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The Design of a Turbine Emulator for a Pico-Hydrokinetic Power Generation System

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Abstract

Pico-Hydrokinetic Power Plants (PHKPP) utilize the kinetic energy of flowing water as a sustainable alternative to fossil-based energy. However, higher education remains largely theoretical due to limited laboratory facilities, restricted access, and inadequate simulation tools. This study develops a cost-effective PHKPP emulator to support experiential learning and represent real-world operating conditions. A quantitative approach is used, integrating the ADDIE model with experimental testing. The emulator consists of two independent units that simulate a turbine using a three-phase induction motor controlled by Variable Speed Drives (VDRs), while power generation is achieved through a single-phase induction generator. Evaluation results indicate that the emulator effectively supports learning, enabling analysis of turbine performance, control strategies, and energy conversion efficiency. Student responses demonstrated a high level of acceptance, with an average score of 4.43 across all aspects of functionality, usability, relevance, and design. These findings confirm that the emulator effectively enhances conceptual understanding and is an appropriate learning solution for PHKPP learning.

Keywords: *Emulator, Hydrokinetic Energy, Power Generation*

Abstrak

Pembangkit Listrik Piko-Hidrokinetik (PHKPP) memanfaatkan energi kinetik dari aliran air sebagai alternatif berkelanjutan untuk energi berbasis fosil. Namun, pendidikan tinggi sebagian besar masih bersifat teoritis karena keterbatasan fasilitas laboratorium, akses terbatas, dan alat simulasi yang tidak memadai. Studi ini mengembangkan emulator PHKPP yang hemat biaya untuk mendukung pembelajaran berbasis pengalaman dan merepresentasikan kondisi operasi nyata. Pendekatan kuantitatif digunakan, mengintegrasikan model ADDIE dengan pengujian eksperimental. Emulator terdiri dari dua unit independen yang mensimulasikan turbin menggunakan motor induksi tiga fasa yang dikendalikan oleh Variable Speed Drives (VDR), sementara pembangkitan daya dicapai melalui generator induksi satu fasa. Hasil evaluasi menunjukkan bahwa emulator secara efektif mendukung pembelajaran, memungkinkan analisis kinerja turbin, strategi kontrol, dan efisiensi konversi energi. Respons siswa menunjukkan tingkat penerimaan yang tinggi, dengan skor rata-rata 4,43 seluruh aspek fungsionalitas, kegunaan, relevansi, dan desain. Temuan ini menegaskan bahwa emulator efektif meningkatkan pemahaman konseptual dan solusi pembelajaran tepat untuk pembelajaran PHKPP.

Kata kunci: Emulator, Energi Hidrokinetik, Pembangkit Listrik

Introduction

In the global energy transition toward sustainable power systems, renewable energy—particularly hydrokinetic energy—has gained increasing attention as a viable solution for meeting growing energy demands while reducing carbon emissions [1], [2], [3]. Hydrokinetic power generation systems harness the kinetic energy of flowing water and convert it directly into electrical energy [4], [5], making them a promising alternative to fossil fuel–based energy sources [6]. Despite their potential, the development and deployment of hydrokinetic technologies require a comprehensive understanding of system dynamics, which can only be achieved through experimental platforms capable of replicating realistic operational conditions and complex flow–turbine interactions [7], [8].

In practice, hydrokinetic power plant topics in many educational institutions are predominantly delivered through theoretical instruction, with limited opportunities for hands-on engagement [9], [10], [11]. This limitation is primarily driven by several constraints. First, many laboratories lack the infrastructure and equipment required to construct or simulate hydrokinetic systems using physical components such as turbines, generators, and water flow control mechanisms[12], [13], [14]. Second, field-based implementation is often impractical, as hydrokinetic systems require access to water resources with sufficiently strong and stable flow conditions, which are frequently difficult to access due to logistical and regulatory challenges[15], [16]. Third, existing computer-based simulation tools are typically costly and may not be affordable for many institutions, while also offering limited representation of physical component interaction, particularly in relation to turbine and generator behavior [17], [18], [19].

Beyond these pedagogical limitations, a more fundamental scientific and technical challenge remains largely unaddressed. The core scientific problem addressed in this research is the absence of an emulator-based framework capable of representing wake effect interactions in pico-hydrokinetic power systems. In real hydrokinetic installations, especially in multi-turbine configurations, wake effects play a critical role in influencing turbine dynamics, power output degradation, and overall system efficiency [20], [21]. However, existing emulator designs and laboratory-scale platforms typically neglect wake interactions, resulting in oversimplified system representations that fail to capture essential physical phenomena.

