Challenges and Solutions in Hydropower: Analyzing Francis Turbine Performance and Operational Dynamics

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***Abstract*—This paper addresses the global challenge of sustainable energy, exploring alternatives to dwindling fossil fuels and rising CO2. While renewables like solar and wind offer potential, they face geographical and intermittent limitations. Thermal and nuclear energies are discouraged due to severe environmental and health impacts. Hydropower emerges as a highly reliable and favored global solution, harnessing energy from flowing water, tides, and dams. It's the most prevalent renewable source for electricity, offering consistent, dependable, and emission-free supply. The Francis turbine is crucial to hydropower, known for its high efficiency. Its spiral casing, runner, and guide vanes efficiently convert water's energy into electricity. Water flows from a reservoir to the turbine, where guide vanes regulate entry to the runner, driving a generator. Our analysis reveals key factors affecting hydropower performance: energy source, guide vane opening, servomotor performance, and governor control system. Sediment accumulation at the inlet causes head loss, reducing optimal output. Misaligned guide vane openings can drop rotational speed, leading to suboptimal load. Servomotor issues like wear also require maintenance. A 5% speed drop setting effectively manages water pressure and flow, enabling smooth load escalation.**

Keywords*—*Hydropower, Renewable Energy, Francis Turbine, Turbine Performance, Sediment Accumulation

I. INTRODUCTION

The generation of sustainable energy poses a significant global challenge. With the continuous depletion of fossil fuel reserves and the escalating atmospheric concentrations of carbon dioxide contributing to global warming, researchers are actively pursuing alternative energy sources [1, 2].

Renewable Energy (RE) resources, including solar, wind, geothermal, and hydropower, are abundant worldwide [3,4,5]. However, the viability of some of these energy sources is constrained by geographical limitations. Solar energy, for instance, is often available for limited durations and cannot be harnessed effectively during cloudy or rainy conditions [6-10]. Despite these limitations, solar energy significantly contributes to pollution reduction and fossil fuel conservation. The two principal forms of solar energy are solar thermal energy, which directly heats a working fluid via solar thermal collectors [11,12,13], and solar electricity, generated by photovoltaic panels [14-15]. Similarly, the power output from wind energy is heavily contingent on a region's annual wind patterns and climatic conditions.

Conversely, both thermal (fossil fuel) and nuclear energy generation are widely discouraged due to their severe environmental impacts and their established links to various human health risks. In stark contrast, hydropower is considered an ideal and highly reliable source for electricity generation, making it the most prevalent and favored method of power production globally.

Hydropower, or hydel energy, harnesses the energy present in various forms of water: flowing water found in rivers, streams, and channels; the kinetic energy of moving ocean tides; and the potential energy of water stored behind dams. Hydro-turbine units are typically employed to convert this potential energy of falling water and the kinetic energy of moving water into usable electrical energy. Over the past century, a wide array of hydroelectric turbines have been developed to efficiently transform this hydroelectric energy into mechanical energy.

Hydropower stands as the most widespread renewable energy source for electricity generation in many nations. It presents an appealing alternative to fossil fuels largely because it produces no carbon dioxide or other harmful atmospheric emissions. Additionally, it offers a consistent and dependable source of electricity by utilizing a steady water supply, such as a river or an elevated lake, thereby contributing significantly to sustainable energy generation.

II. METHODS

A. Francis Turbine: Components, Operation, and Efficiency

The Francis turbine is comprised of three primary components: the spiral casing, the runner, and the surrounding guide vanes. All these components are submerged in water during operation. Francis turbines are widely adopted due to their high efficiency across a broad range of operating conditions. Water head and flow capacity are crucial input parameters that significantly influence the turbine's performance. Notably, Francis turbines maintain high efficiency even with substantial variations in incoming water flow parameters, typically handling a head of 45-400 m and capacities ranging from 10-700 m^3/s [16].

The operational scheme of a Francis turbine is as follows:

a. Water impounded in a reservoir or lake flows through the intake channel and then through the penstock to reach the turbine, leveraging the initial height at the inlet.
b. The water exiting the penstock is then directed towards the turbine runner.
c. The guide vanes are opened to a position determined by the operator's allowable load. Water then flows into the runner and exits into the draft tube. As the turbine runner rotates, it drives the turbine shaft, which is directly connected to the generator, thereby producing electricity.

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d. The electricity generated from the rotating shaft and connected generator is then transmitted to the switchgear. From there, it is distributed via the transmission grid to consumers.

