Survey of Low-Speed Alternator Designs Suitable for Hydro Power Plants in Bidirectional Flowing Rivers

Julius A. Idajor[1], Iyemeh, Uchendu[2], Obasi-sam Ojobe Ojah[3], Ruth Asi[4], Ogri, J Ushie[5]

[1]*Department of Computer Engineering, Faculty of Engineering and Technology, University of Calabar.*

[2, 3, 4 & 5] *Department of Electrical and Electronics Engineering, Faculty of Engineering and Technology, University of Calabar.*

[1]juliusidajor@unical.edu.ng
[2] iyemehuchendu@unical.edu.ng
[3]obasisamojobe@unical.edu.ng
[4]*ruthasi@unical.edu.ng*
[5]*ogri.ushie@unical.edu.ng*

Abstract*-- Low-speed alternators (LSAs) are critical components for energy conversion in hydrokinetic systems operating under low-head and bidirectional flow conditions. However, their practical deployment is constrained by low rotational speeds, high torque requirements, and challenges in voltage regulation and frequency control. This paper presents a technically grounded review of low-speed alternator design, emphasizing electromagnetic, mechanical, and power conditioning considerations. A refined theoretical framework based on electromagnetic induction and synchronous machine principles is provided, highlighting the dependence of induced electromotive force (EMF) on frequency, pole count, and flux linkage. The study systematically evaluates state-of-the-art machine topologies—including axial flux permanent magnet machines (AFPMs), permanent magnet synchronous generators (PMSGs), and multi-pole configurations while critically assessing their performance under micro-hydro (50–300 rpm) and tidal stream (100–500 rpm) operating regimes. Key limitations such as material cost, structural complexity, torque ripple, thermal constraints, and the need for power electronic interfaces are discussed. Furthermore, design improvement strategies focusing on high pole-density architectures, enhanced stator winding configurations, and hybrid excitation mechanisms are examined. The paper concludes that while LSAs present a viable solution for decentralized hydrokinetic energy systems, their large-scale adoption depends on integrated optimization of electromagnetic design, mechanical robustness, and power electronics for variable-speed operation.

Index terms: Low-speed alternator, hydrokinetic energy, axial flux machine, permanent magnet generator, micro-hydro systems, variable-speed generation

I. INTRODUCTION

Electric power generation in the twenty-first century is characterized by a transition from centralized fossil-fuel-based systems to distributed and renewable energy technologies [1], [2]. Conventional generation systems—primarily coal, natural gas, and petroleum—continue to dominate due to established infrastructure and dispatchability [2]. However, increasing environmental concerns, fuel price volatility, and global decarbonization targets have accelerated the deployment of renewable energy systems [3]. Among these, hydropower remains one of the most mature and efficient technologies due to its high energy conversion efficiency, predictability, and long operational lifespan [4]

Conventional hydropower systems rely on high hydraulic head and unidirectional flow, typically achieved through large dam infrastructures [5]. These systems convert gravitational potential energy into mechanical and subsequently electrical energy via turbines and synchronous generators. Despite their efficiency, such installations are geographically constrained and unsuitable for regions characterized by low-head, low-flow, or bidirectional water movement [6]

In regions such as Nigeria, significant untapped hydrokinetic energy exists in rivers, estuaries, and coastal environments exhibiting tidal or oscillatory flow patterns [7]). These environments are characterized by low flow velocities (typically 0.5–2.5 m/s) and minimal hydraulic head, making them incompatible with conventional dam-based systems [6]. Harnessing energy from such environments requires technologies capable of operating efficiently under low rotational speeds and variable flow directions.

Recent research has therefore focused on hydrokinetic energy conversion systems such as run-of-river turbines, tidal stream generators, and floating-hydro power plants (FHPPs) [8]*;* [6]. These systems extract kinetic energy directly from flowing water without requiring large civil infrastructure. However, their effectiveness is fundamentally limited by the performance of the electrical generator, particularly under low-speed operating conditions [9]

An alternator converts mechanical energy into electrical energy through electromagnetic induction [10]. In conventional grid-connected systems, alternators operate at synchronous speeds of 1500 rpm (50 Hz, 4-pole) or 3000 rpm (50 Hz, 2-pole). In contrast, hydrokinetic turbines in micro-hydro applications typically operate in the range of 50–300 rpm, while tidal stream systems may reach 100–500 rpm depending on flow velocity and turbine design [6], [8]. At such low speeds, the induced EMF is significantly reduced, necessitating alternative design strategies [11]

To compensate for reduced rotational speed, LSAs employ increased pole counts, higher magnetic flux densities, and optimized winding configurations [11], [12] However, these design modifications introduce trade-offs, including increased machine size, higher material costs (especially for rare-earth magnets), mechanical stress due to high torque, and challenges in thermal management [12]. Furthermore, variable-speed operation in hydrokinetic systems requires power electronic converters for voltage regulation, frequency stabilization, and grid compatibility [13].

