

Voltage–Frequency Stability of a 300W Portable Cross-Flow Pico-Hydropower System under Low-Flow Conditions

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ABSTRACT

Pico-hydropower systems are widely recognized as a reliable solution for rural electrification; however, their performance is highly sensitive to hydraulic and load variations, particularly under low-flow conditions. This study presents an experimental investigation of voltage–frequency stability in a 300 W portable cross-flow pico-hydropower system. The system consists of a simple weir intake, a variable-diameter PVC penstock, a cross-flow turbine, and a directly coupled single-phase AC generator without a governing mechanism. Experimental tests were conducted by applying six resistive load levels ranging from 0 to 100 W to evaluate the output voltage, frequency, generator rotational speed, overall system efficiency, and voltage regulation. The results show a significant frequency drop from 77 Hz at no-load to 57 Hz at full-load, corresponding to a deviation of approximately 35%. The system also exhibits a low overall efficiency of 15.21% and a voltage regulation of 36.6%, indicating poor energy conversion and unstable voltage performance. These findings reveal that the absence of a speed control mechanism and turbine–generator mismatch significantly affect system stability. The study concludes that load variation alone is insufficient to maintain stable operation, highlighting the need for advanced control strategies such as ELC to improve the voltage and frequency stability.



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1. INTRODUCTION

The increasing global demand for sustainable energy has significantly accelerated the development of decentralized power generation systems, particularly for rural and off-grid applications [1], [2]. Among the various available technologies, pico-hydropower systems are widely recognized for their reliability, primarily due to their ability to provide continuous and predictable energy output, in contrast to intermittent renewable sources such as solar and wind energy. Cross-flow turbines are extensively employed in pico-hydropower systems owing to their simple construction, cost-effectiveness, and suitability for operation under low-head conditions [2], [6]. Previous studies have demonstrated that cross-flow turbines exhibit relatively stable performance under varying flow conditions and continue to attract considerable research attention in pico-hydropower applications due to their robustness, operational flexibility, and adaptability [1], [6], [10]. However, standalone pico-hydropower systems face significant challenges in maintaining voltage and frequency stability under variable load conditions.

In isolated or weak electrical systems, load disturbances may lead to significant voltage and frequency deviations, thereby reducing power quality and system reliability [3]–[5]. These issues become more critical in systems without control mechanisms such as governors or electronic load controllers (ELC), which are commonly employed to maintain voltage and frequency stability in standalone pico-hydropower systems [8].

Although several studies have reported electrical output characteristics of pico-hydro systems [1], [2], recent reviews indicate that quantitative investigations of voltage regulation, frequency deviation, and the interaction between mechanical and electrical parameters remain limited, particularly for portable pico-hydropower systems [9], [10]. This study experimentally investigates the voltage–frequency behavior of a 300 W portable cross-flow pico-hydropower system operating under low-flow conditions and variable electrical loads. The experimental evaluation includes voltage regulation, frequency deviation, generator rotational speed, and the mechanical–electrical coupling to provide a comprehensive assessment of the system stability under standalone operating conditions. Unlike previous studies, which primarily focused on turbine hydraulic performance or electrical output characteristics separately, this work integrates the analysis of electrical and mechanical response parameters in a portable direct-coupled turbine–generator system under actual field conditions. The findings are expected to provide valuable experimental data for the development of effective voltage and frequency control strategies, particularly through the implementation of ELC, in portable standalone pico-hydropower systems.

2. RESEARCH METHOD

2.1. System Configuration

The experimental setup consists of a portable pico-hydropower system utilizing a cross-flow turbine coupled to a 300 W single-phase AC generator. The main components of the system include a water intake and flow channel, penstock pipeline, cross-flow turbine runner, mechanical shaft coupling, AC generator (300 W), voltage regulator (post-generator), and a resistive load bank based on a lamp loading system. The overall configuration of the system is illustrated in Figure 1, which presents the main components in three sections: (a) water intake, (b) penstock pipeline, and (c) turbine–generator assembly. The water intake system, shown in Figure 1(a), employs a simple weir structure designed to collect water from a natural spring source, which provides a relatively continuous flow throughout the year. The weir has a cross-sectional area of approximately 0.256 m², allowing sufficient water accumulation before entering the conveyance system. This configuration is selected due to its simplicity, low construction cost, and suitability for rural and off-grid applications.

