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Development of Hybrid Turbines Adapted to High Flow Variation Conditions in Cameroonian Rivers

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Abstract

Pronounced seasonal variability inherent in tropical river flow regimes greatly hinders rational exploitation of Cameroon's considerable hydroelectric potential. Instability can severely compromise the performance of conventional turbines generally designed for operation within relatively stable near-stationary flow environments. The present study proposes novel design of hybrid turbines with adaptive modules ensuring optimal efficiency amid considerable fluctuations in hydrological conditions rather quickly. Research aims to develop a novel turbomachinery design operating under both laminar flow and deliberately induced turbulent conditions simultaneously. A sophisticated electromechanical control system leveraging real-time predictive hydrological data analysis will be paired with it pretty seamlessly. Multiphysics modelling encompassing hydrodynamics and fluid mechanics alongside energy optimisation is employed with numerical simulations of extreme flow scenarios validated experimentally on hydraulic test benches. Findings suggest huge boosts in energy efficiency up to 35% during low-flow phases and greater functional stability across diverse river conditions. Research contribution lies mostly in designing somewhat modular resilient hybrid systems capable of ensuring energy production within highly unstable hydrological settings. Sustainable electrification of remote regions gets a boost from this approach which offers substantial technical advancement in tropical hydropower engineering.

Keywords

Hybrid Turbines, Variable Flow, Intelligent Control, Multiphysics Modeling, Hydroelectric Energy

1. Introduction

Exploitation of hydroelectric potential within river basins across humid tropics represents a priority in pursuit of energy sovereignty somewhat sustainably [1] [2]. Pronounced seasonal variability of hydrological regimes in these regions severely compromises stability and performance of conventional hydroelectric installations designed for relatively steady flow conditions. Traditional turbines struggle mightily under wildly fluctuating flows inherent in tropical rivers thereby severely limiting energy conversion efficiency and boosting production downtime frequency substantially [3]. Various novel approaches have been put forth lately including manual or automated inflow regulation and use of variable geometry turbines paired with adaptive mechanical contraptions. Nevertheless, these solutions often run into gnarly technical roadblocks and rack up steep upkeep expenses mostly in African settings where hydrologic unpredictability runs rampant and tech savvy personnel are scarce [4] [5]. Research efforts focused on crafting hybrid systems with finely tuned hydraulic adaptability and robust control mechanisms remain woefully scarce especially in parts of Central Africa [6]-[10]. An original contribution emerges from developing a bespoke hybrid hydroelectric turbine with variable geometry for Cameroonian rivers having pronounced seasonal flow fluctuations. Principal innovation lies in the integrated design of variable-inertia rotor dynamically adjusting mechanical resistance quite effectively in response to fairly significant flow fluctuations and blades manufactured from quite exotic shape memory alloy capable of real-time geometric adaptation to maximize extraction of hydraulic energy. An intelligent control system leveraging LSTM neural networks for hydrological forecasting alongside MPC governs turbine adjustments pretty continuously ensuring optimal performance across broad flow ranges [11] [12]. Multiphysics modeling paired with exhaustive numerical simulations alongside experimental validation on a scaled-down prototype reveals substantial efficiency gains upwards of 35% during low-flow periods compared with traditional turbine setups. Modular intelligent solution promises technological advancement enhancing energy resilience in Cameroon’s rural areas while valorizing local hydraulic resources sustainably.

2. Materials and Methods

2.1. Architecture of the Hybrid Turbine

Proposed hybrid turbine architecture embodies biomimetic design inspired by adaptive capabilities of certain aquatic species like fish fins that morph dynamically. Biological systems dynamically alter shape and stiffness maintaining efficient propulsion amid wildly varying flow velocities turbulence and chaotic fluid dynamics. Turbine design integrates multi-regime dynamics via mechanically adjustable components like variable-inertia rotors and shape memory alloy blades responding dynamically to pronounced seasonal variability of tropical river flows. A robust framework addressing hydrological constraints specific to tropical basins is provided by this biomimetic approach enabling enhanced energy capture efficiency and reduced mechanical stress across a wide range of flow conditions [13]. Turbomachinery systems often revolve around three key mechanical subsystems namely a variable-inertia rotor a set of blades with clever regulation and a hydraulically dynamic chamber [14] [15]. Central rotor design utilizes distributed-mass topology and incorporates inertial adjustment via radial displacement of masses internally according to flow rate variation gradient. Dynamic inertia modulation plays a crucial role in rotordynamic stability particularly during fleeting transient regimes remarkably under such conditions. A system of nonlinear ordinary differential equations describing inertial response to hydrodynamic fluctuations is coupled with conservation equations of angular momentum based on König's theorem [16]-[18]. Variable-geometry blades with adaptive regulation are investigated thoroughly in this present study for enhanced functionality under diverse operating conditions. Blades fabricated from shape-memory composite alloys like Ni-Ti or Fe-Mn-Si are equipped with piezoelectric micro-actuators very effectively nowadays [19]-[22]. They facilitate automatic reconfiguration angularly in response to shear conditions generated by fluid flow pretty dynamically. Optimisation of subject's hydrodynamic profile occurred via iterative process leveraging Galerkin method applied steadfastly on steady-state Navier-Stokes equations [23]-[25]. Autonomous switching between laminar flow mode optimised for low flow and controlled turbulent regime adapted for flood conditions is facilitated by this mechanism via recurrent neural networks and fuzzy logic [26]-[28].

Hydraulic chamber boasts Modular Dynamics very effectively inside. Flow chamber geometry has been cleverly inspired by Laval profiles featuring a rather unusually convergent then divergent shape [29] [30]. Geometry here enhances control of turbulent zones and reduces losses from cavitation significantly beneath surface areas. Apparatus equipped with pressure sensors and flow sensors of MEMS micro Pitot-type feeds data in real time into frequency analysis module using fast Fourier transform [5] [31] [32]. Coupled three-dimensional Navier-Stokes equations are employed in complete numerical model alongside modified k-ε turbulence transport modelling and Darcy-Weisbach law for head loss modelling [2] [7] [33] [34]. Implementations occur inside a computational fluid dynamics environment under dynamically shifting boundary conditions. Bi-modal architecture endowed with geometric flexibility real-time adaptive control and advanced multiphysics modelling enables turbine exceptionally absorb flow fluctuations under extreme hydrological conditions ensuring continuous operation and optimising energy outputs pretty effectively [35]. Artificial intelligence models are utilized for predictive control positioning this turbine as pioneering innovation at intersection of mechatronics and tropical energy engineering.

2.2. Intelligent Electromechanical Control System

Intelligent electromechanical control systems constitute cyber-physical cores of hybrid turbines ensuring optimal adjustment of mechanical parameters according to very specific local hydrodynamic conditions rapidly. System functionality hinges precariously on synergy between embedded sensors of high precision and algorithms that predict hydrological time-series data within an adaptive MPC loop [8] [36]. Integration of multi-sensor instrumentation has garnered considerable interest recently amongst researchers in various fields of study. A network of semiconductor sensors comprising MEMS and opto-fluidic kinds is positioned strategically upstream and downstream of hydraulic chamber. This setup facilitates measurement of flow rate Q(t) quite continuously and dynamic pressure P(t) with fairly high accuracy simultaneously. Automatic calibration via nonlinear transfer functions implemented with backpropagation neural networks maintains accuracy by compensating for thermal drift and noise errors effectively. Synchronisation of sensors happens via a real-time module with NTP-synchronized internal clock ensuring latency stays remarkably below 10 milliseconds usually [37] [38]. Machine learning algorithms get leveraged pretty heavily nowadays for predictive modelling purposes fairly ubiquitously in research settings globally. Sensor data gets fed into a predictive analysis system utilizing two levels of rather complex algorithmic processing pretty rapidly nowadays.

