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A REVIEW OF EFFICIENCY IMPROVEMENT OF HYDRO-TURBINE GENERATOR

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Abstract

Endowed with favorable topography and tremendous amount of rainfall annually, allowed Malaysia to boost its hydroelectric power plant with Bakun Hydroelectric Dam in Sarawak as the largest supplier of hydroelectric energy. Hydroelectric not only acts as flood mitigation but also an alternative of electricity that slowly replaces conventional electric sources like natural gases and coal. However, efficiency of hydro-turbine should be taken into consideration to minimize energy loss while simultaneously optimizing total output power. The review also highlights major challenges, such as material limitations, infrastructure constraints, and the complexities of integrating artificial intelligence into control and optimization processes. Overall, the findings show that improving system efficiency requires simultaneous advancements in material selection, monitoring technologies, control strategies, and predictive tools to create more reliable and higher-performing hydropower systems.

Keywords: hydroelectric power; hydro turbine efficiency; hydropower optimization; renewable energy.

1.0 INTRODUCTION

The idea of generating electricity using hydropower generation starts with converting the energy in flowing water into mechanical motion and, finally, electrical power. In a typical hydro-turbine system, the water moving downhill due to gravity contains both kinetic and potential energy, which is directed to a turbine blade, causing it to spin faster [1]. The energy in the water is then transferred to the turbine, then to a shaft, and finally to a rotor. Through electromagnetic induction, this motion generates an alternating current [2]. The efficiency of a hydro-turbine generator is defined as how effectively the system converts the mechanical energy of moving water into electricity by minimizing power loss [1]. This power loss phenomena are contributed by mechanical and electrical losses, such as friction, turbulence, and resistive heating, which can affect overall system performance and reliability. Apart from that, a highly efficient hydro-turbine generator is also defined as lower operating costs, and sustainable. [2]. Although hydropower systems are reliable, maintaining high efficiency is challenging due to mechanical wear, water quality, and ageing electrical components [3]. All these limitations highlight the significance of understanding electrical and mechanical factors, as they directly influence generator performance. The following sections will examine these factors in detail to show how they affect overall efficiency. A comprehensive review of efficiency improvement is now necessary because the hydropower sector is undergoing a massive transition toward digitalization and variable-speed operation to accommodate the volatility of modern power grids. Traditional fixed-speed systems often suffer from significant efficiency drops when operating away from their design point, leading to cavitation and increased maintenance costs. By reviewing these disparate fields in a single framework, this work provides a roadmap for engineers and policymakers to navigate the technical trade-offs between capital investment and long-term efficiency gains.

2.0 FACTOR AFFECTING SYSTEM EFFICIENCY

2.1 Losses associated with hydro-turbine generator system

Electrical factors play a crucial role in determining the overall efficiency of a hydro-turbine generator system. One of the primary contributors is copper (winding) loss, which occurs when current flows through the stator and rotor coils. According to Joule's law, copper loss can be expressed as:

$$P_c = I^2 R \tag{1}$$

As load rises, copper loss becomes a dominant factor affecting temperature and overall performance. Recent reviews have shown that excessive copper loss leads to significant thermal buildup, and effective cooling systems are necessary to remove this heat and prevent efficiency degradation in electrical machines [4].

Another major contributor is core (iron) loss, which includes hysteresis and eddy-current losses in the magnetic cores of the stator and rotor. Hysteresis loss is the energy needed to constantly realign magnetic domains in the steel, while eddy current loss comes from circulating currents induced by the changing magnetic field. According to modern core-loss modelling approaches [5], the total core loss P_{core} is often expressed as

$$P_{core} = P_h + P_e \tag{2}$$

with

$$P_h = k_h f B_{max}^n,\ P_e = k_e f^2 B_{max}^2 t^2 \tag{3}$$

where P_h is the hysteresis losses, P_e is eddy current losses, k_h is the hysteresis constant, f is the frequency, B_{max} is the maximum flux density, and n is the Steinmetz exponent.

