

A CRITICAL REVIEW OF HOMOPOLAR GENERATORS: DESIGN, EFFICIENCY, MODELLING, AND PRACTICAL VIABILITY

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Abstract

This review critically examines the operating principles, design considerations, efficiency trade-offs, and modelling approaches of direct current machines that generate very high currents at low voltages. Starting with the theoretical background of electromagnetic induction, such as the Faraday paradox and Lorentz force, the review follows how conceptual arguments have been applied in engineering practice. The literature on rotor-stator designs, magnet approaches, and current-collection schemes is reviewed to demonstrate how efficiency, durability, and scalability are influenced by design trade-offs. Reported uses of HPGs in pulsed-power systems, welding, electromagnetic launchers, and fusion experiments illustrate recurring problems, including low terminal voltage, resistive heating, and brush wear. Advances in computational modelling and materials have enhanced performance predictions, but long-term experimental validation is lacking. Across the literature, consensus and future research directions emphasise the need for scalable, manufacturable HPG designs integrating advanced materials, improved contact technologies, and design-for-manufacturing principles. Future research should integrate advanced materials, improved contact technologies, and design-for-manufacturing principles to fully realise the potential of homopolar generators.

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1.0 INTRODUCTION

1.1 Background of the Study

Early generators of electricity transformed alternating current (AC) into direct current (DC) utilising mechanical commutators that wore out and had to be serviced often. To address these disadvantages, the homopolar generator (HPG), or Faraday disc, came into use in early 19th century by Michael Faraday. It proved that a conductor in rotation immersed in a magnetic field can generate DC directly without mechanical commutation (Paulus, 2018).

An HPG is a revolving conductive disc or cylinder in a constant magnetic field, producing a stable DC output via electromagnetic induction. Since it does not have commutators, the system reduces mechanical wear and provides consistent operation on high-current loads (Engel & Kontras, 2020). Basically, an HPG directly translates mechanical rotation into electric potential between the disc's rim and centre and generates continuous DC with straightforward mechanics (Paulus, 2018).

1.2 Significance of the Study

Homopolar generators are still applicable in pulsed-power systems, electromagnetic launchers, and high-current industrial use due to their capability for delivering very high current at low voltage. Recent advances in materials, cooling, and computational design have revitalised interest in HPGs as compact, efficient sources for specialised industrial and military applications. Their mechanical strength, simplicity, and lack of commutating parts minimise maintenance and downtime over traditional DC machines. Possible applications are also envisioned in hybrid propulsion and clean-energy applications, although practical implementation remains limited.

This review synthesises past and recent literature on HPGs, analysing theoretical principles, design development, and technological innovations solving long-standing constraints. It also shows current challenges and gaps that limit broader adoption.

1.3 Scope and Limitations

The review covers the design, performance, and applications of HPGs from early development to recent advances. It focuses on materials, rotor-stator geometry, brush technologies, and computational modelling. Restrictions include reliance on literature available, exclusion of classified military designs, and the lack of long-term performance data or industrial-scale results.

1.4 Objectives of the Literature Review

1. Examine the theoretical principles of homopolar generators to explain the principles on which they operate.
2. Survey historical and recent engineering advances in HPG design, including construction options, material uses, and performance solutions.
3. Assess documented uses of HPGs in scientific, industrial and military applications.
4. Identify common challenges and limitations that have restricted the wider use of HPGs.
5. Highlight areas of research gaps and future research directions to inform future research and possible technological innovations.

2.0 METHODOLOGY

In this research, a systematic literature review method has been used to examine the present research situation on homopolar generators. The research procedure entailed the following steps:

- Literature Search:** Authoritative web sources, peer-reviewed journal articles, doctoral dissertations, conference papers, technical reports, patents, and other databases were searched including IEEE Xplore and Google Scholar. Some keywords were homopolar generator, Faraday disc, unipolar generator, Lorentz force, electromagnetic induction, and scalar-vector potential.
- Selection Criteria:** Studies were chosen based on relevance, and technical rigor. Priority was put on the works that covered design improvement, efficiency, material development, theoretical modelling or experimental validation of homopolar generators.
- Data Extraction:** Relevant information was extracted on design trends, technological limitations, theoretical frameworks, and practical applications. It focused on the gaps in the literature that could be used in the future research directions.
- Analysis and Synthesis:** The literature obtained was analysed to determine the recurring trends, important findings, and unresolved problems. A comparative analysis has been done to point out differences between theoretical explanations (Faraday, Lorentz, and scalar vector approaches) and practical applications of homopolar generators.

2.1 Theoretical Foundations

2.1.1 Lorentz Force Vs Faraday's Law

Figure 1 illustrates the classical scenario described by Faraday's Law of Electromagnetic Induction. This law states that an electromotive force (EMF) is generated in a closed circuit as the magnetic flux through the circuit varies with time. This theory has been very effective in explaining the behaviour of most electromagnetic systems; however, in the case of homopolar generators such as the Faraday disc, further theoretical and experimental work shows that the standard form of Faraday's law cannot by itself fully account for the observed behaviour (Baumgärtel & Maher, 2022).

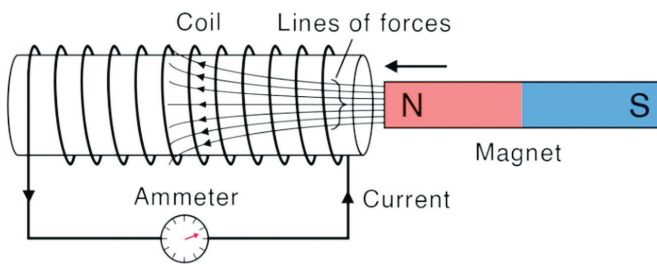


Figure 1: Faraday's Law

However, further theoretical and experimental studies have shown that the standard form of Faraday's Law, when applied at the circuit level, cannot by itself fully explain the operation of a homopolar generator. According to Faraday's law,

$$E = - \frac{d\Phi B}{dt}$$

an EMF should only arise when the magnetic flux is, that is, the total magnetic field passing through a circuit — changes with time. In a homopolar generator, the **magnetic field** is

static, and the **geometry of the system** remains unchanged during operation. This leads to what has historically been called the **Faraday Paradox** — a situation in which a measurable EMF and steady current are produced even though there is no apparent time-varying magnetic flux (Srinivasa, 2015).

