(a). This design achieved a 3.05% reduction in the inner rotor's PM volume while maintaining output torque and significantly reducing torque ripple. This demonstrates that passive conductors can enable a slight but direct reduction in REPM while enhancing dynamic performance.

3.5 Fully Electromagnetic Gears

The most radical approach to eliminating REPMs is the development of fully electromagnetic gears (EMGs), which replace all PMs with controlled DC windings or electromagnetic coils. These systems enable on-demand magnetic pole configuration, allowing for variable gear ratios and real-time torque control. Cao et al. [4] proposed an EMG, as illustrated in the linearized structure of Figure 13(b), using DC field windings on rotor teeth to create controllable poles. By altering the current distribution, the number of pole pairs can be reconfigured for smooth gear shifting and torque control. This offers a clear advantage over both fixed-ratio magnetic gears and earlier magnetic variable gears (MVGs) that still rely on partially magnetized PMs [103–105]. A more recent design by Megahed et al. [106] replaces all PMs with coils in both rotors, enabling five different gear ratios from a single structure. These designs achieve 0% REPM consumption. However, this comes with substantial trade-offs: continuous power is required for excitation, leading to higher operational losses; torque density is significantly lower than in REPM-based gears; and control complexity increases drastically. EMGs represent a promising direction only where flexibility and the complete elimination of REPMs are prioritized over power density and simplicity.

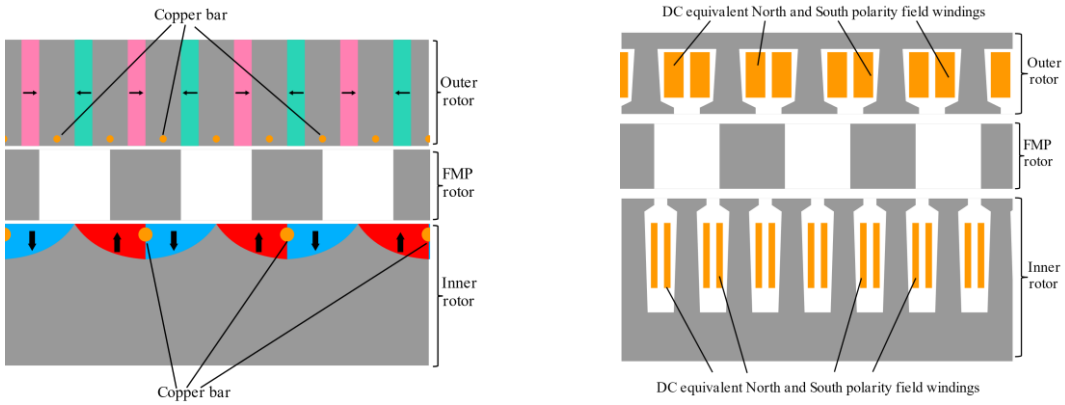


Figure 13. Linearized comparison of conductor-based CMG structures: (a) CMG with passive copper bars embedded in the inner and outer rotors [102]; and (b) Fully electromagnetic gear with DC field windings on both rotors [4]

3.6 Critical Discussion and Synthesis of Rare-Earth Permanent Magnets Reduction Pathways

Table 3 provides a synthesized critical comparison of the REPM reduction strategies discussed in this section. An overarching analysis reveals several key insights and conflicts:

- The Performance-Reduction-Complexity Trilemma: A consistent trilemma exists. Strategies that offer the highest REPM reduction (e.g., EMGs, complete ferrite substitution) incur the most significant penalties in terms of torque density or system complexity. Conversely, strategies that preserve high performance (e.g., hybrid PMs, topological optimization) offer more modest reductions in REPM.
- The Simulation-Prototype Gap: A significant portion of results, especially for innovative designs like hybrid arrays and MGMs, are simulation-based. The scarcity of experimental prototypes limits the validation of loss calculations, thermal management, and long-term reliability.
- Overlooked Structural and Lifecycle Analysis: The literature predominantly focuses on electromagnetic performance. There is a notable lack of integrated structural analysis for high-stress components and a comprehensive lifecycle assessment, including the recyclability of hybrid magnet arrays.

In conclusion, while the strategies in this section provide valuable pathways to reduce REPM dependency, each comes with significant compromises. This critical impasse highlights the need for a more fundamental paradigm shift in how magnetic flux is generated in CMGs, which directly leads to the exploration of hybrid excitation in Section 4.