These losses occur even at no-load conditions and depend on the material, lamination quality, flux density, and operating frequency. P. Kuhn et al. [6] confirm that reducing lamination thickness and using optimized soft-magnetic materials significantly lowers both hysteresis and eddy-current losses, improving core-loss performance. Therefore, to improve the electrical efficiency of hydro-turbine generators, especially under variable load and flux conditions, it is crucial to combine both winding and core losses and minimize them by careful design (winding resistance, core material, lamination and cooling).

2.2 Electrical Factors

Mechanical factors also influence the overall efficiency of a hydro-turbine generator system, particularly through the selection of the most suitable turbine type for the given hydraulic conditions. Turbines are energy-producing devices that extract energy from the fluid (as water, steam, or air) and transfer most of that energy to some form of mechanical energy output, typically in the form of a rotating shaft [7]. Turbines are commonly used in power production systems to drive generators and generate electricity**.** There are several types of turbine designs that can be used to generate electricity for wind and water energy sources, as shown in **Table 1.**

Table 1: Example type of turbines

Head Classification	**Turbine Type**		
	Impulse	***Reaction***	***Gravity***
High (>50m)	• Pelton • Turgo	-	-
Medium (10-50m)	• Crossflow • Turgo • Multi-jet Pelton	• Francis (Spiral case)	-
Low (<10m)	• Crossflow • Undershot waterwheel	• Propeller • Kaplan • Francis (Open flume)	• Overshot waterwheel • Archimedes Screw

Therefore, the most suitable type depends entirely on the site-specific combination of head and flow conditions, as shown in **Table 1**. Selecting a turbine that matches the site’s head range is crucial, as its efficiency will drop significantly when operating outside its optimal design conditions

3.0 GENERATOR DESIGN AND CONTROL SYSTEM

In hydropower plants, the ability to work at different speeds is what makes the electromechanical subsystems more efficient. Synchronous generators are of the traditional and fixed-speed type. The problem is that they get locked to the frequency of the grid and lose a lot of efficiency during partial-load operation. At varied-speed operation, the turbine can adjust to the ideal conditions. This causes a greater decoupling of efficient hydraulic, mechanical and electric speeds to be achieved. Higher hydraulic efficiency in the system is obtained, mechanical vibrations are lower and advanced grid services can be performed [8].

3.1 Type of Generator

In the context of large-scale pumped storage hydropower, the Doubly-Fed Induction Generator (DFIG) stands as the established industry standard, particularly for units exceeding 100 MW. This architecture is favored primarily for its cost-efficiency, as it utilizes a partially rated power converter [9]. By connecting the stator directly to the grid and using the converter only to manage the rotor's "slip" power, which typically represents only 20–30% of the total rated capacity—the system minimizes the size and cost of the power electronics. This configuration offers a speed variation of approximately ±10% to ±20%, a range that is generally sufficient to align the turbine's operation with its peak efficiency points on the hydraulic "hill chart" [10].

Conversely, Full-Size Converter (FSC) topologies, such as the Converter-Fed Synchronous Machine (CFSM) and Permanent Magnet Synchronous Generator (PMSG), are gaining significant traction in modernization and refurbishment projects. These systems decouple the generator from the grid entirely, requiring the converter to process 100% of the power flow. This architecture provides a limitless speed range from 0 to 100%, offering unparalleled operational flexibility [28]. This is particularly advantageous for sites with extreme head variations or those requiring rapid transitions between pumping and generating modes to support grid stability.

While PMSGs are noted for high partial-load efficiency by eliminating rotor excitation losses, recent developments in high-voltage modular multilevel converters (MMC) have positioned CFSMs as a formidable competitor. Real-world applications, such as the refurbishment of the Malta Oberstufe plant, demonstrate that CFSMs can drastically expand a plant's operating envelope and startup capabilities [29]. Unlike the DFIG, which is restricted by its slip-dependent speed range, the FSC approach allows for smoother grid integration and superior fault ride-through capabilities, making it the preferred choice for modern grids demanding high levels of ancillary services.

3.2 Power Electronics

The capabilities of these variable-speed generators are ultimately defined by their power electronic converters. For DFIGs, the standard solution is the Back-to-Back Voltage Source Converter (VSC), which manages active and reactive power by regulating rotor currents.

