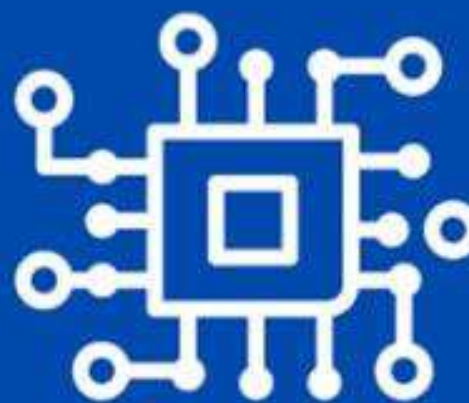




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INTEGRATED MATLAB/SIMULINK-SIMSCAPE MODELING AND PI-BASED CLOSED-LOOP CONTROL OF A MICRO-HYDROPOWER PLANT

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Annotation. This study presents the development of an integrated dynamic model of a micro-hydropower plant using the MATLAB/Simulink and Sims cape environments. The proposed model combines hydraulic, mechanical, control, and electrical subsystems within a single computational framework in order to investigate the transient and steady-state behavior of the energy-conversion process under variable operating conditions. The hydraulic subsystem represents the water source, conduit losses, and a variable-area flow restriction controlling water admission to the turbine. Hydraulic energy is converted into mechanical rotational power through a hydromechanical converter, while shaft inertia and angular motion are included to represent the dynamic response of the turbine-generator system. A proportional-integral (PI) controller regulates the shaft rotational speed by continuously adjusting the hydraulic restriction according to the difference between the reference and measured angular velocities. The mechanical subsystem is coupled to an electrical circuit through an electromechanical converter, and voltage, current, and generated electrical power are monitored as the principal electrical output parameters. The mathematical formulation includes hydraulic power, net hydraulic head, friction and local losses, turbine torque, shaft dynamics, PI control, electromechanical conversion, and overall energy efficiency. The developed model provides the capability to investigate variations in water discharge, hydraulic head, electrical load, valve opening, rotational speed, voltage, current, and power output. The proposed MATLAB/Simulink-Sims cape framework can serve as a practical numerical tool for analyzing, controlling, and optimizing micro-hydropower plants operating under variable hydraulic conditions and can subsequently be validated using laboratory or field measurements.

Keywords: micro-hydropower plant; MATLAB/Simulink; Sims cape; dynamic modeling; PI controller; hydraulic turbine; rotational speed; electrical power; renewable energy.

**MIKRO-GESNING MATLAB/SIMULINK-SIMSCAPE MUHITIDA
INTEGRATSIYALASHGAN MODELLASHTIRILISHI VA PI-REGULYATOR
ASOSIDAGI YOPIQ KONTURLI BOSHQARUVI**

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“Toshkent irrigatsiya va qishloq xo'jaligini mexanizatsiyalash muhandislari instituti” milliy tadqiqot universiteti

Annotatsiya. Ushbu tadqiqotda MATLAB/Simulink va Simscape muhitlaridan foydalangan holda mikro-GESning integratsiyalashgan dinamik modeli ishlab chiqilishi bayon etilgan. Taklif etilgan model o'zgaruvchan ish sharoitlarida energiya aylantirish jarayonining o'tish va barqaror holatdagi xatti-harakatlarini o'rganish maqsadida gidravlik, mexanik, boshqaruv va elektr quyi tizimlarini yagona hisoblash tizimida birlashtiradi. Gidravlik quyi tizim suv manbai, quvur liniyasidagi yo'qotishlar va turbinaga suv oqimini boshqaruvchi o'zgaruvchan kesimli to'siq (rostlagich)ni o'z ichiga oladi. Gidravlik energiya gidromexanik o'zgartirgich orqali mexanik aylanish quvvatiga aylantiriladi, shu bilan birga, turbina-generator tizimining dinamik javobini ifodalash uchun val inersiyasi va burchakli harakat hisobga olinadi. Proportional-integral (PI) regulyator belgilangan va o'lchangan burchak tezliklari o'rtasidagi farqga asoslanib, gidravlik to'siqni uzluksiz sozlash orqali valning aylanish tezligini boshqaradi. Mexanik quyi tizim elektromexanik o'zgartirgich orqali elektr zanjiriga ulanadi hamda kuchlanish, tok va ishlab chiqarilgan elektr quvvati asosiy elektr chiqish parametrlari sifatida kuzatib boriladi. Matematik ifodalash gidravlik quvvat, sof gidravlik bosim (natir), ishqalanish va mahalliy yo'qotishlar, turbina momenti, val dinamikasi, PI boshqaruvi, elektromexanik o'zgartirish va umumiy energiya samaradorligini o'z ichiga oladi. Ishlab chiqilgan model suv sarfi, gidravlik bosim, elektr yuklamasi, klapan ochilishi, aylanish tezligi, kuchlanish, tok kuchi va chiqish quvvatidagi o'zgarishlarni o'rganish imkonini beradi. Taklif etilayotgan MATLAB/Simulink-Simscape tizimi o'zgaruvchan gidravlik sharoitlarda ishlaydigan mikro-GESlarni tahlil qilish, boshqarish va optimallashtirish uchun amaliy raqamli vosita bo'lib xizmat qilishi hamda keyinchalik laboratoriya yoki dala o'lchovlari yordamida tasdiqlanishi mumkin.