B. Guide Vane Functionality and Impact on Turbine Efficiency

The guide vanes are critical components that direct the water flow from the spiral casing into the turbine runner. This precise guidance ensures that each turbine blade receives the optimal angle of attack from the water, ultimately enhancing the overall efficiency of the water flow system. The operational mechanism involves a pivot (shaft) connected to the guide vane, allowing for a controlled gap or opening to be set.

Positioned at the end of the water-directing medium leading to the turbine, the guide vanes control the flow direction by adjusting their opening. This regulated flow direction directly impacts the turbine's rotational speed, consequently controlling the output generated by the turbine-driven generator.

C. Woodward Governor Operating Principles at Garung Hydroelectric Power Plant

The Woodward governor at the Garung Hydroelectric Power Plant operates as follows:

a. When the engine is running, oil from the sump tank is supplied by a gear pump. The gear pump increases oil pressure to a set value determined by the spring relief valve.
b. This oil pressure is then maintained within the annular space of the pilot valve plunger.
c. When the opposing forces on the pilot valve plunger are balanced, the plunger closes the lower port on the pilot valve bushing. If the engine load increases, engine speed decreases. This reduction in engine speed causes the flyweights to contract. The pressurized oil is then directed to the servomotor piston, causing an upward movement. This upward motion of the servomotor piston is transmitted via a connecting rod to adjust the guide vanes, setting them to achieve the desired 750 RPM and 50 Hz frequency.
d. The oil pushing the servomotor piston upwards also forces the buffer piston to move upwards due to the pressure differential on both sides. This upward movement of the buffer piston compresses the upper buffer spring and releases tension on the lower buffer spring. This action equalizes the pressure, causing the servomotor piston to stop its movement.

III. RESULTS AND DISCUSSION

A. Analysis of Factors Causing Load Disturbances in Unit 1 of the Garung Hydropower Plant

The operation of generating units at the Garung Hydropower Plant for normal load demand is limited to the hours of 17:00-21:00, as dictated by the load dispatch instructions from PLN P2B (Pusat Pengatur Beban) and the availability of primary energy (water elevation) in the Garung reservoir. When the water elevation is high, the plant can operate with two units; conversely, during periods of low water elevation, only one unit may run, or operations may be temporarily suspended to allow reservoir levels to recover.

This highlights the critical influence of primary energy on unit loading, as the reservoir's water elevation which drives the turbine runner must maintain sufficient head pressure. A higher head facilitates smoother and more efficient attainment of peak load, particularly when two units are in operation.

Table 1. Head Calculation Result

Elevation Reservoir	Elevation Tailrace	Head
1190,89	973	217,89
1190,76	973	217,76
1190,63	973	217,63
1190,51	973	217,51
1190,39	973	217,39
1190,17	973	217,17
1190,56	973	217,56

Water discharge does not always flow smoothly due to sediment accumulation at the inlet screen. When water passes through the intake's inlet screen, the sediment buildup restricts optimal water flow into the penstock. Consequently, the settled sediment in front of the trash rack or inlet screen creates a difference in water elevation between the upstream and downstream sides of the screen.

Table 2. Elevation Upstream Dan Downstream

Elevation Upstream (m)	Elevation Downstream (m)	Delta Head
1190,89	1189,8	1,09
1190,76	1189,6	1,16
1190,63	1189,2	1,43
1190,51	1189,3	1,21
1190,39	1189,1	1,29
1190,17	1188,9	1,27
1190,56	1189,32	1,242

Based on the aforementioned data, the measured Δh (head loss) deviates from the standard range of 30-50 cm, adversely affecting both water flow pressure and outflow directed toward the turbine. Since the rotational speed of the turbine runner is governed by the hydraulic pressure entering the runner, and turbine power output is contingent upon discharge flow rate, any disruption in these parameters leads to suboptimal performance.

The hydraulic pressure is primarily determined by the intake gate opening greater height and width of the gate opening result in higher pressure delivered to the turbine. Consequently, sediment accumulation at the inlet screen obstructs water passage, reducing outflow and diminishing turbine efficiency. A longitudinal assessment of inlet screen conditions over successive years is presented in Tables 3 and 4.