However, the technology shifts when dealing with high-power CFSM applications. Here, the Modular Multilevel Converter (MMC) has emerged as the preferred technology over older thyristor-based Load Commutated Inverters (LCI). MMCs use cascading sub-modules to build a high-quality voltage waveform; this structure minimizes harmonic distortion, significantly cuts switching losses, and removes the need for the bulky output filters required by legacy systems [11].

The "brains" behind these systems have also evolved. To maximize grid stability and efficiency, modern plants are moving away from traditional PID regulators in favour of Model Predictive Control (MPC). By utilizing a real-time mathematical model of both hydraulic and electrical systems, MPC algorithms can predict behaviour and optimize control actions. This approach has been shown to improve reference tracking by up to 99% while handling non-linear physical phenomena, such as water hammer, much more effectively [12].

Finally, reliability remains a priority. Robust Fault Ride-Through (FRT) strategies are essential to ensure the plant stays connected during grid disturbances. These strategies typically involve active crowbar circuits for DFIGs or DC braking choppers for full-size converters, both of which serve to dissipate excess energy and maintain stability during faults [8].

4.0 METHODS FOR EFFICIENCY

4.1 Predictive Maintenance

Predictive maintenance (PdM) operates as a maintenance system which uses real-time data and intelligent monitoring tools to identify equipment deterioration before equipment failure occurs. The generator system maintenance approach now performs scheduled maintenance only when equipment shows signs of deterioration instead of following traditional scheduled maintenance protocols [13]. The continuous observation of operating conditions through PdM enables organizations to prevent unexpected equipment failures which results in better generator unit availability and longer component lifespan.

The fundamental principle of PdM depends on condition monitoring systems. The system tracks vibration data and temperature readings and voltage and current measurements and humidity levels and rotational speed data to identify potential equipment problems [13]. The collected data enables operators to detect mechanical problems including imbalance and misalignment and insulation degradation and cooling system failures before they develop into major issues.

The generator parts Remaining Useful Life (RUL) estimation process uses Prognostics and Health Management (PHM) to predict when components will reach their failure thresholds. The PHM system uses historical degradation data and mathematical models and predictive models to predict component failure times which enables better maintenance planning without requiring unnecessary system shutdowns [14]. The implementation of artificial intelligence and machine learning technologies has enhanced PdM methods through recent advancements. The ability of deep learning models including LSTM networks and autoencoders to detect hidden patterns in sensor data makes them superior to traditional limit-based monitoring systems for complex failure detection. Research shows that these models in hydropower generators enable operators to detect faults before they occur, which results in a 34-hour advance warning period that enhances system dependability [15].

The implementation of PdM in real-world operations has proven to deliver operational advantages. The generator monitoring solutions of ABB and GE and Siemens have implemented predictive maintenance which has delivered substantial improvements in asset performance and operational savings to their customers. The system developed by ABB has achieved a 30% reduction in unplanned outages because it combines real-time sensing with predictive algorithms and digital twin technology [16]. The combination of continuous monitoring with PHM strategies and AI-based diagnostics through PdM enables generator systems to achieve peak operational efficiency while minimizing long-term maintenance expenses and enhancing energy production infrastructure reliability [13–14] The diagram of CBM and PHM cycles are shown in Figure 1 (a) and The PHM architecture diagram is shown in Figure 1 (b).