Table 3. Critical comparison of REPM reduction strategies for CMGs in Section 3

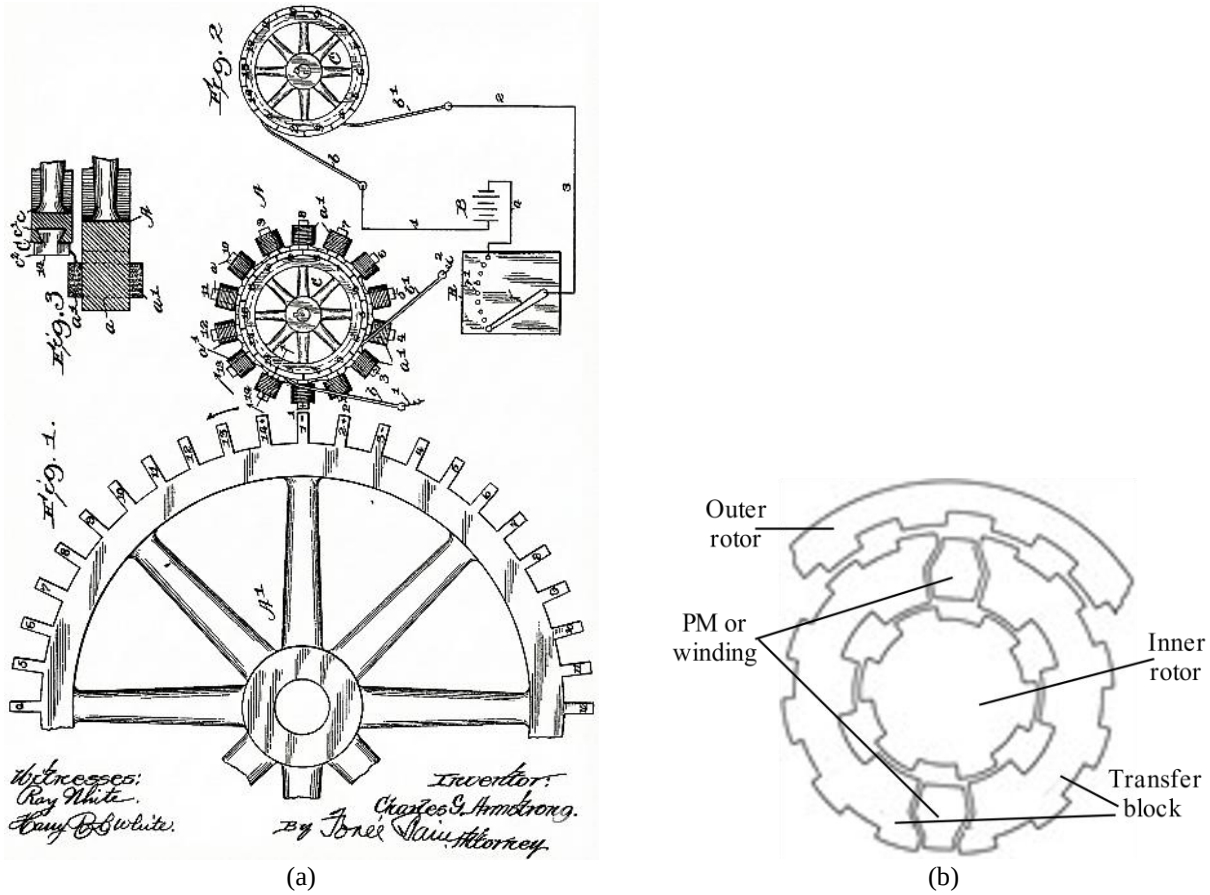
Subsection & Topology	Approach	Typical REPM Reduction	Impact on Torque Density	Key Advantage	Key Challenge & Research Gap	Estimated Technology Readiness Level (TRL)
3.1 Magnetic Geared Motors (MGMs)	System-level PM sharing	Low to Moderate	Minimal decrease	Reduces total system PM count; compact design.	Complex magnetic and structural analysis; control complexity; limited experimental validation.	3-4
3.2 Ferrite Substitution	Material replacement	100% (Full replacement)	Significant decrease	Very low cost; no REPM supply chain risk; no eddy current loss in PMs.	Large size for equivalent torque; low demagnetization resistance.	6-7
3.2 Hybrid PM Materials	Material mixing (NdFeB + Ferrite)	Moderate to High	Minimal decrease to slight increase	Good cost-performance trade-off; enhanced flux focusing.	Complex multi-objective optimization	6-7
3.3 Topological Optimization	PM shape & arrangement optimization	Moderate to high	Increase	Improves torque density and reduces PM use	Limited by physical constraints and complex manufacturing.	8-9
3.4 Passive Conductors	Partial replacement with copper damping bars	Low	Negligible to slightly positive	Reduces torque ripple & PM use without torque loss	Limited PM reduction; mechanical stress at interfaces	3-4
3.5 Fully Electromagnetic Gears (EMGs)	Full replacement with windings	100%	Significant decrease	No REPMs; enables variable gear ratios	Potential high excitation losses, low efficiency & power density, complex control.	3-4

4. The Paradigm Shift: Hybrid Excitation as A Path Beyond Permanent Magnets

Sections 2 and 3 of this review arrive at a convergent and critical impasse. Topological innovations, while boosting torque density, have largely cemented the dependency on REPMs. Conversely, strategies aimed directly at reducing REPM achieve their goals only through significant trade-offs in performance, size, or complexity, as summarized in Table 3. This stalemate indicates that incremental advances within the existing paradigm of permanent magnet excitation are yielding diminishing returns. This necessitates a fundamental rethinking of the excitation source itself. This section proposes that the most promising pathway forward is a paradigm shift toward hybrid excitation (HE), which involves integrating electromagnetic windings to work in concert with, or even supplant, permanent magnets.

In traditional electrical machines, key challenges, such as efficiency limitations, high torque ripple, cogging torque, thermal management issues, and control complexity [107, 108], have been identified by researchers. These challenges are also dependent on rare-earth materials [107-109]. By using HE, it has been demonstrated that HE provides various benefits across different electrical machine topologies [110-119], which include addressing all the aforementioned problems. The solution provided by hybrid excitation has motivated the implementation of this method in traditional electrical machines such as motors and generators. Consequently, several research questions have emerged among MG researchers regarding whether hybrid excitation can address the challenges faced by MGs. Traditionally, gears are viewed merely as components that facilitate the transfer of motion and torque rather than as standalone machines. However, with the introduction of the flux modulation principle, MGs have evolved into flux-modulated machines on their own right.

The integration of electromagnetic elements in gearing is not a new concept. Indeed, the very first magnetic gear, invented by Armstrong in 1901 and shown in Figure 14(a), relied solely on electromagnetic coils to generate magnetic force [120]. While the first purely PM-based magnetic gear was invented in 1941 [121] and Martin patented a CMG in 1964 [122], early designs often struggled with performance. A notable 1980 design, conceptually illustrated in Figure 14(b), utilized a DC coil or PM in a stationary transfer block to operate on the principle of reluctance torque, but achieved only 34.6% efficiency [123]. The paradigm shifted decisively with the advent of high-energy REPMs, culminating in Atallah's seminal 2001 CMG design [124]. This breakthrough sparked the modern era of PM-dominated magnetic gearing, as reflected in the surge in publication trends shown in Figure 2.