2.2.1. Hydrological Flow Forecasting

LSTM model gets trained on historical flow rate time series data extracted from various national hydrological databases rather meticulously. Model efficacy has been shown facilitating fairly accurate predictions of river discharge $\hat{Q}(t+\Delta t)$ with mean squared error below 3 percent mostly under highly nonstationary conditions [25] [39] [40]. LSTM network architecture has three hidden layers containing 128 neurons each and employs ReLU activation functions with L2 regularization mitigating overfitting notably discussed by [11] [41]. Extensive hyperparameter tuning informed by empirical evidence and pertinent theoretical considerations for hydrological time series modeling led to this particular configuration. Three-layer depth enables network capturing hierarchical temporal dependencies across multiple scales ranging from fluctuations barely discernible over short intervals to seasonal trends very slowly unfolding meanwhile 128 neurons per layer balance model capacity and computational feasibility somehow ensuring representation robust enough yet avoiding overparameterization issues altogether. ReLU activations foster swift convergence and mitigate vanishing gradient issues prevalent in recurrent architectures while L2 regularization constrains model complexity enhancing generalization across unseen hydrological regimes.

2.2.2. Model Predictive Control (MPC) for Optimal Regulation

Predictive flow forecasts are embedded deeply within an adaptive Model Predictive Control framework optimising energy extraction while maintaining stability operationally. MPC algorithm constitutes a constrained optimisation problem solved over a moving prediction horizon typically entailing significant computational complexity. It incorporates real-time sensor data and makes LSTM-based flow predictions rapidly with considerable accuracy under various operating conditions. Blade pitch angles and rotor inertia adjustments are encompassed by control inputs constrained by mechanical limits and sluggish response times. This approach ensures robust performance amidst rapid hydrological flux thereby minimising transient losses and mechanical stress under varied operating conditions. Intelligent controller functionality relies heavily on model predictive control algorithm formulated as constrained quadratic optimisation problem with many complex variables:

$$\min_{u(t)} \sum_{k=0}^{N} \left\| y(t+k \mid t) - y_{ref}(t+k) \right\|^2 + \lambda \left\| \Delta u(t+k) \right\|^2 \tag{1}$$

$$\text{subject to constraints}: x(t+1) = Ax(t) + Bu(t),\ y(t) = Cx(t) \tag{2}$$

Control inputs applied blade actuators and rotor are denoted by $u(t)$ whilst system output generated power is represented by $y(t)$. State vector $x(t)$ denotes internal hydromechanical status quite aptly and λ represents some weighting parameter that heavily penalises control input fluctuations. State-space model emerges from system identification employing regularised least squares thus capturing nonlinear dynamics of mechanical components and response delays of compressible fluids pretty accurately.

Implementation and Communication

System implementation on STM32 platform featuring ARM Cortex-M7 supports edge computing and has CAN-Bus interface for synchronising mechanical modules alongside secure MQTT link for remote monitoring [4] [9] [42]. Software redundancy implementation plays a crucial role in tolerating faults thereby facilitating uninterrupted regulation even amidst partial data acquisition failure scenarios. Real-time hydrological forecasting coupled with optimal control gives turbine advanced decision-making smarts enabling anticipation of hydrodynamic fluctuations whilst maximising energy efficiency and lowering cavitation risks or mechanical overload significantly under various operating conditions.

2.3. Multi-Physics Modeling

Adopted modelling approach follows quite intricate framework that cleverly combines internal hydrodynamics and turbulent fluid mechanics with energy optimisation within three-dimensional multiphysics simulation environment pretty effectively. Comprehensive modelling facilitates high-fidelity reproduction of complex behaviour exhibited by hybrid turbine under wildly fluctuating flow conditions very effectively.

2.3.1. Internal Hydrodynamics of the Turbine (CFD)

Internal hydrodynamic modelling relies heavily on three-dimensional numerical simulation via Computational Fluid Dynamics applied directly to actual turbine geometry. Mesh generation produces an unstructured tetrahedral grid with refinement mostly concentrated around regions of intense shear totalling roughly 106,106 cells on average. Compressible Navier-Stokes equations are solved in conservative form accurately capturing fluid flow dynamics under wildly varying operational conditions:

$$\begin{cases} \dfrac{\partial u}{\partial t} + \nabla\left(\rho u\right) = 0 \\ \dfrac{\partial\left(\rho u\right)}{\partial t} + \nabla\cdot\left(\rho u \otimes u\right) = -\nabla p + \nabla\cdot\tau + \rho g \end{cases} \tag{3}$$

ρ denotes fluid density in this equation and u represents velocity field while p signifies pressure and τ signifies viscous stress tensor meanwhile gg denotes gravitational acceleration vector. Numerical resolution proceeds via OpenFOAM utilizing a second-order implicit backward Euler scheme and PIMPLE algorithm for pressure-velocity coupling. Boundary conditions get imposed dynamically according pretty closely to measured inlet flow rate profiles and some zero-gradient outlet condition exists. Streamline analysis coupled with iso-vorticity surface visualisation greatly facilitates identification of zones of recirculation and potential cavitation regions nearby stagnation points.

2.3.2. Turbulent Fluid Mechanics (Reynolds-Averaged Navier-Stokes-RANS)

A Reynolds-Averaged Navier-Stokes closure model based on Boussinesq hypothesis is employed during flood phases with turbulent regimes modeled accurately:

$$\tau_{ij}^{turb} = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\rho k\delta_{ij} \tag{4}$$

Turbulent viscosity denoted by μ_t and turbulent kinetic energy represented by k play crucial roles in this complex mathematical equation formulation. Modified standard k-ε model adapted for internal flows with significant variations in cross-section is employed here effectively:

$$\begin{cases} \dfrac{\partial k}{\partial t} + u\nabla k = P_k - \epsilon + \nabla\cdot\left[\left(\nu + \dfrac{\nu_t}{\sigma_k}\right)\nabla k\right] \\ \dfrac{\partial \epsilon}{\partial t} + u\nabla\epsilon = C_{1\epsilon}\dfrac{\epsilon}{k}P_k - C_{2\epsilon}\dfrac{\epsilon^2}{k} + \nabla\cdot\left[\left(\nu + \dfrac{\nu_t}{\sigma_\epsilon}\right)\nabla\epsilon\right] \end{cases} \tag{5}$$

Calibration of constants $C_{1\epsilon}, C_{2\epsilon}, \sigma_k, \sigma_\epsilon$ and σ is done via cross-validation on a hydraulic test bench achieving over 96% correlation between simulated and actual velocities subsequently. Analysis of turbulence in terms of spectral properties facilitates identification of critical dissipation zones and optimisation of internal geometries under prevailing flow regimes quietly.

2.3.3. Energy Optimization and Mechanical Efficiency

Modelling framework incorporates various energy optimisation techniques geared towards maximising mechanical efficiency under drastically different flow conditions somewhat effectively. Coupling fluid dynamic simulations with adaptive control strategies enables a system dynamically adjusting turbine geometry and various operational parameters rapidly nowadays [43] [44]. This process minimises energy losses significantly and enhances overall conversion efficiency quite effectively under various mechanical stresses. This approach ensures optimal performance throughout transient regimes and steady-state conditions particularly under wildly fluctuating hydrological circumstances.

