Permanent magnet generator for small and medium-scale hydropower: a systematic review

Ngatono[1,2], Raja Nor Firdaus Kashfi Raja Othman[1,3], M. Nazri Othman[1,3], M. Zulkifli Ab Rahman[1,4]
[1]Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia
[2]Department of Computer Systems, Faculty of Information Technology, Universitas Serang Raya, Banten, Indonesia
[3]Electric Vehicle, Power Electronics and Drives Research Group, CeRIA, UTeM, Melaka, Malaysia
[4]Department of Electrical Engineering, Politeknik Sultan Mizan Zainal Abidin, Dungun, Malaysia

Article Info

Article history:

Received Oct 25, 2024
Revised Jan 6, 2026
Accepted Feb 11, 2026

Keywords:

Design
Hydropower
Optimization
Permanent magnet generator
Renewable energy

ABSTRACT

Renewable energy, particularly hydropower, is a key focus in reducing reliance on fossil fuels and mitigating environmental impacts. Permanent magnet generator (PMG) has emerged as a highly efficient option for converting hydro-energy into electricity, offering advantages such as high efficiency, compact design, and minimal maintenance. This review explores the latest developments in PMG technology, particularly for small and medium-scale hydropower applications. A systematic review method was used to analyze 617 papers and narrow them down to 20 relevant studies. Key findings highlight advancements in PMG design, including modular stators, counter-rotating turbines, and cordless designs that enhance efficiency and adaptability in low-speed environments. However, significant challenges remain, including the high cost of magnetic materials like Neodymium Iron Boron (NdFeB), thermal stability issues, and more robust control systems to manage variable water flow conditions. The review concludes that while PMG holds great potential for hydropower applications, Further research is needed to optimize material usage, improve design, and reduce costs. Future work should focus on developing new magnetic materials and innovative rotor designs to ensure PMG can provide a scalable and sustainable solution for global energy needs.

Corresponding Author:

Raja Nor Firdaus Kashfi Raja Othman
Faculty of Electrical Technology and Engineering (FTKE), Universiti Teknikal Malaysia Melaka (UTeM)
Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
Email: norfirdaus@utem.edu.my

1. INTRODUCTION

Renewable energy has become a central focus in global efforts to reduce dependence on fossil fuels and mitigate the environmental impacts caused by traditional energy generation. One of the most promising sources of renewable energy is hydropower, which harnesses the flow of water to generate electricity. According to data from the International Energy Agency (IEA), hydropower accounts for nearly 16% of the world's total electricity generation capacity and over 70% of all renewable energy produced globally [1].

In order to transmute hydroelectric energy into electrical energy, a device known as a generator is indispensable. Among the frequently employed varieties of generators are the induction generator and the permanent magnet generator (PMG) [2]. Amid the growing global demand for clean and sustainable energy, PMG technology has emerged as an efficient solution for maximizing hydro energy conversion into electrical energy across various scales, from large hydropower plants to small-scale applications like Pico-Hydro [3], [4].

PMG offers several advantages over conventional generators, such as induction or synchronous generators that rely on electromagnetic excitation. The primary advantage of PMG lies in its higher efficiency, simpler design without the need for external excitation, smaller size and weight for the same power output. In the context of hydropower, PMG is particularly relevant due to its ability to operate efficiently at low rotational speeds, which are often encountered in water turbines [5]. Additionally, PMG is more reliable due to fewer moving parts, which reduces the risk of mechanical failure and lowers maintenance costs [6].

Various studies have explored the development and application of PMG in hydropower generation [7]. For instance, research conducted by Zariatin *et al.* [8] demonstrated that using PMG in small-scale hydropower applications, such as Pico-Hydro, can improve system efficiency by up to 10% compared to induction generators. In another study, Kallaste *et al*. [9] investigated the use of PMG in low-capacity hydropower plants, emphasizing the importance of selecting appropriate magnetic materials to enhance generator performance under varying environmental conditions. Magnetic materials like Neodymium Iron Boron (NdFeB) have become the material of choice due to their high magnetic energy density, although they also have drawbacks in terms of resistance to high temperatures [10].

In addition to efficiency, one of the primary challenges in developing PMG for hydropower applications is optimizing the design of the magnets and rotor. Choi *et al*. [11] highlighted the importance of permanent magnet configuration in improving magnetic flux density and maximizing power output. They proposed a rotor design with tangentially placed magnets, which showed significant performance improvements in generator output. This aligns with findings reported by Gandzha *et al.* [12], who explored various rotor configurations and demonstrated that a radial magnet arrangement can yield better results at low speeds, making it ideal for hydropower applications.

Beyond advancements in magnet design, experimental and simulation studies have contributed to a better understanding of the electromagnetic characteristics of PMG under different operational conditions [13], [14]. Through finite element method (FEM)-based simulations, Kumar *et al.* [15] identified critical design parameters that enhance PMG efficiency under partial load conditions, which are common in small-scale hydropower systems. Their findings indicate that careful design optimization can improve overall system performance and reduce energy losses due to load variation.

Despite the many advantages offered by PMG, there are still several challenges to be addressed in its implementation in hydropower systems. One of the main issues is the high cost of permanent magnetic materials, especially when using high-performance materials like NdFeB [16], [17]. As reported by Bharanikhumar *et al* [18], the cost of magnetic materials contributes more than 30% of the total cost of manufacturing PMG, which can be a barrier to adopting this technology in cost-sensitive markets.

Therefore, further research is needed to identify more affordable alternatives that still offer good performance. Moreover, the thermal stability of magnetic materials is also a critical concern in hydropower applications. Permanent magnets tend to lose some of their strength at high temperatures, which can affect the long-term performance of PMG, particularly in extreme environments [19]. A study conducted by Liu *et al.* [20] suggested the use of passive and active cooling techniques to keep PMG operating temperatures within a safe range while minimizing the risk of demagnetization. As technology continues to evolve, these challenges present opportunities for further research. One promising area is the development of new magnetic materials with better magnetic and thermal properties as well as lower production costs. Additionally, the implementation of innovative design techniques, such as new magnet arrangements and using composite materials for rotors, is an interesting topic for further exploration [21], [22]. In conclusion, the advancements in PMG technology offer great potential for improving the efficiency and reliability of hydropower generation. However, in-depth research is required on design optimization, material selection, and the development of more cost-effective production methods. This article aims to provide a systematic review of the existing literature, with a focus on current trends, challenges, and research gaps in the development of PMG for small and medium-scale hydropower applications.

2. PERMANENT MAGNET GENERATOR

PMG is instrumental in augmenting the efficacy of small hydropower plants, especially within low-head scenarios. These generators capitalize on the benefits of variable speed technology and superior efficiency, rendering them appropriate for the exploitation of unutilized hydropower resources. The subsequent sections delineate fundamental characteristics of PMGs within hydropower systems.