The penstock pipeline, as depicted in Figure 1(b), is constructed using PVC pipes with a gradually decreasing diameter to enhance the hydraulic pressure at the turbine inlet. The pipe diameters are reduced from 6 inches to 4 inches and finally to 3 inches at the nozzle end. The total length of the penstock is 23.83 m. This design aims to minimize hydraulic losses while increasing flow velocity at the turbine entrance. The system operates under an effective head of 2.95 m, with a measured flow rate of 0.02705 m³/s at the outlet.

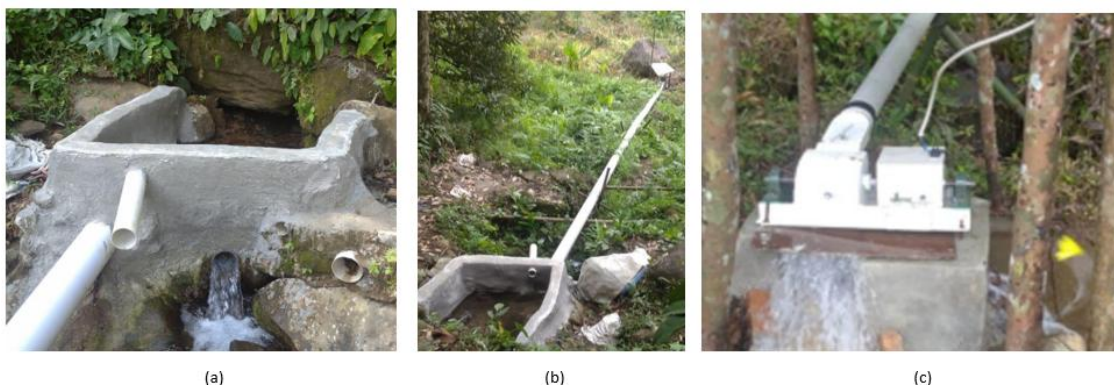


Figure 1. Experimental setup of the portable pico-hydropower system: (a) weir structure, (b) penstock pipeline, and (c) turbine–generator assembly

The turbine-generator assembly shown in Figure 1(c) adopts a direct-coupled single-shaft configuration, in which the cross-flow turbine and the single-phase AC generator are mounted coaxially on the same shaft without intermediate transmission components such as belts or gearboxes. This arrangement minimizes mechanical transmission losses, improves rotational power transfer, and provides a compact structure suitable for portable applications. The complete assembly is supported by a detachable steel-frame structure, allowing convenient transportation, installation, and maintenance in remote locations. The detailed mechanical and electrical specifications of the prototype are summarized in Table 1.

Table 1. Geometrical and electrical specifications of Pico-Hydropower

Item	Specification
Nozzle Inclination	45°
Inlet Nozzle Diameter	3 in
Turbine	
Runner Diameter	10 cm
Shaft Diameter	5 cm
Runner Width	12.5 cm
Number of Runner Blades	14
Generator Rated Power	300 W

The experimental pico-hydropower was installed at the Bukit Aur Durian Plantation, Limau Manis Village, Pauh District, Padang City, West Sumatra, Indonesia. The geographical location of the experimental site is shown in Figure 2. The site is located approximately 4.1 km from Politeknik Negeri Padang and 33 km from Minangkabau International Airport, with an average travel time of approximately 12 min by motorcycle from the campus. Geographically, the installation site is located at 0°55'08.22" S, 100°28'53.12" E (-0.918949, 100.481296) at an elevation of 419 m above mean sea level. The site was selected because it is supplied by a perennial spring capable of providing a continuous water flow suitable for evaluating the performance of the portable pico-hydropower system under actual field conditions.