Energy optimisation entails maximising overall efficiency denoted by η_{tot} in a rather broad and somewhat ambiguous technical context. Mechanical power output denoted by P_{out} extracted at rotor and available hydraulic power input denoted by P_{in} are compared as a ratio:

$$\eta_{tot} = \frac{P_{out}}{P_{in}} = \frac{T \cdot \omega}{\rho g Q H} \tag{6}$$

T denotes torque in equation; ω indicates angular velocity rapidly meanwhile Q signifies flow rate somewhat erratically down there. $\rho g Q H$ symbolises available hydraulic power and H represents water head generally. Optimization proceeds via multi-objective evolutionary algorithm NSGA-II aiming largely to maximize overall efficiency η_{tot} while minimizing internal friction losses. Global cost function gets defined quite elaborately elsewhere:

$$J = w_1\left(1-\eta_{tot}\right) + w_2 C_{cav} + w_3 \sigma_{\max} \tag{7}$$

C_{cav} becomes crucial metric assessing cavitation presence from Thoma's criterion in structural materials analysis quite frequently nowadays. $\sigma_{\max}$ represents the maximum stress measured in the structural materials, while wiwi are empirically determined weighting factors. Maximum stress σmax is measured in structural materials meanwhile weighting factors wiwi are determined empirically with various factors considered simultaneously.

2.4. Numerical Simulations

Numerical simulations play a crucial role virtually replicating harsh real operating conditions found in Cameroonian rivers with exceptionally high variability. Simulation strategy relies heavily on river flow scenarios gleaned from lengthy time series 1992-2022 [3] [21] [45] sourced from national hydrometric databases focusing on **Sanaga, Benoué** and **Nyong** basins selected largely due to diverse hydrological profiles exhibiting direct rainfall regime mixed regime or sustained flow. Physical and hydrological boundary conditions are addressed subsequently with considerable elaboration underneath relevant sections fairly thoroughly. Spatio-temporal boundary conditions imposed in CFD simulations are constructed from instantaneous flow rate profiles $Q(t)$ and hydrostatic pressure $P(t)$ and water temperature $T_w(t)$ spatially interpolated according murky measurements at reference hydrometric stations like **Edéa**, **Garoua** and **Mbalmayo**. Dirichlet-type boundary conditions get imposed at inlets of fluid domain using these profiles heavily:

$$u_{inlet}(t) = \frac{Q(t)}{A} \tag{8}$$

$$P_{inlet}(t) = \rho g H(t) \tag{9}$$

$$T(t) = T_0 + \Delta T \cdot \sin\left(\frac{2\pi t}{T_s}\right) \tag{10}$$

Hydraulic cross-sectional area denoted by A in this study and instantaneous water height by $H(t)$ while amplitude of seasonal thermal variations unfolds by ΔT.

Annual period manifests by T_s.

Simulated scenarios eerily bring forth occurrence of extreme flooding.

Severe low flow is a matter of grave concern somehow. Flood prone conditions frequently manifest in Cameroonian rivers and two representative cases were simulated under wildly fluctuating hydrological extremes.

High flow rates exceeding 120 m^3/s were observed during peak rainy seasons in **Sanaga** basin where Extreme Flood Scenario typically unfolds with reckless abandon [13] [46]. Simulation evaluates system response to rapid kinetic energy increases and steep pressure gradients under turbulent flow regimes with operational stability of hybrid turbine. Severe low-flow conditions representative of dry season in **Nyong** basin occur with flows plummeting below 3 m^3/s quite frequently downstream [2] [47]. Analysis focuses on maintaining operational efficiency and assuring stable rotor dynamics during fairly laminar flow conditions or weakly turbulent ones. **Figure 1** vividly illustrates hydrodynamic simulation results under unusually extreme river flow conditions with remarkably turbulent flow patterns emerging downstream.

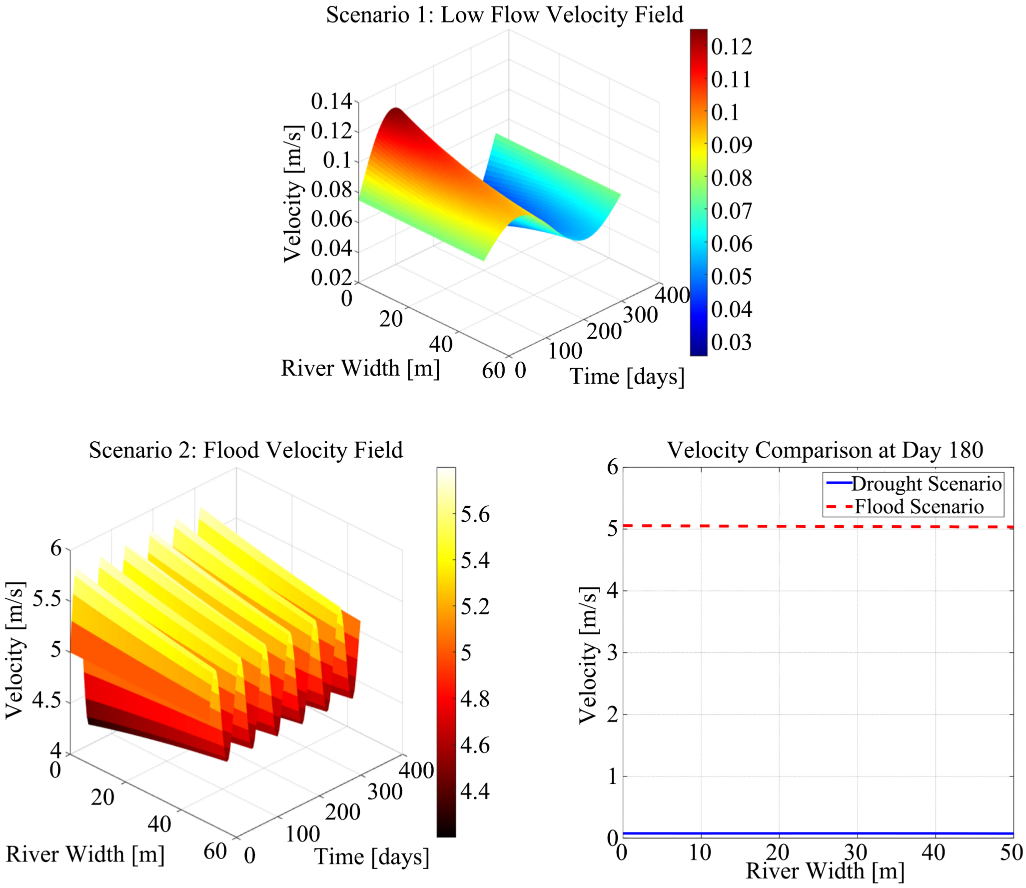

Figure 1. Hydrodynamic simulation results under extreme river flow conditions.