The design of LSAs is therefore a multidisciplinary problem involving electromagnetic design, mechanical integrity, thermal performance, and power electronics integration. While numerous studies address individual aspects of low-speed generator design, a comprehensive and technically consistent synthesis remains limited [9].

This paper aims to provide a rigorous review of low-speed alternator technologies, focusing on their applicability to low-head and bidirectional hydro systems. It evaluates existing machine topologies, identifies performance limitations, and outlines engineering strategies for improved design. Particular emphasis is placed on realistic operational constraints, including torque requirements, efficiency limits, and control challenges associated with variable-speed generation.

The remainder of this paper is structured as follows:

I. Section 2 presents the theoretical foundation of alternator operation.

II. Section 3 reviews state-of-the-art low-speed generator technologies.

III. Section 4 discusses design improvement strategies.

IV. Section 5 concludes the study.

II. Background to the Study

The alternator is one of the most fundamental electromechanical devices in modern electrical engineering and energy conversion systems. Fundamentally, an alternator converts mechanical energy into electrical energy in the form of alternating current (AC) through the principle of electromagnetic induction. According to Faraday's Law, an electromotive force (EMF) is induced in a conductor whenever it experiences a change in magnetic flux [14]. Mathematically, the induced EMF is expressed as:

$$E = N\frac{d\Phi}{dt} \quad (1)$$

Where E is the induced EMF in volts, N is the number of turns in the coil, and Φ is the magnetic flux in webers. This principle underpins all alternating current generators, from portable devices to large-scale utility alternators. Essentially, alternators operate by either rotating conductors within a magnetic field or rotating magnetic fields around stationary conductors, so that the time rate of change of magnetic flux induces an AC voltage [15].

The simplest alternator configuration typically comprises a magnetic field source (permanent magnet or electromagnet), a rotating or stationary coil, and brush assemblies to maintain electrical contact with moving parts. As the coil cuts through the magnetic flux during rotation, it generates an alternating EMF at the terminals. Classical designs rely on brushes and slip rings for current transfer, although modern brushless configurations maintain the same operating principle: mechanical rotation produces voltage proportional to the rate of flux cutting [15].

Alternators are widely applied across various sectors. In large-scale energy production, they form the core of thermal, hydroelectric, and nuclear power stations, where turbine shafts provide the mechanical input. In renewable energy systems, they are employed in wind turbines and micro-hydropower installations. Additionally, alternators are essential in automotive electrical systems, portable generators, and emergency backup power solutions due to their reliability, robustness, and ability to operate under varying loads [14], [16]

For single-phase alternators, the RMS value of the output EMF is given by:

$$E = 4.44fN\Phi \quad (2)$$

Where f is the frequency (Hz), related to the rotor speed Ns (RPM) and the number of poles P by:

$$f = \frac{PNs}{20} \quad (3)$$

These expressions highlight that both frequency and EMF magnitude are directly influenced by rotational speed and pole count. Consequently, maintaining desired voltage output at low speeds requires compensatory measures such as increasing the number of poles, flux density, or winding turns [15].

This dependence on rotational speed presents a significant challenge for low-speed alternators (LSAs). Whereas high-speed alternators, common in automotive and conventional power plants, generate sufficient EMF at compact sizes, LSAs operate at rotational speeds as low as 40–500 RPM,

typical in tidal streams, low-head rivers, and mechanically constrained renewable devices [14], [16]. At these speeds, the rate of flux change—and hence induced voltage—is considerably reduced unless mitigated by design enhancements such as high-flux-density rare-earth magnets (e.g., NdFeB) and increased pole counts.[11], [12].