(a) (b)

Figure 14. Historical evolution of electromagnetic integration in magnetic gears: (a) The first magnetic gear, an electromagnetic transmission system designed by Armstrong in 1901 (U.S. Patent 687,292), digitally restored [120]; and (b) Schematic of a reluctance-based magnetic gear from 1980, utilizing a DC coil or PM for excitation (Redrawn from [123])

In contemporary research, a sophisticated return to electromagnetic integration represents not a regression, but an evolution, offering a direct solution to the core challenge of sustainability. However, a systematic review of the literature reveals a lack of conceptual clarity. The term "hybrid excitation" is often applied generically to a wide range of designs,

obscuring their fundamentally different objectives and mechanisms. To clarify this ambiguity and establish a strategic framework for future research, this section presents a crucial two-tier taxonomy for electromagnetic components in CMGs, as illustrated in the conceptual framework of this review (Figure 5).

i) Auxiliary Electromagnetic Integration: The incorporation of conductive elements or dedicated windings to enhance specific performance aspects such as stability or levitation without replacing the PMs as the primary excitation source.
ii) True Hybrid Excitation: The integration of windings that serve as a co-primary source of magnetic flux, working in concert with the PMs to enable advanced functionalities like variable gear ratios, performance enhancement, or, most critically, the direct displacement of REPM volume.

This classification is indispensable. It moves beyond vague terminology and establishes a clear research trajectory, underscoring that the most strategic avenue for developing sustainable CMGs is the targeted development of proper hybrid excitation.

4.1 Auxiliary Integration: Enhancing Functionality within the PM-Dominated Paradigm

This category encompasses designs where electromagnetic elements, typically passive conductors or specialized windings, are added to improve specific operational aspects. Passive copper elements such as bars, cages, or windings are integrated into MGs not as primary flux sources, but as auxiliary components that leverage induced eddy currents to enhance dynamic performance and torque capacity. Their function is purely secondary, activated by changes in the PM-dominated magnetic field to improve stability and overload resilience.

4.1.1 Suppression of transient oscillations

A well-established application of passive conductors is the suppression of torsional oscillations, a common issue in MGs due to their relatively low torsional stiffness compared to mechanical gears [125-127]. The concept is directly adopted from the damper windings used in synchronous machines to mitigate these oscillations [128], [129]. Research on concentric planetary MGs has demonstrated that integrating a squirrel-cage winding, comprising copper bars embedded in the high-speed rotor and short-circuited by end rings, can drastically reduce speed and torque oscillations during transients [125-127, 130]. Figure 15(a) illustrates the linearized inner rotor structure of this design, showing the embedded cage configuration.

The operating principle is passive and automatic: during a transient event, the relative movement between the rotors and the steady PM-induced magnetic field induces currents in the copper cage. According to Lenz's law, the resulting magnetic field opposes the relative motion, producing a damping torque. Extensive finite element analysis (FEA) studies have optimized this design, demonstrating that lower bar resistance (achieved through a larger diameter), an uninterrupted cage, and placement closer to the air gap maximize damping effectiveness, reducing settling time by over 80% in some cases [125, 127]. A notable alternative configuration proposed in [126] places the damper bars within the free spaces of the stationary ferromagnetic modulator, as illustrated in the linearized FMP rotor of Figure 15(b). This design reported even more rapid oscillation damping than the rotor-mounted designs, although a complete performance analysis was noted for future work.

4.1.2 Improvement of torque capacity and ripple reduction

Beyond transient damping, passive copper conductors can enhance steady-state torque and stability. In [42], copper bars were integrated into the slotted inner rotor, as illustrated in Figure 15(c), which increased the output torque from 178.04 Nm to 207.66 Nm. This boost is attributed to the magnetoresistance effect of the eddy currents, which beneficially modifies the air-gap field, thereby enhancing the gear's carrying capacity. A similar concept, as shown in the linearized outer rotor of Figure 15(d), was used in [142]. It used Halbach arrays for the inner rotor PMs and radial arrays for the outer rotor PMs, and slotted the outer rotor's yoke to add copper bars. This design improved air-gap harmonics, increased output torque, reduced torque ripple, and reduced eddy current and iron losses.

Crucially, [102] provides a precise mechanism: when the rotor speeds are synchronized, the copper bars are inactive. However, during speed discrepancies (e.g., from load disturbances), induced currents in the bars generate a stabilizing magnetic field that smooths torque transmission. This results in a significant reduction in torque ripple, by 34.42% on the inner rotor and 21.93% on the outer rotor, while also allowing for a 3.049% reduction in PM volume [102], as discussed in Section 3.4.

4.1.3 Active windings for bearingless operation

A distinct application of auxiliary windings is the creation of a bearingless magnetic gearbox. Here, a three-phase winding embedded between the FMPs, as shown in the linearized FMP rotor of Figure 15(e), is actively controlled to generate a controllable radial force on the high-speed shaft, providing magnetic levitation independent of torque transmission [132, 133]. It is critical to classify this as an auxiliary function because these windings are dedicated solely to levitation and do not participate in or control the main torque-producing magnetic field. FEA confirmed that this winding does not compromise torque performance, making it a promising solution for applications that require self-alignment and vibration suppression, such as helicopter transmissions. In summary, auxiliary integrations represent a mature and beneficial class of solutions for refining CMG performance. However, they leave the fundamental REPM dependency and fixed-ratio operation unchallenged.