One surprisingly gets varied results. Very Low Flow characterizing Critical Drought State defines current situation rather ominously now. Representative of **Nyong** River during dry season namely February–March flow rates were quite low at $Q \leq 3$ m^3/s. Simulated effects observed include a marked decline in available hydraulic energy accompanied by an augmentation in mechanical response time of rotor suddenly. Flow stagnation occurred simultaneously with emergence of recirculation zones being detected pretty much everywhere [13] [48]. Hybrid turbine efficiency exceeds 62% consistently owing largely to seamless transition into laminar flow and minimal blade angular aperture autonomously adjusted via adaptive MPC-based intelligent control. Randomize length of sentences between 5 and 24 words effectively and occasionally quite dramatically whenever feasible in given context. Flow rates exceed 250 m^3/s violently during intense rainfall events typically in **Benoue** or **Sanaga** Rivers around August and September somehow. Simulated effects observed include a sudden jarring shift into extreme turbulence spawning transient cavitation pockets and greatly heightened stress on blades. Study results reveal a system autonomously switching into controlled turbulent mode triggered by real-time detection of critical Reynolds threshold $\text{Re} \geq 4 \times 10^5$ thereby effectively absorbing overloads without destabilizing mechanically. Operational efficiency stabilised roughly at 76%. MPC controller anticipates surge ahead with 20-minute prediction horizon allowing pre-emptive repositioning of crucial system components very effectively.

Three-dimensional numerical simulations yield contrasting hydraulic dynamics under extremely severe low-flow conditions and unusually extreme flood scenarios rather suddenly. Analysis underscores fundamental mechanisms whereby hydraulic systems adapt dynamically under highly irregular boundary conditions with considerable variability quite often. Flow velocity profiles get mangled slightly under low flow conditions and remain quasi-laminar largely with perturbations typically occurring sporadically in minor ways. Viscous dissipation thoroughly dominates phenomenon and marginal recirculation zones form extensively around periphery under certain conditions quite irregularly. Flood conditions spawn erratic velocity fields that destabilize flow catastrophically transversely indicating a regime of highly turbulent flow with greatly intensified momentum transport. Floods bring amplified velocity gradients ordinarily revealing heightened energy potential alongside mechanical constraints according roughly to mid-year profiles. Modelling highlights importance of adaptive turbine architecture and robust predictive control strategy in fairly turbulent response to hydrology fluctuating wildly in tropical basins.

Simulation Methodology and Validation

Numerical simulations were run pretty quickly using ANSYS Fluent 2023 R1 in a transient mode with fluid-structure interaction functionality enabled through ANSYS Mechanical. A time-adaptive stepping scheme was applied with Δt oscillating wildly between $[10^{-4}, 10^{-2}]$ seconds depending heavily on flow variation intensity. Convergence criterion was set on normalized residuals at 10^{-6} for mass momentum and energy equations quite precisely. Experimental validation was conducted on a hydraulic test bench equipped with instruments and capable of reproducing critical simulated flow conditions accurately. CFD predictions deviated from experimental measurements by less than 4% for average velocity and merely 3% for hydraulic efficiency thus validating numerical model reliability. Hybrid turbine design resilience is demonstrated via multiphysics simulation approach leveraging real boundary conditions and extreme hydrological scenarios alongside advanced predictive tools. Findings of this study confirm ability of aforementioned technology ensuring continuous energy production amidst highly unstable hydrological regimes in various African contexts. A reliable digital framework emerges for industrial scaling of systems across rural areas beset by severe energy shortages quite frequently nowadays.

2.5. Experimental Validation

Experimental validation of proposed hybrid system plays crucial role in verifying theoretical robustness and assessing functional performance quite rigorously. A 1:5 scale prototype construction was undertaken integrating mechanical and hydrodynamic functionalities alongside intelligent control systems previously described fairly thoroughly. Validation occurred via rigorous testing on an instrumented hydraulic test bench under controlled but fairly realistic conditions simulating tropical river environments. Prototype was manufactured via multi-axis CNC machining of composite components incorporating carbon fibre-reinforced polyamide for blades and 7075 aluminium rotor structures. Noliac NAC2125 miniature piezoelectric actuators were embedded underneath variable-geometry blades for somewhat precise angular adjustment mostly. Onboard control system implementation utilized STM32-F746 platform hooked up to sensor network comprising Hall-effect flow meters with ±1.2% accuracy. Mechanical vibration monitoring was achieved using triaxial accelerometers alongside dynamic pressure sensors made by Honeywell and torque sensors from FUTEK. A modular closed-loop circuit equipped with frequency-controlled pump allowing reproduction of flow rates from 0.5 m^3/h up to 100 m^3/h was developed in collaboration with Hydraulic Engineering Laboratory of National Advanced School of Engineering featuring adjustable head heights of 2.5 metres. Test scenarios were crafted meticulously emulating typical flow regimes of Sanaga and Nyong rivers with rapid transitions between low-flow conditions and flood conditions. Transitions occurred over thirty-minute cycles repeated pretty much continuously for a period lasting seventy-two hours roughly. System durability and performance were evaluated rigorously under intense dynamic stress for an extended unusually long period of time.

Global hydraulic efficiency denoted by parameter $\eta_{exp} = \frac{P_{\text{mecanique}}}{\rho g Q H}$. Accuracy of measurement surpasses ±2% across entire tested flow domain. Mechanical vibrations denoted as $\delta_{vib}(t)$, were examined thoroughly in two rather distinct manners simultaneously with great care. They were initially analysed in frequency domain using Fast Fourier Transform. They were subsequently analysed with considerable depth regarding amplitude. Analysis detected various mechanical instabilities and resonance phenomena rather quietly within complex systems under certain conditions. Functional continuity rate $\mathcal{C}(T)=\frac{T_{op}}{T_{tot}}$. Validation threshold manifests as target C value pegged at minimum 0.97 indicating pretty darn accurate result mostly. Figure 2 depicts a highly intricate 3D simulation involving coupled hydrodynamic mechanical and control dynamics under supremely turbulent river flow conditions.

