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Experimental optimization of voltage stability and power output in PMDC micro-hydropower systems using a buck–boost converter

Firdiansyah[1,2], Indrayani[1,3]*, Rusdianasari[1,4]
[1]Master of Applied Renewable Energy Engineering, Sriwijaya State Polytechnic, Palembang 30139, Indonesia
[2]Department of Energy and Mineral Resources of South Sumatra Province
[3]Civil Engineering, Sriwijaya State Polytechnic, Palembang 30139, Indonesia
[4]Chemical Engineering Department, Sriwijaya State Polytechnic, Palembang, Indonesia
*Corresponding author: iin_indrayani@polsri.ac.id

Abstract

Low-head micro-hydropower systems often experience voltage instability due to fluctuating water flow and low turbine rotational speeds, limiting their ability to supply reliable power to standalone electrical loads. This study aims to experimentally optimize the output performance of a permanent magnet DC (PMDC) generator integrated with a buck–boost DC-DC converter in a low-head micro-hydropower system for improved voltage regulation, power output, and system efficiency. Experiments were performed by varying the generator rotational speed from 29.83 to 144.80 RPM with a 30 W LED load, while the converter maintained a constant 14.6 V set-point. Measured parameters included generator input voltage, input current, regulated output voltage, load current, electrical power, and system efficiency. The experimental results show that the system can operate at an ultra-low input voltage of 3.61 V at 29.83 RPM. The optimal operating condition was achieved at 63.78 RPM, where the system reached a maximum efficiency of 74.7% and an output power of 27.7 W. The converter maintained a stable output voltage close to the required load voltage, within the rotational speed range of 68.20-132.40 RPM. These results demonstrate that integrating a PMDC generator with a buck-boost converter improves voltage stability and expands the usable operating range of low-head micro-hydropower systems, making the proposed configuration suitable for off-grid and rural electrification applications.

Keywords:
Micro-hydropower; permanent magnet DC generator; buck-boost converter; low-head system; voltage regulation; performance optimization.

1 Introduction

Micro-hydropower systems play an important role in expanding electricity access in rural and remote areas due to their reliability, low operating cost, and minimal environmental impact [1][2]. Small hydropower can contribute to decentralized electricity generation [3]. Indonesia's abundant rivers present a significant opportunity for alternative energy, such as micro-hydro power plants, which harness small-scale water resources to drive turbines and generate electricity, with the energy output primarily determined by water flow and the height of the fall [4]. Water potential energy is the difference in head (height) between incoming and outgoing water, which produces energy. The greater the height difference, the greater the potential for water energy [5].

A small hydropower plant (SHP) is one of the cost-effective RE technologies, especially for electricity generation in rural areas of developing countries [6]. Among various hydropower configurations, low-head micro-hydropower systems are particularly attractive because they can utilize shallow rivers, irrigation channels, and low-elevation water flows without requiring large dams or reservoirs [7]. However, despite their potential, low-head systems often suffer from unstable electrical output due to fluctuating water discharge and low turbine rotational speeds, which significantly limit their applicability for supplying reliable standalone electrical loads [7][8].

In addition to hydraulic factors, the mechanical characteristics of the power generation system, such as rotational speed and turbine configuration, play a significant role in determining the electrical power output. Performance testing of micro-hydropower turbines conducted by Okdinata et al. indicates that variations in operating parameters substantially affect the output power, highlighting the need for adaptive energy conversion systems under fluctuating operating conditions [9].

The use of micro- and pico-hydropower systems is a viable solution for regions with limited head and low water discharge, particularly for small-scale, off-grid electricity applications. The study by Yogi Dinata et al. confirms that variations in water discharge under low-head conditions retain significant electrical power potential when an appropriate system design approach is applied [10].

The performance of micro-hydropower plants is strongly influenced by the characteristics of the available water discharge at the installation site, as the discharge directly determines the amount of mechanical power that can be extracted from the river flow. A study conducted by Firmansyah et al. demonstrates that an accurate analysis of existing water discharge is a key factor in ensuring sufficient power output and the sustainable operation of micro-hydropower systems in rural areas [11].