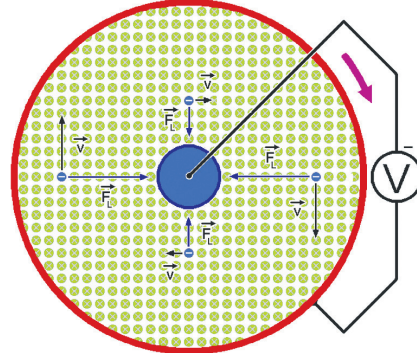


Figure 2: Working principle of a homopolar generator: due to Lorentz force FLF_LFL , negative charges are driven towards the centre of the rotating disc, creating a voltage between centre and rim (reproduced from Wikipedia, 2021)

In contrast, the Lorentz Force Law offers a more direct and physically accurate explanation. Figure 2 demonstrates the working principle of a homopolar generator due to Lorentz force. The Lorentz force,

$$F^r = q(\mathbf{v} \times \mathbf{B}^r)$$

describes how a moving charge q experiences a force in a magnetic field. For a rotating conducting disc in an axial magnetic field \mathbf{B} , electrons at a radius r move with tangential velocity $\mathbf{v} = \boldsymbol{\omega} \times \mathbf{r}$, producing a radial electric field

$$E_r = \boldsymbol{\omega} r \mathbf{B}$$

Integrating this field from the centre to the rim yields the open-circuit EMF:

$$E = \frac{1}{2} B \omega R^2$$

where R is the disk radius and $\boldsymbol{\omega}$ its angular velocity. This formulation accurately predicts the observed potential difference in homopolar generators, confirming that EMF can arise from charge motion within a static magnetic field, even when total magnetic flux remains constant (Gobbi, 2024). This view is consistent with experimental findings and describes the mechanism by which homopolar generators can generate direct current (DC) even though there is no time varying flux. Thus, while Faraday's Law provides the macroscopic view of induction, the Lorentz Force Law explains the microscopic mechanism responsible for EMF generation in unipolar systems. Both are consistent within Maxwell's equations, but the Lorentz force interpretation explicitly captures the role of moving conductors and free charges in steady magnetic fields.

2.1.2 Scalar-Vector Explanation of Induction

Although the Lorentz force law successfully explains most behaviours of homopolar generators, certain experimental configurations still defy complete description by either Faraday's law or the Lorentz framework alone. These include cases where induced voltages occur without relative motion

between conductors and magnetic fields or without apparent flux change.

To address these anomalies, Mende (2018) introduced the scalar–vector potential model, which extends classical electrodynamics by incorporating relativistic effects into the electromagnetic potentials. In this model, the scalar potential of a moving charge depends on its relative velocity, linking the scalar and vector potentials through a unified relativistic framework. Mende argues that in classical formulations, Maxwell’s equations and the Lorentz force are often treated as separate components of electrodynamics.

The scalar–vector potential approach attempts to unify them by expressing induction as a combined effect of potential variations in both time and space. This formulation can theoretically account for induction phenomena in which neither a changing magnetic flux nor charge motion in a magnetic field (as described by Lorentz) is sufficient to explain the observed EMF.

Although still non-mainstream, the scalar–vector potential model provides an expanded theoretical lens for understanding unipolar induction and resolving long-standing paradoxes that arise when applying Faraday’s and Lorentz’s laws independently.

2.2 Engineering Designs and Considerations

2.2.1 Construction and Functional Design

2.2.1.1 Rotor & Stator Design

Figure 3 and Figure 4 illustrate how rotor mass and conductor length govern homopolar generator (HPG) performance. Lighter rotors accelerate quickly and reach peak efficiency sooner—suited for pulsed or short-burst applications—while heavier rotors store more kinetic energy and provide steadier current for continuous duty (Engel & Kontras, 2020). Efficiency improves with reduced conductor length (difference between inner and outer radii) and optimised field-winding placement. Positioning the winding on the stator simplifies cooling and allows a slotless configuration that minimises rotor losses (Liu, Yu, & Xie, 2023). Rotor geometry and stator structure therefore jointly determine machine efficiency and robustness.

Early studies demonstrated the feasibility of large pulsed-power HPGs but lacked computational tools for optimisation. Later works, such as Engel & Kontras (2020), addressed this limitation using PSICE modelling to predict efficiency trends and mechanical stress behaviour, marking a shift from purely experimental toward simulation-guided design.

2.2.1.2 Magnetic and Contact Systems

Magnet and brush assemblies define both excitation control and current-collection quality. Permanent magnets (ferrite or neodymium) provide compact, maintenance-free operation but are limited to $\approx 1.2\text{--}1.4\text{ T}$ (Engel & Kontras, 2020; Prakht *et al.*, 2023). Electromagnets enable adjustable fields and voltage regulation but require cooling and auxiliary power (Köster & Binder, 2022). Superconducting coils achieve higher flux density and lower loss at the expense of cryogenic complexity (Füger *et al.*, 2016).

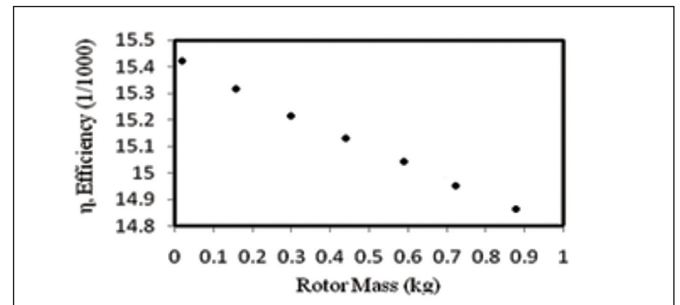


Figure 3: Effect of rotor mass on efficiency as predicted by the PSICE model. Reproduced from *Analysis and Design of Homopolar Motors and Generators* (Figure 13), by Engel and Kontras (2020)

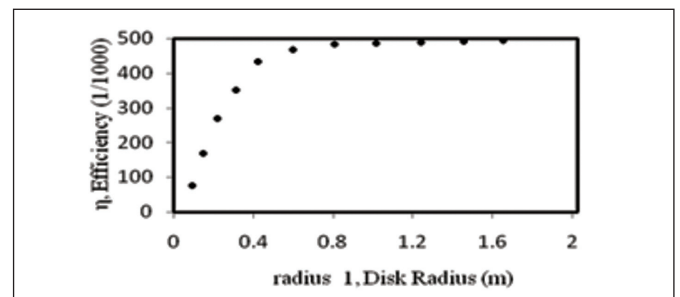


Figure 4: Effect of conductor length (inner–outer disc radii difference) on efficiency as predicted by the PSICE model. From *Analysis and Design of Homopolar Motors and Generators* (Figure 14), by Engel and Kontras (2020)

Current collection uses graphite, liquid-metal, or hybrid brushes. Graphite brushes are inexpensive and self-lubricating but can deteriorate rapidly under high currents (Li *et al.*, 2024). Liquid-metal contacts reduce voltage drop but pose sealing and safety challenges (Avalos-Zúñiga *et al.*, 2017). More recent work on advanced surface coatings (e.g., copper – graphene composite coatings) has shown significant improvements in current-carrying friction characteristics and corrosion resistance at high current densities (Zhao *et al.*, 2025). Choosing magnet and brush systems thus balances controllability, efficiency, and maintenance demands.