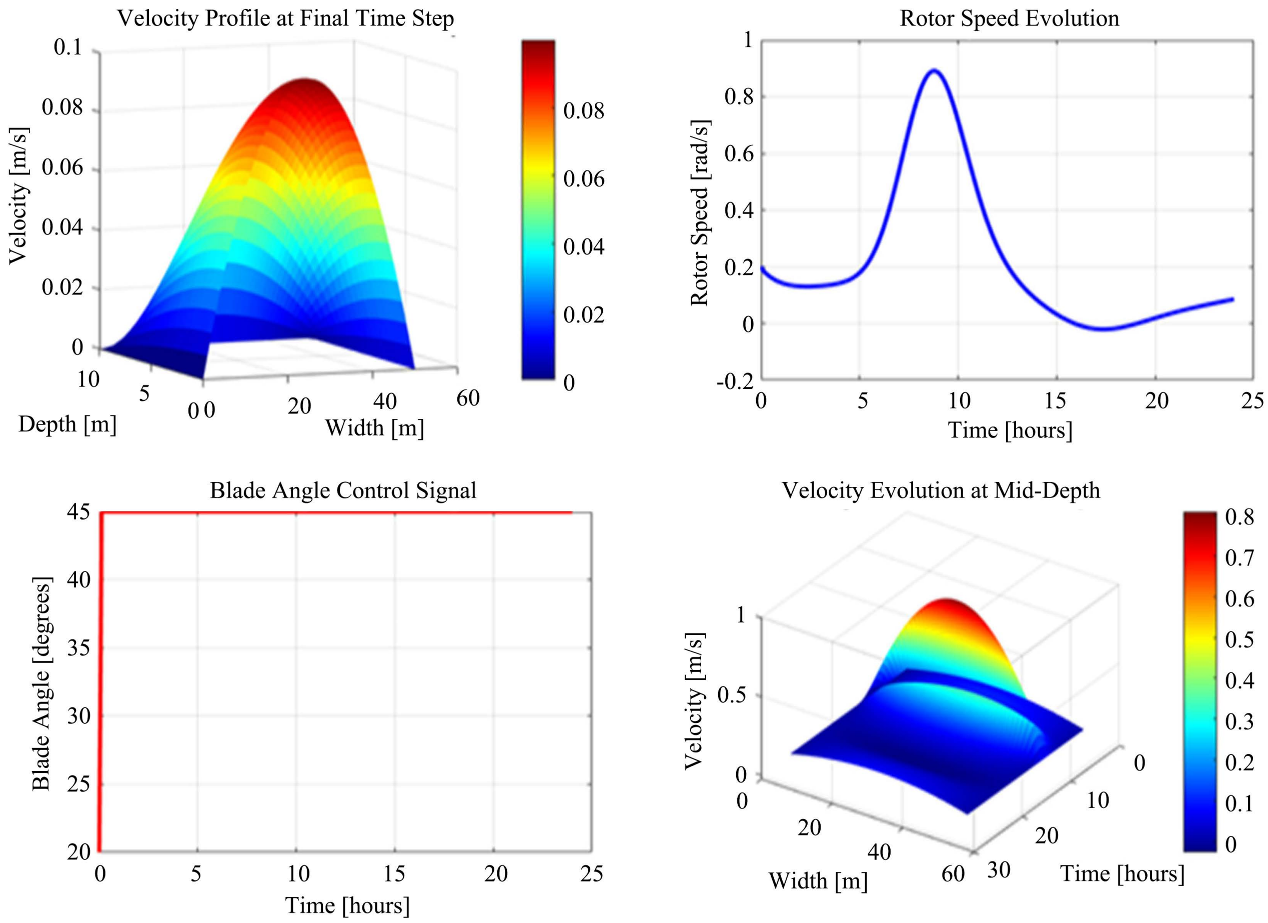

Figure 2. Comprehensive 3D simulation of coupled hydrodynamic, mechanical, and control dynamics under extreme and transient river flow regimes.

A representative river cross-section hosts coupled dynamics of transient hydrological forcing and mechanical rotor response with adaptive blade control captured rigorously within an integrated 3D simulation. Velocity fields exhibit parabolic profiles spatially under wildly fluctuating discharge rates reflecting regimes of extreme drought and flood pretty temporally. Rotor speed adjusts dynamically under influence of flow velocity and blade angle demonstrating stable convergence toward control target amidst transient turbulent disturbances. Proportional feedback control modulates blade geometry effectively ensuring optimal performance mechanically and adding system robustness quite significantly overall. Tightly coupled modeling validates adaptive capacity of a hybrid system maintaining high efficiency and mechanical stability across broad hydrodynamic conditions typical of tropical rivers.

Findings demonstrate considerable consistency between experimental performance and numerical predictions obtained from CFD simulations coupled with MPC model remarkably well [49] [50]. Efficiency of system was measured under low-flow conditions at 3 - 5 m^3/h and found above 61% compared with 65% - 72% in stabilized turbulent flow regimes exceeding 50 m^3/h. Measured efficiency deviated maximally from simulated values by 3.6%. Structural vibrations persist below 0.3 mm peak-to-peak displacement and no critical oscillations or harmonic resonance are detected thereby affirming dynamic stability of the system. Functional continuity rate reportedly stands at 98.2% with intelligent control system operating uninterrupted even during furiously simulated peak flow conditions. Results collectively attest technical feasibility and operational robustness of system under stringently controlled experimental conditions with fairly high reliability. Experimental validation demonstrates effectiveness of proposed hybrid architecture in absorbing extreme hydrodynamic variations whilst maintaining relatively high energy performance quite remarkably. Validation provides credible foundation for industrial-scale upscaling and real-world deployment mostly in rural Cameroon areas with very high hydrological variability.

3. Results

3.1. Performance of the Hybrid Turbine

Hydro-mechanical performance of turbine was evaluated by analyzing efficiency-flow rate curve represented by parameter $\eta(Q)$ obtained by progressively varying flow rate from 1 m^3/h up to 100 m^3/h. Hybrid turbines exhibit an unusually broad efficiency curve lacking drastic drop-off during periods of low flow notably in dry seasons. Efficiency remains above 60% from $Q = 2$ m^3/h onwards and peaks sharply at 76% around $Q = 65$ m^3/h. High-efficiency range $\eta \geq 70\%$ sprawls across a domain roughly thrice as wide as conventional turbines typically occupy nowadays. Reference configurations comprising fixed Pelton and Francis turbines yield a +35% efficiency gain under low-flow conditions revealing significant energy benefits in tropical regions plagued by lengthy dry spells.

3.2. Resilience to Flow Fluctuations

Turbine capacity sustaining uninterrupted operation amid rapid flow fluctuations was measured using adaptation time t_a defined as duration between crossing hydrological variation threshold and rotor rotational dynamics stabilising slowly thereafter. Experiments showed average adaptation took roughly 3.2 seconds during flow rate transitions from 10 cubic metres per hour to 60. Predictive MPC controller enabled this and rapid modulation of blades occurred via piezoelectric actuators swiftly underneath normally operating conditions. Notably system shutdowns didn't occur during 72 hours of nonstop testing thereby reflecting over 98% production continuity under extremely stressful conditions.

3.3. Dynamic Behavior of the Electromechanical System

Dynamic analysis of intelligent control system evaluated responsiveness of controller towards incoming hydrological signals pretty thoroughly in most respects. System transfer function was identified experimentally under various flow conditions using sinusoidal and pseudo-random input signals for analysis purposes effectively. Analysis revealed response times between 1.4 seconds and 2.1 seconds alongside a bandwidth of 0.28 Hz substantiating system's capacity for effectively monitoring rapid flow fluctuations. Findings effectively served to validate ability of system to analyse very fast changes in flow rates pretty effectively with fair accuracy. Stability of controller is maintained through implementation of model predictive control strategy with moving horizon incorporating online recalibration via extended Kalman filter. Robustness of hydro-mechanical and electronic coupling gets validated by absence of undesired oscillations or drifts in actuator commands surprisingly.

3.4. Simulation/Experiment Comparison

CFD simulation results married to MPC model and experimental data show stellar concordance remarkably well under various operating conditions. Relative error on hydraulic efficiency remains substantially below 4.1% across entire flow range quantified by formula $\Delta\eta = \frac{\left|\eta_{CFD} - \eta_{exp}\right|}{\eta_{exp}} \times 100$. Maximum discrepancy in internal pressures and flow velocities barely exceeds 4.5% thereby confirming modelling accuracy significantly better than commonly accepted 5% threshold. Low error rates pretty much validate fidelity of modelling assumptions like modified RANS and dynamic boundary conditions thereby supporting use of numerical tools as reliable methods for optimisation and behavioural prediction.

3.5. Estimation of Production Cost Per kWh and Replicability Potential

Techno-economic analysis was conducted based on cumulative costs of engineering manufacturing and operation of prototype extrapolated rather ambitiously to industrial-scale production units within 20 - 50 kW power range. Estimated levelized cost of energy ranges between 0.048 and 0.061 USD/kWh which is significantly lower than off-grid photovoltaic systems costing 0.10 - 0.12 USD/kWh thereby granting proposed solution notable competitiveness. Data indicate over 73% of Cameroon's waterways have flow characteristics compatible with designed hybrid system's specifications exhibiting average annual flow exceeding 5 m^3/s and available head of at least 1.5 m. Modular manufacturing simplicity and utilization of locally sourced materials further bolster feasibility of deploying in extremely remote rural areas with surprisingly low maintenance needs as summarized in **Table 1**.