2.1. Working principle

The working principle of a PMG is similar to that of a conventional synchronous generator, where the magnetic field generated by a permanent magnet interacts with the stator winding to produce an electric current through electromagnetic induction. As the rotor containing the permanent magnet rotates, the magnetic field cuts through the stator winding, inducing a voltage in the coils. The induced voltage can be calculated using Faraday's law of electromagnetic induction in (1).

$$e(t) = N \cdot \frac{d\Phi}{dt} \quad (1)$$

Where e(t) is the induced voltage, N is the number of coil turns, Φ is the magnetic flux produced by the permanent magnets, dq/dt is the rate of change of magnetic flux with time [23]. The input of a PMG can be calculated using the basic mechanical power formula in (2).

$$P = \frac{1}{2} \cdot \omega \cdot T \quad (2)$$

Where P is the input power (in watts), ω is the angular speed of the rotor (rad/s), *T* is the torque produced by the interaction in the magnetic field.

2.2. Basic structure of PMG

In an axial flux permanent magnet generator (AFPMG), the magnetic flux flows parallel to the rotor shaft direction. Figure 1 shows the working principle of an axial and radial flux permanent magnet machine. AFPMG are typically more compact and suitable for applications with limited space or systems with low rotational speeds, such as wind turbines or Pico-Hydro applications. The primary advantage of AFPMG is its high-power density and improved efficiency over radial designs in some low-speed applications. This design allows for more optimal integration of permanent magnets since the magnetic flux moves along the rotor axis, reducing the generator’s weight and volume. Additionally, AFPMG provides a more uniform flux distribution over the rotor surface, which can reduce eddy current losses in the stator.

Radial flux permanent magnet generator (RFPMG**)** is the more commonly used configuration, where the magnetic flux moves radially from the rotor center outward to the stator or vice versa. RFPMGs are easier to manufacture and typically require less material, making them more cost-effective for large-scale applications, such as in a wind power plant generator. RFPMG usually exhibits stable performance at high rotational speed, making them ideal for applications requiring significant power. The main advantage of RFPMG is its ease of fabrication and the broader availability of permanent magnet materials. RFPMG also has a simpler topology, which makes the design more flexible for various types of turbines.

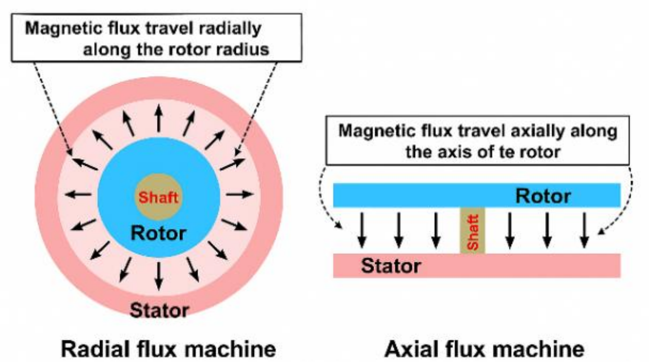

Figure 1. Axial and radial flux permanent magnet machine [24]

3. METHOD

The methodology used in this review follows a systematic approach that includes the processes of identifying, selecting, analyzing, and synthesizing literature from various reputable sources, such as peer-reviewed journals and international conference proceedings.

3.1. Review method

A present result of a systematic literature review of peer-reviewed articles concerning PMG for hydropower. A systematic literature review is a protocol-driven approach that enables the identification of significant future research opportunities [25], [26]. This method minimizes researcher bias, ensuring a rigorous and transparent process for identifying, synthesizing, and evaluating all available evidence. Consequently, this review provides robust, empirically-based answers to the predetermined research questions.

3.2. Identification

In the present study, the authors have adopted the Preferred Reporting Items for systematic reviews and meta-analysis (PRISMA) protocol as the framework for this systematic review [27]. The systematic review process consists of three main phases used to select several relevant papers for this study. The first phase involves identifying keywords and searching for related terms using thesauruses, dictionaries, encyclopedias, and prior research. After gathering all relevant terms, search strings were created for the Scopus, IEEE Explore, and Mendeley databases see Table 1. In the first phase of this systematic review process, our research successfully retrieved 617 papers from both databases.

Table 1. The search string

Data base	Search string
Scopus	TITLE-ABS-KEY (permanent AND magnet AND generator AND for AND hydro AND power) AND PUBYEAR > 2013 AND PUBYEAR < 2024 AND (EXCLUDE =SUBJAREA, "CHEM") OR EXCLUDE (SUBJAREA, "DECI") OR EXCLUDE (SUBJAREA, "ECON") OR EXCLUDE (SUBJAREA, "MEDI") OR EXCLUDE =SUBJAREA, "EART") OR EXCLUDE (SUBJAREA, "SOCI") OR EXCLUDE
IEEE Xplore	("All Metadata": PERMANENT MAGNET GENERATOR) AND ("All Metadata": PERMANENT MAGNET GENERATOR) AND ("All Metadata": FOR HYDROPOWER)
Mendeley	("permanent magnet generator" AND "hydropower") OR ("PMG" AND "renewable energy" NOT "wind energy")

3.3. Screening

In the initial screening phase, duplicate papers were removed, resulting in the exclusion of 5 articles. The second phase involved screening 50 articles using a set of inclusion and exclusion criteria established by the researchers. The primary inclusion criterion was research articles, which provide the most practical information. Other publication types, such as systematic reviews, reviews, meta-analyses, meta-syntheses, book series, books, and chapters, were excluded from the study. It is worth noting that this study covered ten years from 2014 to 2023. Additionally, only studies conducted in English were selected to align with the research objectives. In total, 467 publications were excluded based on these specific criteria.

3.4. Eligibility

For the third step, known as the eligibility phase, a total of 50 articles were prepared. At this stage, all article titles and key content were thoroughly reviewed to ensure they met the inclusion criteria and aligned with the current research objectives. As a result, 30 reports were excluded because they were not relevant to the field, had insignificant titles, or their abstracts did not align with the objectives of the study. Finally, 20 articles were deemed suitable for further review (see Table 2).

Table 2. The selection criterion is searching

Criterion	Inclusion	Exclusion
Language	English	Non-English
Time line	2014–2023	< 2014
Literature type	Journal (article)	Conference, book, review
Publication stage	Final	In press

3.5. Data extraction and analysis

An integrative analysis was employed as one of the assessment strategies in this study to examine and synthesize various research designs, quantitative, qualitative, and mixed methods. The primary goal of this study was to identify relevant topics and subtopics. The data collection phase was the initial step in the theme development process. Figure 2 illustrates that the authors meticulously analyzed a compilation of 50 publications to find statements or materials pertinent to the current topics of study. Subsequently, the authors evaluated significant existing studies related to the classification of PMG for hydropower in line with the research questions.