Permanent magnet DC (PMDC) generators are widely used in low-speed renewable energy applications due to their simple construction, absence of external excitation, and ability to generate electricity at relatively low rotational speeds [12]. A synchronous generator with permanent magnets is used to eliminate transmission losses and increase efficiency across a wide range of loads [1]. These characteristics make PMDC generators suitable for low-head micro-hydropower systems. Nevertheless, the output voltage of PMDC generators is highly dependent on rotational speed. Variations in water flow directly affect turbine speed and, consequently, cause significant voltage fluctuations at the generator output. Without proper regulation, these fluctuations can reduce power quality, limit usable output power, and potentially damage connected loads [13].

To address voltage instability issues in micro-hydropower systems, various control and regulation strategies have been proposed, including mechanical flow control, electronic load controllers, and power electronic converters. Among these approaches, DC-DC power converters are particularly effective for regulating generator output voltage under variable operating conditions. The buck-boost converter topology is especially suitable for low-head micro-hydropower applications because it can operate in both step-up (boost) and step-down (buck) modes, enabling voltage regulation over a wide range of input conditions [14].

The performance of a micro-hydropower system is influenced not only by the characteristics of the generator and power electronic systems, but also by the design and operation of the turbine, which provides the primary mechanical energy. Previous studies have shown that the number of turbine blades significantly affects the distribution of flow velocity and pressure, thereby directly influencing turbine rotational characteristics and potential power output. Computational Fluid Dynamics (CFD) analysis indicates that specific turbine blade configurations can produce higher flow velocities with lower pressure levels, thereby enhancing the performance of small-scale micro-hydropower systems [15].

Experimental studies on portable low-head pico-hydropower systems have further confirmed their feasibility for rural energy supply. However, output voltage stability remains a critical challenge under varying load and flow conditions [16][17].

Despite extensive research on micro-hydropower technologies, most previous studies have focused on individual system components such as turbine design, generator performance, or power electronic converters. Experimental investigations that integrate these components into a single operational low-head micro-hydropower system remain limited.

This study introduces an experimentally integrated micro-hydropower system comprising an Archimedes screw turbine, a permanent-magnet DC generator, and a buck-boost DC-DC converter specifically designed for ultra-low rotational-speed operation.

The system in this study aims to achieve stable voltage regulation across a range of input voltages, a feature rarely reported in previous micro-hydro studies. Maintaining a stable DC output voltage in low-head micro-hydropower systems operating at fluctuating rotational speeds remains a major technical challenge, particularly in standalone and off-grid applications. Unlike previous works that investigate individual components in isolation, this study presents a fully integrated system. It experimentally demonstrates stable voltage regulation starting from an input voltage as low as 3.61 V at 29.83 RPM. In addition, this study identifies the optimal operating conditions of the integrated system and determines its efficiency. This provides practical insights for improving voltage usability and energy conversion efficiency in low-pressure micro-hydro systems for rural electrification.

2 Research methods

2.1 Experimental setup

a. Turbine Design

A study highlights that the Archimedes screw turbine offers a sustainable, efficient, and environmentally friendly solution for mini, micro, and pico hydropower applications, particularly in low-head sites, due to its stable performance across variable flows, high torque at low rotational speeds, minimal ecological impact, and suitability for decentralized and rural energy generation [18] [19].

The Archimedes screw turbine used in the micro-hydro power plant system works by utilizing the flow of water down the rotating screw. The rotational motion generates mechanical energy, which is then transmitted to the generator shaft for conversion to electrical energy. The turbine calculation and design are shown in Table 1 and Fig. 1.

Table 1. Archimedes turbine design data

No.	Parameters	Value
1	Helix angle	9.8 °
2	Angle Turbine	26 °
3	Turbine diameter	0.20 m
4	Turbine shaft diameter	0.048 m
5	Turbine length	0.87 m
6	Turbine pitch	0.10875 m
7	Number of threads	8

Fig. 1. Archimedes turbine design

The operating principle of the Archimedes screw turbine involves water entering from the upper end and flowing through the spaces between the blades, where the combined effect of gravity and hydrostatic pressure differences along the rotor drives the screw blades to rotate the rotor about its axis, thereby transmitting mechanical energy to an electric generator connected to the upper end of the turbine shaft [20]. A study shows that the turbine's angle of inclination affects mechanical performance [21].

b. Generator

In pico- and micro-hydropower applications, permanent magnet generators are increasingly preferred due to their compact size, high efficiency, and ability to operate effectively at low rotational speeds. Several studies have demonstrated that integrating permanent magnet generators with power electronic converters can extend the operating range of pico-hydropower systems while maintaining acceptable voltage quality and harmonic distortion levels [22].

