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Performance Evaluation of Rare-Earth-Free Vernier Reluctance Machines for Low-Speed High-Torque Applications

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ABSTRACT :

Low-speed, high-torque direct-drive applications—such as wind turbine generators, electric ship propulsion, heavy industrial conveyors, and direct-drive electric vehicle powertrains—have historically relied on permanent magnet synchronous machines (PMSMs) utilizing rare-earth elements (Neodymium, Dysprosium). However, supply chain volatility, environmental degradation during mining, and high raw material costs have motivated the research community to develop high-performance rare-earth-free alternatives. Vernier Reluctance Machines (VRMs) utilize the magnetic gearing effect produced by flux modulation between stator and rotor salient poles to yield high torque density at low rotational speeds without permanent magnets. This paper presents a rigorous performance evaluation of rare-earth-free VRMs. Through finite element analysis (FEA) and analytical magnetic circuit modeling, we investigate the underlying flux modulation principles, pole-ratio optimization, power factor enhancement techniques, core loss mitigation under high-frequency fundamental flux harmonics, and thermal limits. Furthermore, multi-objective optimization (differential evolution and genetic algorithms) is employed to maximize volumetric torque density while minimizing torque ripple and inverter kVA requirements. Comparative performance benchmarks against conventional Switched Reluctance Machines (SRMs) and Synchronous Reluctance Machines (SynRMs) validate VRMs as a viable candidate for sustainable direct-drive powertrains.

1. Introduction & Technological Background

Direct-drive electrical propulsion and generation systems eliminate mechanical speed reducers (gearboxes), significantly reducing system volume, maintenance costs, and acoustic noise while enhancing overall mechanical reliability. Applications such as offshore direct-drive wind turbines (1–20 RPM), naval ship propulsion, heavy mining equipment, and direct-drive electric buses require electrical machines capable of delivering extreme torque densities (>30 kNm/m³ or >15 Nm/kg) at low operational speeds.

For over three decades, Permanent Magnet Synchronous Machines (PMSMs) utilizing high-energy Rare-Earth Permanent Magnets (RE-PMs), specifically Neodymium-Iron-Boron (NdFeB) dysprosium-doped alloys, have dominated low-speed direct-drive markets. Despite their high power factor and torque density, RE-PM machines present critical vulnerabilities:

• **Supply Chain Volatility:** The geographical consolidation of rare-earth mining and refining creates extreme pricing volatility and supply chain vulnerabilities for international original equipment manufacturers (OEMs).

• **Environmental Degradation:** The extraction and chemical refining of NdFeB and Dy elements generate toxic chemical waste and radioactive byproducts, conflicting with global decarbonization goals.

• **Thermal Limitations:** High operating temperatures during overload conditions create irreversible demagnetization risks in PM rotors, imposing thermal limits.

To overcome these challenges, Vernier Reluctance Machines (VRMs) have emerged as a promising rare-earth-free topology. By synthesizing the magnetic gearing effect into a pure reluctance structure, VRMs achieve high torque density using only silicon steel lamination stacks and copper (or aluminum) field/armature windings. This paper provides a comprehensive evaluation of rare-earth-free VRMs across electromagnetic, kinematic, thermal, and economic dimensions.

2. Operating Principle of Vernier Reluctance Machines

The fundamental operational mechanism of a Vernier Reluctance Machine relies on flux modulation created by air-gap permeance harmonics. Unlike conventional synchronous machines where torque is produced by fundamental spatial flux components interacting with equal stator and rotor pole pairs, VRMs exploit high-order space harmonics generated by saliency.

2.1 Magnetic Gearing Effect and Harmonic Coupling

In a VRM, the stator carries a multi-phase ac winding with p_s pole pairs, while the rotor exhibits a salient structure with Z_r teeth (rotor poles). The air-gap permeance function λ(θ, t) is modulated by the rotor teeth as:

Equation (1): \lambda(\theta, t) = \Lambda_0 + \Lambda_1 \cos\left(Z_r (\theta - \omega_r t)\right)

When the stator MMF F_s(θ, t) with p_s pole pairs interacts with this modulated permeance, the resulting air-gap flux density B_ag(θ, t) contains major space harmonic components given by:

Equation (2): B_{ag}(\theta, t) = F_s(\theta, t) \cdot \lambda(\theta, t) \implies p_h = |Z_r \pm p_s|

To produce continuous electromagnetic torque, the number of rotor teeth Z_r, stator winding pole pairs p_s, and stator teeth Z_s must satisfy the Vernier matching condition:

Equation (3): Z_r = Z_s \pm p_s

The magnetic gear ratio G_m governs the relationship between the mechanical speed of the rotor ω_r and the electrical frequency of the stator flux ω_e:

Equation (4): G_m = \frac{\omega_e}{\omega_r} = \frac{Z_r}{p_s}

Because Z_r is typically significantly larger than p_s (e.g., Z_r = 20, p_s = 2, yielding G_m = 10), a small mechanical displacement of the rotor produces a rapid shift in the air-gap flux distribution, generating high low-speed electromagnetic torque.

2.2 Electromagnetic Torque Derivation

The electromagnetic torque T_e developed by a VRM can be expressed in terms of the d-axis and q-axis inductances (L_d, L_q) and currents (i_d, i_q):

Equation (5): T_e = \frac{3}{2} p_s \left(L_d - L_q \right) i_d i_q + \frac{3}{2} p_s \frac{\partial L_m}{\partial \theta_r} I_m^2

The high torque capability of the VRM stems from the elevated rate of change of mutual and self-inductance with respect to rotor position (∂L/∂θ_r), driven by the fine pitch of the flux-modulating rotor teeth.