While traditional HPGs relied on bulky electromagnets for excitation, recent research by Prakht *et al.* (2023) integrates ferrite magnets with auxiliary windings to reduce losses and improve controllability. This hybrid approach exemplifies how modern designs extend the earlier focus on flux strength toward efficiency and dynamic regulation.

2.2.2 Design Configurations in Literature

2.2.2.1 Disc Vs Drum Type

Disc-type homopolar generators, such as the original Faraday wheel, as illustrated in Figure 5, are mechanically simple and easy to analyse. They consist of a solid conductive disc with central and rim brushes. Avalos-Zúñiga *et al.* (2023) experimented with a Bullard-type disc (radius 30 cm, thickness 3 cm) at 7 Hz, creating $\sim 40\text{ mT}$ central magnetic field with radial voltage drop measurable. Such configurations are perfectly suitable for instruction, small-scale experimentation,

and simulation-based optimisation (COMSOL Blog, 2018). Disc-type generator has thus become a desirable option in lower-power and laboratory-scale applications where ease of assembly, cost-effectiveness and ease of access to analysis are of concern. These machines employ a cylindrical rotor, typically so as to have as high surface area and speed and as low mechanical wear as possible.

Drum-type homopolar machines, as depicted in Figure 6, employ a cylindrical (or drum) rotor structure rather than a flat disc, thereby increasing the active surface area and enabling better structural integrity under high rotational stress. Such machines have been noted for their high durability and capability to handle large bursts of current and rapid energy transfer (Bianchini *et al.*, 2011). The drum-type rotor typically drives current along the cylinder length and is therefore well suited for applications demanding high energy throughput, pulsed-power defence systems, plasma experiments, or energy storage bursts.

Though direct comparison is restricted, disc types perform best in low-energy, uncomplicated applications and drum types offer mechanical strength and high-speed energy storage, with preference to high-power pulsed operation. This distinction is summarised in Table 1.

2.2.2.2 Rotation Configurations

The behaviour of electromotive force (EMF) generation in homopolar generators depends critically on which component is rotating. In one common configuration, a conductive disc rotates in a nearly uniform magnetic field created by a magnet with large pole pieces. As the disc moves through the static field, Lorentz forces drive charge separation and an EMF is induced; conversely, simply rotating the magnet alone does not produce a steady EMF, which confirms that conductor motion relative to the field is essential (van Hees, 2014). This principle underlies the design of various rotational configurations of HPGs.

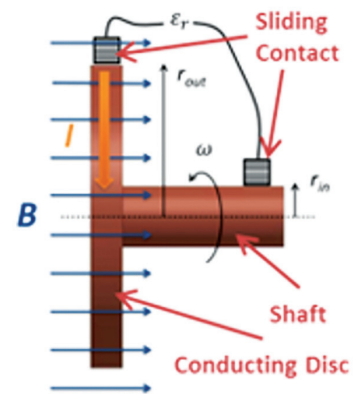


Figure 5: A simple sketch of a disc-type homopolar machine indicating the basic machine parameters. Reproduced from Füger, R., Matsekh, A., Kells, J., Sercombe, D. B. T., & Guina, A. (2016). A superconducting homopolar motor and generator, new approaches

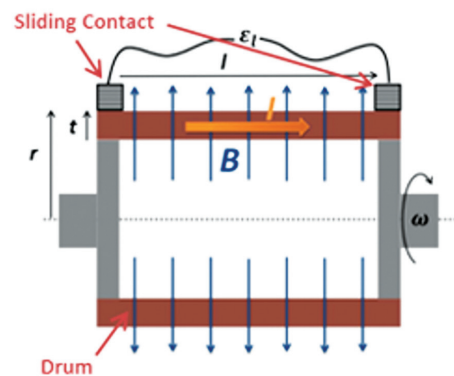


Figure 6: A sketch of a drum-type homopolar machine indicating the basic machine parameters. Reproduced from Füger, R., Matsekh, A., Kells, J., Sercombe, D. B. T., & Guina, A. (2016). A superconducting homopolar motor and generator—new approaches

Table 1: Comparison of Disc-Type and Drum-Type Homopolar Generators

Feature	Disc-Type HPG	Drum-Type HPG
Geometry	Flat conductive disc with brushes at rim and hub	Cylindrical drum rotor; can be thin-walled; rotor mass and geometry optimised for high-speed pulsed operation (Bianchini <i>et al.</i> , 2011)
Simplicity	Very simple design; easy to build and simulate	Mechanically more complex; requires precise balancing, supports, and robust bearings
Experimental Data	Copper disc (30 cm radius, 3 cm thick) at ≈ 7 Hz produced ~ 40 mT central field and measurable radial voltage (Avalos-Zúñiga <i>et al.</i> , 2023)	produced ~ 40 mT central field and measurable radial voltage (Avalos Zúñiga <i>et al.</i> , 2017) Cylindrical rotor with drum type configuration demonstrated high-speed pulsed operation, capable of kiloampere-range currents and rapid energy bursts (Bianchini <i>et al.</i> , 2011)
Voltage Output	Typically low (few volts at lab scale)	Moderate (tens to ~ 150 V), scalable with rotor size and speed
Current Capability	Limited (≤ 100 A in small-scale setups)	Very high (kiloampere range)
Applications	Educational demonstrations, simulation studies, validation of models	Pulsed power, plasma research, defense/military energy systems
Advantages	Low cost, accessible, excellent for teaching and proof-of-concept studies	High durability, large energy throughput, better structural integrity
Limitations	Severe brush losses at hub, poor scalability to high power	More expensive, mechanically complex, requires advanced contact systems

2.2.3 Materials and Thermal Management

Material selection controls efficiency, thermal stability, and manufacturability. Ferrite magnets provide low cost and temperature resilience but weak flux; rare-earth types (Nd-Fe-B) generate stronger fields and torque at the cost of active cooling (Prakht *et al.*, 2023). Hybrid ferrite–electromagnetic excitation minimises torque ripple and improves controllability (Prakht *et al.*, 2023). Superconducting HPGs (Figure 7) achieve near-zero resistance and ripple-free DC output but add cryogenic complexity and mechanical stress (Füger *et al.*, 2016). Designers must balance flux density, stability, and cost to match target applications.