The generator used in this micro-hydro power plant system is a permanent-magnet DC generator derived from a BLDC wheel motor that has been modified to operate as a generator. This generator is equipped with an internal reduction gear mechanism comprising a planetary gear and a one-way clutch, enabling it to generate electrical output at low screw turbine speeds. The internal planetary gear allows the generator rotor speed to increase without an additional external transmission system, enabling the system to operate more compactly and efficiently.

The mechanical transmission system uses a 1:1 ratio sprocket, with the sprocket diameter on the turbine shaft matched to that on the generator shaft. In this study, a sprocket with 14 teeth on each shaft was used, allowing the turbine rotation to be transferred directly to the generator without any gear ratio changes. Selecting a 1:1 transmission ratio aims to maintain the natural rotation characteristics of the screw turbine and to maximize the utilization of the generator's internal reduction gear. In addition, the sprocket placement is designed to avoid interfering with the water flow at the turbine inlet. The generator specification is shown in Table 2 and Fig. 2.

Table 2. Generator specification

No.	Parameters	Value
1	Engine Type	Brushless DC Motor (BLDC)
2	Output	220 Watts
3	Rated Current	6.1 A
4	Volt	36 Volt DC
5	Speed	365 rpm
6	Internal System	Planetary gear and one-way clutch

Fig. 2. Permanent magnet DC generator

The experimental system consisted of a low-head micro-hydropower configuration driving a permanent magnet DC (PMDC) generator. The experimental system consists of an Archimedes screw turbine, a permanent magnet DC generator, and a non-inverting buck–boost DC–DC converter. The turbine converts hydraulic energy from flowing water into mechanical rotational energy, which is transmitted to the generator shaft through a sprocket transmission system with a 1:1 ratio.

The permanent-magnet DC generator converts mechanical energy into DC electrical power. The generated voltage is then regulated using a buck–boost DC-DC converter, which stabilizes the output voltage at a constant 14.6 V set-point. The regulated output voltage is supplied to a 30 W LED load, representing a typical standalone lighting system commonly used in rural electrification applications.

The mechanical input to the generator was varied to simulate changes in water flow conditions typically encountered in low-head micro-hydropower installations. The generator shaft was coupled to the turbine system, and its electrical output was directly connected to a non-inverting buck–boost DC-DC converter designed for voltage regulation.

The experimental configuration of the low-head micro-hydropower system, consisting of an Archimedes screw turbine, a permanent magnet DC generator, a buck-boost converter, and an LED load, is shown in Fig. 3.

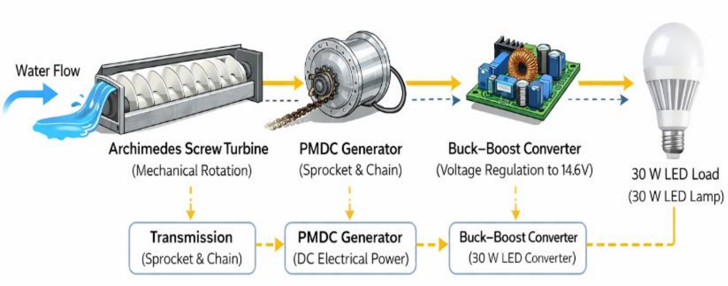

Fig. 3. Experimental configuration of the low-head micro-hydropower system

2.2 Electrical load selection

A regulated DC output voltage set-point of 14.6 V was selected to represent a typical voltage requirement for standalone DC loads, particularly LED-based rural lighting systems. This voltage level is commonly used in off-grid DC applications and allows efficient operation of low-power lighting loads without additional voltage conditioning.

A 30 W LED lamp was used as the electrical load during the experiments. This load was selected to represent a realistic standalone DC application for rural and off-grid electrification, such as street lighting or community lighting systems. The use of a constant and practical load enables direct evaluation of system performance under conditions representative of real-world micro-hydropower applications.