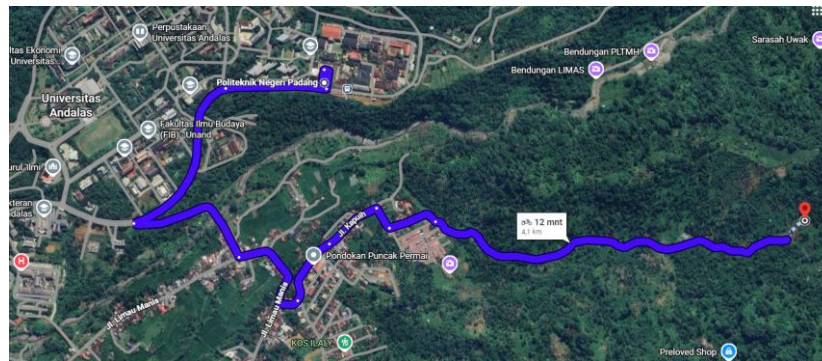


Figure 2. Geographic location of the portable pico-hydropower experimental site in Bukit Aur Durian Plantation, Limau Manis, Pauh District, Padang City, West Sumatra, Indonesia
(Source: Google Maps, accessed July 2026)

2.2. Experimental Parameters

The key parameters used in this study are based on actual measured and calculated values: Water flow rate: $Q=0.02705 \text{ m}^3/\text{s}$, Effective head: $H=2.95\text{m}$, Gravitational acceleration: $g=9.81\text{m}/\text{s}^2$, Water density: $\rho=1000 \text{ kg}/\text{m}^3$. The theoretical hydraulic power is calculated using:

$$P_{hyd} = \rho g Q H \quad (1)$$

In this equation, P_{hyd} represents the hydraulic power available in the system (W), while ρ , g , Q , and H correspond to the water density (kg/m^3), gravitational acceleration (m/s^2), volumetric flow rate (m^3/s), and effective head (m), respectively. This equation represents the maximum available power from the water source prior to any conversion losses in the turbine and generator system [13], [21].

2.3. Measurement and Instrumentation

To ensure consistency with the reported results, several key parameters were measured during the experiment. The output voltage (V) was measured and used for voltage regulation analysis, while the output current (I) was recorded for electrical power calculation. The output frequency (Hz) was monitored to evaluate frequency stability, and the rotational speed (rpm) was measured to analyze the mechanical performance of the system.

The measurements were carried out using standard electrical instruments, including a digital multimeter for voltage measurement, a clamp meter for current measurement, a frequency meter for frequency monitoring, and a tachometer for rotational speed measurement. These instruments are commonly used in experimental analysis of small-scale power systems [19].

According to the manufacturer's specifications, the Everwell MT87 provides an AC voltage measurement range of 200/750 V with an accuracy of $\pm(1.0\% + 5 \text{ digits})$ and an AC current measurement range of 20 A with an accuracy of $\pm(2.5\% + 10 \text{ digits})$. Prior to the experiments, all measuring instruments were inspected for proper operation, and their readings were verified against known reference values following the manufacturer's recommended procedures to minimize measurement errors. These specifications and verification procedures were considered throughout the experimental campaign to improve the reliability of the acquired data.