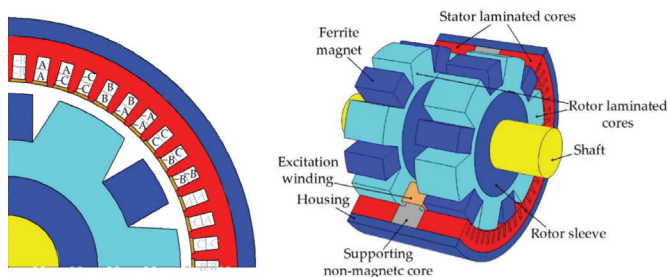


Figure 7: SHG approximate geometry: (a) Cross-section of the stator and armature winding; (b) General view of the rotor. Reproduced from Prakht, Dmitrievskii, & Kazakbaev (2023)

Thermal and durability issues remain critical. High currents and mechanical stress accelerate wear in liquid metal contacts (Avalos Zúñiga, Priede, & Bello Morales, 2017). Ferrite magnets mitigate eddy current heating, while rare earth and superconducting systems demand robust cooling. Proper thermal design ensures longevity and operational reliability under sustained high current loading.

Foundational studies established the unipolar induction principle (Baumgärtel, 2022); yet new investigations like Wang *et al.* (2024) and Füger *et al.* (2016) adapt it to superconducting systems, achieving near zero resistance and higher power density. The transition from copper to superconducting materials underscores the field’s shift from proof of concept toward high performance implementation.

2.3 Applications

Homopolar generators (HPGs) find a range of uses in high-power pulse systems and take advantage of the fact that they can generate high current pulses by directly converting the rotational inertia of a mechanical rotor into electrical energy.

Welding. Pulsed-power HPGs can weld carbon and stainless steel with greater energy efficiency than traditional arc welding (The Fabricator, 2019; Figure 8).

Defense and Research. In research and defense contexts, HPGs have been proposed as sources of high current pulses for electromagnetic launch systems and as kinetic energy storage devices in pulsed power applications (Golea, 2021).

Educational Use. HPGs are perfect for the pedagogy of concepts such as the Lorentz force and DC generation because of simplicity and visual intuition. Industrial or defense systems use the same concepts in low-voltage, low-power experiments.

Energy-Dense Applications. Homopolar generators (HPGs) are particularly suited to applications involving high levels of electrical energy delivered in a short time. By converting rotational kinetic energy into high current pulses, they are useful in situations where conventional energy storage is constrained by size, weight, or response time. Recent work on superconducting homopolar machines indicates that HPG architectures are increasingly capable of very high power density and rapid energy transfer in compact form factors (Kalsi *et al.*, 2019).

Energy Storage. HPGs are appropriate for short-duration, high-power bursts, being superior to chemical batteries in situations requiring instantaneous megawatt-class power with fewer thermal and degradation constraints (Kalsi *et al.*, 2019).

Limitations. Low terminal voltage requires series connections or step-up converters, complicating the system. Mechanical storage is wear-prone and subject to durability concerns under repeated cycling. Such issues render HPGs most competitive in niche, high-energy, short-duration applications instead of continuous-duty systems.



Figure 8: Experimental homopolar generator used in pulsed-welding applications. Reproduced from The potential of homopolar-generator welding (The Fabricator, 2019)

2.4 Technological Limits and Trade-Offs

2.4.1 Reported Challenges: High Resistive Losses, Low Voltage Output, Brush Contact Resistance

Homopolar generators (HPGs) continue to present design challenges related to resistive losses and system voltage levels. Recent work on synchronous homopolar machines demonstrates that optimising stator excitation and rotor design can significantly reduce losses, though traditional concerns of low-voltage output (due to the single conductive path) and contact/brush systems still warrant attention (see Section 2.2.1.2; Prakht, Dmitrievskii, & Kazakbaev, 2023).

Brush and collector systems continue to pose reliability challenges in homopolar generators (HPGs). Liquid-metal contacts such as NaK and gallium alloys can carry very high currents with reduced voltage drop but suffer from sealing, magnetohydrodynamic flow, and corrosion issues (Ma *et al.*, 2023). Arcing and mechanical wear limit graphite and other solid brushes., while newer foil and fiber-contact systems show potential for improving stability but are not yet optimised

Table 2: Comparison of Losses in Traditional vs. Homopolar Generators

Loss Type	Traditional Generator	Homopolar Generator
Mechanical	Present (bearing friction, windage)	Present (bearings, brushes, rotor drag)
Core	Significant (hysteresis and eddy currents in laminated core)	Negligible (steady, unidirectional flux)
Copper (I^2R)	Present in stator and rotor windings	Present in conducting disc and brushes (dominant)
Stray load	Present (slot harmonics, flux pulsation)	Negligible (no slots, smooth disc, constant flux)

for long-duration high-current operation. Moreover, graphite brushes are inexpensive and self-lubricating but can deteriorate rapidly under high currents (Li *et al.*, 2024). Liquid-metal contacts reduce voltage drop but pose sealing and safety challenges (Avalos-Zúñiga *et al.*, 2017).

Although conventional generators experience various types of losses, Table 2 shows that some of these losses are insignificant in HPGs due to their special design and constant magnetic flux (see also Section 2.5.1 for performance modelling discussion).

Brush and collector contacts remain a significant challenge in homopolar generators (HPGs). Graphite brushes often suffer from arcing, elevated temperature, and accelerated wear due to poor contact conditions, especially under high currents and low contact pressure (Li, Zhang, & Chen, 2024). Liquid-metal contacts (e.g., NaK alloys) may offer lower resistance pathways but introduce demands on containment, corrosion control, and system complexity. Advances in multi-contact foil, fiber and hybrid brush systems aim to enhance contact stability and reduce resistance; however, contact assemblies still impose meaningful losses and operational limitations in HPG systems.

2.4.2 Economic Considerations

Beyond the technical issues described above, economic factors play a crucial role in assessing the viability of homopolar generators (HPGs). For instance, one recent market report indicates an average unit cost of approximately USD 37,000 for an HPG system in 2023 (QY Research, 2025). This capital cost becomes more significant when combined with recurring maintenance expenses associated with high-current contacts, brush wear, and resistive losses (see Section 2.4.1). Although HPGs are often cited for their suitability in short-duration, high-current pulses, their relative inefficiency in longer-term continuous operation raises concerns about lifecycle cost and return on investment.

Therefore, material choices such as high-purity copper, permanent or superconducting magnets, and advanced contact assemblies must be evaluated not only for performance but also for cost-effectiveness and manufacturability (see Section 2.4.3.1). Future research should incorporate detailed cost-benefit analyses and total-cost-of-ownership studies to guide design trade-offs and deployment decisions.