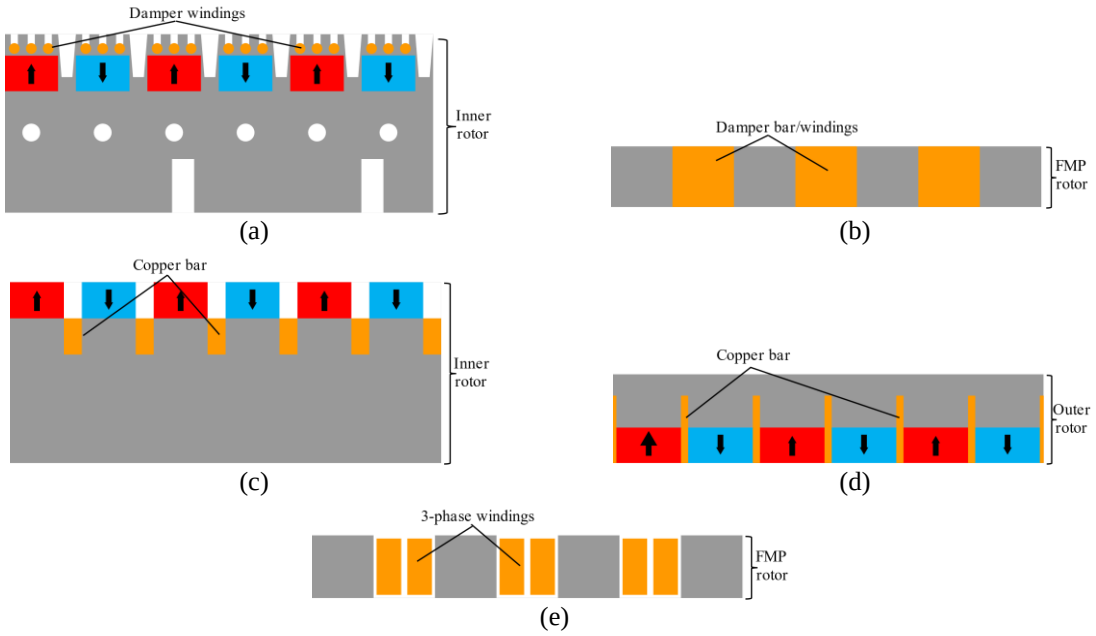


Figure 15. Linearized comparison of Auxiliary Electromagnetic Integrations focusing on rotor novelty: (a) Inner rotor with embedded squirrel-cage damper bars [127]; (b) FMP rotor with inter-pole damper bars [126]; (c) Slotted inner rotor with passive copper bars [42]; (d) Slotted outer rotor yoke with passive copper bars [131]; and (e) FMP rotor with embedded 3-phase active levitation windings [132, 133]

4.2 True Hybrid Excitation for Performance Control, Flux Regulation, and REPM Reduction

In contrast to auxiliary components, true hybrid-excited CMGs (HE-CMGs) integrate windings that serve as a co-primary source of magnetic flux, working in concert with the PMs. This enables active control of the machine's fundamental magnetic field, allowing for advanced functionalities.

4.2.1 Achieving variable gear ratios

The integration of hybrid excitation in MGs is particularly advantageous for transmission systems due to its potential for achieving a continuously variable gear ratio [134]. The development of variable-ratio CMGs is heavily inspired by the "memory machine" concept, which features an electrically controllable magnetization level. Ostovic initially proposed this concept for wide-speed range PM machines [135]. A key mechanism involves using an AC-excited armature current to magnetize or demagnetize Alnico PMs, thereby achieving a controllable air-gap flux density. Subsequently, DC-excited memory machines were developed, incorporating a small DC magnetizing winding into the stator to enable online magnetization control of the Alnico PMs [136, 137]. Generally, the DC-excited topology offers superior mechanical reliability and controllability compared to its AC-excited counterpart. Building on the memory machine concept, the work by Chen et al. [103-105] represents a seminal implementation of proper hybrid excitation. Their Magnetic Variable Gear (MVG) series features DC magnetizing windings integrated into the stationary modulator to dynamically remagnetize low-coercivity Alnico PMs, allowing for online, discrete changes to the fundamental pole pair numbers.

Figures 16(a) to 16(c) illustrate the linearized structural evolution of this concept. The original topology, shown in Figure 16(a), established the baseline mechanism but required a high magnetizing current [103]. The improved design, depicted in Figure 16(b), optimized the magnetic circuit to enhance efficiency [104]. Finally, the proposed MVG with a sophisticated stationary ring, illustrated in Figure 16(c), represents the culmination of this research lineage [105]. This trajectory successfully addressed key challenges, including reducing the required magnetizing current from 10 A to 1.5 A, increasing the number of available gear ratios from 6 to 16, and significantly improving torque density from 3.06 kNm/m³ to 24.76 kNm/m³. This demonstrates that proper hybrid excitation can unlock functionality impossible for conventional fixed-ratio magnetic gears, providing a contactless pathway to electronic continuously variable transmissions (E-CVTs).

A different strategy for achieving variable gear ratios, exemplified by the design of Padmanathan and Bird [138] and shown in Figure 16(d), employs a stator with a 3-phase AC winding that replaces the outer PM rotor. The AC excitation from this stator interacts with the magnetic field of the inner PM rotor, enabling continuous ratio control by regulating the electrical frequency. A further evolution of this power-splitting principle is presented by Wang et al. [139, 140]. Their magnetic continuously variable transmission (m-CVT) integrates a complete brushless PM machine as a "control rotor" within a magnetic gear. By actively controlling the speed of this rotor via its own stator, the system achieves a continuously variable gear ratio between the input and output shafts. This integrated magnetics approach has been experimentally validated, demonstrating high efficiency exceeding 97.5% [140]. It is essential to distinguish these variable-ratio systems, based on power splitting and integrated machines [138-140], from actual hybrid-excited topologies

[48, 103-105, 141, 142, 143, 144]. The former achieves variability through speed control of a free rotor, while the latter achieves it through direct control of the magnetic flux in the air gap.

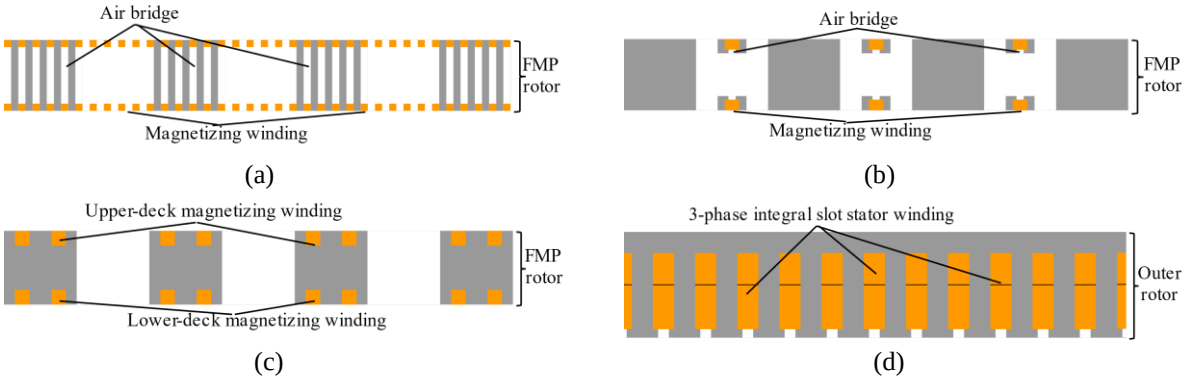


Figure 16. Linearized comparison of Variable Gear Ratio topologies: (a) Original modulator design [103]; (b) Improved modulator construction [104]; (c) Final proposed stationary ring topology [105]; and (d) 3-phase AC stator winding for continuous variable magnetic gear (CVMG) [138]