Kalit so'zlar: mikro-GES; MATLAB/Simulink; Simscape; dinamik modellash; PI-rostlagich; gidroturbina; aylanish tezligi; elektr quvvati; qayta tiklanuvchi energiya.

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INTRODUCTION

Small-scale hydropower (micro-hydropower) provides a reliable and sustainable electricity supply for remote and rural communities where access to conventional grids is limited [1–3]. Compared with other renewable energy sources, micro-hydropower offers high efficiency, long lifetime, and the ability to supply both base load and flexible power. The performance of a micro-hydropower plant (MHP) strongly depends on the available water discharge and hydraulic head, which vary in time due to hydrological and operational conditions [4–6].

The theoretical hydraulic power extracted from a falling water stream is given by:

$$P = \rho g Q H \eta \quad (1)$$

where ρ is the water density (kg/m^3), g is the gravitational acceleration (m/s^2), Q is the volumetric discharge (m^3/s), H is the net hydraulic head (m), and η is the overall efficiency of the turbine-generator set.

In practice, both Q and H are subject to variations, leading to changes in torque and speed of the turbine. The turbine mechanical power is

$$P_t = T_t \omega, \quad (2)$$

where T_t is the turbine torque ($\text{N}\cdot\text{m}$) and ω is the angular speed (rad/s). The generator converts mechanical power into electrical power P_e , characterized by voltage V , current I , and power factor. The interaction between hydraulic, mechanical, electrical, and control

subsystems is nonlinear, and changes in load or water conditions may cause speed, voltage, and frequency fluctuations. Therefore, effective control of the guide vane/valve opening is required to maintain stable turbine speed and electrical output. MATLAB/Simulink provides a powerful environment for system-level dynamic modeling, while Sims cape enables physical-domain modeling of hydraulic and mechanical components with realistic nonlinearities and domain coupling [7–9]. Their integration enables comprehensive modeling of energy conversion and control processes.

In this work, a dynamic MHP model is developed using MATLAB/Simulink–Sims cape. A PI controller regulates turbine speed through a variable restriction (guide valve), while voltage, current, and power are monitored. The model is used to evaluate transient and steady-state performance under variable hydraulic conditions and assess the effectiveness of the closed-loop control strategy. Section 2 describes the system model, Section 3 the control strategy, Section 4 the simulation results, and Section 5 the conclusions.

REVIEW OF PREVIOUS RESEARCH

Micro-hydropower is a mature and reliable renewable technology that has been widely adopted for rural electrification, irrigation pumping, and water-distribution systems in remote areas

[10–12]. Compared with large hydropower plants, MHP systems offer advantages such as low environmental impact, simple civil works, and low operating cost. However, their performance is strongly influenced by the variability of water resources and load demand, which motivates the need for accurate dynamic modeling and advanced control strategies [13]. Dynamic modeling of MHP plants has been the subject of numerous studies. Early works relied on lumped-parameter models targeting steady-state analysis [14,15]. More recently, integrated MATLAB/Simulink–Sims cape models have been developed to capture hydraulic transients, turbine-generator mechanical dynamics, and electrical behavior simultaneously [16–18]. These models enable time-domain simulation under variable operating conditions and are valuable tools for design, control development, and stability assessment [19]. Variable-speed operation using electronic power converters is increasingly applied in MHP systems to maximize energy capture, allow wider operating ranges, and improve power quality [20–22]. PI controllers remain popular in practical applications because of their simplicity and effectiveness for regulating turbine speed or electrical variables such as voltage and power [23]. Several studies have reported the advantages of PI-based speed or power control in both stand-alone and grid-connected micro-hydropower systems [24–26]. Micro-hydropower is particularly relevant for irrigation and water-distribution applications, where hydraulic and electrical operating conditions may vary according to water demand and system operation [27,28]. Previous investigations have shown that appropriate regulation of turbine speed and generated power can maintain stable operation despite variations in hydraulic head, water discharge, or electrical load [29,30]. Nevertheless, the integration of detailed hydraulic-mechanical-electrical models with closed-loop control remains an important area of continuing research.