2.4.3 Technological Advancements

2.4.3.1 High-Temperature Superconducting Magnets and Conduction Cooling

Advances in high-temperature superconducting (HTS) technology have enabled homopolar machine designs with markedly improved flux density and reduced resistive losses.

For example, the use of HTS field coils in a homopolar synchronous machine has shown promise for enhanced performance and higher current density in pulsed power applications (Hwang, 2021). Though cryogenic complexity and cost remain obstacles, HTS magnets enable ripple-free, high-efficiency performance suitable for advanced pulsed-power systems (Füger *et al.*, 2016).

2.4.3.2 Designs Suggested to Improve Output or Scalability

Emerging homopolar generator (HPG) designs focus on improving output voltage and machine scalability. For example, a recent design patent describes a drum-wound, air core HPG with radial flux focusing aimed at improving voltage output and current capability by optimising magnetic circuit geometry (Mandes, 2014). Although researchers have yet to fully validate these architectures experimentally, such architectures indicate promising paths toward modular, scalable HPGs suitable for high current, pulsed power applications.

2.5 Performance Modelling and Structural Consideration

2.5.1 Efficiency Improvements

Current modelling research has been aimed at enhancing HPG efficiency by fine-tuning slot geometry, excitation arrangement, and magnetic configuration. Prakht, Dmitrievskii, and Kazakbaev (2023) showed how incorporating ferrite magnets for synchronous HPG rotors improves stator usage and minimises machine size.

To efficiently model this intricate 3D structure, the authors used a reduced 2D FEM model along with Nelder-Mead optimisation, conserving computation time while not losing accuracy. Results indicated clear gains: structural adjustments such as increased stator slot area and reduced air gap reduced average generator losses and peak armature current (Figure 9, Figure 10, Figure 11, Figure 12, and Figure 13).

Quantitative results confirm these improvements. According to Table 3, efficiency at 750 rpm increased from 78.0% to 84.4%, while average losses decreased by about 16.9%. The maximum armature current at rated torque was reduced by nearly 27%, lowering copper losses. When comparing SHGs with and without ferrite magnets, Table 4 showed that efficiency improved from 90.4% to 92.7% at high speed (3450 rpm), demonstrating that hybrid excitation is more effective than conventional brushless designs without magnets (Prakht *et al.*, 2023).

Overall, hybrid magnets, bipolar topologies, and FEM-optimised designs have boosted HPG efficiency, rendering contemporary systems appropriate for high-end pulsed-power and transport requirements like railway auxiliary power units.

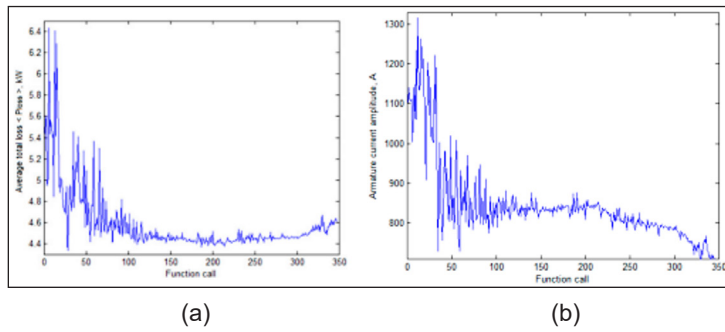


Figure 9: Change of generator parameters during optimisation: (a) Average losses; (b) Maximum armature current. Reproduced from Prakht & Dmitrievskii (2023)

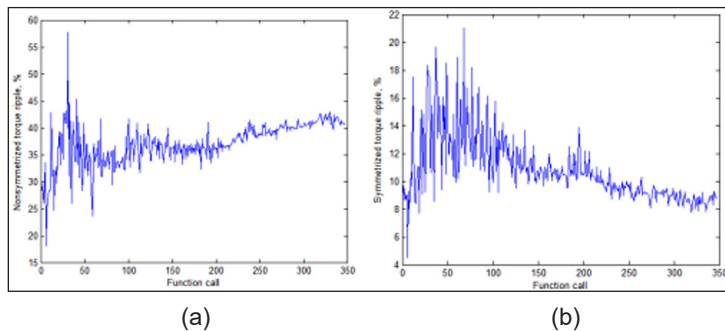


Figure 10: Torque ripple changes during optimisation: (a) Nonsymmetrised; (b) Symmetrised output. Reproduced from Prakht & Dmitrievskii (2023)

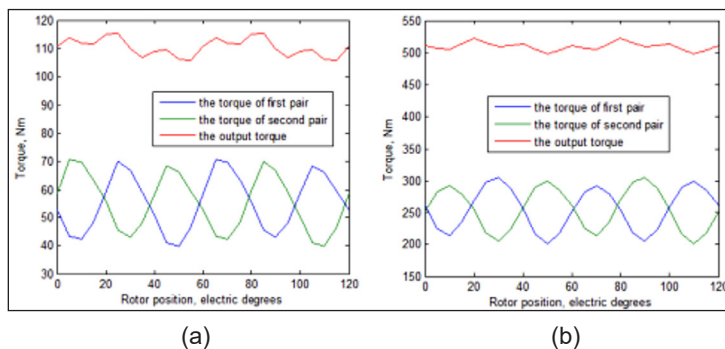


Figure 11: The torque ripple of the individual SRSC and the symmetrised (output) torque ripple after optimisation: (a) at 3450 rpm; (b) at 75. Reproduced from Prakht and Dmitrievskii (2023), *Optimal Design of Synchronous Homopolar Generator with Ferrite Magnets for Railway Passenger Cars*

2.6 Critiques and Gaps in the Literature

2.6.1 Experimental Weaknesses

Experimental work on homopolar generators (HPGs) remains constrained by short test durations, contact system instability, and losses arising from high speed rotor conditions. In one recent experiment, leakage of liquid metal contacts at elevated rotation rates led to voltage fluctuations and limited continuous operation of a homopolar disc dynamo (Avalos Zúñiga, Priede, & Bello Morales, 2017).

More broadly, studies of current transfer mechanisms in homopolar machines highlight sliding or liquid metal contacts as sources of high loss and maintenance burden (Masson, 2024).