To address both the technical and instructional gaps, this study proposes the design and implementation of a water turbine emulator capable of replicating the performance characteristics of a pico-hydrokinetic power generation system while explicitly incorporating wake effect modeling. The novelty of this work lies in the integration of wake effect considerations into a low-cost, laboratory-scale emulator framework, enabling controlled analysis of wake-induced performance variations. Through this approach, the emulator serves not only as an effective learning tool, but also as a technical platform for investigating turbine interaction behavior. By utilizing the proposed emulator, students, researchers, and practitioners are expected to gain deeper insight into turbine dynamics, control strategies, and energy efficiency, while enhancing their ability to design and manage hydrokinetic power generation systems. Ultimately, this research aims to contribute to the development of future professionals with strong technical competencies in the hydrokinetic energy domain.

Method

In this study, the ADDIE model, as illustrated in Figure 1, is applied to structure the systematic development process of the proposed emulator, ensuring that the resulting platform meets both technical and instructional requirements. The experimental method is employed to construct the emulator and evaluate its operational performance, including electrical parameters such as voltage, active and reactive power, frequency response, and operational stability during parallel operation of two induction generators.

The analysis phase involves identifying learning objectives, targeted competencies, relevant technologies and components, and the selection of an appropriate power system topology. During the design phase, the mechanical, electrical, and control system architectures are developed, along with the preparation of user manuals and laboratory practice guidelines. The development phase focuses on refining the emulator by identifying and addressing deficiencies observed during preliminary testing. Improvements implemented at this stage not only correct identified weaknesses but may also lead to modifications of the initial design to better align with system performance requirements and learning objectives.

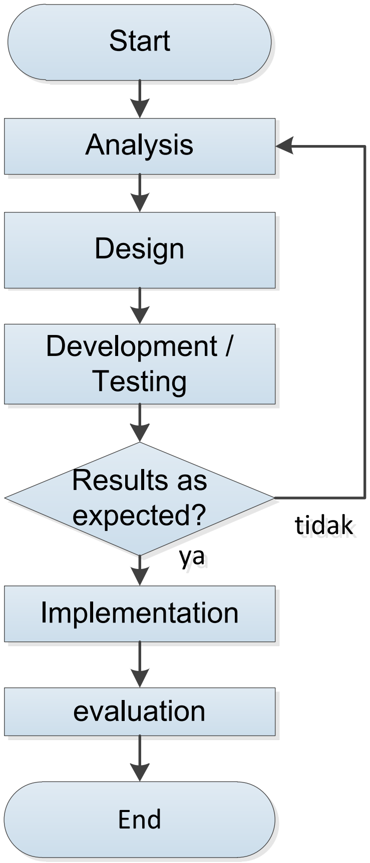

Figure 1. Research Workflow

In the subsequent implementation phase, the emulator is deployed in an instructional setting through trial use with students to assess its functionality and applicability as a pico-hydrokinetic emulator. The research sample consists of students enrolled in the Electric Motor Control Laboratory course, conducted during the even semester of the 2024/2025 academic year. Evaluation is carried out through formative assessment during both the development and implementation stages, as well as summative assessment to determine the overall effectiveness of the emulator based on system performance, learning outcomes, and feedback from both students and instructors.

Two primary instruments are employed in this study. The first consists of physical testing and measurement instruments used to evaluate the technical performance of the PHKPP emulator system. Table 1 presents the categories of technical tests conducted, which include electrical output behavior, system stability, and operational response under various load and synchronization conditions.

The second is an assessment instrument administered to students during the implementation phase. Data obtained from both measurement and assessment processes serve as input for the evaluation stage. It comprising five evaluation criteria: functionality, ease of use, relevance to learning objectives, design and build quality, and overall impressions and recommendations. The detailed questionnaire items are presented in Table 2.