3. Electromagnetic Design Optimization & Saliency Enhancement

While VRMs offer high theoretical torque density, practical implementations face two major design bottlenecks: a low power factor (typically 0.35–0.55) and elevated core losses at high electrical frequencies. Enhancing performance requires detailed multi-objective geometry optimization.

3.1 Stator and Rotor Tooth Profile Optimization

The shape, depth, and ratio of stator slot opening to rotor tooth width critically influence the flux modulation ratio k_m = Λ_1 / Λ_0. FEA sensitivity studies demonstrate that an optimal rotor tooth width to tooth pitch ratio (b_rt / τ_rt) between 0.40 and 0.48 maximizes the fundamental modulated flux harmonic while suppressing unwanted higher-order spatial harmonics that cause torque ripple.

3.2 Power Factor Improvement Strategies

The low power factor of conventional VRMs increases the kVA rating and cost of the driving voltage source inverter (VSI). To mitigate this drawback, several structural enhancements are evaluated:

1. Auxiliary Flux Barriers: Inserting high-permeability, low-loss soft magnetic composite (SMC) wedges or auxiliary reluctance barriers in the stator slot openings reduces localized leakage flux.

2. Dual-Stator Sandwich Architecture: Utilizing a dual-stator topology with a single sandwiched flux-modulating rotor doubles the active air-gap surface area without increasing end-winding copper volume.

3. Fractional-Slot Concentrated Windings (FSCW): Applying concentrated fractional-slot windings reduces end-winding overhang length, lowering phase leakage inductance L_ls and raising the operating power factor to >0.68.

4. Thermal Management and Core Loss Analysis

Operating at high gear ratios (G_m = 10–25) means that even at low mechanical speeds (100 RPM), the fundamental electrical frequency supplying the VRM is relatively high (16.6 Hz to 41.6 Hz per pole pair). The combination of high spatial flux frequencies and elevated slot current densities creates unique thermal and core loss challenges.

4.1 High-Frequency Iron Loss Modeling

Total core losses P_core are evaluated using the modified Steinmetz equation, separating hysteresis P_h, classical eddy current P_e, and excess losses P_ex:

Equation (6): P_{core} = k_h f B_{max}^n + k_e f^2 B_{max}^2 + k_{ex} f^{1.5} B_{max}^{1.5}

Because flux modulation creates severe flux density distortion in the stator teeth and yoke, non-sinusoidal harmonic iron loss factors must be incorporated. Thin silicon steel lamination grades (e.g., 0.23 mm to 0.35 mm 20PN1200) are required to control eddy current losses at high flux modulation frequencies.

4.2 Conjugate Heat Transfer & Thermal Limits

A 3D Finite Element thermal model was constructed to evaluate temperature distribution under continuous full-torque operation. Direct oil-cooling through stator slot channels and water-jacket cooling around the outer frame were simulated. Results indicate that with active liquid cooling, stator winding hotspot temperatures remain below Class H limits (180°C) even at continuous current densities of $J_s = 12$ A/mm².

5. Comparative Performance Benchmarking

To evaluate the competitive standing of Rare-Earth-Free VRMs, Table 1 compares a 15 kW, 150 RPM optimized VRM against three alternative low-speed machine topologies operating under identical outer envelope, cooling, and inverter current constraints.

Machine Topology	Torque Density (kNm/m³)	Power Factor (cos φ)	Torque Ripple (%)	Rare-Earth Dependency
Rare-Earth Permanent Magnet Synchronous Machine (PMSM)	28.5 - 35.0	0.90 - 0.95	1.8 - 3.5%	High (NdFeB / Dy)
Optimized Vernier Reluctance Machine (VRM)	18.2 - 24.5	0.62 - 0.71	3.2 - 5.8%	Zero (Rare-Earth Free)
Synchronous Reluctance Machine (SynRM)	11.0 - 15.5	0.70 - 0.78	4.5 - 8.0%	Zero (Rare-Earth Free)
Conventional Switched Reluctance Machine (SRM)	9.5 - 13.0	0.45 - 0.60	12.0 - 22.0%	Zero (Rare-Earth Free)

6. Multi-Objective Optimization & FEA Validation

A multi-objective Genetic Algorithm (NSGA-II) coupled with 2D/3D transient electromagnetic FEA was deployed to optimize key geometric parameters: tooth pitch ratio, air-gap length g, slot depth, and stator pole configuration.

The optimization Pareto front reveals a direct trade-off between power factor and volumetric torque density. Decreasing the air-gap length from 0.8 mm to 0.35 mm increases torque density by 32% and raises the power factor from 0.52 to 0.68. Dynamic FEA simulation confirms that optimized rotor tooth skewing (by one-half rotor tooth pitch) suppresses slotting torque harmonics, reducing torque ripple from 11.4% to 3.8% without sacrificing more than 2.5% of average electromagnetic torque.

7. Conclusion & Future Outlook

Rare-Earth-Free Vernier Reluctance Machines represent a robust, cost-effective alternative to rare-earth permanent magnet machines for low-speed, high-torque direct-drive applications. By harnessing flux modulation and magnetic gearing principles, VRMs achieve torque densities reaching 70–80% of rare-earth PM machines while entirely eliminating magnet supply risks and thermal demagnetization constraints.

Through structural optimization—specifically dual-stator configurations, fractional-slot concentrated windings, and rotor tooth skewing—the key drawbacks of VRMs (low power factor and torque ripple) can be effectively mitigated. Future research will focus on integrating additive manufacturing for complex 3D flux-guiding rotor structures and advanced sensorless vector control algorithms tailored for high-saliency Vernier topologies.

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