Beyond electromagnetic design, LSAs encounter notable mechanical challenges. Lower angular speeds necessitate higher torque to deliver equivalent power, increasing mechanical stresses on the rotor, shaft, and bearings [16] Consequently, LSAs demand robust mechanical design to ensure structural stability, precise alignment, and minimal mechanical losses. Thermal management is equally critical, as larger machine size and higher copper losses exacerbate temperature rise, potentially limiting efficiency and operational lifespan if inadequately addressed [14]

Technological innovations have targeted these constraints. Axial flux permanent magnet (AFPM) machines, coreless stator designs, and modular segmented windings improve torque density, efficiency, and manufacturability [14], [16]. AFPM machines are particularly suited for low-speed applications due to their large air-gap diameters and compact axial dimensions, enabling higher torque production without excessive mass. Coreless stators reduce iron losses and eliminate cogging torque, facilitating smoother operation under variable flow, while segmented windings enhance cooling and maintenance efficiency [14], [16].

Additionally, modern engineering tools have enhanced the precision and performance of LSAs. Finite element analysis (FEA) enables detailed modeling of magnetic flux distributions, optimized pole-slot combinations, and dynamic behavior predictions. Advanced cooling methods, including liquid channels, heat pipes, and thermally efficient composites, mitigate temperature rise. Power electronic converters allow LSAs to interface with variable-speed inputs efficiently, enabling stable voltage output for grid or battery integration [15], [14].

Despite these advancements, research on LSAs remains fragmented across electrical, mechanical, and materials engineering disciplines. Existing literature often addresses isolated topics such as magnetic optimization, thermal analysis, or control strategies without providing an integrated synthesis tailored to low-speed hydrokinetic applications [16]. Consequently, designers must navigate dispersed sources, limiting the accessibility of comprehensive knowledge essential for innovation.

With the growing global shift toward renewable energy and the need to exploit low-head, variable-flow water resources—particularly in countries such as Nigeria—there is an increasing demand for consolidated LSA knowledge. This review aims to synthesize foundational design principles, evaluate state-of-the-art innovations, and identify critical challenges and opportunities for high-performance low-speed alternator development in hydrokinetic and micro-hydropower systems [14], [16].

III. State-of-the-Art (Structured Comparative Analysis)

A number of low-speed alternator designs have been proposed and analyzed in the literature, each targeting improved performance under reduced rotational speeds. These studies vary in methodology, operating conditions, and output characteristics. However, a comparative overview is necessary to highlight key differences in design approaches, performance levels, and practical limitations. Table I summarizes selected existing designs, focusing on their operating speeds, electrical outputs, and notable observations. [6], [8], [9], [11], [17]-[21].

Table 1: Classification of Low-Speed Generator Applications

Application Type	Typical Flow Speed (m/s)	Rotor Speed (RPM)	Generator Type Commonly Used	Key Challenges
Micro-hydro (waterwheel, small turbines)	0.5 – 1.5	50-300	PMG, AFPM, Induction	Low torque, voltage instability
Tidal stream system	1.0 – 2.5	100 – 500	PMSG, AFMP	Bidirectional flow, fatigue loading
Floating Hydro Power Plant (FHPP)	0.5 – 2.5	80 – 400	AFMP, Multi-rotor PMG	Mooring stability, hydrodynamic losses
Small wind turbines	Variable	100 – 600	PMSG, DFIG	Speed variability, control complexity

IV. Comparison of Generator Topologies for Low-Speed Operation

Different low-speed alternator configurations exhibit varying characteristics depending on their structural design and excitation methods. These differences influence efficiency, cost, complexity, and suitability for hydrokinetic applications. A structured comparison helps identify the strengths and limitations of each configuration. Table II presents a comparative analysis of common low-speed alternator types used in renewable energy systems. [11], [12], [14], [16].

Table 2: Comparison of Generator Topologies for Low-Speed Operation

Generator Type	Key Features	Advantage	Limitation	Suitability
Permanent Magnet Generator (PMG)	Uses NdFeB magnets for excitation	High efficiency, no excitation loss	High magnet cost, demagnetization risk	Micro-hydro, wind
Permanent Magnet Synchronous Generator (PMSG)	Synchronous operation with PM rotor	Stable output, high torque density	Requires power electronics for control	Tidal, FHPP
Axial Flux PM Generator (AFPMG)	Disc-shaped, large air-gap radius	High torque at low speed, compact	Complex manufacturing, cooling issues	FHPP, micro-hydro
Induction Generator	Rotor currents induced electromagnetically	Robust, low cost	Poor efficiency at low speed, needs excitation	Limited micro-hydro use
Multi-stator/Multi-rotor PMG	Multiple flux interaction layers	High torque density, reduced ripple	Increased complexity, alignment issues	Advanced FHPP systems

V. Performance Comparison of Reported Low-Speed Alternator Designs

The performance of low-speed alternators in bidirectional flow environments is influenced by several mechanical, electrical, and hydrodynamic factors. Understanding these challenges is essential for developing effective design improvements. Table 3. outlines the key challenges and corresponding engineering solutions for enhancing system performance. [17]-[21].