2.3 Experimental procedure

The generator rotational speed was varied from 29.83 to 144.80 RPM to simulate different operating conditions associated with varying water flow rates in low-head micro-hydropower systems. The rotational speed was measured using a digital tachometer to ensure accurate experimental data acquisition. For each rotational speed, the following parameters were measured using calibrated digital instruments:

- Generator input voltage (Vin)
- Generator input current (Iin)
- Regulated output voltage (Vout)
- Load current (Iout)

The input power (Pin) and output power (Pout) were calculated from the measured voltage and current. System efficiency (η) was determined as the ratio of output power to input power. The operating mode of the buck–boost converter (boost or buck) was determined from the relationship between the generator input voltage and the regulated output voltage. All measurements were conducted under steady-state conditions to ensure repeatability and minimize transient effects.

3 Result and discussion

3.1 Voltage regulation performance

The experimental results demonstrate that the output voltage of the permanent magnet DC generator is strongly influenced by rotational speed. As summarized in Table 1, the generator produced an input voltage of only 3.61 V at a rotational speed of 29.83 RPM, indicating the extremely low-voltage operating condition of the system. Under these conditions, the buck-boost converter operated in boost mode, increasing the output voltage to 9.0 V, enabling partial load operation.

Table 3. Experimental results of the PMDC generator integrated with a buck-boost converter

No	RPM	Vin (V)	Iin (A)	Pin (W)	Vout (V)	Iout (A)	Pout (W)	η (%)	Mode
1	29,83	3,61	5,0	18,1	9,0	1,15	10,4	57,5	Boost (under)
2	38,45	6,53	4,3	28,1	11,6	1,50	17,4	61,9	Boost (under)
3	47,33	8,12	3,9	31,7	12,8	1,65	21,1	66,6	Boost
4	52,60	9,37	3,6	33,7	13,2	1,75	23,1	68,5	Boost
5	58,44	9,86	3,5	34,5	13,8	1,85	25,5	73,9	Boost
6	63,78	10,90	3,4	37,1	14,6	1,90	27,7	74,7	Boost @ set-point
7	68,20	11,70	3,3	38,6	14,6	1,95	28,5	73,8	Boost @ set-point
8	71,22	12,40	3,2	39,7	14,6	1,98	28,9	72,8	Boost @ set-point
9	75,80	13,10	3,1	40,6	14,6	2,00	29,2	71,9	Boost @ set-point
10	79,55	13,80	3,0	41,4	14,6	2,05	29,9	72,2	Boost @ set-point
11	83,60	14,10	2,9	40,9	14,6	2,05	29,9	73,1	Boost @ set-point
12	88,30	14,40	2,8	40,3	14,6	2,05	29,9	74,2	Boost @ set-point
13	92,10	14,55	2,8	40,7	14,6	2,05	29,9	73,5	Stable
14	97,42	14,75	2,7	40,2	14,6	2,00	29,2	72,6	Buck
15	108,15	15,10	2,7	40,8	14,6	2,00	29,2	71,6	Buck
16	120,60	15,30	2,6	39,8	14,6	1,95	28,5	71,6	Buck
17	132,40	15,60	2,6	40,6	14,6	1,95	28,5	70,2	Buck
18	144,80	15,90	2,5	39,8	14,6	1,90	27,7	69,6	Buck

The relationship between generator rotational speed and output voltage is illustrated in Fig. 4.