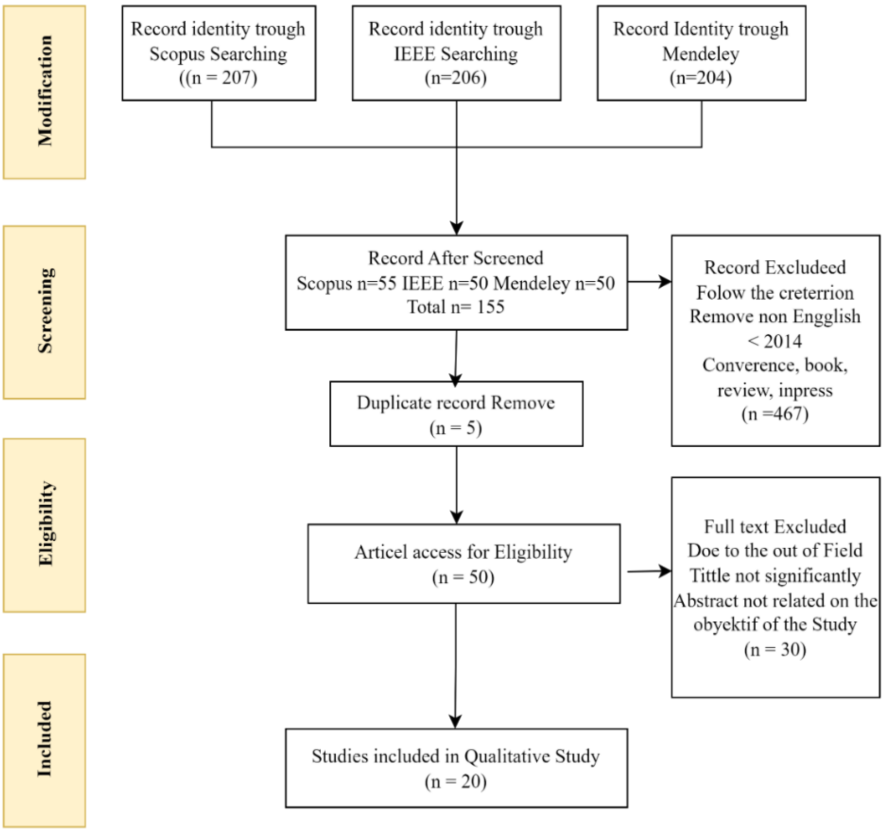

Figure 2. Flow diagram of the proposed searching study

4. DESCRIPTIVE ANALYSIS

This is a basic statistical analysis of the selected articles' key attributes, such as the number of publications per year, distribution by journal, and research themes. Its purpose is to provide a general overview of research trends within the topic under review.

4.1. Chronological pattern of publications

In this section, the author presents the results of the literature review based on the final selected references. This analysis includes the number of studies, year distribution, types of studies, and key findings related to the theme. Number of studies and year distribution out of a total of 617 references found, after the screening and final selection process, only 20 relevant and high-quality articles were selected for review. The year distribution of these articles is shown in Figure 3, 2014: 1 article, 2015: 0 article, 2016: 1 article, 2017: 1 article, 2018: 2 articles, 2019: 1 article, 2020: 4 articles, 2021: 3 articles, 2022: 5 articles, 2023: 2 articles. This year's distribution shows an increasing interest in research on PMG for hydropower, especially in the last ten years.

4.2. Theme of studies

Types of studies, as shown in Figure 4, the review of 20 articles revealed that the study types include design and construction 45% (9 articles each), performance and efficiency 15% (3 articles each), control and regulation system 25% (5 articles each), practical application and implementation 15% (3 articles each). These types of studies reflect the main research focus on innovative design, performance enhancement, control strategies, and evaluation of PMG impacts in hydropower systems.

These data provide an overview of the distribution of articles analyzed in the systematic review of permanent magnet generators for hydropower. The distribution of publication years indicates that research on this topic has increased in recent years, peaking in 2020 and 2022. The thematic distribution shows a balanced focus between design and construction, as well as efficiency and performance, with significant attention also given to control systems and practical implementation.

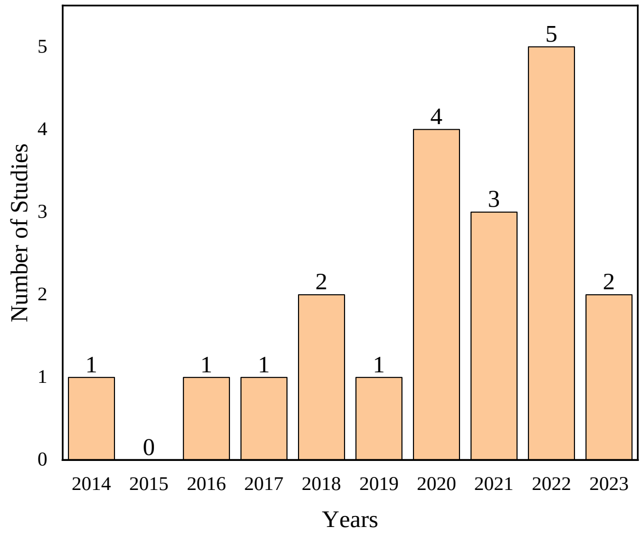

Figure 3. Distribution year of publications

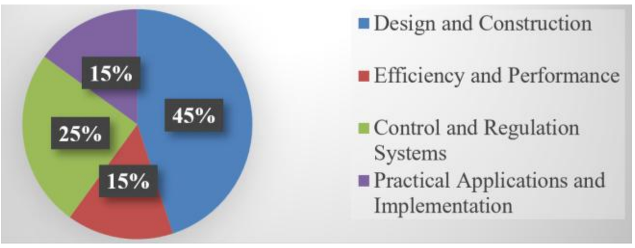

Figure 4. Percentage-type study of the article reviewed

5. SUBSTANTIVE ANALYSIS

Based on the above statistics, several sub-topics can be identified and grouped as promising areas for further study, providing insights that help indicate the direction of future research.

5.1. Design and construction

In recent years, significant advancements in the design and construction of PMG for hydropower applications have been observed, driven by the need for increased efficiency, modularity, and adaptability. Borkowski *et al.* [28] introduce a universal modular permanent magnet synchronous generator (PMSG) aimed at small, low-head hydropower plants, highlighting a modular design approach that leverages universal segments to accommodate a range of power outputs and rotational speeds, effectively reducing production costs. Figure 5 shows a cross-section of a 3D model of a 3-segment modular generator. In contrast, Shuaibu and Ho [29] focus on the development of a spiral planar coil for cordless axial flux PMG, optimizing it for Pico-Hydro applications. At the same time, Asiful and Che [5] propose an axial flux PM generator designed specifically for residential use, validated through FEA. Figure 6 shows an open-source PMG topology. Marfori *et al.* [30] present a different perspective, exploring an open-source axial flux PMG, emphasizing its design and testing for Pico-Hydro systems, an approach intended to promote accessibility and adaptability. Santoshkumar *et al.* [31] introduce a dual-stator PMSG with a non-magnetic rotor and five-phase design, which includes a thermal analysis tailored for larger-scale hydropower plants. Similarly, Violante *et al.* [32] propose a PMG for counter-rotating micro-hydro turbines, optimized for straight flow conditions [32]. At the same time, Huzlik and Ondrusek [33] focus on the development of a cordless axial PMG for small-scale hydropower systems. Topor *et al.* [34] take a more advanced approach by presenting a homo-heteropolar synchronous machine designed for variable-speed, low-power hydro and wind applications, validated through 3D FEM. Finally, Gupta *et al.* [35] examine the fabrication challenges involved in constructing a dual-stator PMSG, providing detailed insights into the technical complexities and the solutions applied to address them.