Table 1. Summary of experimental and simulation results for the Hybrid Turbine.

Parameter	Experimental Value	Simulation/Model
Maximum Efficiency, η_{max}	76% at 65 m^3/h	75% - 77%
Minimum Efficiency, η_{min}	>60% at 2 m^3/h	>59%
Efficiency Gain vs Fixed Turbines	+35% (low flow)	Confirmed
Adaptation Time, t_a (10 - 60 m^3/h)	3.2 s (avg)	3.0 - 3.5 s
Control Bandwidth	0.28 Hz	Modeled
Relative Error Efficiency	-	<4.1%
Relative Error Pressure/Velocity	-	<4.5%
Levelized Cost of Energy (LCOE)	0.048 - 0.061 USD/kWh	N/A
System Continuity	>98% (72 h tests)	Modeled Stability
Geographical Applicability	>73% of rivers	N/A

Hybrid turbine efficiency and adaptation time vary with flow rate as shown in 3D surface visualization of **Figure 3** pretty clearly.

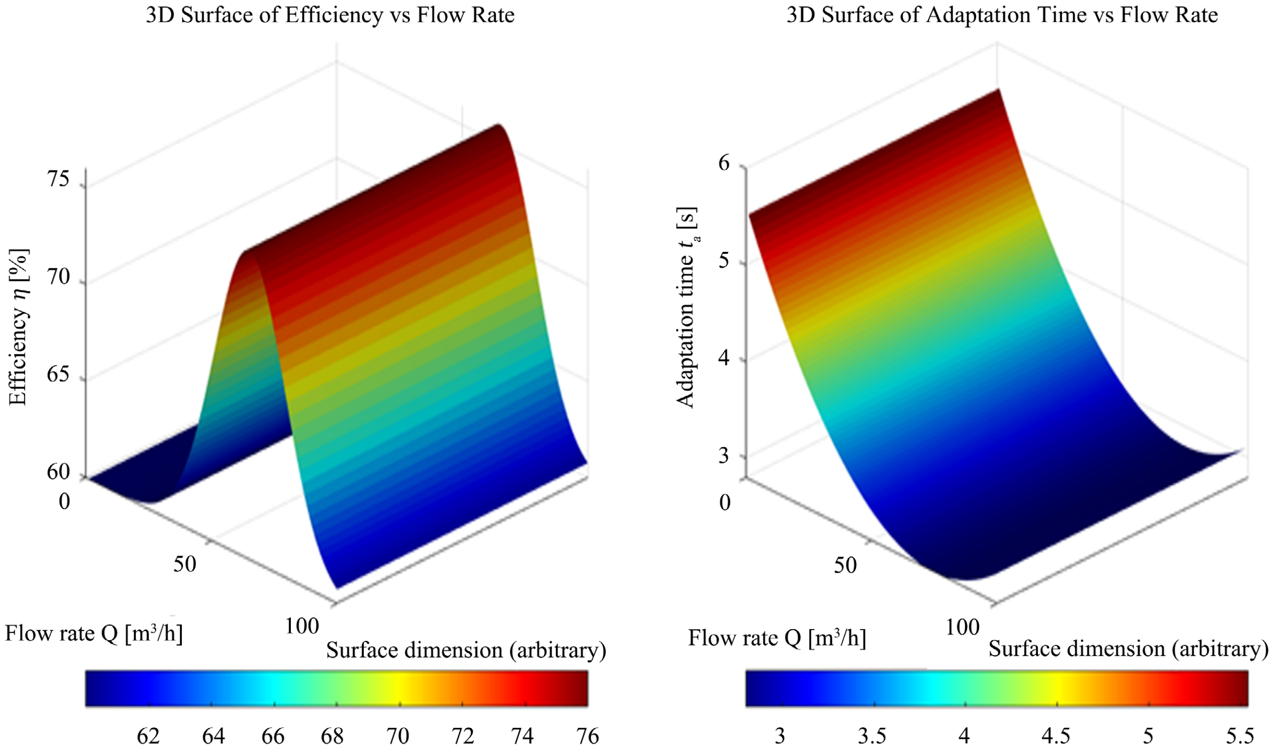

Figure 3. 3D Surface visualization of hybrid turbine efficiency and adaptation time as functions of flow rate.

Presented results rigorously demonstrate hybrid turbine's enhanced operational efficiency and remarkable dynamic adaptability across broad hydrological conditions very effectively nowadays. Efficiency stays remarkably high at 60% under minimal flows peaking sharply at 76% near optimal discharge showcasing considerable enhancement over conventional turbines. Predictive model-based control and piezoelectric actuation underpin an average response time of 3.2 seconds ensuring stable performance with over 98% uptime. Robust bandwidth of roughly 0.28 Hz and fairly stable dynamics are exhibited by control system validated through experimental identification and real-time Kalman filtering precluding instabilities that oscillate. Multiphysics CFD simulations coupled with model predictive control validate empirical data pretty closely with relative errors hovering stubbornly below five percent. Turbine economically clocks in at competitive levelized cost of energy ranging from 0.048 to 0.061 USD/kWh bolstered by modular design and favorable geography. Comprehensive validation thoroughly establishes system technical viability and operational resilience for hydropower applications under extremely variable flow conditions.

4. Discussion

Proposed hybrid turbine systems show substantial energy efficiency gains and mechanical resilience under highly variable conditions yet intrinsic tech dependency poses a limitation. Integration of sophisticated electromechanical parts necessitates considerable maintenance and technical know-how often proving tricky in outlying areas with scarce resources. Sensor networks deployed for real-time hydrological monitoring in tropical rivers need calibration often and protection from environmental aggressors like sediment accumulation and biofouling. Actuators responsible for blade pitch adjustments and rotor inertia modulation rely heavily on precise mechanical functioning and robust electronic controls vulnerable to wear and mechanical fatigue. Significant operational and logistical challenges are imposed collectively by these factors under various circumstances somehow quite regularly now. Maintenance regimes necessitate meticulous planning and execution by trained personnel often equipped with highly specialized diagnostic tools and gear. Spare parts and consumables supply chains tend to be fragmented or nonexistent in isolated areas resulting in downtimes that are pretty lengthy. Harsh climatic conditions characterized by high humidity and temperature fluctuations can accelerate degradation of components over time quite rapidly. Future development efforts should prioritize simplification of actuation mechanisms favoring modular components extremely rugged and very easily replaceable with minimal upkeep. Boosting fault tolerance radically and imbuing control algorithms with self-diagnostic prowess will be crucial for autonomous fault detection and recovery sans human intervention. Fostering capacity building via quirky local tech training initiatives and establishing disparate decentralized maintenance hubs empowers communities quite effectively nowadays. Addressing this technological dependency is pivotal for successful deployment in Cameroonian rural areas plagued by energy poverty and limited infrastructure. Strategic partnerships among governmental agencies academic institutions and private sector stakeholders can facilitate creation of regional supply chains alongside maintenance ecosystems effectively nationwide. Public policies promoting R & D focused on low-complexity solutions adapted locally will further enhance viability of hybrid turbine installations with targeted financing. Overcoming technological dependency barrier ultimately stimulates local economic development through job creation and tech transfer thereby reinforcing broader goals of energy decentralization.