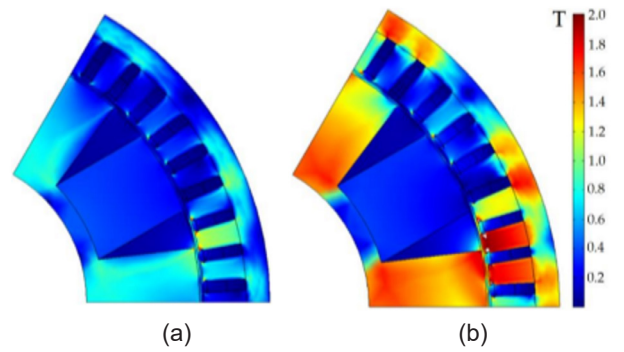


Figure 12: Pole-sector geometry of the generator for the initial design: (a) Maximum speed; (b) Maximum torque. Reproduced from Prakht and Dmitrievskii (2023), *Optimal Design of Synchronous Homopolar Generator with Ferrite Magnets for Railway Passenger Cars*

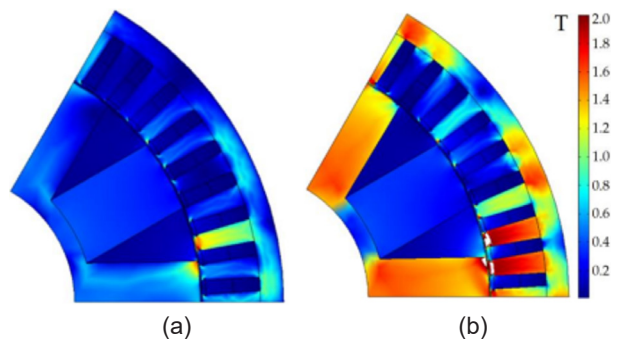


Figure 13: Pole-sector geometry of the generator for the optimised design: (a) Maximum speed; (b) Maximum torque. Reproduced from Prakht and Dmitrievskii (2023), *Optimal Design of Synchronous Homopolar Generator with Ferrite Magnets for Railway Passenger Cars*

Furthermore, experimental theoretical analysis of contemporary unipolar machines reveals that measurable losses and deviations from model predictions remain significant, indicating that practical HPG systems have yet to realise their full theoretical performance potential (Patrinos, 2024).

A number of experimental studies on homopolar generators point out various limitations that influence reliability and generalisability of findings. Table 5 summarises the reported weaknesses in the selected studies.

These weaknesses indicate that although experimental data can provide insights into component-level performance, broader validation of homopolar generators remains limited by methodological and operational constraints. Factors such as contact-system instability, high-speed rotor losses, liquid metal leakage, and divergence from theoretical models restrict long-term and high-power evaluation. Consequently, while laboratory tests inform design and optimisation, the full practical potential of HPGs has yet to be realised (Avalos Zúñiga, Priede, & Bello Morales, 2017; Masson, 2024; Patrinos, 2024).

Table 3: Generator characteristics before and after optimisation. Reproduced from Prakht and Dmitrievskii (2023), Optimal Design of Synchronous Homopolar Generator with Ferrite Magnets for Railway Passenger Cars

Characteristics	Initial Design 1	Initial Design 2	Optimised Design 1	Optimised Design 2
Loading case, i	1	2	1	2
Rotational speed, n (rpm)	3450	750	3450	750
Armature phase current amplitude, I_{arm} (A)	408	1035	375	700
Efficiency, %	94.5	78.0	92.7	84.4
Mechanical power on the generator shaft, P_{mech} (kW)	40	40	40	40
Shaft torque, N·m	111	510	111	510
Output electrical power, P_I (kW)	37.97	32.36	37.22	34.90
Armature DC copper loss, $P_{arm DC}$ (kW)	1.12	7.21	1.29	4.51
Armature eddy-current copper loss, $P_{arm AC}$ (W)	123	46	402	157
Stator laminated steel loss, $P_{iron st}$ (W)	756	379	960	411
Rotor laminated steel loss, $P_{iron rt}$ (W)	33	9	121	24
Excitation copper loss, P_{ex} (W)	187	1170	151	1123
Total loss, P_{loss} (kW)	2.22	8.81	2.93	6.22
Average losses, (P_{loss}) (kW)	5.51	-	4.58	-
Turns number in the armature slot	4.41	-	6.82	-
Required rectifier power (kW)	104.0	-	70.3	-
Power factor	0.926	0.804	0.989	0.854
Line-to-line voltage amplitude, V_{arm} (V)	116.0	44.9	116.0	67.4
Nonsymmetrised torque ripple, %	35	28	56	41
Symmetrised torque ripple, %	9.8	4.3	8.6	4.5
Flux density in the non-laminated parts of the magnetic core, T	0.4	1.3	0.1	1.5

Table 4: Characteristics of generators without magnets and with ferrite magnets. Reproduced from Prakht and Dmitrievskii (2023), Optimal Design of Synchronous Homopolar Generator with Ferrite Magnets for Railway Passenger Cars

Characteristics	SHG without Magnets (i=1)	SHG without Magnets (i=2)	SHG with Ferrite Magnets (i=1)	SHG with Ferrite Magnets (i=2)
Rotational speed n , rpm	3450	750	3450	750
Armature phase current amplitude I_{arm} , A	369.5	676.2	375	700
Efficiency, %	90.4	79.8	92.7	84.4
Mechanical power on the generator shaft P_{mech} , kW	40	40	40	40
Shaft torque, N·m	111	510	111	510
Output electrical power P_I , kW	36.58	33.12	37.22	34.90
Armature DC copper loss $P_{arm DC}$, kW	1.90	6.37	1.29	4.51
Armature eddy-current copper loss $P_{arm AC}$, W	417	131	402	157
Stator laminated steel loss $P_{iron st}$, W	961	403	960	411
Rotor laminated steel loss $P_{iron rt}$, W	192	0	121	24
Excitation copper loss P_{ex} , W	368	1169	151	1123
Total loss P_{loss} , kW	3.84	8.10	2.93	6.22
Average losses	5.97		4.58	
Turns number in the armature slot	7.75		6.82	
Required rectifier power, kW	67.9		70.3	
Power factor	1	0.747	0.989	0.854
Line-to-line voltage amplitude V_a , V	116.0	75.3	116.0	67.4
Nonsymmetrised torque ripple, %	97.8	47.0	56	41
Symmetrised torque ripple, %	11.3	4.5	8.6	4.5
Flux density in the rotor sleeve and in the stator housing, T	0.84	1.60	0.1	1.5

Table 5: Summary of Reported Weaknesses in Experimental Studies of Homopolar Generators

Study	Focus of Experiment	Reported Weaknesses / Limitations
Avalos Zúñiga, Priede, & Bello Morales (2017)	Rotating disc with liquid metal sliding contacts	Leakage of liquid metal contacts at elevated rotation rates; voltage fluctuations; limited continuous operation (~minutes); instability in current collection; thermal and parasitic losses
Masson (2024)	Sliding and liquid metal contacts in homopolar machines	High resistive losses; maintenance burden; efficiency limitations (<98%); performance constrained by brush/contact instability under high current and speed
Patrinos (2024)	Experimental theoretical study of unipolar generator	Significant deviations between theoretical predictions and experimental outcomes; measurable losses not captured by models; rotor dynamics and high-speed operation reveal practical limitations; test durations restricted