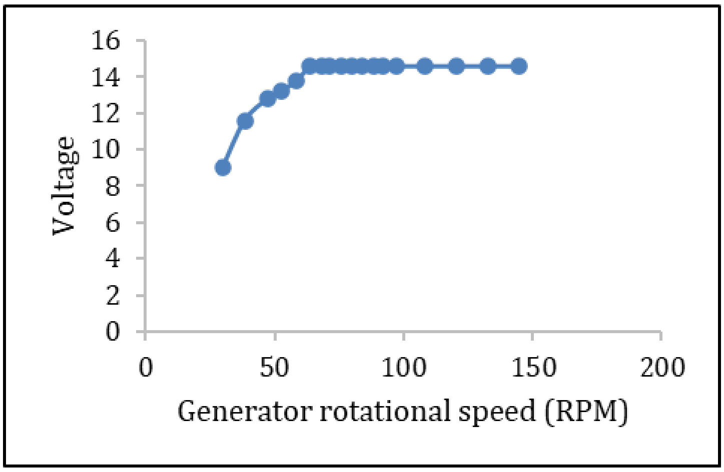

Fig. 4. Generator rotational speed versus input and output voltage

As shown in the figure, the generator input voltage (Vin) increases proportionally with rotational speed. In contrast, the regulated output voltage (Vout) rises until it reaches the set-point value of 14.6 V. Beyond this point, the output voltage remains nearly constant despite further increases in rotational speed. This behavior confirms the buck–boost converter's effectiveness in maintaining voltage stability under fluctuating mechanical input conditions, which is essential for low-head micro-hydropower applications.

This transient analysis provides additional insight into the dynamic behavior of the integrated system. Further, it confirms the suitability of the proposed configuration for low-head micro-hydropower applications, which are typically characterized by wide variations in rotational speed and input voltage. The buck-boost converter offers advantages such as simple control implementation and improved efficiency; however, it also has certain limitations, including boundary oscillations and relatively poor dynamic performance under specific operating conditions [23].

Several studies have demonstrated that DC-DC converters are widely applied in renewable energy systems to regulate voltage levels and improve power conversion efficiency. High step-up converter topologies combining boost and buck-boost configurations have also been developed to enhance voltage gain and maintain stable output voltage in renewable energy applications [14]

Small-scale hydropower projects may provide clean, reliable, and inexpensive energy to remote and underserved communities, improving their socioeconomic conditions and quality of life [24]. Low-head micro-hydropower plants have attracted increasing attention due to their ability to utilize existing irrigation and river infrastructures with minimal civil construction. However, fixed-speed operation often results in reduced efficiency and shortened operating hours under fluctuating flow conditions. Previous studies have shown that variable-speed operation can significantly improve power output, operational flexibility, and economic performance in micro-hydropower systems [7].

Furthermore, optimization of low-head turbine designs, including screw and axial-type turbines, has been shown to enhance power output and efficiency at low flow rates, making them suitable for small-scale micro-hydropower applications [13].

3.2 Output power characteristics

The variation of output power with respect to generator rotational speed is presented in Table 3 and further visualized in Fig. 5. At low rotational speeds, the output power was relatively small due to limited mechanical input power. For instance, at 29.83 RPM, the output power was only 10.4 W, well below the nominal load rating.

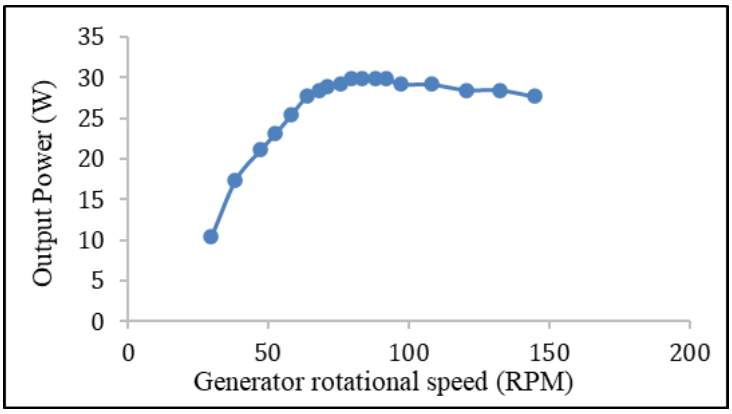

Fig. 5. Generator rotational speed versus output power

As the rotational speed increased, the output power rose sharply and approached the nominal load power of 30 W. The system consistently delivered output power of 28.5-29.9 W over a rotational speed range of 68.20-132.40 RPM. This indicates that the integrated system can reliably meet the load's power demand over a wide operating range, a critical requirement for practical standalone micro-hydropower installations.

Several factors influence the overall performance of micro-hydropower generation systems. One of the most critical parameters is the water discharge available at the installation site, since the flow rate directly determines the amount of mechanical power that can be extracted from the river. A study highlighted that accurate assessment of water discharge is a key factor in ensuring adequate power output and sustainable operation of micro-hydropower systems, particularly in rural areas where hydrological conditions may vary significantly [11].