4.2.2 Mitigation of permanent magnets demagnetization under overload

Hybrid excitation effectively safeguards against irreversible PM demagnetization during overload. As illustrated in Figure 17(a), a design from [141, 142] incorporates DC field windings into a round-head slotted outer rotor. During a 200 Nm overload, a conventional CMG suffers a severe flux density drop at a PM point from 1.33 T to 0.42 T. In contrast, the HE-CMG utilizes its windings to generate a counteracting field, thereby maintaining flux density and ensuring system stability.

4.2.3 Suppression of eddy current losses at high speeds

At high speeds, hybrid excitation mitigates the efficiency loss caused by dominant eddy currents. A study on RPMG [48] introduced DC stator windings and evaluated different slot designs. Figures 17(b), 17(c), and 17(d) illustrate the linearized structures of the open slot, fully closed slot, and partially closed slot, respectively. The analysis demonstrated that a partially closed slot structure (Figure 17(d)) achieved the highest gear efficiency of 95.34% at an output speed of 12,256 rpm. By actively reinforcing the air-gap field, the hybrid excitation helps maintain torque while the optimized geometry reduces losses, showcasing its role in enhancing high-speed performance.

4.2.4 Direct reduction of rare-earth permanent magnet volume

The most strategically significant application of true HE is the direct substitution of REPM volume with ampere-conductors, directly addressing the core sustainability challenge. A foundational study [143] on a passive hybrid-excited CMG (PHE-CMG) took a critical first step. The design, derived from an RPMG, focused its innovation on the outer rotor structure. As illustrated in Figure 17(e), the consequent-pole outer rotor halves the number of PMs by replacing them with rectangular slotted iron poles. The key finding was that slotting the iron poles increases the total torque per unit of excitation material. Furthermore, without active excitation, the passive field excitation coils (FECs) acted as a parasitic mass, reducing excitation torque density and underscoring the necessity of active current injection to recover performance.

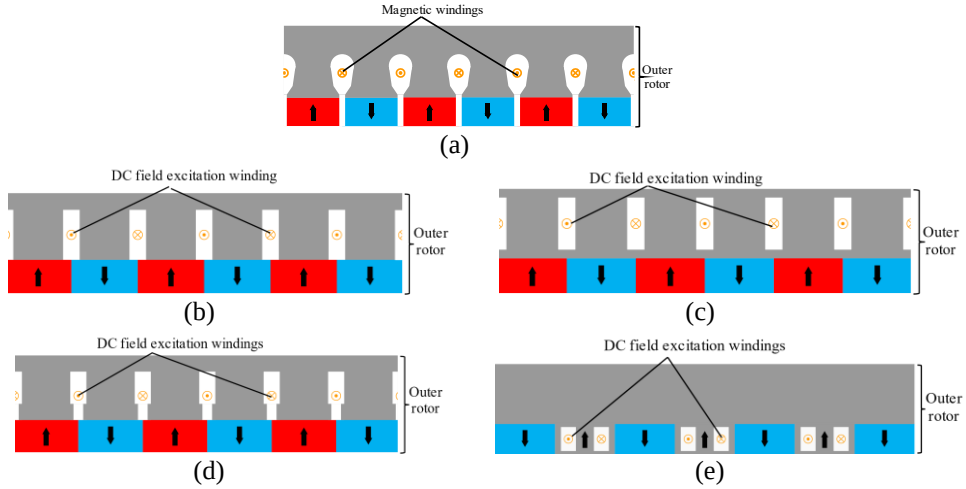


Figure 17. Linearized comparison of Overload, High-Speed, and Hybrid topologies focusing on rotor novelty: (a) Round-head slotted outer rotor yoke with magnetic windings [140, 141]; (b)-(d) Outer rotor structures with DC field excitation coils (FECs) featuring open, fully closed, and partially closed slots, respectively [48]; and (e) Consequent-pole outer rotor with rectangular slots and DC FECs [143, 144]

The conclusive progression of this concept is presented in [144], which details an actively excited HE-CMG. Utilizing the same outer rotor topology shown in Figure 17(e), this design actively energizes the FECs using a direct current (DC) supply. The study provided critical quantitative evidence that active excitation could increase torque by over 13% and achieve a 28% reduction in PM mass (0.292 kg) by supplementing with only 0.125 kg of copper, assuming advanced cooling strategies to manage the high current density (30 A/mm^2) required for peak torque. This demonstrates that HE can maintain high material efficiency while drastically reducing REPM content, establishing a viable pathway toward sustainable magnetic gearing.

4.3 Critical Synthesis and Future Roadmap

Table 4 synthesizes this taxonomy, providing a critical comparison of the different electromagnetic integration pathways. The analysis reveals a clear hierarchy of strategic importance. While auxiliary integrations are more technologically mature (TRL 5-6), they do not solve the REPM dilemma. True HE for performance control (TRL 3-4) offers exciting functionality but remains a complex solution. However, the application of true HE for direct REPM volume reduction (TRL 3) is the most strategically aligned yet least mature research frontier. Its underdevelopment is the primary bottleneck to sustainable CMGs. Future research must therefore be fiercely focused on this objective, addressing the critical gaps:

- Bridging the Simulation-Prototype Gap: The overwhelming majority of HE-CMGs, especially for REPM reduction, are simulation-based. Building and testing prototypes is the most critical step to validate thermal management, control strategies, and long-term reliability.
- Multi-Physics Co-Design: Future designs must integrate electromagnetic, structural, and thermal analysis from the outset to ensure mechanical integrity and manage heat from the windings.
- Advanced Control and Lifecycle Analysis: Developing sophisticated algorithms to manage the PM-electromagnet interaction optimally is crucial. Concurrently, the recyclability and full lifecycle impact of these hybrid material systems must be investigated.