Table 6: Validation Gaps in Homopolar Generator Studies

Study	Simulation Tool(s)	Experimental Validation	Key Omitted Effects	Impact on Accuracy
Weise, Porzig, Ziolkowski, & Brauer (2018)	FEM (COMSOL-type), coupled EM-thermal	Partial (temperature only)	Mesh dependencies, simplifications in conductor modelling	Risk of overestimating efficiency and underestimating heat build-up in rotor
Patrinos (2024)	Analytical + simulation	Limited (voltage, torque)	Contact resistance, uneven current distribution	Misrepresents saturation and efficiency under real operation
Masson (2024)	Field-emission HPG simulations	Minimal	Brush wear, sliding contact effects	Overestimates efficiency at high speeds

2.6.2 Overreliance on Simulation without Validation

The majority of HPG investigations rely heavily on computational simulations—FEM, COMSOL, OPERA 3D, MATLAB—while experimental validation remains limited. These codes typically account for field distribution and induced voltages but omit secondary effects such as brush wear, contact resistance, or armature reaction. As a result, performance predictions based purely on simulation tend to be overly optimistic (Weise, Porzig, Ziolkowski, & Brauer, 2018; Patrinos, 2024; Masson, 2024). Table 6 highlights representative examples of such overreliance.

These gaps underscore that simulation-only approaches can misrepresent practical HPG behaviour. As demonstrated by Patrinos (2024), even minor unmodeled effects such as non-uniform current distribution significantly impact efficiency and saturation characteristics, emphasising the need for systematic experimental validation.

3.0 SYNTHESIS OF INSIGHTS

3.1 Patterns and Agreements

Throughout the literature, there is a consensus that homopolar generators (HPGs) are most appropriate for low-voltage, high-current applications with compact, mechanically uncomplicated DC sources. Their commutator-free operation and direct current output render them suitable for pulsed-power applications, like welding, railguns, and plasma experiments. Performance is mostly contingent upon magnet configuration, brush style, and rotor-stator geometry.

Although there has been a great deal of simulation-based investigation, the majority of experimental data consist of short-term laboratory experiments without standardised protocols, culminating in a consensus that HPGs' full potential remains bounded by design and operational limitations. The Lorentz force model is the best theoretical description of HPG operation, with historical context supplied by Faraday's law. Competing

scalar-vector potential models add theoretical scope but with restricted experimental support.

3.2 Ongoing Debates

- **Practicality vs. Laboratory Success:** Controlled setups report high efficiency, but real-world use suffers from heating, contact wear, and current imbalance.
- **Magnet Strategy:** Permanent magnets simplify design but cap flux density; electromagnets and superconducting coils achieve higher fields but increase complexity.
- **Contact Design:** Liquid-metal brushes minimise resistance yet pose safety and stability issues; solid brushes wear rapidly under high current.
- **Model vs. Experiment:** Simplified simulations often neglect eddy currents and thermal effects, overstating efficiency.
- **Theoretical Completeness:** Debate persists over whether classical electrodynamics fully describes unipolar induction or if relativistic formulations are required.

3.3 Emerging Research Directions

- **Hybrid Excitation and Materials:** Using ferrite magnets and windings in the stator can decrease torque ripple and increase controllability.
- **Superconducting Designs:** HTS coils provide enhanced magnetic flux and efficiency but encounter cost and integration challenges.
- **Advanced Contact Systems:** Brushless HPGs and multi-contact fibre or foil brushes seek to increase durability and heavy-load stability.
- **System-Level Testing:** Researchers demand comprehensive studies incorporating thermal, vibration, and electromagnetic effects to fill laboratory and industry scales.
- **Improved Modelling:** Synchronising electromagnetic, thermal, and mechanical simulations may yield more accurate performance predictions for design optimisation.

4.0 CONCLUSION

4.1 Summary of Literature Trends

Modern HPG research focuses on enhancing efficiency, scalability, and reliability through design optimisation, hybrid magnet excitation, and high-end modelling. Materials science advances such as in rare-earth magnets, ferrites, and superconductors, have alleviated some historical limitations such as low voltage and resistive losses. FEM analysis is now central to prototyping and verification, while applications are still largely focused in pulsed-power, defense, and welding systems, with growing interest in renewables integration and transportation technologies.

4.2 Identified Gaps

- **Brush Contact Resistance:** Still constrains efficiency and life due to wear and arcing.
- **Thermal Management:** Ineffective cooling measures for extended high-current operation.
- **Material Constraints:** Relatively few studies of contemporary composites for contacts, stators, and rotors.
- **Experimental Validation:** Heavy reliance on simulation with too little long-term testing.
- **Economic Feasibility:** Very limited lifecycle or cost–benefit analyses relative to batteries or flywheels.
- **Reliability Data:** No systematic analysis of ageing, maintenance, or degradation during extended operation.

4.3 Recommended Future Research Directions

In order to bring the results of homopolar generator research to a practical technology, it is important to focus future research on three strategic areas:

1. **Design and Manufacturing Optimisation:** Integrate *design-for-manufacturing* (DFM) principles to develop modular, scalable prototypes. The target outcome is to develop a reproducible HPG design by use of standardised parts which can be fabricated by commercial companies.
2. **Experimental Validation under Realistic Conditions:** Conduct long-duration and variable-load experiments to assess *thermal behaviour, mechanical wear, and fault response*, in order to prove valid datasets between the results of the simulation and the real performance measures.
3. **System-Level Integration and Economic Feasibility:** Investigate how HPGs can complement renewable energy systems and microgrids, focusing on *rapid energy discharge and high-power buffering*. Provide comprehensive techno-economic case studies of lifecycle costs, periods of maintenances, and other energy density with other technologies such as power batteries or flywheel power.