2.4. Experimental Procedure

The experimental procedure is illustrated in Figure 3. Prior to each test, the portable pico-hydropower system was operated under no-load conditions until steady-state operation was achieved. During the experiments, the hydraulic input parameters, including the effective head and water flow rate, were maintained as constant as possible to ensure consistent operating conditions [13], [18]. The electrical load was increased sequentially in 20 W intervals, from 0 W to 100 W, resulting in six loading conditions (0, 20, 40, 60, 80, and 100 W). At each load level, the system was allowed to stabilize before measurements were taken to minimize transient effects associated with sudden load changes. Once steady-state conditions were reached, the output voltage, current, frequency, and generator rotational speed were recorded [19]. Each loading condition was tested three times, and the average values were used for subsequent analysis to improve the repeatability and reliability of the experimental results. The entire experimental campaign was conducted over seven consecutive days under nearly constant hydraulic conditions so that the observed variations in electrical performance were primarily attributed to changes in the applied electrical load rather than fluctuations in the available water resource [24].

2.5. Performance Analysis

1. Electrical Power Output

The electrical output power is calculated using:

$$P_{out} = V \times I \quad (2)$$

In this equation, P_{out} represents the electrical output power, whereas V and I denote the terminal voltage and load current, respectively. This formulation is commonly used for electrical power calculation in AC systems [19].

2. System Efficiency

The efficiency of the pico hydro system is determined by:

$$\eta_{sys} = \frac{P_{out}}{P_{hyd}} \times 100\% \quad (3)$$

Where η_{sys} represents the system efficiency (%), P_{out} is the electrical output power and P_{hyd} is the theoretical hydraulic power available from the water source (W). his efficiency definition is widely used in small hydropower system analysis [13], [21].

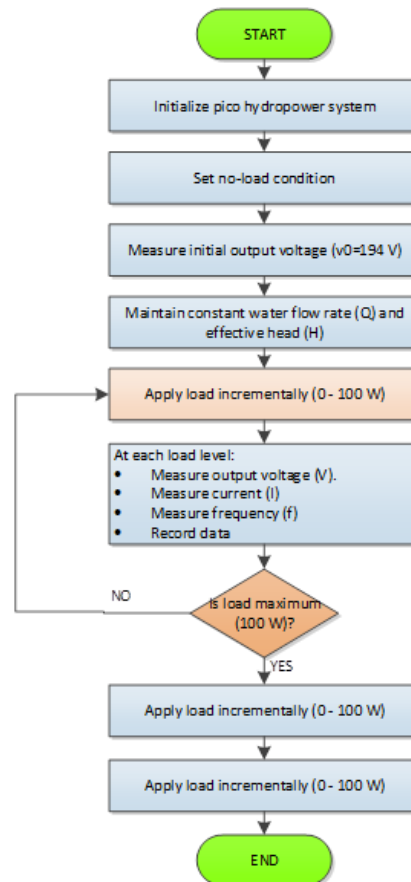


Figure 3. Flowchart of the experimental procedure

3. Voltage Regulation

Voltage regulation is evaluated to determine system stability:

$$VR = \frac{V_{no-load} - V_{full-load}}{V_{full-load}} \times 100\% \quad (4)$$

Where VR represents the voltage regulation (%), $V_{no-load}$ is the output voltage at no-load condition, and $V_{full-load}$ is the output voltage at full-load condition. Voltage regulation is a key indicator of power quality in electrical systems [11], [16].

4. Frequency Stability

Frequency deviation is evaluated to assess generator performance under varying load conditions and is calculated as:

$$FD = \frac{f_{no-load} - f_{full-load}}{f_{full-load}} \times 100\% \quad (5)$$

In this equation, FD represents the percentage frequency deviation, whereas $f_{no-load}$ and $f_{full-load}$ correspond to the system frequencies under no-load and full-load conditions, respectively. Frequency stability plays a crucial role in ensuring the reliability and operational continuity of standalone power systems [16], [22]. Moreover, the relationship between rotational speed and output frequency is systematically analyzed to evaluate the electromechanical coupling behavior of the system. This relationship follows the fundamental generator equation:

$$f = \frac{P \times N}{120} \quad (6)$$

where f represents the electrical frequency (Hz), while P and N denote the number of poles and the rotational speed (rpm), respectively [19].