In conclusion, this section has articulated the need for a necessary paradigm shift. The path forward for concentric magnetic gears lies not in further refining the arrangement of permanent magnets, but in fundamentally re-engineering the source of magnetic flux. True hybrid excitation is the key that unlocks this new paradigm, offering a definitive route to break the industry's costly dependence on rare-earth materials.

Table 4. Taxonomy and critical analysis of electromagnetic intergrations in CMGs in Section 4

Category	Primary Function	Excitation Role	Key Benefit	Key Challenge & Research Gap	Estimated Technology Readiness Level (TRL)
4.1.1 Damper Windings/ Bars	Suppress transient torsional oscillations caused by changes in speed or load.	Passive Reactive (Damps Oscillations)	Dramatically improves dynamic stability and reduces settling time (e.g., by more than 80%), thereby preventing mechanical stress.	Trade-off with torque density and steady-state losses. The conductive cage occupies space that could be used for magnets or flux paths.	5-6
4.1.2 Passive Stabilizing Conductors	Enhance steady-state performance: Increase torque capacity and/or reduce torque ripple (improves steady-state stability).	Passive Reactive (Shapes Air-Gap Field)	Increases torque density and creates a smoother torque output. It can also reduce the volume of PMs required and suppress non-working harmonics.	Complex interaction with the magnetic field. The effect is difficult to model analytically and is highly dependent on geometry and load.	3-4
4.1.3 Active Auxiliary Windings	Provide magnetic levitation (bearingless operation), enabling non-contact suspension.	Active Auxiliary (Generates Levitation Force)	Enables a fully magnetically levitated gearbox, eliminating the need for mechanical bearings and their associated maintenance, friction, and lubrication requirements.	High system complexity and cost. Requires integration of sensors, power electronics, and a real-time control system.	3-4
4.2.1 True Hybrid Excitation	Variable Gear Ratio & Flux Regulation	Active Co-Primary (Controls or Rewrites PM Field)	Enables discrete, online gear ratio changes; eliminates the need for complex mechanical gearboxes; uses non-rare-earth Alnico PMs.	Complex mechanical structure with embedded windings; requires precise rotor positioning during gear change.	3-4
4.2.2 True Hybrid Excitation	Overload & Loss Mitigation	Active Co-Primary (Regulates PM Field)	Prevents PM demagnetization under overload; improves torque density.	Increased thermal load from windings requires dedicated thermal management strategies and optimal integration of windings without compromising torque density.	5-6
4.2.3 True Hybrid Excitation	Enhanced Performance at High Speed	Active Co-Primary (Reinforces Air-Gap Field)	Suppresses eddy current losses; maintains high efficiency (>95%) and torque capability at very high speeds.	Complex magnetic circuit design (e.g., slot geometry); limited improvement magnitude with current topologies; trade-off between slot space and structural integrity.	3
4.2.4 True Hybrid Excitation	REPM Volume Reduction	Active Co-Primary (Replaces PM Field)	Directly reduces rare-earth dependency, addresses cost and supply chain risks, and enables tunable torque control.	Cooling of slotted consequent-pole rotors with integrated coils is unverified; it requires external power electronics for active excitation, adding system complexity.	3

5. A Quantitative Synthesis of the Concentric magnetic gears Research Landscape

The preceding critical discussion is powerfully substantiated by a comprehensive quantitative analysis of the design specifications compiled from over 50 studies in this review, as detailed in Tables 5-13. This data-driven synthesis presents a coherent and compelling narrative that spans the entire field of study. The specifications detailed in Section 2, as outlined in Tables 5, 6, and 7, provide unequivocal evidence of a pervasive dependency on NdFeB rare-earth magnets, confirming that topological innovations have primarily served to optimize performance within the constraints of REPM usage rather than to circumvent them. The sole significant exception, Reluctance CMGs, quantitatively validates the associated trade-off by demonstrating a substantial sacrifice in torque density for their reduction in REPMs.

Table 5. Design specifications of reviewed CMGs in Subsection 2.1

Reference	FMP	Reluctance Rotor Teeth	OPP	Excitation Source	Gear Ratio	Torque Density (kNm/m³)	Prototype Availability
[32] (VTIC-SP-CRMG)	15	9	12	NdFeB PMs	1.66	2.33	No
[32] (VTMC-SP-CRMG)	15	9	12	NdFeB PMs	1.66	2.35	No
[32] (FTAG-SP-CRMG)	15	9	12	NdFeB PMs	1.66	2.53	No
[32] (FB-CRMG)	15	9	12	NdFeB PMs	1.66	5.63	Yes

FMP: Ferromagnetic Pole Piece, OPP: Outer Pole Pair

Table 6. Design specifications of reviewed CMGs in Subsection 2.1

Reference	FMP	Inner Rotor Teeth	OPP	Excitation Source	Gear ratio	Torque Density (kNm/m³)	Prototype Availability
[33]	N/A (Parametric Study)			NdFeB PMs	N/A (Parametric Study)		No