Table 1. Categories of Technical Tests

No.	Test Aspect	Parameters	Measuring Instruments	Testing Method
1	Turbine Emulator Hydrodynamic Characteristics	Turbine rotational speed (RPM),	Tachometer, power meter	Speed variation is indirectly evaluated through rotational speed measurements
2	Generator Electrical Characteristics	Voltage, current, electrical output power	Multimeter, oscilloscope, power meter, synchroscope	Generator testing is conducted under various load conditions, with analysis of voltage and current stability during synchronization and steady-state operation

Table 2. Student Questionnaire Items

No.	Criteria	Questionnaire Item
1	Emulator Functionality	a. The emulator is able to effectively simulate the operating principles of a pico-hydrokinetic power plant. b. The emulator outputs and measurement results are consistent with the theoretical concepts presented in the course. c. The emulator operates stably throughout the testing process.
2	Ease of Use	d. The emulator is easy for students to use by

		following the provided guidelines. e. The emulator interface and control system are easy to understand. f. The setup and operation of the emulator can be performed without significant difficulty.
3	Relevance to Learning	g. The emulator helps students to better understand pico-hydrokinetic power plant concepts. h. The use of the emulator increases students' interest in learning about renewable energy.
4	Emulator Design and Quality	i. The physical design of the emulator appears robust and safe for operation. j. The components used in the emulator are appropriate and of good quality. k. The emulator has an attractive and professional appearance.
5	Overall Impression and Suggestions	l. I am satisfied with my experience using this emulator. m. I would like to see further development of this emulator with more advanced features.

Result and Discussion

1. Emulator Design

The proposed emulator design scheme is illustrated in Figure 2. The system consists of two emulator units, namely Emulator 1 and Emulator 2. Each emulator is equipped with a 1.5 HP Variable Speed Drive (VSD 1 and VSD 2), an RS-485–based analog control system with a 4–20 mA interface (A1 and A2), and a three-phase induction motor (IM 1 and IM 2).

To complete the electrical system configuration, each emulator is coupled to a single-phase induction generator (IG 1 and IG 2) fitted with excitation capacitors connected to the stator windings. These capacitors are required to supply the reactive power necessary for the self-excitation of the induction generators. The induction motors are employed to convert electrical energy into mechanical energy, thereby emulating the operational behavior of water turbines, while the induction generators convert the mechanical input into electrical energy, which is subsequently measured using a power meter.

Emulator operation is controlled by a microcontroller responsible for adjusting key parameters such as turbine rotational speed, whereas generator synchronization is performed manually. Data acquired from the turbine speed sensors are utilized to support the mathematical water turbine model embedded within the microprocessor-based control system.

2. Hardware Testing Result

The emulator unit was successfully assembled, as shown in Figure 3. The main control panel is equipped with several key components that support the learning and experimental process of generator synchronization and parallel operation, as follows:

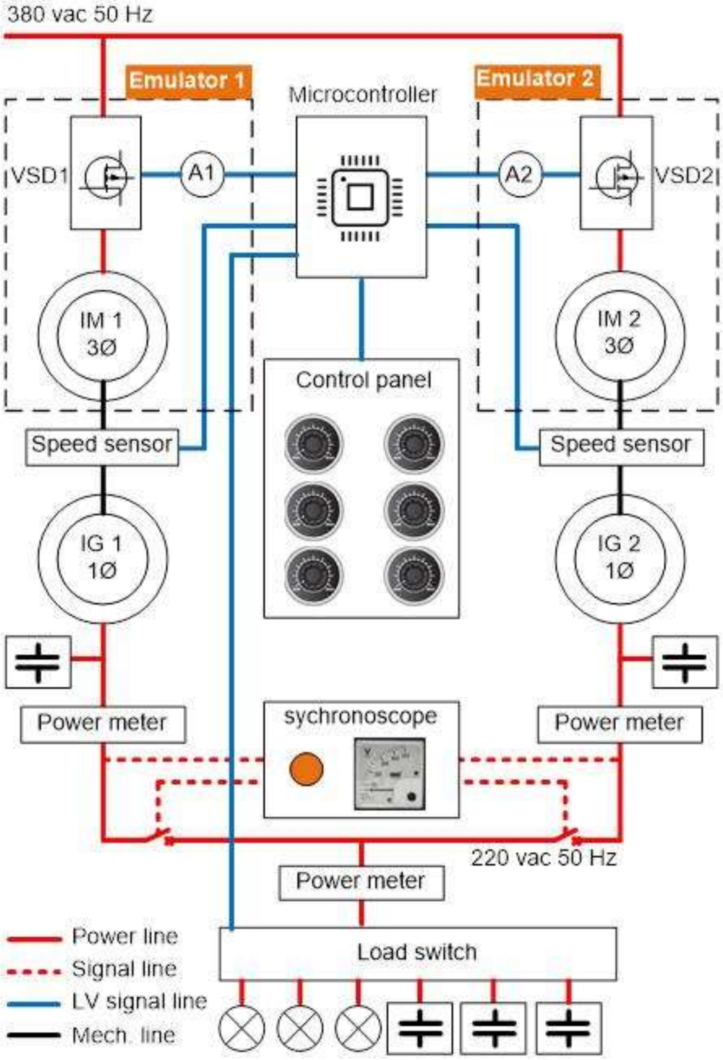

Figure 2. Emulator Design

1. Single-phase synchronoscope with a single indicator lamp, which serves as the primary visual indicator for determining the appropriate synchronization moment. The indicator lamp turns off when the voltage, frequency, and phase angle of both generators are properly matched.
2. Three ammeters, used to monitor the real-time current values at three critical points, namely Generator 1 current, Generator 2 current, and the total load current.
3. Two Variable Speed Drives (VSDs), which function as speed controllers for the turbine prime movers of each generator. The VSDs allow precise adjustment of the generator output frequency, which is a critical step in the synchronization process.
4. A 200 W lamp load, which acts as a simulated electrical load supplied after the two generators are connected in parallel.

5. An MCB synchronization switch, namely a Miniature Circuit Breaker, which operates as a safe main disconnect and connecting switch used to connect the generators to the busbar once synchronous conditions have been achieved.

Figure 3. Pico-Hydrokinetic Power Plants Emulator

Figure 3 illustrates the single-phase synchronoscope unit integrated with a voltmeter. This device functions as the primary visual indicator during the synchronization process while simultaneously monitoring the voltage difference between the two generator emulators. The voltmeter is specifically designed to display voltage discrepancies; when one generator produces a higher voltage, the difference is clearly indicated by the deflection of the voltmeter needle.

Under asynchronous conditions, the synchronoscope indicator lamp illuminates brightly and blinks periodically. The blinking frequency of the lamp is directly proportional to the frequency difference between the two generators, where a faster blinking rate indicates a larger frequency mismatch. This visual feedback enables users to adjust the generator operating parameters effectively until synchronous conditions are safely and accurately achieved.

Table 3. Technical Testing Results of the Emulator

No	Parameter	Value
1	Turbine rotational speed	1514 RPM
2	Frequency	50 Hz
3	Voltage	160 VAC

As presented in Table 3, the technical testing results reveal that the emulator operates with output voltage levels below the standard range. This condition is primarily caused by insufficient excitation capacitance, which limits the reactive power supply required by the induction generator. Consequently, the generator is unable to maintain the rated voltage under the tested operating conditions [22]. Figure 4 illustrates the voltage waveforms of Induction Generator 1 and Induction Generator 2 under synchronized operating conditions.

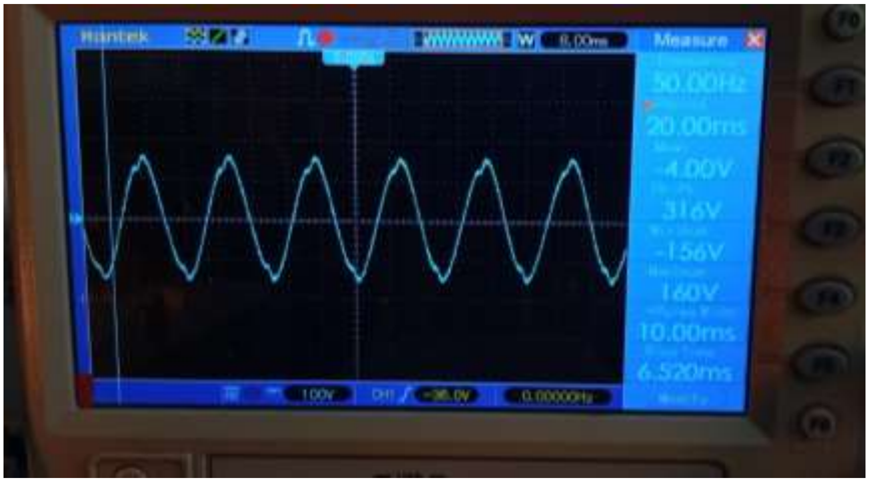

Figure 4. Generator Voltage

Figure 5 illustrates both asynchronous and synchronous operating conditions. In the asynchronous condition, the indicator lamp is illuminated, and the generator voltage waveforms observed on the oscilloscope are not superimposed. Conversely, in the synchronous condition, the voltage waveforms coincide, and the indicator lamp remains off. The absence of illumination indicates that no voltage difference exists between the two generators, resulting in zero current flow through the lamp.