Table 3: Performance Comparison of Reported Low-Speed Alternator Designs

Study / Author	Speed (RPM)	No. of Poles	Voltage Output	Current	Power Output	Generator Type	Key observatiom	Validation Level
Syafriyudin et al. (2020)	200	30	100 VA(50 Hz)	Not stated	Not stated	AFPM(NdFeB)	High pole density enables grid frequency at low speed	Experimental
BayuSovan et al. (2021)	200-500	24	24-48.3V	Up to 24.6A	1168W	PMG(Simulated)	Good output but lacks physical validation	Simulation
Darmawi (2014)	450	Not stated	12V	Not stated	100W	PMG	Low voltage, no regulation discussed	Experimental (limited)
Khedekar et al. (2024)	150-400	18	21-67V	Not stated	300W	PMG	Suitable for human-powered systems	Experimental
Cistelecan et al. (2007)	~200	24	Not stated	Not stated	Up to 10KW	PMSG	Good efficiency, low cogging torque	Experimental

VI. Multi-Stator and Multi-Rotor Configurations

To enhance power output and torque density in low-speed alternators, researchers have explored multi-stator and multi-rotor configurations. These designs utilize multiple magnetic interaction layers to increase electromagnetic coupling without significantly increasing rotational speed. Such configurations are particularly suitable for hydrokinetic applications where space constraints are less critical than efficiency and output stability. However, they also introduce additional design complexity, magnetic interference, and higher manufacturing costs. Table IV presents an overview of multi-stator and multi-rotor configurations, highlighting their structural characteristics, advantages, and associated limitations [11], [12].

Table 4: Multi-Stator and Multi-Rotor Configurations

Table 6: Floating-Hydro Power Plants (FHPP): Engineering Considerations

XI. Salient Pole Rotor Application in Low-Speed Machines

Salient pole rotor designs are widely adopted in low-speed electrical machines due to their ability to produce high

Observation	Engineering Implication
Increasing pole count reduces required speed	Leads to larger machine size and complexity
High torque requirement at low speed	Requires stronger shaft and bearings
PMGs dominate low-speed applications	Cost and material availability are limiting factors
Simulation results often optimistic	Field validation is essential
Voltage output varies significantly	Requires regulation using power electronics

torque at relatively rotational speeds[14],[16]. Their projecting pole structure allows for increased magnetic flux interaction, making them particularly suitable for hydroelectric and other slow-speed applications. Despite these advantages, salient pole machines also present limitations such as increased mechanical size, magnetic losses, and operational constraints at higher speeds. A clear understanding of their application characteristics is necessary for effective design selection. Table VII summarizes the key features, advantages, and limitations of salient pole rotor applications in low-speed machines**.**

Table 7: Salient Pole Rotor Application in Low-Speed Machines

Feature	Description
Rotor Structure	Projecting poles with field
Speed Range	120 – 400 rpm
Advantages	High flux concentration, suitable for low speed
Limitation	Not suitable for high-speed due to mechanical stress

Correction Applied:

Salient pole machines are designed for the following reasons:

a) Reduced windage losses at low speed

b) Mechanical suitability for high torque applications[14],[16]

X. Key Engineering Observations from Literature

A comprehensive review of existing studies on low-speed alternators reveals several recurring trends, challenges, and design considerations. Synthesizing these findings provides valuable insight into the current state of research and highlights critical gaps that must be addressed for practical implementation. Such observations help guide future design improvements and research directions. Table VIII presents a summary of key engineering observations derived from the literature, emphasizing performance limitations, design trade-offs, and potential areas for innovation[11],[12],[17]-[21].