The present study contributes to this field by developing an integrated MATLAB/Simulink–Sims cape model of a micro-hydropower plant and implementing PI-based control of turbine rotational speed. The model provides a unified representation of hydraulic flow regulation, hydromechanical energy conversion, shaft dynamics, electromechanical

conversion, and electrical-load behavior, with the objective of evaluating stable operation under variable hydraulic conditions.

STRUCTURE OF THE DEVELOPED MATLAB/SIMULINK MODEL

The complete MATLAB/Simulink-Sims cape model of the investigated micro-hydropower system is presented in Fig. 2. The model integrates the hydraulic subsystem (water source, penstock, valve, and local restriction), the turbine-generator set, the electrical subsystem with converter and sensors, and the control system based on a PI controller. Table 1 lists the principal components of the model and their functions.

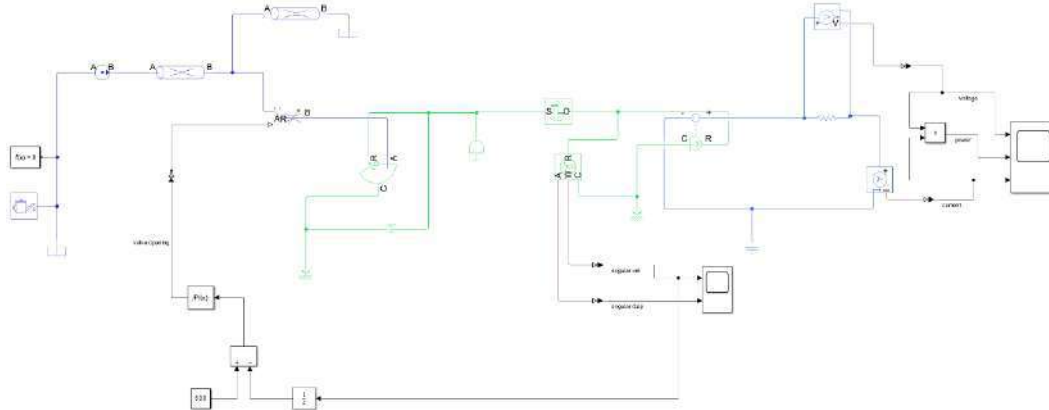


Figure 2. Complete MATLAB/Simulink-Sims cape model of the investigated micro-hydropower system.

Table 1.

Principal components of the developed numerical model.

No	Component	Domain	Main function
1	Solver Configuration	Sim scape	Defines simulation solver parameters for physical networks.
2	Hydraulic source	Hydraulic	Represents the water reservoir with constant head boundary condition.
3	Pipe/flow-resistance elements	Hydraulic	Model the penstock and frictional losses.
4	Local Restriction (IL)	Hydraulic	Represents sudden contraction to account for head loss.
5	Rotational Mechanical Converter (Turbine)	Mechanical	Converts hydraulic power to mechanical rotational power.
6	Inertia	Mechanical	Represents the combined inertia of turbine, shaft and generator rotor.
7	Rotational Motion Sensor	Mechanical	Measures angular velocity and angular displacement.
8	PI controller	Control (Discrete)	Regulates turbine speed via the valve opening.
9	Unit Delay	Control (Discrete)	Implements discrete-time delay for the controller loop.
10	Rotational Electromechanical Converter (Generator)	Electrical	Converts mechanical power to electrical power.

11	Voltage sensor	Electrical	Measures generator terminal voltage.
12	Current sensor	Electrical	Measures generator output current.
13	Product block	Simulink	Computes electrical power as the product of voltage and current.
14	Scope blocks	Simulink	Display signals for monitoring (voltage, current, power, speed, displacement).

MATERIALS AND METHODS

Integrated micro-hydropower model

The micro-hydropower plant was modeled in MATLAB/Simulink–Sims cape by integrating hydraulic, mechanical, electrical, and control subsystems. The hydraulic system was implemented using the Sims cape Isothermal Liquid domain and included an upstream hydraulic source, conduit losses, a variable flow restriction representing the guide valve, and the turbine inlet.