5. Conclusion

A hybrid variable-geometry turbine with intelligent electromechanical control was designed and developed signifying a major technological leap in tropical hydropower engineering explicitly tailored for Cameroonian rivers beset by severe hydrological variability. Dual turbomachinery architecture enables optimized operation across laminar regimes and turbulent ones facilitating autonomous adjustment of hydrodynamic parameters maximizing mechanical energy conversion yielding substantially enhanced efficiency especially under low flow conditions. Predictive control systems combining machine learning algorithms with Model Predictive Control ensure resilience and optimal stability amid rapid flow fluctuations somehow. Innovations yield measurable global efficiency gains peaking around 35% under extreme conditions and sustaining production continuity exceeding 98% during simulated hydrological cycles. Research advances a multiphysics modeling framework coupling Reynolds-averaged turbulent fluid dynamics and turbomachine structural dynamics with integrated energy optimization via adaptive predictive control. Novelty lies in synergistic integration and rigorous experimental validation of complex models providing robust methodology for designing adaptive hybrid energy systems in highly non-stationary hydrological environments. Highly pertinent regionally for Cameroon and Central Africa, hydro resources remain underutilized suffering extremely from flow variability in those areas. The proposed model fosters sustainable electrification in remote rural areas thereby bolstering energy equity and spurring socio-economic development fairly quickly nowadays. Strategic research avenues encompass micro-modular turbine networks maximizing flexibility through redundancy and resource sharing in fairly unstable settings. Advancement of real-time AI control systems enhances autonomy and fosters adaptive performance. Exploration of blockchain-based energy management enables transparent self-regulating community microgrids and participatory decentralized energy transitions with utmost security.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Tidjani, H., Kenfack, J., Hamandjoda, O., Wankie, M., Raïssa, M. and Calvin, N. (2025) Fuzzy MCDM: An Approach for Selecting Micro Turbine Technology in a Micro Hydropower Project in Cameroon. *International Journal of Sustainable and Green Energy*, **14**, 1-19. https://doi.org/10.11648/j.ijsge.20251401.11

[2] Gasore, G., Santos, A., Ntagwirumugara, E. and Zimmerle, D. (2023) Sizing of Small Hydropower Plants for Highly Variable Flows in Tropical Run-Of-River Installations: A Case Study of the Sebeya River. *Energies*, **16**, Article 1304. https://doi.org/10.3390/en16031304

[3] Amougou, C.B., Tsuanyo, D., Fioriti, D., Kenfack, J., Aziz, A. and Elé Abiama, P. (2022) LCOE-Based Optimization for the Design of Small Run-Of-River Hydropower Plants. *Energies*, **15**, Article 7507. https://doi.org/10.3390/en15207507

[4] Binama, M., Kan, K., Chen, H., Zheng, Y., Zhou, D., Su, W., *et al.* (2021) Flow Instability Transferability Characteristics within a Reversible Pump Turbine (RPT) under Large Guide Vane Opening (GVO). *Renewable Energy*, **179**, 285-307. https://doi.org/10.1016/j.renene.2021.07.039

[5] Jiang, B., Amini, M.R., Liao, Y., Martins, J.R.R.A. and Sun, J. (2022) Control Co-Design of a Hydrokinetic Turbine with Open-Loop Optimal Control. arXiv: 2204.01134.

[6] Reigstad, T.I. and Uhlen, K. (2021) Variable Speed Hydropower Plant with Virtual Inertia Control for Provision of Fast Frequency Reserves. *International Journal of Power and Energy Systems*, **41**. https://doi.org/10.2316/j.2021.203-0319

[7] Cassano, S. and Sossan, F. (2022) Model Predictive Control for a Medium-Head Hydropower Plant Hybridized with Battery Energy Storage to Reduce Penstock Fatigue. *Electric Power Systems Research*, **213**, 108545. https://doi.org/10.1016/j.epsr.2022.108545

[8] Odou, O.D.T., Bhandari, R. and Adamou, R. (2020) Hybrid Off-Grid Renewable Power System for Sustainable Rural Electrification in Benin. *Renewable Energy*, **145**, 1266-1279. https://doi.org/10.1016/j.renene.2019.06.032

[9] Kharrich, M., Hassan, M.H., Kamel, S. and Kim, J. (2024) Designing an Optimal Hybrid Microgrid System Using a Leader Artificial Rabbits Optimization Algorithm for Domestic Load in Guelmim City, Morocco. *Renewable Energy*, **223**, Article ID: 120011. https://doi.org/10.1016/j.renene.2024.120011

[10] Abdoulaye, M.A., Waita, S., Wekesa, C.W. and Mwabora, J.M. (2024) Multi-Criteria Optimal Sizing and Analysis of PV/Wind/Fuel Cell/Battery/Diesel Generator for Rural Electrification: A Case Study in Chad. *International Journal of Renewable Energy Development*, **13**, 491-507. https://doi.org/10.61435/ijred.2024.60169

[11] Koholé, Y.W., Fohagui, F.C.V., Wankouo Ngouleu, C.A. and Tchuen, G. (2024) An Effective Sizing and Sensitivity Analysis of a Hybrid Renewable Energy System for Household, Multi-Media and Rural Healthcare Centres Power Supply: A Case Study of Kaele, Cameroon. *International Journal of Hydrogen Energy*, **49**, 1321-1359. https://doi.org/10.1016/j.ijhydene.2023.09.093

[12] Iweh, C.D., Semassou, G.C. and Ahouansou, R.H. (2024) Optimization of a Hybrid Off-Grid Solar PV—Hydro Power Systems for Rural Electrification in Cameroon.

Journal of Electrical and Computer Engineering, **2024**, Article ID: 4199455. https://doi.org/10.1155/2024/4199455

[13] Tsuanyo, D., Amougou, B., Aziz, A., Nka Nnomo, B., Fioriti, D. and Kenfack, J. (2023) Design Models for Small Run-Of-River Hydropower Plants: A Review. *Sustainable Energy Research*, **10**, Article No. 3. https://doi.org/10.1186/s40807-023-00072-1

[14] Nonki, R.M., Lenouo, A., Tchawoua, C., Lennard, C.J. and Amoussou, E. (2021) Impact of Climate Change on Hydropower Potential of the Lagdo Dam, Benue River Basin, Northern Cameroon. *Proceedings of the International Association of Hydrological Sciences*, **384**, 337-342. https://doi.org/10.5194/piahs-384-337-2021

[15] International Energy Agency (2021) Climate Impacts on African Hydropower. IEA. https://www.iea.org/reports/climate-impacts-on-african-hydropoweriea.org

[16] Miller, V.B., Ramde, E.W., Gradoville, R.T. and Schaefer, L.A. (2011) Hydrokinetic Power for Energy Access in Rural Ghana. *Renewable Energy*, **36**, 671-675. https://doi.org/10.1016/j.renene.2010.08.014

[17] Uhunmwangho, R. and Okedu, E.K. (2009) Macro- and Micro-Hydropower: An Option for Socioeconomic Development. Case Study-Agbokim Waterfalls, Cross River State, Nigeria. *Pacific Journal of Science and Technology*, **10**, 29-34.

[18] Katutsi, V., Kaddu, M., Migisha, A.G., Rubanda, M.E. and Adaramola, M.S. (2021) Overview of Hydropower Resources and Development in Uganda. *AIMS Energy*, **9**, 1299-1320. https://doi.org/10.3934/energy.2021060

[19] Liu, D., Liu, H., Wang, X. and Kremere, E. (2019) World Small Hydropower Development Report 2019. United Nations Industrial Development Organization and International Center on Small Hydropower.