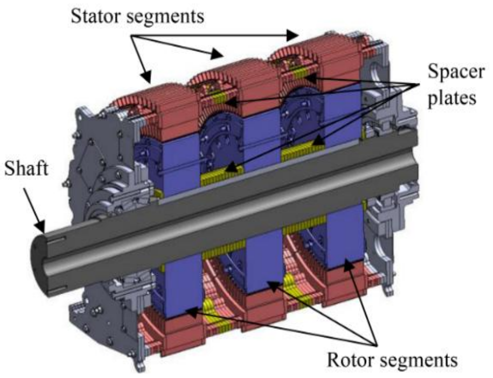

Figure 5. Cross-section of a 3D model of a 3-segment modular generator [28]

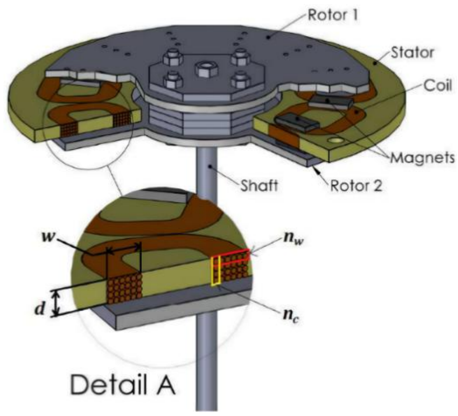

Figure 6. Open-source PMG topology [30]

5.2. Efficiency and performance

In the pursuit of optimizing the efficiency and performance of PMG for hydropower applications, recent studies have focused on advanced structural designs and material optimizations. Latoufis *et al.* [36] investigate the comparison between cordless and soft magnetic composite (SMC) core AFPMG for Pico-Hydro plants. Their study reveals that by introducing SMC cores, the reliance on permanent magnet materials can be reduced, thereby minimizing overall generator mass and production costs while maintaining competitive performance metrics.

Similarly, Irasari *et al.* [37] emphasize the importance of stator modularity, presenting an optimized stator construction to enhance the characteristics of PMG in very low-head hydropower applications. Their findings show that modular stator configurations can improve generator efficiency and adaptability, particularly in low-head hydroelectric systems with limited flow velocity that require more precise electromagnetic design. In addition, this approach helps reduce electromagnetic losses, optimize material use, and support design flexibility so that the PMG can operate more stably and effectively according to the specific needs of small-scale hydropower plants.

Wei *et al.* [38] extend these innovations by developing a low-speed and high-efficiency PMG for micro-hydro applications. Their work focuses on comparing different core materials, identifying the most cost-effective solutions that balance production expenses with high-efficiency performance, Figure 7 shows that the low-speed and high-efficiency permanent magnet (LHPM) generator, which uses a combination of silicon steel 50A1000 and steel plate cold commercial (SPCC) materials, achieves a higher output power of 967 watts, reduces iron losses, and improves efficiency to 85%. Its output power is comparable to that of the generator using only 50A1000, which generates 964.5 watts. However, since the rotor is made from SPCC, the iron losses are slightly higher, and its efficiency is slightly lower at 81.7%. Its output power is comparable to that of the generator using only 50A1000. However, since the rotor is made from SPCC, the iron losses are slightly greater, and the efficiency is marginally lower. Despite this, the LHPM generator with SPCC offers a more cost-effective solution while maintaining good overall performance compared to the version using only 50A1000. This study highlights the crucial role of material selection in achieving optimal efficiency without compromising the structural integrity or operational durability of the generator.

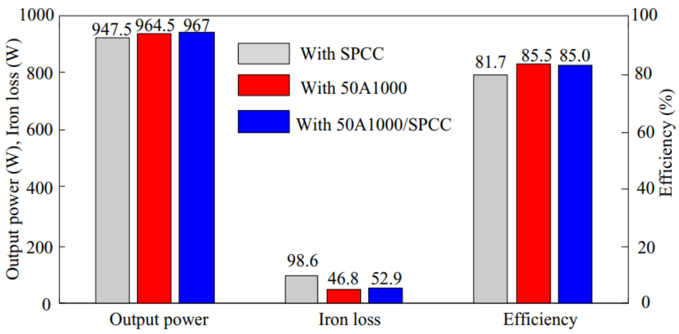

Figure 7. The performance comparison of three types of LHPM generators at n = 200 rpm [38]

5.3. Control and regulation system

In the context of control and regulation systems for PMG in hydropower applications, various studies have presented innovative strategies to optimize performance and ensure operational stability. |Sobhan [39] introduces an automatic generation control mechanism for micro-hydropower plants, utilizing impulse turbines and synchronous generators. By integrating programmable logic controller (PLC) and supervisory control and data acquisition (SCADA), the system enables real-time monitoring and control, enhancing the overall efficiency of the power generation process.

Similarly, Thanajitr *et al*. [40] focus on the development of a converter and control system for variable-speed PMG in small hydropower plants. Their research highlights the implementation of a maximum power point tracking (MPPT) algorithm, which is used to maintain optimal generator performance despite changes in water flow conditions. With this converter and control system, the PMG can adjust its operation to variations in flow velocity, enabling the power plant to operate efficiently and stably even under low water head conditions.

Roy *et al.* [41] take a different approach by applying a cascaded multilevel modular converter (MMCC) with decoupled control to small-scale hydro systems. This technique enables better control over the generator's output, allowing for improved power quality and stability in low-power applications. Meanwhile, Gil-Gonzalez *et al.* [42] propose a passivity-based control method for systems using PMSG and back-to-back voltage source converters (VSC). Their control strategy emphasizes system stability and robustness, particularly under varying load conditions, making it ideal for small hydro plants with fluctuating demand.

Lastly, Chandran *et al.* [43] introduce a combined voltage and frequency control system for PMSG-based small hydro systems. Their approach integrates load leveling using a voltage source converter (VSC) and a battery energy storage system to help stabilize power output during load changes or variations in operating conditions. With this method, power fluctuations can be managed more effectively, allowing power quality to be maintained and grid stability to be preserved in small-scale hydropower systems.