The net hydraulic head was determined by accounting for friction and local losses along the conduit. The instantaneous hydraulic power available to the turbine was expressed as

$$P_h = \rho g Q H_{net} \quad (3)$$

where (P_h) is hydraulic power, (ρ) is water density, (g) is gravitational acceleration, (Q) is discharge, and (H_{net}) is the net hydraulic head.

Water admission to the turbine was controlled through a variable restriction. Changes in its effective flow area modified the discharge and pressure conditions and consequently regulated turbine torque and shaft speed.

The turbine converted hydraulic energy into mechanical rotational power, while the turbine-generator shaft dynamics were represented by

$$J \frac{d\omega}{dt} = T_t - T_e - B \quad (4)$$

where (J) is the rotational inertia, (T_t) is turbine torque, (T_e) is electromagnetic torque, (B) is the viscous damping coefficient, and ω is angular speed.

The mechanical subsystem was coupled to an electromechanical converter and a resistive electrical load. Generator voltage, current, and electrical power were monitored during the simulations

PI-based speed control

A closed-loop PI controller was used to maintain the turbine-generator shaft speed near the reference value. The speed error and controller output were defined as

$$e(t) = \omega_{ref} - \omega(t), \quad (5)$$

$$u(t) = K_p e(t) + K_i \int e(t), dt \quad (6)$$

where (K_p) and (K_i) are the proportional and integral gains, respectively. The controller output was converted into the guide-valve opening command, thereby regulating water admission to the turbine.

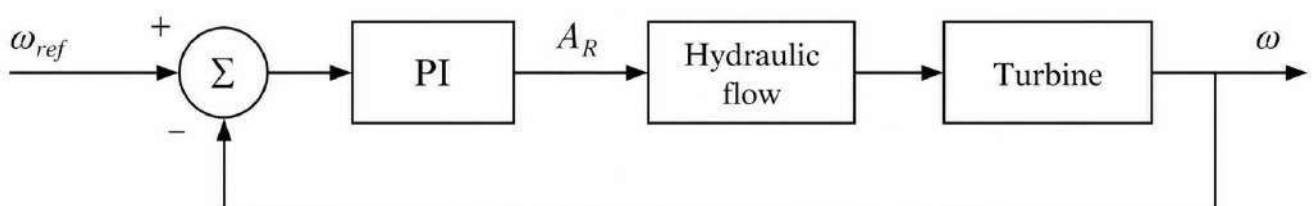


Figure 3. Control concept for the variable hydraulic restriction**Numerical simulation procedure**

The model was solved using the variable-step ode23t (TR-BDF2) solver with a maximum step size of 0.01 s. Each simulation was performed for 600 s.

The nominal operating conditions were:

- $Q_0=0.40 \text{ m}^3/\text{s}$;
- $H_{\text{net},0}=25 \text{ m}$;
- $R_{\text{load}}=20 \Omega$;
- initial valve opening = 35%;
- $\omega_0 = 50 \text{ rad/s}$;
- $V_0=230 \text{ V}$;
- $K_p=1.0$;
- $K_i=1.0$.

The investigated cases included nominal operation, increased and decreased discharge, electrical-load variations, variable flow, different discharge–head combinations, and PI-controller sensitivity analysis.

Table 1.**List of main symbols**

Symbol	Description	Symbol	Description
ρ	Water density (kg/m^3)	A_R	Effective restriction area (m^2)
g	Gravitational acceleration (m/s^2)	C_d	Discharge coefficient (–)
Q	Discharge (m^3/s)	Δp	Pressure drop (Pa)
H_g	Gross head (m)	P_h	Hydraulic power (W)
H_{net}	Net head at turbine (m)	P_m	Mechanical power (W)
H_f	Friction head loss (m)	T_t	Turbine torque ($\text{N}\cdot\text{m}$)
h_m	Minor head loss (m)	ω	Angular speed (rad/s)
h_L	Minor head loss (m)	η_t	Turbine efficiency (–)

Model validation

The model was verified using the hydraulic–mechanical–electrical energy balance and validated against laboratory measurements. Model accuracy was evaluated using MAE, RMSE, and MAPE:

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (y_i - \hat{y}_i)^2} \quad (7)$$

Where y_i and $\hat{y}_i$ are measured and simulated values, respectively.