Table 8: Key Engineering Observations from Literature

XI. Conclusion

The increasing global emphasis on renewable energy and sustainable power generation highlights the critical role of low-speed alternators (LSAs) in harnessing energy from low-velocity and bidirectional water resources[1]-[13]. Unlike conventional high-speed generators, LSAs are specifically engineered to operate efficiently at rotational speeds as low as 40–500 RPM, making them ideal for micro-hydro, tidal, floating-hydro, and other low-speed renewable energy systems. By eliminating the need for complex gearing mechanisms, LSAs offer a practical and reliable solution for energy extraction in geographically constrained or environmentally sensitive sites, thereby supporting decarbonization and expanding access to clean electricity [6],[8],[11].

Technological advances—including high-flux-density permanent magnet materials, axial flux machine topologies, coreless stators, and modular segmented winding configurations—have substantially enhanced the electromagnetic performance, torque density, and thermal management of LSAs[11],[12],[14],[16]. These innovations enable effective voltage generation, smoother operation, and improved efficiency even under variable-speed conditions typical of hydrokinetic environments. Nevertheless, further optimization is required in areas such as high pole-count configurations, flux linkage enhancement, and stator winding design to achieve higher EMF output and overall system compactness [11],[12].

Future progress in LSAs will depend on integrated multidisciplinary research encompassing electromagnetic design, mechanical robustness, thermal control, and power electronics integration[6],[9],[14],[16]. Field validation and performance benchmarking in low-head and bidirectional water systems—particularly in countries like Nigeria with abundant yet underutilized hydrokinetic resources—are crucial to translating laboratory designs into scalable, cost-effective, and environmentally sustainable solutions[7],[8]. Ultimately, LSAs represent a versatile and essential technology for decentralized renewable power generation, bridging the gap between energy accessibility, environmental sustainability, and efficient exploitation of low-speed water resources[1]-[13].

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Author's Profile



Dr. Julius Achirigbor Idajor is a Lecturer I in the Department of Electrical and Electronics Engineering, Faculty of Engineering and Technology, University of Calabar, Calabar, Nigeria. He obtained his B.Sc. degree in Electronics and Computer Technology, M.Sc. in Engineering Physics (Telecommunications), and Ph.D. in Engineering Physics (Electronics), all from the University of Calabar, Nigeria. His academic and research interests span areas of electronics, telecommunications, and applied engineering systems. Dr. Idajor is actively engaged in teaching, research, and academic development within the engineering discipline. He can be reached via his institutional email: juliusidajor@unical.edu.ng.



Dr. Iyemeh Uchendu is currently a Post Doctoral Researcher at the University of Colorado, Boulder. He obtained his PhD in Electronics Engineering in 2018 from the University of Surrey, UK. His current research interest are in wireless systems, RF engineering and renewable energy. iyemehuchendu@unical.edu.ng



Engr. Obasi-Sam Ojobe Ojah, a Lecturer in the Department of Electrical and Electronics Engineering, University of Calabar. He holds B. Eng (Hons), M. Eng, Cross River University of Technology

(CRUTECH), Calabar. PhD in view, University of Port Harcourt. obasisamojobe@unical.edu.ng



Ruth Asi is a COREN-registered Electrical and Electronics Engineer and Lecturer II in the Department of Electrical/Electronic Engineering, University of Calabar, Nigeria. She has over ten years of post-graduation experience in electrical systems, instrumentation, and engineering operations. Her research interests include power systems transmission and distribution, power system stability and control, renewable energy systems, smart grids and intelligent monitoring, signal processing applications in power systems, instrumentation and measurements. She is currently involved in research on low-speed alternators for bi-directional hydropower applications, focusing on system design, testing, and performance optimization. She holds an MSc in Communication Engineering from the University of Manchester, United Kingdom, and a B.Tech in Electrical and Electronic Engineering from Rivers State University, Nigeria formerly known as Rivers State University of Science and Technology where she graduated with a Second Class Upper Division. She is a registered engineer with COREN and has additional training in cybersecurity. Her expertise includes equipment commissioning, maintenance and fault diagnosis.



Dr. Ogri J. Ushie received a B. Eng. in 2002 and MEng in 2008 in Electrical Electronics Engineering from Federal University of Technology-Yola and Abubakar Tafawa Belewa University-Bauchi both in Nigeria respectively. He obtained a PhD degree at Brunel University London in 2016. He is also a member of NIEEE. He is a Cooperate member Nigerian Society of Engineers and a registered Engineer with Council for the Regulation of Engineering in Nigeria. His research interest is in area of ‘Intelligence Optimisation of Analog Electronic Circuit using Machine Learning.