3. RESULTS AND DISCUSSION

3.1. Hydraulic and Generator Power

Based on the experimental data, the generator power output (P_{out}) was recorded at 119 W against a hydraulic power potential P_{hyd} of 782,31 W, resulting in an overall system efficiency η_{sys} of approximately 15.21%. The calculated overall efficiency is considerably lower than that reported for well-designed small hydropower systems, where overall efficiencies typically range from approximately 50% to 70% under favorable operating conditions [13], [20]. This substantial performance degradation can be attributed to severe mechanical friction within the rotating assembly, a pronounced rotational speed (rpm) mismatch between the cross-flow turbine and the generator, or an overestimation of the theoretical hydraulic power relative to the actual operational capacity of the turbine.

3.2. Voltage Characteristics and Regulation

The experimental results show that the output voltage decreases significantly with increasing load, from 194 V at no-load to 142 V at full-load (100 W). The voltage characteristics under varying load conditions are presented in Figure 4. This substantial voltage reduction demonstrates the limited capability of pico-hydropower to maintain a stable output voltage under increasing load demand.

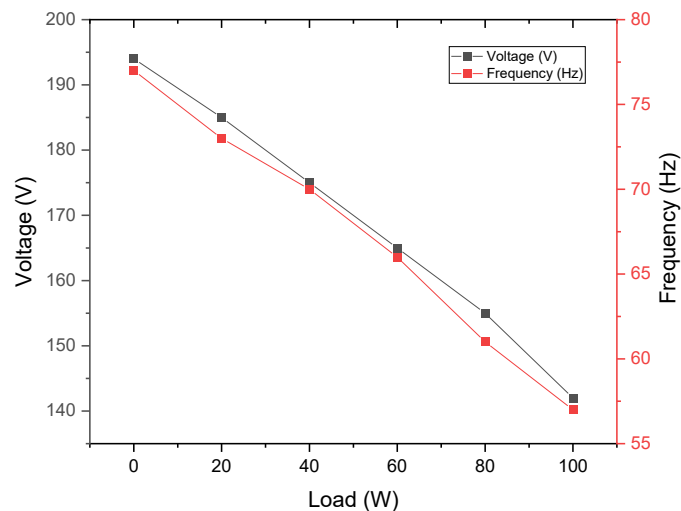


Figure 4. Voltage and frequency characteristics under varying load conditions

According to IEC 60038, the nominal low-voltage supply for 50 Hz systems is 230 V. Considering the commonly accepted operating tolerance of $\pm 10\%$, the acceptable operating voltage range is approximately 207–253 V [12]. In the present study, the measured no-load voltage of 194 V was already below the minimum recommended operating limit by approximately 6.3%. As the electrical load increased, the output voltage further decreased to 142 V, corresponding to a deviation of approximately 31.4% below the minimum acceptable voltage. These results indicate that the prototype operated under undervoltage conditions throughout the entire experimental range and was unable to satisfy the standard voltage requirements even before loading was applied.

This behavior is further reflected by the calculated voltage regulation of the prototype, which was 36.6%. This value is considerably higher than the recommended voltage variation of $\pm 5\text{--}10\%$ for small-scale power systems [11], [12], confirming that the prototype exhibits poor voltage regulation and limited voltage stability under varying load conditions.

The observed voltage degradation is primarily attributed to the reduction in generator rotational speed caused by the increasing mechanical load imposed on the turbine. In direct-coupled pico-hydropower systems without an active governing mechanism, the generated voltage is strongly dependent on turbine speed and generator excitation characteristics [13]. Consequently, the reduction in turbine speed directly lowers the generator terminal voltage as the electrical load increases.