5.4. Practical applications and implementation

In recent advancements of practical applications and implementations of PMG for hydropower, several promising designs have been proposed. Gandzha *et al.* [44] introduce a combined excitation submersible hydro generator aimed at providing an alternative energy source for small and medium rivers. This innovative submersible design enables efficient energy generation in remote locations, offering a sustainable solution for decentralized power production. Violante *et al.* [32] explore the integration of a PM generator within a straight flow, counter-rotating micro-hydro turbine, validating its performance through practical measurements. Figure 8 shows a prototype of the counter-rotating micro-hydro turbine with its two PM-generators. The counter-rotating mechanism significantly improves the energy conversion efficiency, making it ideal for compact hydropower systems. Expanding on this concept, Melly *et al.* [45] developed a 2 kW PM generator for a counter-rotating micro-hydro turbine, conducting extensive prototype testing to assess the system's real-world applicability. These studies demonstrate the effectiveness and scalability of PMG technology in small-scale hydropower applications, offering practical solutions for renewable energy generation in diverse environments.

Figure 8. Prototype of the counter-rotating micro-hydro turbine with its two PM-generators [32]

Overall, research in this field demonstrates significant advancements in PMG development for hydro applications, particularly in efficiency, design, and power control. While many promising innovations have emerged, challenges remain, such as manufacturing complexity, initial costs, and material durability in different environmental conditions. Moving forward, further research is needed to optimize the combination of design, materials, and control systems to enable broader implementation of PMGs in various small-scale hydro conditions, especially in remote areas and renewable energy systems.

6. ISSUES AND CHALLENGES IN THE PERMANENT MAGNET GENERATOR OF HYDROPOWER

PMGs offer several advantages, including high efficiency, simpler structures, and minimal maintenance, making them particularly attractive for hydropower applications. However, there are several key issues and challenges that need to be addressed in their use, especially in small and medium-scale hydropower systems.

6.1. Design and structural optimization

One of the main challenges is designing a PMG that can accommodate variations in water flow and speed. Submersible designs, such as the one proposed by Gandzha *et al.* [12], present challenges related to stability and efficiency under various operational conditions. The structural design must be able to operate optimally across different water flow conditions without significant energy conversion efficiency losses. Additionally, Zhao *et al.* [46] introduced the design of a linear permanent magnet vernier generator (LPMVG): a modular tooth structure arranged in layers reduces cogging forces, while multi-objective optimization enhances power output and efficiency. Figure 9 shows the design of a bilateral linear permanent magnet structure. Finally, Mostaman *et al.* [47] also optimized a radial flux permanent magnet generator (RFPMG): By utilizing the local optimization method, output voltage increased by 13.64%, demonstrating the effectiveness of geometric adjustments in improving operational performance.

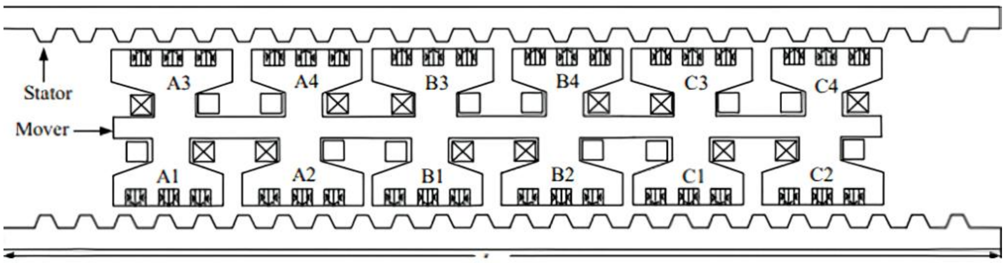

Figure 9. Bilateral linear permanent magnet vernier generator [46]

6.2. Material usage and cost reduction

The use of expensive permanent magnet materials is a significant barrier to developing cost-effective PMG. Designs that optimize material use, such as those studied by Latoufis *et al.* [21], can help reduce reliance on expensive permanent magnet materials without compromising the generator's main performance. Through a more efficient design approach, PMGs can still deliver high efficiency and power output while becoming more economical and suitable for small-scale power generation systems.

Meanwhile, Milicevic *et al.* [48] introduced techno-economic optimization methods, including meta-modeling, which has been employed to evaluate various slot-pole combinations, balancing the cost of active materials and efficiency. Additionally, McGarry *et al.* [49] introduced additive manufacturing, a promising approach to reduce the cost of permanent magnet materials by optimizing the shape and configuration of the magnets, achieving up to a 3% cost reduction without compromising performance [49]. Figure 10 shows magnet configurations, and Figure 11 shows the percentage saving of material cost for scenarios 2-5 in comparison with scenario 1.

6.3. Control and regulation systems

Monitoring and controlling PMG performance pose additional challenges, especially in systems that operate at variable speeds and fluctuating loads. Automatic control systems and MPPT algorithms, as developed by Thanajitr *et al.* [40], offer solutions to maintain optimal performance, but real-world implementation requires further study regarding system reliability and durability under different environmental conditions.

Meanwhile, Clements *et al*. [50], in terms of dynamic voltage control, utilized a voltage source inverter connected to the stator, allowing effective terminal voltage regulation by controlling the DC voltage, addressing the machine's lightly damped dynamics [50]. Finally, Li *et al.* [51] introduced model predictive control (MPC). This method improves performance by managing uncertainty in system parameters, using an advanced hybrid parallel state observer to balance disturbance rejection and noise suppression [51].

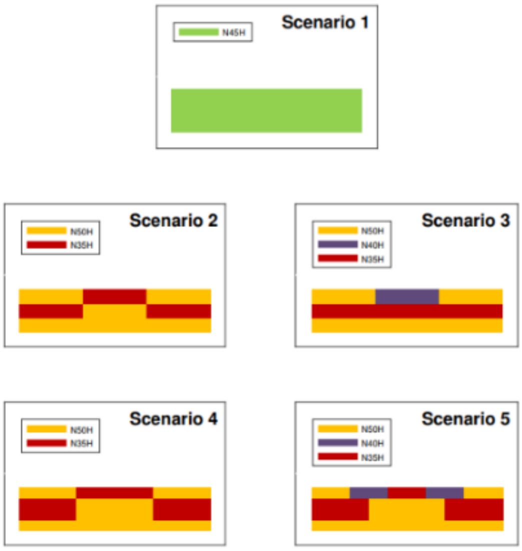

Figure 10. Magnet configurations [48]