FMP: Ferromagnetic Pole Piece, OPP: Outer Pole Pair, N/A: Not Available

Table 7. Design specifications of reviewed CMGs in Subsections 2.2 to 2.9

Reference	Subsection	FMP	IPP	OPP	Excitation Source	Gear ratio	Torque density (kNm/m³)	Prototype availability
[40]	2.2	27	4	23	NdFeB PMs	5.75	162.31	No
[41]	2.2	21	4	17	NdFeB PMs	4.25	121.71	No
[43]	2.3	21	4	17	NdFeB PMs	4.25	N/A	No
[44]	2.3	20	4	16	NdFeB PMs	4	N/A	No
[45]	2.4	14	8	6	NdFeB PMs	2.33	58.05	No
[46]	2.5	20	6	14	NdFeB PMs	3.33	158.20	No
[47]	2.5	30	6	24	NdFeB PMs	5	364.50	No
[57]	2.6	21	4	17	NdFeB PMs	4.25	N/A	No
[58]	2.6	21	4	17,^*34	NdFeB PMs	4.25	N/A	No
[59]	2.6	21	4	17,^^*68	N/A	4.25	158	No
[60]	2.7	20	6	14	NdFeB PMs	2.33	36.87	No
[61]	2.7	21	4	17	NdFeB PMs	4.25	N/A	No
[70]	2.8	27	4	23	N/A	5.75	N/A	No
[78]	2.9	21	4	17	NdFeB PMs	4.25	N/A	No
[79]	2.9	21	4	17	NdFeB PMs	4.25	N/A	No
[80]	2.9	21	4	17	NdFeB PMs	5.25	172.80	No

FMP: Ferromagnetic Pole Piece, IPP: Inner Pole Pair, OPP: Outer Pole Pair, N/A: Not Available, *^: No. of auxiliary flux modulator (AFM) teeth, ^*: No. of outer silicon steel sheets, ^^*: No. of the PM pole at the outer rotor as an additional layer

Moving to the strategies explicitly aimed at REPM reduction in Section 3, the data in Tables 8, 9, and 10 crystallize the fundamental "trilemma" of performance, reduction, and complexity. The specifications illustrate a clear spectrum of trade-offs, ranging from the modest decrease in system integration and the severe performance penalty of complete ferrite substitution to quantified full electrification, which eliminates REPMs but at the cost of high complexity and torque densities that are an order of magnitude lower than those of the best PM-based gears. A critical meta-analysis of the "Prototype Availability" columns across all tables reveals a profound and unifying challenge for the field: a severe gap between simulation and prototype. The overwhelming majority of proposed designs, including the most promising reduction strategies and novel concepts, exist solely in simulation. This gap poses a significant credibility challenge, hindering the validation of real-world performance, thermal management, and long-term reliability.

Table 8. Design specifications of reviewed CMGs in Subsection 3.1

Reference	FMP	No. of Salient Pole Teeth	Field Pole Pair	Excitation Source	Gear Ratio	Torque Density (kNm/m³)	Prototype Availability
[81], (ERMG-SSRM)	84	24	30	Copper (Electromagnet coil)	3.5	24.9	No
[81], (RMG-SSRM)	84	24	30	NdFeB PMs	3.5	49.3	No

FMP: Ferromagnetic Pole Piece

Table 9. Design specifications of reviewed CMGs in Subsections 3.1 to 3.4

Reference	Subsection	FMP	IPP	OPP	Excitation Source	Gear ratio	Torque Density (kNm/m³)	Prototype Availability
[85]	3.1	13	3	10	N/A	N/A	110	No
[91], (Ferrite Model)	3.2	18	2	16	Ferrite PMs	8	N/A	Yes
[91], (NdFeB Model)	3.2	18	2	16	NdFeB PMs	8	N/A	Yes
[98]	3.2	15	3	12	NdFeB PMs, Ferrite PMs	5	N/A	No
[99]	3.2	15	3	12	NdFeB PMs, Ferrite PMs	5	N/A	Yes
[80]	3.2	21	4	17	SmCo PMs	5.25	101.2	No
[80]	3.2	21	4	17	Ferrite PMs	5.25	9.8	No
[80]	3.2	21	4	17	Alnico PMs	5.25	18.7	No
[100]	3.3	586	65	521	NdFeB PMs	9.08	N/A	No
[101]	3.3	15	2	13	N/A	7.5	N/A	Yes
[102]	3.4	21	4	17	NdFeB PMs, *Copper (Torque-Stabilizing Bars)	4.25	N/A	No

FMP: Ferromagnetic Pole Piece, IPP: Inner Pole Pair, OPP: Outer Pole Pair, N/A: Not Available, *: Auxiliary Stability Element

Table 10. Design specifications of reviewed CMGs in Subsection 3.5

Reference	[4]	[106]
FMP	19	25
IPP	3, 15	4, 6, 7, 8, 9
Total No. of Coil Turns (IPP)	1800	4032
OPP	4, 16	16, 17, 18, 19, 21
Total No. of Coil Turns (OPP)	1920	9409
Excitation Source	Copper (DC Field Windings)	Copper (Electromagnet coil)
No. of Gear Ratios	2	5
Gear Ratios	0.267-5.333	1.778-5.25
Torque Density (kNm/m³)	12.15	N/A
Prototype Availability	No	No
Max Current Density (A/mm²)	6	N/A
Tested Current / Flux	N/A	10 A / ~ 0.5 T

FMP: Ferromagnetic Pole Piece, IPP: Inner Pole Pair, OPP: Outer Pole Pair, N/A: Not Available

Within this landscape, the quantitative evidence presented in Section 4, as found in Tables 11-13, positions True Hybrid Excitation as the most strategically viable yet underexplored pathway. It is the only approach that generates designs simultaneously targeting high performance, advanced functionality such as variable gear ratios, and most importantly, direct and significant REPM volume reduction, as conclusively demonstrated by one study that achieved a 28% mass reduction while increasing torque for a hybrid excited consequent pole CMG structure. Therefore, focusing concerted efforts on building and validating True HE prototypes emerges as the most critical and logical step to bridge the field's central gaps and advance the Technology Readiness Level of sustainable, high-performance magnetic gearing.