A more pronounced voltage drop was observed when the load exceeded 80 W, indicating that the turbine-generator set approached its operating limit. Under these conditions, the available hydraulic power was insufficient to sustain the required generator speed, resulting in inadequate electromagnetic energy conversion and a rapid decline in output voltage [15]. Similar voltage instability has been reported in previous studies on cross-flow pico-hydropower systems, where the absence of an ELC prevented the generator from maintaining a stable voltage under varying load conditions [14]. Therefore, the present results confirm that the implementation of an appropriate voltage and frequency control strategy, such as an ELC, is essential to improve the electrical performance and operational stability of standalone portable pico-hydropower systems.

3.3. Frequency Stability Analysis

The frequency response of the system shows a substantial deviation from nominal conditions. At no-load conditions, the measured frequency is 77 Hz, which decreases significantly to 57 Hz under full-load conditions. Based on Equation (5), this variation corresponds to a frequency deviation of approximately 35%, indicating poor frequency stability of the system. The frequency characteristics under varying load conditions are presented in Figure 4.

According to IEC 60038, the nominal supply frequency for low-voltage power systems in Indonesia is 50 Hz [12]. Under normal operating conditions, the system frequency is expected to remain within a narrow tolerance, typically ranging from $\pm 1\%$ to $\pm 5\%$ of the nominal value according to IEEE and IEC recommendations [11], [22]. Compared with the nominal frequency, the measured no-load frequency of 77 Hz was approximately 54% higher than the standard value, indicating that the turbine-generator assembly operated under a severe overspeed condition. Even at full-load operation, the measured frequency remained at 57 Hz, which is approximately 14% above the nominal frequency. These measured frequencies exceed the allowable deviation recommended by IEEE and IEC standards, confirming that the prototype does not satisfy the frequency quality requirements for standalone AC power generation [11], [22].

The experimental data further show that the generator rotational speed decreased from 1695 rpm to 1450 rpm, resulting in a corresponding reduction in output frequency from 77 Hz to 57 Hz. This observation confirms the direct relationship between generator rotational speed and electrical frequency in AC generators [19]. Because the turbine and generator were directly coupled through a single shaft, any variation in turbine speed was immediately reflected in the generator output frequency. The excessively high no-load frequency indicates that the turbine operated beyond the rotational speed required to produce the nominal 50 Hz output. This behavior suggests a mismatch between the available hydraulic power, turbine rotational speed, and generator characteristics, which is commonly observed in standalone pico-hydropower systems operating without an active speed regulation mechanism [17].

Although the output frequency decreased as the electrical load increased, it remained above the nominal 50 Hz throughout the entire experiment. Consequently, the prototype exhibited persistent over-frequency operation rather than stable frequency regulation, indicating that the generated electrical power was unsuitable for direct connection to conventional AC loads [11], [16]. From a practical perspective, the inability to maintain the nominal frequency may adversely affect the operation of conventional electrical loads, particularly induction motors, transformers, and frequency-sensitive electronic equipment [11], [16], [19]. Since the synchronous speed of AC machines is directly proportional to the supply frequency, frequency deviations directly influence motor operating speed, torque characteristics, and overall efficiency [19]. Furthermore, prolonged operation under abnormal frequency conditions may increase thermal stress, reduce equipment efficiency, and shorten equipment service life [11], [16].

The observed results demonstrate that the prototype lacks an effective mechanism for regulating turbine speed under varying load conditions. Without a governing mechanism or an ELC, the turbine speed cannot be maintained at the level required to produce a stable 50 Hz output frequency [18]. Therefore, the implementation of an active speed-control strategy, such as an ELC or governor system, is essential for maintaining generator frequency within the acceptable operating limits and improving the operational reliability of standalone portable pico-hydropower systems.