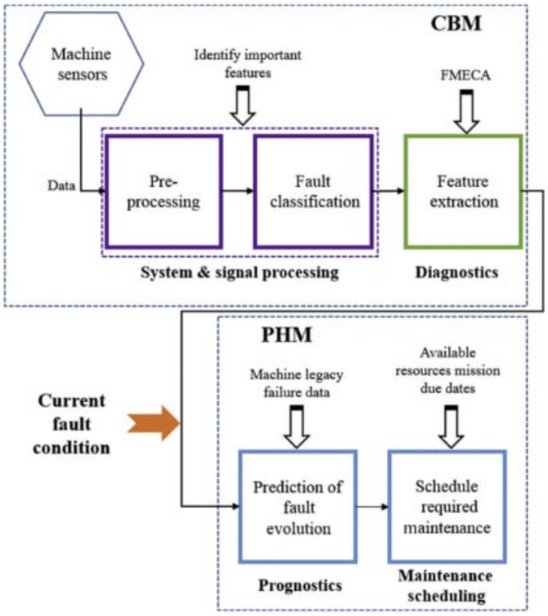

Figure 1(a). CBM and PHM cycles diagram

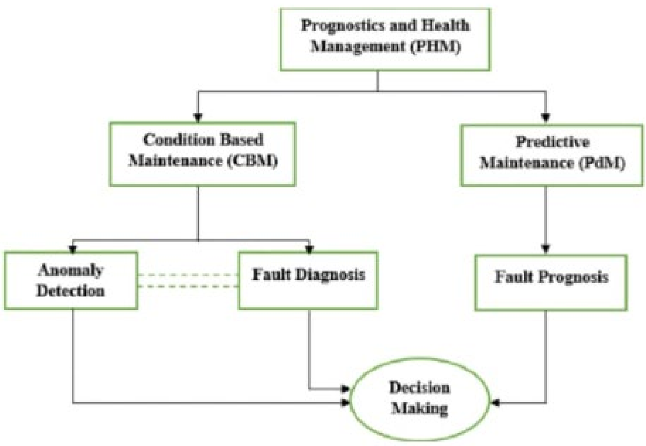

Figure 1(b). PHM architecture diagram

4.2 Smart control system

Smart control systems are used generally in improving and enhancing the performance of hydropower systems. Practically in the hydro-turbine generator system, water flow rate and rotational speed of turbines in hydropower systems are the most crucial parts in maintaining the efficiency of hydropower systems, especially in the country that experiences a high frequency of rainfall events. The water level of water sources becomes unpredictable and in consequence making the water flow rate and pressure changes frequently [17].

First and foremost, in a hydropower system, the turbine acts as the main component that converts the potential and kinetic energy of flowing or pressurized water into rotational mechanical energy, which then drives or moves a generator to produce electricity at a usable frequency. As water is directed through penstocks and onto the turbine blades, the force of the flow causes the turbine shaft to spin, and this rotation becomes the primary input that enables the generator to create electrical power. Because the electrical grid requires a stable frequency (such as 50 Hz in many countries), the turbine must maintain a nearly constant rotational speed even when water levels, flow conditions, or electrical demand fluctuate [17].

Historically, this speed was controlled by a traditional governor system, typically a mechanical or basic hydraulic feedback mechanism that detected changes in turbine speed and adjusted the opening of gates, vanes, or nozzles to increase or reduce water flow. While this system served as the foundation of hydropower control, it had limitations: it responded only after a speed change had already occurred, making it slower and less precise when dealing with rapid load variations; it required manual tuning; it could struggle to maintain tight frequency control during disturbances; and it offered little capacity for efficiency optimization or real-time monitoring. As power grids grew more complex and demand became more dynamic, these limitations led to inefficiencies such as small oscillations in speed, reduced energy output stability, and slower recovery from disturbances [18].

To overcome these issues, modern hydropower systems have upgraded to Smart Speed Control Systems (SSCS), which use digital sensors, computer-based controllers, and sometimes adaptive or predictive algorithms to continuously monitor turbine speed, water flow, pressure, and load conditions. Unlike traditional governors that simply react, SSCS can react faster, tune itself automatically, and even monitor changes, allowing it to maintain a more stable rotation per minute (RPM) and generator frequency while maximizing efficiency and reducing water waste [19].

4.3 Condition Monitoring System

A condition monitoring system (CMS) is basically a tool that constantly keeps an eye on how a machine is doing, almost like giving it regular health check-ups while it's running. Instead of waiting for something to break, the system uses sensors to gather information during normal operation and looks for anything unusual—such as odd vibrations, higher temperatures, strange noises, pressure changes, or electrical irregularities. In simple terms, it helps detect early warning signs so problems can be fixed before they turn into breakdowns or costly downtime. [20].