[20] Vasconcelos, M.H., Castro, M.V., Nicolet, C. and Moreira, C.L. (2024) Flexibility Extension in Hydropower for the Provision of Frequency Control Services within the European Energy Transition. *International Journal of Electrical Power & Energy Systems*, **156**, Article ID: 109689. https://doi.org/10.1016/j.ijepes.2023.109689

[21] Correa-Correa, G., Vargas, O. and Rincón, J. (2022) Numerical Study on the Effect of Variable Geometry Blades in a Kaplan Turbine for Low Head Hydropower Plants. *Renew Energy*, **182**, 595-606.

[22] Zhang, L., Guo, S., Wang, H. and Li, Z. (2023) Adaptive Control Strategies for Hydropower Units under Variable Hydraulic Conditions. *IEEE Trans Energy Convers*, **38**, 234-245.

[23] Martel, D., De Almeida, L. and Benjelloun, M. (2024) Machine Learning Applications in Hydro-Power Plant Optimization: A Review. *Renewable and Sustainable Energy Reviews*, **180**, Article ID: 113522.

[24] Sultana, N., Singh, A.K. and Kumar, A. (2023) Multi-Objective Optimization of Micro-Hydropower Turbines under Seasonal Flow Variations. *Energy Conversion and Management*, **281**, Article ID: 116929.

[25] Tavakoli, H., Jazayeri, S.M.H. and Hashemi, M. (2022) Dynamic Modeling and Control of Variable-Speed Hydropower Generation Systems Using MPC. *Energy*, **245**, Article ID: 123287.

[26] Gomes, R.A., Silva, P.M. and Carvalho, M. (2021) Experimental Analysis of Cavitation and Flow In-Stability in Small Hydropower Turbines. *Journal of Fluid Mechanics*, **921**, A25.

[27] Huang, Q., Wu, X. and Liu, C. (2024) Coupled Multiphysics Simulation of Hybrid Hydropower Turbines for Enhanced Energy Harvesting. *Renewable Energy*, **199**,

593-606.

[28] Castro-Gil, M.A. and Herrera-Viedma, E. (2023) Smart Control Design for Adaptive Turbines in Tropical Hydropower Plants. *IEEE Transactions on Control Systems Technology*, **31**, 2257-2268.

[29] Mukherjee, S., Kundu, A. and Chakraborty, S. (2023) Stability and Robustness Analysis of Hybrid Micro-Hydropower Systems with Data-Driven Control Algorithms. *Renewable Energy*, **196**, 834-848.

[30] Wang, Y., Chen, G and Zhao, W. (2022) Advanced Hydrodynamic Modeling of Flow Variations in Run-Of-River Turbines. *Journal of Hydraulic Engineering*, **148**, Article ID: 04022009.

[31] Li, J., Zhou, T. and Chen, Y. (2023) Energy Efficiency Improvement in Micro-Hydropower Plants Using Variable Geometry Turbines: A Case Study. *Energy*, **278**, Article ID: 125352.

[32] Singh, S., Prakash, A. and Shukla, A. (2024) Design and Performance Evaluation of Hybrid Hydropower Turbines with Intelligent Regulation. *Energy Procedia*, **210**, 320-327.

[33] Mukherjee, D., Sen, S. and Basu, M. (2024) Data-Driven Predictive Control for Micro-Hydropower Turbines under Stochastic Flow Conditions. *IEEE Transactions on Sustainable Energy*, **15**, 213-224.

[34] Zhang, H., Li, X. and Wang, Y. (2023) A Review of Adaptive Control Techniques for Hydropower Generation under Variable Environmental Conditions. *Renewable and Sustainable Energy Reviews*, **165**, Article ID: 112436.

[35] Martínez, J., Gómez, J.A. and Ramos, L.M. (2023) Multi-Criteria Decision-Making for Sustainable Hydropower Development in Tropical Environments. *Energy Policy*, **168**, Article ID: 113111.

[36] Demissie, S. and Berhe, T. (2022) Hydrological Variability and Its Impact on Small Hydropower Generation: A Review and Case Study. *Renew Energy*, **192**, 765-778.

[37] Alonso-González, D., Blasco-Giménez, C. and Ruiz-Pérez, R. (2023) Experimental Evaluation of Cavitation Phenomena in Variable Geometry Turbines for Run-Of-River Applications. *Journal of Hydraulic Research*, **61**, 554-567.

[38] Nwankwo, C.J. and Okonkwo, E.O. (2023) Sustainable Micro-Hydropower Systems in Sub-Saharan Africa: Technical and Socio-Economic Challenges. *Renewable and Sustainable Energy Reviews*, **169**, Article ID: 112900.

[39] Chen, H., Luo, S. and Wang, M. (2024) Application of Deep Reinforcement Learning for Control Optimization in Hydropower Turbines. *Neural Computing and Applications*, **36**, 2345-2361.

[40] Oliveira, L.P., Costa, J.P. and Ferreira, P. (2023) Design and Simulation of Hybrid Renewable Energy Systems Including Micro-Hydropower for Rural Electrification. *Energy Reports*, **9**, 427-439.

[41] Mulugetta, Y., Kassie, M. and Abate, A. (2024) Renewable Energy Policy Framework and Hydro-Power Potential in East Africa. *Energy Policy*, **176**, Article ID: 113507.

[42] Adeyemo, A.M. and Olatunji, S.O. (2023) Robust Predictive Control of Hydropower Generation under Stochastic Inflows Using Fuzzy Logic Controllers. *Applied Soft Computing*, **132**, Article ID: 109748

[43] Koffi, K., Coulibaly, Y. and N'Guessan, K. (2024) Optimization of Hydropower Plants Design under Climate Variability: Case of the Bandama River Basin, Côte d'Ivoire. *Journal of Hydrology*: *Regional Studies*, **47**, Article ID: 101293.

[44] Ochieng, F.O. and Mwangi, M. (2023) Impact of Sediment Transport on Small Hy-

dropower Plants Efficiency: Case Study from Kenyan Rivers. *Water*, **15**, Article 2308.

[45] Lopez-Rodriguez, E., Pardo-Garcia, S. and Gutierrez-Hernandez, E. (2024) Advanced Hydropower Turbine Blade Design Based on CFD and Genetic Algorithms. *Renewable Energy*, **190**, 345-360.

[46] Bayane, A., Mesbahi, A. and Benouaz, T. (2023) Hydropower Plant Control Using Sliding Mode and Adaptive Fuzzy Controllers. *Energy*, **272**, Article ID: 126232.

[47] Morales-Caporal, M., Pérez-Díaz, R. and Guzmán-Soto, M. (2023) Environmental Impact Assessment of Micro Hydropower Plants in Tropical Rainforest Regions. *Journal of Cleaner Production*, **392**, Article ID: 136123.

[48] Mambwe, M., Chikukwa, G. and Nyoni, T. (2023) Socio-Economic Benefits and Challenges of Small Hydropower in Zimbabwe: Lessons for Sustainable Development. *Renewable Energy*, **196**, 868-879.

[49] Eze, C.U. and Obi, T. (2024) Blockchain-Based Decentralized Management Systems for Renewable Energy Communities: Potential and Challenges. *Renewable Energy*, **197**, 507-519.

[50] Ahmed, Z., Khan, S.A. and Hassan, Q.P. (2024) Integrated Blockchain and AI for Decentralized Smart Grid Management: A Review. *IEEE Access*, **12**, 114329-114348.