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Table 3. Data Scren Inlet

Region up-down	4,9 m
long *screen*	6 m
Volume lifting	72,93 m^2
measure sediment from *main dam*	55 m

Table 4. Data Before Dredging Working

Elevation up screen intake	1176 mdpl
Elevation up inlet intake	1173 mdpl
Elevation base inlet screen intake	1168,50 mdpl
Total height screen intake (vertical)	7,5 m
Height screen inlet tunnel intake (vertical)	4,5 m
Elevation base surface screen	1171,79 mdpl
Height screen unclosed	1,21 / 26,89 %
Elevation water surface	1186,47 mdpl
Reading echo-under	14,68 m
Height screen closed	3,29 m/ 73,11 %

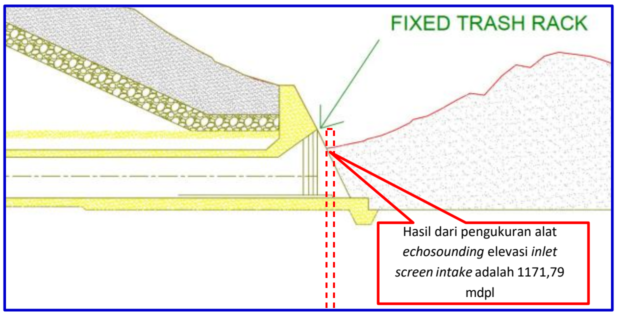

Figure 1. Screen inlet condition

In addition, the entrainment of air within the swirling flow forming vortex structures as water enters the intake is a natural phenomenon during transitional flow conditions, particularly when transitioning from free-surface flow to pressurized flow within a closed conduit. The ingress of air and turbulent flow into the intake can induce hydraulic instabilities in the downstream penstock, leading to flow fluctuations that degrade turbine performance.

The presence of swirling flow in reservoirs containing substantial floating debris or organic matter further exacerbates intake inefficiencies. During the rainy season, surface runoff carries eroded sediment and floating debris into the reservoir, which subsequently converges toward the intake. Over time, accumulated debris intermixed with sediment deposits obstructs the intake openings and restricts water passage. This obstruction critically impairs the hydraulic efficiency of the intake, turbine, and overall hydropower generation system.

A. The governor is instrumental in regulating the guide vane opening, ensuring the turbine maintains a constant rotational speed of 750 rpm. This stability is achieved through precise control of the speed droop setting, which is configured at 5% at PLTA Garung. Our findings indicate a direct correlation between the speed droop percentage and the system's responsiveness to pressure fluctuations within the spiral casing. A reduced speed droop percentage enhances the governor's sensitivity, allowing for more precise and rapid adjustments to maintain the target 750 rpm and a consistent 50 Hz frequency. Data illustrating the impact of frequency variations on regulated load output has been compiled and is presented graphically herein.

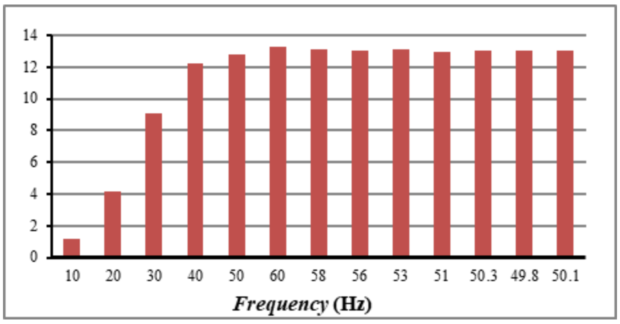

Figure 2. Graph of effect variation *frequency* versus load

Based on the graph, it's evident that a 5% speed droop setting provides high sensitivity to water pressure and flow during initial operation. This sensitivity allows for the load to easily reach its peak, indicating that the Unit 1 speed droop setting is functioning normally. However, less-than-optimal guide vane opening could be attributed to issues with the oil pressure supply to the servomotor. This might involve slight leakage in the oil delivery pipe or its shields, leading to insufficient oil pressure reaching the servomotor and thus hindering its optimal performance. Furthermore, there's a possibility of damage to the control actuator valve and an imbalance in the pressure distribution control. Either of these issues could prevent the servomotor from receiving an optimal supply of oil pressure.

Annual energy production is calculated based on dependable power**.** Dependable power, in turn, is determined by the dependable discharge available to the hydroelectric power plant, which refers to the outflow discharge over an *n*-day period.