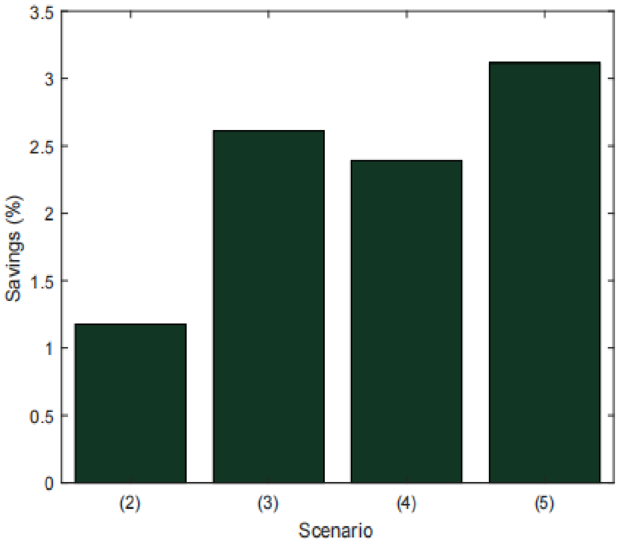

Figure 11. Percentage saving of material cost for scenarios 2-5, compared with scenario 1 [49]

7. CONCLUSION

The literature review highlights significant advancements in PMG technology for small and medium-scale hydropower applications. PMG offers advantages such as high efficiency, compact design, and reduced maintenance needs, making them ideal for hydropower systems, particularly in low-speed, small-scale applications like Pico-Hydro. Key progress includes innovative magnet and rotor designs, improved control systems, and material optimizations to enhance performance while addressing challenges like high magnet costs and thermal stability. However, challenges remain, particularly in reducing the cost of high-performance magnetic materials and optimizing PMG design for varied operational conditions.

Future research should focus on developing cost-effective materials, particularly to reduce reliance on expensive permanent magnet materials without compromising the performance of permanent magnet generators (PMGs). In addition, improved thermal management and enhanced control systems are essential to ensure that PMGs can operate stably under dynamic environmental conditions, such as changes in water flow, load variations, and fluctuations in operating temperature. As PMG technology continues to advance, these developments have significant potential to improve the efficiency, reliability, and sustainability of hydropower generation worldwide.

ACKNOWLEDGEMENTS

The authors express their gratitude to the Ministry of Higher Education Malaysia and Universiti Teknikal Malaysia Melaka (UTeM) for the top-down Research project known as Electrification of Pico-Hydro UTeM Eye Station (PJP/2023/TD/FKE/S01984).

FUNDING INFORMATION

The authors express their gratitude for the financial support provided by various parties throughout the research, particularly the Ministry of Higher Education Malaysia and Universiti Teknikal Malaysia Melaka (UTeM) through the Top-Down project titled Electrification of Pico-Hydro UTeM Eye Station (PJP/2023/TD/FKE/S01984). The authors also extend their appreciation to the UTeM Publication Initiative Scheme 2025–2026, which helped cover the journal publication fees, enabling the research findings to be formally published and supporting the dissemination of academic contributions to the broader scientific community.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Ngatono	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Raja Nor Firdaus Kashfi Raja Othman		✓				✓		✓	✓	✓	✓	✓		
M. Nazri Othman	✓		✓	✓			✓			✓	✓		✓	✓
M. Zulkifli Ab Rahman					✓		✓			✓		✓		✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest regarding this manuscript.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [RNFKRO], upon reasonable request.

REFERENCES

[1] S. A. Abulifa, I. M. Abdaldeam, A. A. Abulifa, M. Amer, and T. M. Ghandoori, "A current assessment of the renewable energy industry," *African Journal of Advanced Pure and Applied Sciences*, vol. 2, no. 1, pp. 122–127, 2023.

[2] F. Manzano-Agugliaro, M. Taher, A. Zapata-Sierra, A. Juaidi, and F. G. Montoya, "An overview of research and energy evolution for small hydropower in Europe," *Renewable and Sustainable Energy Reviews*, vol. 75, pp. 476–489, 2017, doi: 10.1016/j.rser.2016.11.013.

[3] M. J. B. Kabeyi and O. Akanni. Olanrewaju, "Hydropower in the sustainable energy mix," in *Proceedings of the Second Australian International Conference on Industrial Engineering and Operations Management* 2023, pp. 1055–1067, doi: 10.46254/au02.20230247.

[4] L. Chunyuan, Y. Chen, R. Dong, and B. L. Ye, "Optimization design of tubular permanent magnet linear generator based on entropy model for wave energy conversion," *Renewable Energy*, vol. 216, p. 119087, 2023, doi: 10.1016/j.renene.2023.119087.

[5] H. Asiful and H. S. Che, "Design and simulation of axial flux permanent magnet generator for residential Pico-Hydropower generation," in *International Conference on Intelligent and Advanced System, ICIAS 2018*, 2018. doi: 10.1109/ICIAS.2018.8540629.

[6] P. Irasari, A. Muqorobin, P. Widiyanto, T. Nur, I. N. Diasta, and P. Sutikno, "Performance analysis of a compact pico hydropower plant with a wide operating range," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 13, no. 4, pp. 2357–2364, 2022, doi: 10.11591/ijpeds.v13.i4.pp2357-2364.

[7] W. Zhang, L. Dai, Z. Xiang, Q. Wu, S. Huang, and J. Gao, "Optimal design of hydro permanent magnet synchronous generators for improving annual cycle efficiency," *International Journal of Electrical Power and Energy Systems*, vol. 131, 2021, doi: 10.1016/j.ijepes.2021.107096.

[8] D. L. Zariatin, S. N. Fitria, Y. Dewanto, Ismail, and D. Rahmalina, "The performance of the modified pump motor as a generator on the pump as turbine (pat) power plant," in *IOP Conference Series: Earth and Environmental Science*, 2019. doi: 10.1088/1755-1315/277/1/012016.

[9] A. Kallaste, T. Vaimann, and A. Belahcen, "Influence of magnet material selection on the design of slow-speed permanent magnet synchronous generators for wind applications," *Elektronika ir Elektrotechnika*, vol. 23, no. 1, 2017, doi: 10.5755/j01.eie.23.1.17581.

[10] A. A. Tatevosyan, "Mathematical modeling of the magnetic field of a low-speed synchronous generator with permanent magnets," in *Journal of Physics: Conference Series*, 2019. doi: 10.1088/1742-6596/1260/5/052030.

[11] J. Y. Choi, S. M. Jang, and B. M. Song, "Design of a direct-coupled radial-flux permanent magnet generator for wind turbines," in *IEEE PES General Meeting, PES 2010*, 2010, pp. 1–6. doi: 10.1109/PES.2010.5590168.

[12] S. Gandzha, D. Aminov, and A. Sogrin, "Development of water submersible gyro generator of combined excitation for energy development of small and medium rivers," in *Proceedings - 2020 International Conference on Industrial Engineering, Applications and Manufacturing, ICIEAM 2020*, 2020. doi: 10.1109/ICIEAM48468.2020.9112084.