Figure 2 shows that generally, the components forming in hydropower systems are Reservoir, Intake, Dam, Surge tank or forebay, Penstock, Turbine, Shaft, Generator, Transformer, Draft tube, Tail race, and Spillways. All these components are subject to constant use and suffer from faults and degradation that may hinder or interrupt normal operation. Hence, CMS and inspection of these systems must be carried out to prevent, detect, and mitigate possible faults that appear during operation [20].

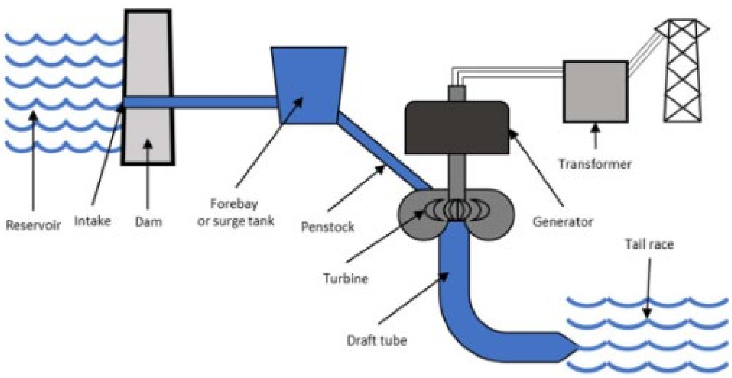

Figure 2. Components of a hydropower system

The data collected from the experiment or 'try and error' is then analysed by software that enables it to detect early signs of wear, imbalance, misalignment, overheating, or abnormal loading long before these issues become serious enough to cause a downfall for the system to function well. This allows operators or engineers to schedule maintenance only when needed, prevent unexpected failures, and avoid costly shutdowns, making the system highly efficient and cost-effective. Compared to traditional maintenance methods—which depend on routine scheduled checks, operator experience, and reactive repairs after a fault occurs—condition monitoring provides far faster detection, greater accuracy, and continuous visibility into equipment health [21].

Traditional systems, for instance like checking the system when something goes wrong, often miss early warning signs because inspections are not frequent enough, and faults are only to be found after performance drops, damage occurs or something unexpected happens. In contrast, modern condition monitoring systems which are using IoT can alert operators immediately when a parameter deviates from normal ranges, allowing problems to be corrected at their earliest stage and improving both safety, efficiency and reliability [22].

5.0 CHALLENGES

5.1 Predictive Maintenance

The efficiency of hydro-turbine generators is significantly influenced by both the materials used in critical components and the quality of infrastructure implemented during installation. The turbine runner, shaft, and generator components must be manufactured from high-strength, anti-corrosion materials, such as stainless steel or specialized alloys, to minimize wear, cavitation, and mechanical losses over time. Gundabattini et al. [4] mention that the selection of high-quality materials in turbine and generator components can improve mechanical and electrical efficiency by 1–3% throughout the operational lifetime of a hydroelectric system.

In addition to material considerations, the stability and design of the physical base and civil works are crucial for maintaining turbine-generator alignment and minimizing vibration. Misalignment or structural instability, even by a few millimetres, can cause significant reductions in mechanical efficiency and accelerate wear on bearings and other moving components [23]. A well-engineered foundation ensures that dynamic and hydraulic loads, including water hammer and transient pressure fluctuations, are safely transmitted to the ground, preventing structural fatigue and prolonging operational reliability.

The dimensions and configuration of key infrastructure, particularly penstocks, play a pivotal role in determining the hydraulic efficiency of the system. Penstock length, diameter, internal roughness, and the number of bends and fittings directly affect frictional losses, commonly referred to as head losses, which reduce the effective water head delivered to the turbine. In the PLTA Saguling project, head losses of approximately 43–45 meters were observed due to long penstocks, leading to a reduction in actual power output by 10–15% compared to theoretical potential. Optimizing penstock dimensions to balance material cost and hydraulic efficiency is therefore essential, as undersized penstocks restrict water flow, while oversized components increase construction costs and impose additional structural demands. Furthermore, accurate accounting for net head — the usable water head after subtracting all hydraulic losses — is critical for predicting realistic system efficiency. The net head can be expressed as:

$$H_{net} = H_{gross} - \sum(head\ losses) \tag{3}$$

Syafiudin et al. [23] mention that failure to optimize infrastructure and material selection can lead to a significant deviation between theoretical and actual output, particularly in small- to medium-scale hydro installations, where total system losses may reduce overall efficiency to 50–60% of the theoretical potential.