The ultimate goal is to close the existing gap between theory and practice and make the homopolar generator, a competitive element in the overall context of sustainable high-power energy systems. ■

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REFERENCES

- [1] Avalos Zúñiga, R., Priede, J., & Bello Morales, C. E. (2017). A homopolar disc dynamo experiment with liquid-metal contacts. *arXiv*. <https://arxiv.org/abs/1703.00467>
- [2] Avalos-Zuñiga, R., & Priede, J. (2023). Realization of Bullard's disc dynamo. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 479(2271). <https://doi.org/10.1098/rspa.2022.0740>
- [3] Baumgärtel, C., & Maher, S. (2022). Resolving the paradox of unipolar induction: New experimental evidence on the influence of the test circuit. *Scientific Reports*, 12, Article 16791. <https://doi.org/10.1038/s41598-022-21155-x>
- [4] Bianchini, C., Cavagnino, A., Biasion, M., Vaschetto, S., & Tenconi, A. (2011). Homopolar generators: An overview. In *Proceedings of the International Conference on Electrical Machines*. https://www.academia.edu/18676622/Homopolar_generators_An_overview
- [5] Circuit Globe. (2025). Faraday's law of electromagnetic induction. <https://circuitglobe.com/what-is-faradays-law-of-electromagnetic-induction.html>
- [6] Engel, T. G., & Kontras, E. A. (2020). *Analysis and design of homopolar motors and generators*. Department of Electrical and Computer Engineering, University of Missouri. <https://iypt.ru/wp-content/uploads/2020/10/Analysis-and-design-of-homopolar-motors-and-generators.pdf>
- [7] Füger, R., Matsekh, A., Kells, J., Sercombe, D. B. T., & Guina, A. (2016). A superconducting homopolar motor and generator: New approaches. *Superconductor Science and Technology*, 29(3), 034001. <https://doi.org/10.1088/0953-2048/29/3/034001>
- [8] Gobbi, J. C. (2024, June 7). Homopolar technology. *GSJournal*. <https://www.gsjournal.net/Science-Journals/Research%20Papers-Engineering%20%28Applied%29/Download/9901>

- [9] Golea, D. G. (2021, July 28). Improvements in modern weapons systems: The use of dielectric materials for the development of advanced models of electric weapons powered by brushless homopolar generator [Working paper]. SSRN. <https://doi.org/10.2139/ssrn.3894975>
- [10] Hwang, Y. J. (2021). Design and characteristic analysis of a homopolar synchronous machine using a NI HTS field coil. *Energies*, 14(18), Article 5658. <https://doi.org/10.3390/en14185658>
- [11] Kalsi, S., Hamilton, K., Buckley, R. G., & Badcock, R. A. (2019). Superconducting AC homopolar machines for high-speed applications. *Energies*, 12(1), Article 86. <https://doi.org/10.3390/en12010086>
- [12] Köster, R., & Binder, A. (2022, June). Electromagnetic design considerations on HTS excited homopolar inductor alternators. In *Proceedings of the 2022 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*. <https://doi.org/10.1109/SPEEDAM53979.2022.9842224>
- [13] Li, C., Zhang, X., & Chen, R. (2024). Exploring the effect of interface contact states on brush/collector ring systems of high current machines. *Lubricants*, 12(12), Article 461. <https://doi.org/10.3390/lubricants12120461>
- [14] Liu, L., Yu, K., & Xie, X. (2023). A high-temperature superconducting homopolar inductor alternator with slotless stator core for high-power pulsed power supply (Version 1). *Preprints.org*. <https://doi.org/10.20944/preprints202307.0226.v1>
- [15] Ma, N., Walker, J., Talmage, G., Brown, S. H., & Sondergaard, N. (2023). Liquid-metal sliding electrical contacts for homopolar motors and generators. In *Proceedings of the 2023 IEEE International Electric Machines & Drives Conference (IEMDC)*. <https://impact.ornl.gov/en/publications/liquid-metal-sliding-electrical-contacts-for-homopolar-motors-and>
- [16] Masson, P. J. (2024). Field emission current transfer for homopolar machines. *OSTI*. <https://doi.org/10.2172/2373078>
- [17] Mende, F. F. (2018). Homopolar induction in the concept of the scalar vector potential. *Global Journal of Science Frontier Research: A Physics and Space Science*, 18(9), 1–12. https://globaljournals.org/GJSFR_Volume18/5-Homopolar-Induction-in-the-Concept.pdf
- [18] Paulus, B. (2018, April 9). Redesigning Faraday's wheel: Creating efficient homopolar generators. *COMSOL Blog*. <https://www.comsol.com/blogs/redesigning-faradays-wheel-creating-efficient-homopolar-generators>
- [19] Patrinos, K. (2024). On the unipolar generator: An experimental and theoretical study. *Journal of Applied Mathematics and Physics*, 12, 2928–2958. <https://doi.org/10.4236/jamp.2024.128176>
- [20] Prakht, V., Dmitrievskii, V., & Kazakbaev, V. (2023). Analysis of performance improvement of passenger car synchronous homopolar generator with the addition of ferrite magnets. *Applied Sciences*, 13(6), Article 3990. <https://doi.org/10.3390/app13063990>
- [21] Prakht, V., Dmitrievskii, V., & Kazakbaev, V. (2023). Optimal design of synchronous homopolar generator with ferrite magnets for railway passenger cars (Preprint). *Preprints*. <https://doi.org/10.20944/preprints202301.0410.v1>
- [22] Prakht, V., Dmitrievskii, V., & Kazakbaev, V. (2023). Synchronous homopolar generator without permanent magnets for railway passenger cars. *Applied Sciences*, 13(4), Article 2070. <https://doi.org/10.3390/app13042070>
- [23] QY Research. (2025, October 22). Global and U.S. homopolar generators market report: Average price USD 37,000 per unit [Press release]. *openPR*. <https://www.openpr.com/news/4233217/global-and-u-s-homopolar-generators-market-report-published>
- [24] Srinivasa, Y. (2015). *Homopolar generator: Faraday generator*. <https://www.scribd.com/document/254189683/Homopolar-Generator>
- [25] The Fabricator. (2019, August 9). The potential of homopolar-generator welding. *The Fabricator*. <https://www.thefabricator.com/thefabricator/article/assembly/the-potential-of-homopolar-generator-welding>
- [26] Van Hees, H. (2014). *The homopolar generator: An analytical example*. <https://itp.uni-frankfurt.de/~hees/gen-phys/homopolar.pdf>
- [27] Weise, K., Porzig, K., Ziolkowski, M., & Brauer, H. (2018). Modelling and simulation of a simple homopolar motor of Faraday's type. In *Advances in Electrical Machines & Drives*.
- [28] Wikipedia contributors. (2021). Homopolar generator. In *Wikipedia*. https://en.m.wikipedia.org/wiki/Homopolar_generator
- [29] Zhao, M., Li, J., Li, C., Li, Y., & Zhang, X. (2025). Study on current carrying friction characteristics and corrosion resistance of carbon brush/collector ring by copper-graphene electrodeposition process. *Lubricants*, 13(4), Article 162. <https://doi.org/10.3390/lubricants13040162>

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