Table 5. Power And Energy Calculation Results Data

Head (m)	Daya (KW)	Energi (KWh)	Energi actual (KWh)
217,89	26279,97507	105119,9003	100500
217,76	25987,44077	103949,7631	99200
217,63	26027,26451	104109,058	123800
217,51	26141,96381	104567,8552	99600
217,39	26293,37198	105173,4879	126300
217,17	25990,6582	103962,6328	74400

From the power calculation data, the Garung Hydroelectric Power Plant Sub-Unit is experiencing a derating status. A derating status indicates a condition where a power generation unit is not ready to operate at its optimal capacity (26,400 kW). Based on the data and the graph provided, it appears that the actual energy output is sometimes not operating at its maximum potential. This is primarily due to two factors: load disturbance issues and operational periods of less than four hours.

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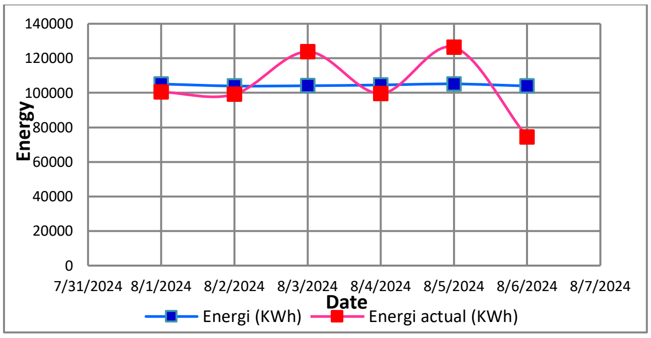

Figure 3. Comparison Graph of Actual Energy Versus Calculated Energy

B. Mitigation and Remedial Actions for Unit Load Disturbances

This section outlines strategies and interventions to address factors contributing to load disturbances within the power generation unit.

1. Inlet Screen Issues Affecting Head and Water Pressure
   Based on data from August 2024, significant sediment accumulation at the inlet screen has been identified as a factor impacting both head and water pressure. To restore the unit's load capacity to 13.2 MW, it is imperative to undertake sediment dredging in the area obstructing the intake. This dredging operation commenced in October 2024 at the front of the inlet screen. Additionally, routine sediment removal from the Serayu Dam settling basin is crucial. This proactive measure will prevent sediment from being carried downstream into the Telaga Menjer reservoir, thereby mitigating future accumulation.
2. Guide Vane Opening Malfunctions
   To rectify issues with the guide vane opening, it is necessary to recalibrate the feedback mechanism for spiral casing pressure. This ensures that the pressure remains consistent with the requested guide vane opening (gate limit), thereby optimizing water flow and pressure to the runner.
3. Friction Between Facing Plate and Guide Vane
   Addressing friction between the facing plate and the guide vane requires adjusting the clearance between the runner and guide vane to meet standard specifications. Furthermore, if the guide vane bushing is problematic, it should be replaced. For any disposited lengths, their position should be normalized, or they should be replaced if damage is detected.
4. Servomotor Malfunctions
   Servomotor issues can be resolved through the replacement of critical components, including the rubber gasket, bushings on the crosshead side, bushing nut, V-type packing, and gland packing. Normalizing the ring key and nut positions is also a viable solution. Additionally, cleaning the piston oil port area can alleviate certain servomotor problems.
5. Relay/Control Valve Servomotor and Joint Issues
   If the relay/control valve servomotor shows signs of damage, it should be normalized or replaced. Similarly, problematic joints can be normalized with a small application of grease or replaced if significant damage is evident.
6. Leakage and Control Component Failures
   In cases of detected leakage, the affected shields should be replaced. For issues concerning the pressure distribution control and actuator valve control, normalization or replacement of these components is recommended if they show signs of damage.

IV. CONCLUSION

Based on the data analysis and discussion, the following conclusions can be drawn:

1. The most influential components in the loading process consist of the primary energy source, the guide vane opening percentage, the performance of the servomotor, and the governor control system.
2. The primary energy issue stems from sediment accumulation at the inlet screen, leading to an increased ΔH (head loss), which reduces the maximum outflow. Consequently, the unit's power output fails to reach its optimal capacity.
3. A guide vane opening percentage that does not match the runner's requirements will cause a drop in rotational speed, resulting in a frequency below 50 Hz. This, in turn, leads to a suboptimal load output compared to the ideal operating conditions.
4. Measurement results indicate potential issues with the servomotor, such as wear on the crosshead bushing side, nut, V-type packing, packing gland, or rubber gasket, as well as misalignment in the nut or ring key. Therefore, further inspection and corrective maintenance are necessary.
5. According to the graphed data above, a speed drop setting of 5% demonstrates high sensitivity to water pressure and flow rate during initial operation, facilitating smooth load escalation to peak capacity. In other words, the speed drop setting for Unit 1 remains within normal operational parameters.

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