(a) (b)

Figure 5 Testing Condition of a Single-Phase Synchroscope
(A) Asynchronous Condition (B) Synchronous Condition

3. Questionnaire Response Results

The questionnaire was distributed to 12 students from the Electrical Engineering Education Study Program at UIN Ar-Raniry Banda Aceh who had completed the Renewable Energy and Electrical Machines courses. The questionnaire results are summarized in Figure 6. A total of 16 statements were included, in which students selected responses ranging from Strongly Agree (SS), Agree (S), Neutral (N), Disagree (TS), to Strongly Disagree (STS).

Based on the responses collected from students who used the pico-hydrokinetic power plant (PLTPhk) emulator, several conclusions can be drawn regarding the effectiveness of the device as a practical learning medium. Overall, respondents' perceptions of the developed emulator were highly positive.

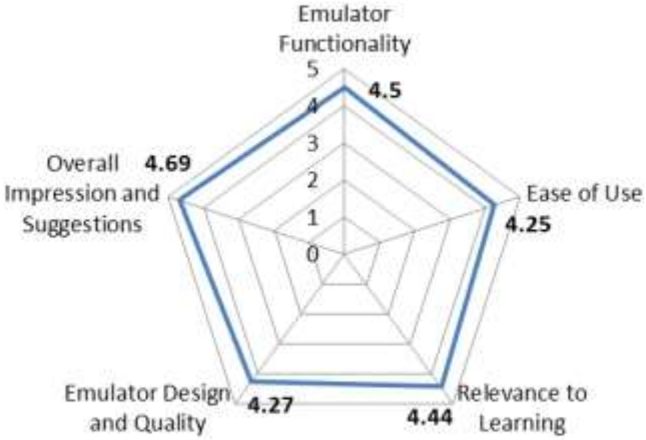

Figure 6. Questionnaire Response Results

The questionnaire results provide strong empirical validation of the success of this research. The developed pico-hydrokinetic power plant (PLTPhk) emulator not only meets technical and functional criteria, but also proves to be an effective learning medium that enhances students' conceptual understanding, is highly recommended for sustainable implementation within the curriculum, and is inspirational in fostering students' interest in renewable energy topics. Therefore, it can be concluded that the emulator prototype has successfully achieved its design objectives and is ready to be adopted as a practical learning tool, while simultaneously serving as a solid foundation for further development and future research.

Conclusions

Based on the design and experimental testing results, it can be concluded that the single-phase generator synchronization emulator prototype has been successfully developed and its performance has been properly evaluated. The system integrates several key components, including a synchronoscope with indicator lamps and a voltmeter to monitor voltage and frequency differences, three ammeters to observe generator and load currents, and two Schneider Altivar 312 Variable Speed Drives (VSDs) controlled via 4–20 mA signals to regulate generator rotational speed. As a control interface, the system is equipped with a microprocessor module, a TTL-to-RS485 converter, and a 4–20 mA module, enabling both automatic and manual speed control through a potentiometer.

System testing using a resistive incandescent lamp load of 2 × 100 W demonstrated that the emulator is capable of performing the synchronization process effectively. This is indicated by the extinction of the synchronoscope lamps and the achievement of in-phase voltage and frequency conditions. In addition, a 6 A-rated miniature circuit breaker (MCB) was successfully implemented as both a control switch and a protection device during parallel operation, ensuring the overall safety and reliability of the system.

However, the experimental results also show that under certain operating conditions, the generator output voltage was slightly lower than the nominal value. This condition is mainly caused by insufficient reactive power, which commonly occurs in single-phase generator systems operating under load. This limitation can be addressed through the addition of capacitors as a reactive power compensation method. By supplying the required reactive current, the capacitors are able to improve voltage regulation, stabilize the output voltage, and enhance overall system performance, particularly during synchronization and parallel operation. Therefore, the implementation of appropriately sized capacitors is recommended as part of future system improvements.

The technical performance of the emulator is further supported by the questionnaire results collected from 12 students of the Electrical Engineering Education Study Program. The evaluation shows that the emulator received very positive responses across all assessed aspects, including functionality, ease of use, relevance to learning, design and physical quality, and overall impression, with an overall average score of 4.43 out of 5. The students indicated that the emulator effectively improves their conceptual understanding of generator synchronization and pico-hydrokinetic power plant operation, is highly recommended for continued use in practical courses, and increases their interest in renewable energy topics.

Therefore, it can be concluded that the developed emulator not only fulfills technical and functional requirements, but also proves to be an effective and well-accepted practical learning medium. The prototype is ready to be adopted for laboratory-based learning activities and serves as a strong foundation for further development and future research, particularly in the enhancement of reactive power compensation and advanced control features.

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