In addition, the performance of micro-hydropower systems is affected by the characteristics of the generator, the power electronic components, and the turbine, which serves as the primary mechanical energy source. Previous research has demonstrated that the number of turbine blades significantly influences the flow velocity distribution and pressure characteristics within the turbine, which in turn affects the rotational behavior and the potential power output [15]. Furthermore, the optimization of low-head turbine designs, including screw turbines and axial turbines, has been shown to improve power output and efficiency under low-flow conditions, making them suitable for small-scale micro-hydropower applications [13].

Another study reported that operating micro-hydropower generators at variable speeds, combined with accurate modeling and advanced control strategies such as Maximum Power Point Tracking (MPPT), can enhance overall efficiency and power output. This approach also provides better system performance than fixed-speed systems under fluctuating water flow conditions [25].

Research has also shown that the SIDO buck-boost converter developed for midpoint converter configurations performs well across various practical operating conditions. The presence of input and output inductors significantly reduces ripple in both the PV output current and the DC-link current, thereby minimizing the required size of electrolytic capacitors on both sides of the converter [26]. In another study, simulation and hardware implementation of a Permanent Magnet Synchronous Generator (PMSG) integrated with a DC-DC buck–boost converter controlled by an STM32VET407 microcontroller showed stable operation. The output voltage consistently tracked the desired reference voltage, even as the PMSG's rotational speed varied [27].

3.3 System efficiency analysis

System efficiency was evaluated by comparing the output power to the input power at different rotational speeds, as summarized in Table 3. The efficiency trend with respect to rotational speed is depicted in Fig. 6.

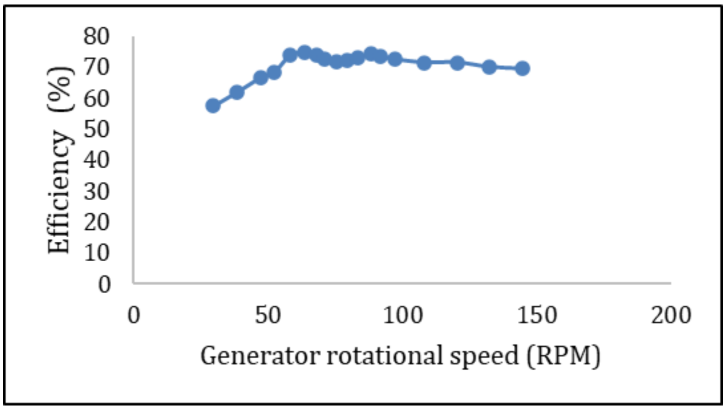

Fig. 6. Generator rotational speed versus system efficiency

At low rotational speeds, the efficiency was relatively low due to high conduction losses associated with large input currents required during boost operation. At low rotational speeds, the generator produces relatively low voltage, requiring the converter to operate in boost mode to increase the output voltage to the regulated set point. Under these conditions, the converter must draw higher input current, increasing conduction losses in the power electronic components and reducing overall system efficiency.

As the rotational speed increases, the generator produces higher input voltage, allowing the converter to operate closer to the regulated voltage threshold. This operating region reduces current stress on the converter components and improves the balance between mechanical input power and electrical conversion losses.

The maximum efficiency of 74.7% achieved at 63.78 RPM represents the optimal operating condition of the system. At this point, the generator output voltage approaches the converter regulation threshold, enabling efficient energy conversion while maintaining stable voltage regulation.

This operating point represents the optimal balance between mechanical input power, electrical conversion losses, and regulated output power delivery. At higher rotational speeds, the efficiency gradually decreased as the converter transitioned to buck mode. This reduction is attributed to increased switching and conduction losses when the converter operates to reduce excess input voltage. Nevertheless, the efficiency values remained acceptable for small-scale low-head micro-hydropower systems operating under variable conditions.

These findings are consistent with theoretical principles suggesting that one effective approach to maintaining voltage stability in micro-hydropower systems is the use of a DC-DC buck-boost converter. This converter can either increase (boost) or decrease (buck) the output voltage, depending on system requirements, with regulation achieved through duty-cycle control [28]. The buck-boost method is particularly suitable for addressing voltage fluctuations caused by variations in water discharge. When the water flow is low and the generator output voltage decreases, the converter operates in boost mode to raise the voltage. Conversely, when the water discharge increases and the generator voltage becomes excessively high, the converter switches to buck mode to reduce the voltage [29].