3.4. Mechanical Performance and Speed Behavior

The rotational speed of the generator decreases progressively with increasing load, declining from 1695 rpm under no-load conditions to 1450 rpm at full-load. This behavior is consistent with theoretical expectations, as higher electrical loads impose greater mechanical torque on the turbine, resulting in a reduction in rotational speed. However, it is observed that the rate of frequency reduction is more pronounced than the decrease in rotational speed, indicating the presence of additional system losses. These losses can be attributed to several factors, including mechanical friction within the rotating components, generator slip, and electrical losses in the stator windings. Figure 5 depicts the relationship between generator rotational speed and load variation, highlighting this nonlinear behavior. Such losses are commonly reported in small-scale generation systems and tend to become more significant in low-power applications [19]. Furthermore, the absence of a speed governing mechanism exacerbates this issue, as the turbine is unable to maintain a constant rotational speed under varying load conditions, leading to further instability in system performance [20].

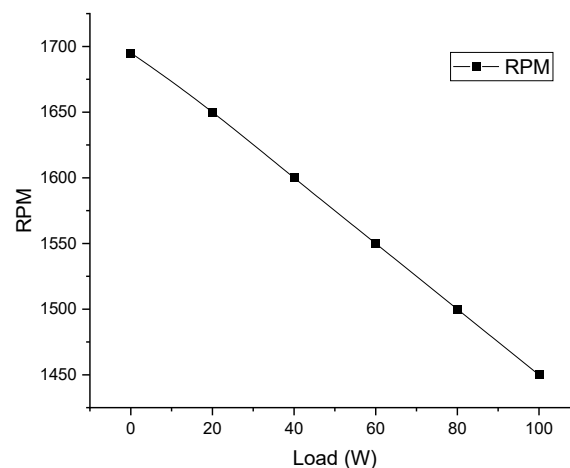


Figure 5. Rotational speed characteristics under varying load conditions

3.5. Discussion and Comparison with Previous Studies

The results of this study are in close agreement with prior research on pico-hydropower systems, which consistently emphasize the challenges associated with maintaining voltage and frequency stability in the absence of advanced control mechanisms. Recent studies [7], [8], [22], [23] report that small-scale pico-hydropower systems without electronic load controllers often experience voltage drops exceeding 20% and significant frequency deviations under variable load conditions. Similarly, [17] emphasizes that direct coupling between turbine and generator leads to poor dynamic response under load variations. The strong correlation between rotational speed, voltage, and frequency observed in this study confirms the dominant influence of electromechanical coupling in uncontrolled pico-hydropower systems. Compared to these studies, the present system exhibits even higher voltage regulation (36.6%) and frequency deviation (77–57 Hz), indicating that portable configurations are more vulnerable to instability due to their simplified design and lack of control mechanisms.

3.6. Implications for System Improvement

The findings clearly indicate that the current system configuration is not suitable for providing a stable electrical supply without the implementation of additional control mechanisms. To enhance system performance, several improvement strategies can be considered. These include the integration of an ELC to stabilize frequency, the use of an inverter-based system for both voltage and frequency regulation, the implementation of a mechanical or electronic governor to control turbine speed, and the optimization of turbine-generator matching to ensure efficient energy transfer. These approaches have been widely reported to significantly improve the stability and overall performance of pico-hydropower systems [16], [20], [22].

4. CONCLUSION

The experimental results demonstrate that the 300 W portable pico-hydropower system exhibits significant voltage and frequency instability under varying load conditions. The output voltage decreases from 194 V to 142 V, corresponding to a voltage regulation of 36.6%, while the frequency decreases from 77 Hz to 57 Hz as the electrical load increases. In addition, the generator rotational speed decreases proportionally with increasing load, confirming a strong coupling between the mechanical input and electrical output of the direct-drive system. The overall system efficiency obtained in this study is 15,21%, indicating considerable potential for performance improvement. The observed instability is primarily attributed to the absence of an active governing mechanism for maintaining constant generator speed under dynamic loading conditions. Therefore, the implementation of an ELC or other power electronic control strategies is essential to improve voltage and frequency stability in standalone pico-hydropower systems. Future work will focus on the design, implementation, and experimental validation of an ELC-based control system to evaluate its effectiveness in enhancing voltage regulation, frequency stability, and overall system performance under dynamic load conditions.

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