[13] K. Wirtayasa, P. Irasari, M. Kasim, P. Widiyanto, and M. Hikmawan, "Design of an axial-flux permanent-magnet generator (AFPMG) 1 KW, 220 Volt, 300 RPM, 1 phase for pico hydropower plants," in *Proceeding - ICSEEA 2017 International Conference on Sustainable Energy Engineering and Application & Continuous Improvement of Sustainable Energy for Eco-Mobility"*, 2017, pp. 172–179. doi: 10.1109/ICSEEA.2017.8267704.

[14] E. M. Munawaroh, Sutedjo, and E. Wahjono, "Design and modified radial flux synchronous generator using v-shaped permanent magnet method," in *2021 56th International Universities Power Engineering Conference: Powering Net Zero Emissions, UPEC 2021 - Proceedings*, 2021, pp. 1–6. doi: 10.1109/UPEC50034.2021.9548232.

[15] R. R. Kumar, S. Gogoi, A. Kumari, P. Devi, and C. Chetri, "Design and thermal analysis of a dual stator nonmagnetic rotor five-phase permanent magnet synchronous generator for hydropower plant," in *9th IEEE International Conference on Power Electronics, Drives and Energy Systems, PEDES 2020*, 2020. doi: 10.1109/PEDES49360.2020.9379662.

[16] I. Petrov and J. Pyrhonen, "Performance of low-cost permanent magnet material in PM synchronous machines," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 6, pp. 2131–2138, 2013, doi: 10.1109/TIE.2012.2191757.

[17] J. M. D. Coey, "Perspective and prospects for rare earth permanent magnets," *Engineering*, vol. 6, no. 2, pp. 119–131, 2020, doi: 10.1016/j.eng.2018.11.034.

[18] R. Bharanikumar, K. T. Maheswari, and A. N. Kumar, "Comparative analysis of permanent magnet materials for wind turbine driven permanent magnet generator." pp. 1–8. [Online]. Available: www.jee.ro.

[19] A. A. Achitaev *et al.*, "Application of electromagnetic continuous variable transmission in hydraulic turbines to increase stability of an off-grid power system," *Renewable Energy*, vol. 196, pp. 125–136, 2022, doi: 10.1016/j.renene.2022.06.062.

[20] W. Liu, H. Feng, J. Li, and B. Jia, "Electromagnetic–thermal characteristics analysis of a tubular permanent magnet linear generator for free-piston engines," *Applied Sciences (Switzerland)*, vol. 14, no. 5, 2024, doi: 10.3390/app14051900.

[21] K. Latoufis, A. Konstantinidis, S. Giala-Fikari, and N. Hatziargyriou, "Comparison of coreless and soft magnetic composite core axial flux permanent magnet generators for locally manufactured Pico-Hydro plants," in *Proceedings of 2018 IEEE International Conference on Power Electronics, Drives and Energy Systems, PEDES 2018*, 2018. doi: 10.1109/PEDES.2018.8707758.

[22] C. Yuan, K. Wei, and X. Wang, "Coupled-field thermal analysis of high-speed permanent magnetic generator applied in micro-turbine generator," in *ICEMS 2005: Proceedings of the Eighth International Conference on Electrical Machines and Systems*, 2005, pp. 2458–2461. doi: 10.1109/icems.2005.203016.

[23] P. Kinsler, "Faraday's law and magnetic induction: cause and effect, experiment and theory," *Physics (Switzerland)*, vol. 2, no. 2, pp. 150–163, 2020, doi: 10.3390/physics2020009.

[24] A. Habib *et al.*, "A systematic review on current research and developments on coreless axial-flux permanent-magnet machines," *IET Electric Power Applications*, vol. 16, no. 10, pp. 1095–1116, 2022, doi: 10.1049/elp2.12218.

[25] M. Petticrew and H. Roberts, *Systematic reviews in the social sciences: a practical guide*. Blackwell Publishing, 2008. doi: 10.1002/9780470754887.

[26] A. García-Holgado, S. Marcos-Pablos, and F. J. García-Peñalvo, "Guidelines for performing systematic research projects reviews," *International Journal of Interactive Multimedia and Artificial Intelligence*, vol. 6, no. 2, 2020, doi: 10.9781/ijimai.2020.05.005.

[27] A. Liberati *et al.*, "The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration," *Journal of Clinical Epidemiology*, vol. 62, no. 10, 2009, doi: 10.1016/j.jclinepi.2009.06.006.

[28] D. Borkowski, T. Wegiel, P. Kisielewski, and D. Liszka, "Universal modular permanent magnet synchronous generator for small low-head hydropower plants," *IEEE Transactions on Energy Conversion*, vol. 38, no. 4, 2023, doi: 10.1109/TEC.2023.3288129.

[29] I. Shuaibu and E. T. W. Ho, "Investigation of a spiral planar coil on coreless axial flux pm generator for Pico-Hydro applications," in *2023 IEEE Conference on Energy Conversion, CENCON 2023*, 2023, pp. 58–63. doi: 10.1109/CENCON58932.2023.10369297.

[30] I. A. V. Marfori, J. A. Gonzaga, and M. D. Era, "Design and testing of an open-source permanent magnet generator for Pico-Hydro systems," in *2022 IEEE 14th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management, HNICEM 2022*, 2022, pp. 1–5. doi: 10.1109/HNICEM57413.2022.10109483.

[31] M. Santoshkumar *et al.*, "Design and development of Pico-Hydropower system by irrigation water," *International Research Journal of Engineering and Technology*. pp. 1904–1910, 2016.

[32] D. Violante, L. Farner, C. Münch, and S. Chevailler, "Design of a PM-generator for a straight flow counter-rotating micro-hydro turbine," in *2017 19th European Conference on Power Electronics and Applications, EPE 2017 ECCE Europe*, 2017. doi: 10.23919/EPE17ECCEEurope.2017.8098926.

[33] R. Huzlik and C. Ondrusek, "Design of axial coreless permanent magnet generator for small hydropower plant," in *Proceedings - 2016 22nd International Conference on Electrical Machines, ICEM 2016*, 2016, pp. 1539–1544. doi: 10.1109/ICELMACH.2016.7732728.

[34] M. Topor, S. I. Deaconu, and L. N. Tutelea, "Homo-heteropolar synchronous machine for low power variable speed wind or hydro applications: design, 3d fem validation and control," in *2014 16th European Conference on Power Electronics and Applications, EPE-ECCE Europe 2014*, 2014, pp. 1–10. doi: 10.1109/EPE.2014.6910885.

[35] S. K. Gupta, A. Dwivedi, and R. K. Srivastava, "Fabrication of dual-stator permanent magnet synchronous generator," in *12th IEEE International Conference Electronics, Energy, Environment, Communication, Computer, Control: (E3-C3), INDICON 2015*, 2016. doi: 10.1109/INDICON.2015.7443782.

[36] K. C. Latoufis, T. V. Pazios, and N. D. Hatziargyriou, "Locally manufactured small wind turbines: empowering communities for sustainable rural electrification," *IEEE Electrification Magazine*, vol. 3, no. 1. pp. 68–78, 2015. doi: 10.1109/MELE.2014.2380073.