Table 11. Design specifications of reviewed CMGs in Subsection 4.1

Reference	FMP	IPP	OPP	Excitation Source	Gear ratio	Torque Density (kNm/m³)	Prototype Availability
[125]	26	4	22	NdFeB PMs, *Copper (Damper Bars)	5.5	N/A	No
[126]	26	4	22	NdFeB PMs, *Copper (Damper Bars)	5.5	N/A	No
[127]	26	4	22	NdFeB PMs, *Copper (Damper Bars)	5.5	N/A	No
[130]	25	3	22	PMs, *Copper (Damper Windings)	7.33	N/A	Yes
[42]	21	4	17	NdFeB PMs, *Copper (Torque-Enhancing Bars)	5.25	N/A	No
[131]	21	4	17	NdFeB PMs, *Copper (Harmonic Suppression Bars)	4.25	N/A	No
[132]	21	2	19	NdFeB PMs, **Copper (Active 3-Phase Levitation Windings)	9.5	N/A	No
[133]	21	2	19	NdFeB PMs, **Copper (Active 3-Phase Levitation Windings)	9.5	N/A	No

FMP: Ferromagnetic Pole Piece, IPP: Inner Pole Pair, OPP: Outer Pole Pair, N/A: Not Available, *: Auxiliary Stability Element, **: Active Element

Table 12. Design specifications of reviewed CMGs in Subsection 4.2

Reference	[103]	[104]	[105]	[141]	[142]	[48]
FMP	11	19	23	27	27	46
IPP	3-8	15,14,12,7,5,4	4-19	4	4	6
OPP	8-3	4,5,7,12,14,15	19-4	23	23	40
Excitation Source	Alnico PMs, Copper (DC Magnetizing Windings)	Alnico PMs, Copper (DC Magnetizing Windings)	Alnico PMs, Copper (DC Magnetizing Windings)	NdFeB PMs, Copper (DC Field Windings)	NdFeB PMs, Copper (DC Field Windings)	NdFeB PMs, Copper (DC Field Windings)
No. of Gear Ratios	6	6	16	1	1	1
Gear Ratios	0.38-2.67	0.27-3.75	0.21-4.75	6.75	6.75	7.66
Torque Density (kNm/m³)	3.06	12.04	24.76	N/A	135.15	N/A
Prototype Availability	No	No	No	No	Yes	No
Max Current Density (A/mm²)	-	-	-	-	4.52	20
Tested Current / Flux	10 A (Magnetizing Current)	6 A (Magnetizing Current)	1.5 A (Magnetizing Current)	-	-	-

FMP: Ferromagnetic Pole Piece, IPP: Inner Pole Pair, OPP: Outer Pole Pair, N/A: Not Available

Table 13. Design specifications of reviewed CMGs in Subsection 4.2

Reference	[143]	[144]
FMP	12	12
IPP	5	5
OPP	3.5	3.5
Excitation Source	NdFeB PMs, Copper (Passive Induced Coils)	NdFeB PMs, Copper (DC Field Windings)
No. of Gear Ratios	1	1
Gear Ratio	2.4	2.4
Torque Density (kNm/m³)	90.92	103.26
Prototype Availability	No	No
Max Current Density (A/mm²)	0	30
Tested Current / Flux	Induced Flux: ~0.216 Wb	Up to 500 A-turns per coil

FMP: Ferromagnetic Pole Piece, IPP: Inner Pole Pair, OPP: Outer Pole Pair, N/A: Not Available

6. Conclusions

This review has systematically examined the challenge of REPM dependency in CMGs, a critical barrier to their sustainable adoption in next-generation applications, such as electric vehicle drivetrains. The analysis leads to several definitive conclusions. First, it is evident that while topological innovations in CMGs, such as slotted structures, rotating pole pieces, and advanced Halbach arrays, have successfully pushed the boundaries of torque density, they have, with the notable exception of reluctance-based designs, largely failed to mitigate the fundamental reliance on costly and supply-chain-risky REPMs. Second, a critical assessment of direct REPM reduction strategies, including material substitution, system integration, and topological optimization, reveals a persistent performance-reduction-complexity trilemma. These strategies offer valuable but incremental gains, often achieved at the cost of increased size, lower torque density, or heightened system complexity.

In response to these limitations, this review has identified and articulated a necessary paradigm shift: the transition from permanent magnet-dominated designs to those incorporating HE. A central contribution of this work is the establishment of a clear, two-tier taxonomy that distinguishes between auxiliary electromagnetic integrations for enhanced functionality and proper hybrid excitation, where windings act as a co-primary source of magnetic flux. The analysis concludes that hybrid excited CMG is the most strategic and viable pathway forward, uniquely capable of enabling advanced features like variable gear ratios and, most critically, the direct displacement of REPM volume, as quantitatively demonstrated by recent studies.

To translate this potential into practical reality, a focused future roadmap is essential. The following research priorities, informed by the gaps identified in this review, are critical:

i) Advanced Material Science and Recycling Strategies: Future work must extend beyond NdFeB-ferrite hybrids to explore the integration of other non-rare-earth magnets (e.g., Alnico, MnAlC) within HE topologies. Concurrently, research into the disassembly, separation, and recycling of these hybrid magnetic material systems is imperative for ensuring full lifecycle sustainability.

ii) Multi-Physics Co-Design and Thermal Management: The integration of windings introduces new challenges in thermal management and mechanical integrity. Future designs must employ coupled electromagnetic, structural, and thermal finite element analysis from the outset. This is crucial for developing effective cooling strategies for excitation windings and for ensuring structural robustness, particularly in high-torque applications and for novel gear tooth topologies and flux modulator geometries that arise in HE architectures.

iii) Sophisticated Control Systems and Modeling: The dynamic interaction between permanent magnets and electromagnets in HE-CMGs demands sophisticated control algorithms. Research into the real-time optimization of excitation currents for objectives such as torque ripple minimization, efficiency maximization, and seamless gear shifting is necessary. Furthermore, the development of advanced analytical models that accurately capture the complex meshing methods and magnetic gearing principles in HE environments will be vital for guiding these control strategies and future design iterations.

In conclusion, while the path toward fully sustainable magnetic gearing is complex, it is clearly charted. The era of incremental optimization of permanent magnet circuits is giving way to a new paradigm of flux-controlled magnetic gearing. By championing a focused, multi-disciplinary research effort on hybrid-excited CMG topologies, the field can finally overcome the rare-earth magnet dilemma and unlock the full potential of this transformative technology for a sustainable electrified future.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

Authors Contribution

S.R. Tharma Raja (Conceptualization, Investigation, Formal Analysis, Writing - Original Draft)
M.F.M. Ab Halim (Supervision, Validation, Resources)
A. Ab Rahman (Co-supervision, Methodology, Resources)
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