Finally, long-term reliability, maintenance requirements, and operational stability are also closely linked to material and infrastructure quality. Components that are durable and well-supported reduce downtime caused by structural fatigue, corrosion, or mechanical failures, indirectly improving annual energy output. Syafiudin et al. [23] suggest that implementing structural monitoring and using high-quality materials can decrease maintenance-induced downtime by 5–10%, resulting in a 1–2% increase in annual efficiency. Collectively, these considerations demonstrate that careful optimization of materials, civil works, and infrastructure dimensions is essential for achieving high reliability and maximizing the efficiency of hydro-turbine generator systems.

5.2 Implementation of AI in Optimizing Efficiency and Control Systems

The efficiency of hydro-turbine generators is significantly influenced by both the materials used in critical components and the quality of infrastructure implemented during installation. The turbine runner, shaft, and generator components must be manufactured from high-strength, anti-corrosion materials, such as stainless steel or specialized alloys, to minimize wear, cavitation, and mechanical losses over time. Gundabattini et al. [4] mention that the selection of high-quality materials in turbine and generator components can improve mechanical and electrical efficiency by 1–3% throughout the operational lifetime of a hydroelectric system.

AI significantly enhances maintenance strategies in hydropower plants by providing early detection of faults and system degradation. Machine learning models analyse vibration signals, bearing temperatures, pressure fluctuations, and generator electrical signatures to identify abnormal patterns before failures occur [24]. This enables detection of issues such as cavitation, turbine blade erosion, bearing wear, and generator misalignment at an early stage. Deep learning–

based anomaly detection can also differentiate between normal operational variations and critical fault conditions more accurately than rule-based systems [25].

AI-driven predictive maintenance platforms use historical and real-time data to forecast the remaining useful life (RUL) of components and optimize maintenance schedules based on actual machine condition rather than time-based intervals [26]. This minimizes unplanned downtime, reduces repair costs, and improves overall plant reliability [26]. Integration of predictive analytics with digital twins further strengthens fault diagnosis by comparing real operational data with simulated ideal behaviour [27].

6.0 CONCLUSION

The efficiency of hydro-turbine generator systems is governed by a complex interplay of electrical, mechanical, structural, and technological factors. To achieve optimal performance, it is critical to minimize electrical losses—such as copper and core losses—through the selection of high-efficiency generator architectures like the DFIG or FSC. This must be complemented by the selection of turbine designs, such as Francis or Kaplan units, that are precisely matched to the site's hydraulic head and flow characteristics. By utilizing variable-speed technology, operators can ensure the system remains within its peak efficiency zone on the turbine "hill chart," even amidst fluctuating environmental conditions.

The integration of modern control technologies is equally vital for maximizing reliability and minimizing operational downtime. Moving away from traditional, schedule-based maintenance, the industry is increasingly adopting predictive maintenance strategies powered by AI-driven diagnostics and real-time condition monitoring. These systems utilize a network of sensors to create a "Digital Twin" of the plant, allowing for the detection of subtle anomalies in vibration or temperature that signal impending component failure. This proactive approach not only extends the lifespan of the equipment but also ensures that the plant provides a stable and resilient contribution to the power grid.

Looking ahead, advances in digital technology and material science promise to significantly enhance hydropower efficiency, even as the industry grapples with current challenges like aging infrastructure and the high cost of specialized materials. High-strength, corrosion-resistant alloys and advanced computational fluid dynamics (CFD) are reshaping how turbine runners are designed to handle extreme stress. Further interdisciplinary studies, grounded in both experimental data and advanced simulations, are essential to refine these models. Ultimately, the future of hydropower lies in its transformation into a highly flexible, digitally optimized asset capable of meeting the dynamic demands of a renewable-heavy energy landscape.

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