[37] P. Irasari, M. Kasim, M. Hikmawan, P. Widiyanto, K. Wirtayasa, and Q. M. B. Soesanto, "Optimization of modular stator construction to improve permanent magnet generator characteristics for very low head hydropower application," in *Proceeding - ICSEEA 2017 International Conference on Sustainable Energy Engineering and Application: & Continuous Improvement of Sustainable Energy for Eco-Mobility;*, 2017, pp. 156–163. doi: 10.1109/ICSEEA.2017.8267702.

[38] L. Wei, T. Nakamura, and K. Imai, "Development and optimization of low-speed and high-efficiency permanent magnet generator for micro hydro-electrical generation system," *Renewable Energy*, vol. 147, pp. 1653–1662, 2020, doi: 10.1016/j.renene.2019.09.049.

[39] N. Sobhan, "Automatic generation control and monitoring the mechanism of micro hydropower plant with impulse turbine and synchronous generator," in *2016 2nd International Conference on Robotics and Artificial Intelligence, ICRAI 2016*, 2016, pp. 175–179. doi: 10.1109/ICRAI.2016.7791249.

[40] C. Thanajitr, S. Polmai, and S. Kittiratsatcha, "Development of converter and control system for variable speed permanent magnet synchronous generator in small hydropower plant model," in *2022 International Conference on Electrical Machines and Systems, ICEMS 2022*, 2022. doi: 10.1109/ICEMS56177.2022.9982886.

[41] R. Roy *et al.*, "MMCC-based decoupled control of PMSG for small scale hydropower plants," in *IECON Proceedings (Industrial Electronics Conference)*, 2021. doi: 10.1109/IECON48115.2021.9589944.

[42] W. Gil-Gonzalez, A. Garces, and O. B. Fosso, "Passivity-based control for small hydro-power generation with PMSG and VSC," *IEEE Access*, vol. 8, pp. 153001–153010, 2020, doi: 10.1109/ACCESS.2020.3018027.

[43] V. P. Chandran, S. Murshid, and B. Singh, "Design and analysis of improved second order generalized integrator-based voltage and frequency controller for permanent magnet synchronous generator operating in small-hydro system feeding single-phase loads," *International Transactions on Electrical Energy Systems*, vol. 29, no. 5, 2019, doi: 10.1002/2050-7038.2827.

[44] S. Gandzha, D. Aminov, and B. Kosimov, "Application of the combined excitation submersible hydrogenerator as an alternative energy source for small and medium rivers," in *Proceedings - 2019 IEEE Russian Workshop on Power Engineering and Automation of Metallurgy Industry: Research and Practice, PEAMI 2019*, 2019, pp. 30–35. doi: 10.1109/PEAMI.2019.8915294.

[45] D. Melly, R. Horta, C. Münch, H. Biner, and S. Chevailler, "Development of a PM-generator for a counter-rotating micro-hydro turbine," in *Proceedings - 2014 International Conference on Electrical Machines, ICEM 2014*, 2014, pp. 124–129. doi: 10.1109/ICELMACH.2014.6960169.

[46] M. Zhao *et al.*, "Design and optimization of linear permanent magnet vernier generator for direct drive wave energy converter," *Energies*, vol. 16, no. 7, 2023, doi: 10.3390/en16073164.
[47] N. A. Mostaman, E. Sulaiman, and M. Jenal, "Design optimization and analysis of radial flux permanent magnet generator using local optimization method," *El-Cezeri Journal of Science and Engineering*, vol. 11, no. 1, pp. 58–64, 2024, doi: 10.31202/ecjse.1319963.
[48] L. Milicevic, M. Hlupic, and S. Stipetic, "Techno-economic optimization of a spoke-type ferrite magnet generator for hydropower plant based on metamodeling," in *2022 14th International Symposium on Industrial Electronics and Applications, INDEL 2022 - Proceedings*, 2022, pp. 1–7. doi: 10.1109/INDEL55690.2022.9965533.
[49] C. McGarry, A. McDonald, and N. Alotaibi, "Optimisation of additively manufactured permanent magnets for wind turbine generators," in *2019 IEEE International Electric Machines and Drives Conference, IEMDC 2019*, 2019, pp. 656–663. doi: 10.1109/IEMDC.2019.8785119.
[50] N. Clements, G. Venkataramanan, and T. M. Jahns, "Regulation of permanent magnet generators using angle control of stator-connected voltage source inverters," in *2010 IEEE Energy Conversion Congress and Exposition, ECCE 2010 - Proceedings*, 2010, pp. 1166–1172. doi: 10.1109/ECCE.2010.5617837.
[51] J. Li, O. Babayomi, Z. Zhang, and Z. Li, "Robust predictive current control of PMSG wind turbines with sensor noise suppression," *Energies*, vol. 16, no. 17, 2023, doi: 10.3390/en16176255.

BIOGRAPHIES OF AUTHORS

Ngatono is currently a Ph.D. candidate in electrical engineering at the Universiti Teknikal Malaysia Melaka (UTeM). In 2007 and 2015, he graduated with a Bachelor of Engineering from Universitas Sultan Ageng Tirtayasa and a Master of Engineering from Universitas Mercu Buana. He can be contacted at email: ngatono077@gmail.com.

Raja Nor Firdaus Kashfi Raja Othman is an associate professor at the Faculty of Electrical Technology and Engineering (FTKE), Universiti Teknikal Malaysia Melaka (UTeM) since 2014. He received a B.Eng., M.Sc., and Ph.D. in electrical engineering from Universiti Putra Malaysia in 2006, 2009, and 2013, respectively. His research includes the field of applied magnetics, electrical machines, magnetic sensors, and drives. He can be contacted at email: norfirdaus@utem.edu.my.

M. Nazri Othman received his B.Sc. in electrical power from Memphis State University, USA. While M.Sc. in power electronics and drives, and a Ph.D. degree in electrical engineering from the University of Nottingham, UK. Currently, he is serving as an associate professor at Universiti Teknikal Malaysia Melaka (UTeM), Malaysia. His research interests are electric machine design and renewable energy. He can be contacted at email: nazri@utem.edu.my.

M. Zulkifli Ab Rahman received his B.Eng. in electrical and electronics engineering from Universiti Putra Malaysia (UPM), Serdang, Selangor, Malaysia, in 2005, and his master's in electrical power from Universiti Teknikal Malaysia Melaka (UTeM), Malaysia, in 2021. He is currently pursuing a Ph.D. degree in electrical engineering at Universiti Teknikal Malaysia Melaka, Malaysia. His research interests include brushless DC motor (BLDC), permanent magnet synchronous motor (PMSM) design, soft magnetic material, amorphous, and soft magnetic composite. He can be contacted at email: marcjue@gmail.com.