3.4 Transition of buck-boost converter operating modes

The transition between boost and buck operating modes of the buck–boost converter is illustrated in Fig. 7. At low to medium rotational speeds, the generator input voltage remains below the regulated output voltage of 14.6 V, resulting in the converter operating in boost mode. As the rotational speed increases, the input voltage gradually approaches the output voltage.

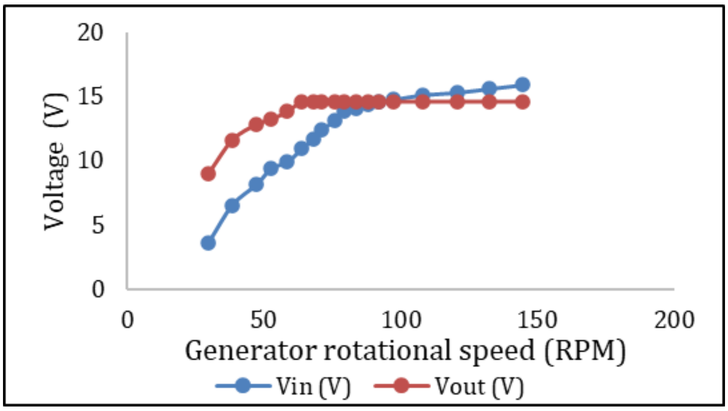

Fig. 7. Transition of buck-boost converter operating modes with respect to generator rotational speed

As shown in Fig. 6, the transition from boost mode to buck mode occurs when the input voltage exceeds the regulated output voltage, which takes place at approximately 92-97 RPM. Beyond this point, the converter operates in buck mode to reduce excess voltage and maintain a stable output. This smooth transition demonstrates the converter's adaptive capability to respond to varying mechanical input conditions without introducing voltage instability or load disturbances.

The inclusion of this transition analysis provides additional insight into the dynamic behavior of the integrated system. Further, it confirms the suitability of the proposed configuration for low-head micro-hydropower applications characterized by wide variations in rotational speed and input voltage.

An experimental integration of permanent magnet generators with buck-boost converters has also been demonstrated to provide stable voltage regulation under varying generator rotational speeds [27]. Similar converter topologies have also been applied in electric vehicle energy systems where buck-boost converters improve voltage regulation and enhance overall system efficiency under fluctuating operating conditions [30].

The integration of inductive components in buck-boost converter configurations has also been shown to significantly reduce current ripple and improve voltage stability in renewable energy systems [26]. Previous studies have reported that buck-boost converters offer flexible voltage regulation and relatively simple control strategies, making them suitable for applications with wide input-voltage variations. However, issues such as boundary oscillations and dynamic response must be carefully addressed in converter design [23].

The buck-boost converter offers simple control and improved efficiency, yet has limitations in the presence of boundary oscillation and poor dynamic performance [23]. The use of buck-boost converters in micro-hydro power plants is similar to their application in electric vehicle systems, where the main energy source also experiences voltage variations during operation. Several studies show that the application of buck-boost converters can improve system efficiency, improve voltage regulation, and increase the reliability of renewable energy-based power generation systems [30]. Thus, buck-boost converters can be an effective solution to support the performance and stability of micro-hydro power generation systems.

4 Conclusion

This study demonstrated that integrating a permanent magnet DC (PMDC) generator with a buck-boost DC-DC converter effectively improves the electrical performance of low-head micro-hydropower systems. The system maintains the output voltage of 14.6 V despite significant variations in rotational speed. The experimental results show that the system can operate at an ultra-low input voltage of 3.61 V at 29.83 RPM, confirming its suitability for low-head, low-flow hydropower environments. The optimal operating condition was achieved at 63.78 RPM with the maximum efficiency of 74.7% while delivering output power close to the nominal load requirement. The smooth transition between boost and buck operating modes further confirms the adaptive behavior and robustness of the proposed voltage regulation strategy. Compared to conventional configurations without active regulation, this approach enhances voltage usability and overall efficiency, extending the practical operating range of PMDC-based systems. The proposed configuration is particularly suitable for standalone and rural electrification applications that require stable DC power despite fluctuating water flow conditions. Future work may focus on long-term field testing, implementation of adaptive control strategies such as MPPT and scaling for higher power application.

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