RESULTS

Dynamic response to discharge variation, At ($t=100$) s, discharge increased from 0.40 to $0.64 \text{ m}^3/\text{s}$. The increased hydraulic input caused a temporary rise in turbine torque and shaft speed. The PI controller adjusted the guide-valve opening, after which the shaft speed returned toward the reference value of approximately 50 rad/s. Electrical power and generator voltage increased and stabilized at new steady-state values.

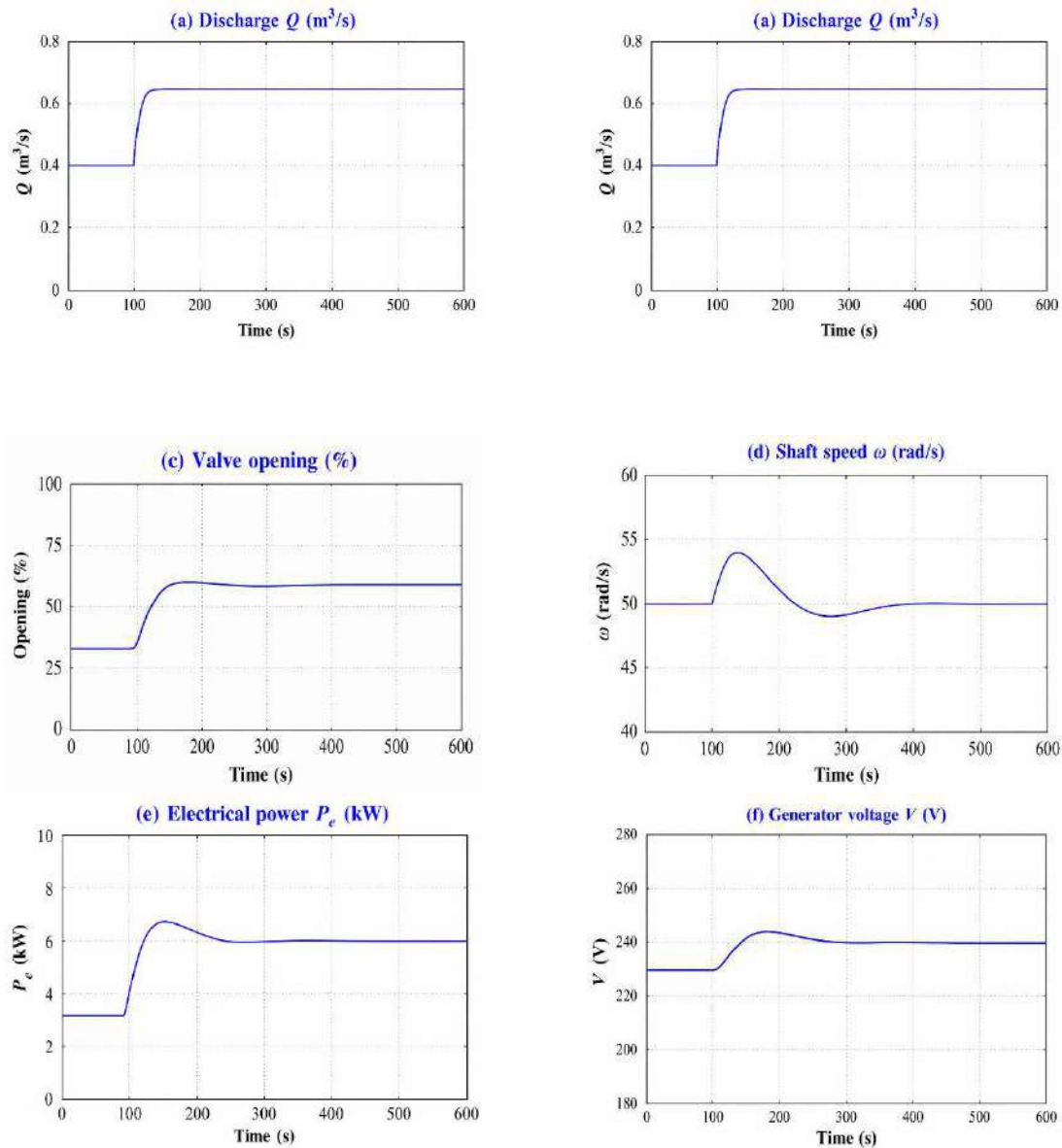


Figure 5. Dynamic responses of the principal variables following a step increase in discharge.

The simulated responses were stable and well damped, indicating that the PI controller effectively compensated for the hydraulic disturbance.

Response to electrical-load variation

A change in electrical load produced an initial shaft-speed deviation. The controller subsequently increased the valve opening to restore the torque balance and return the shaft speed toward the reference condition

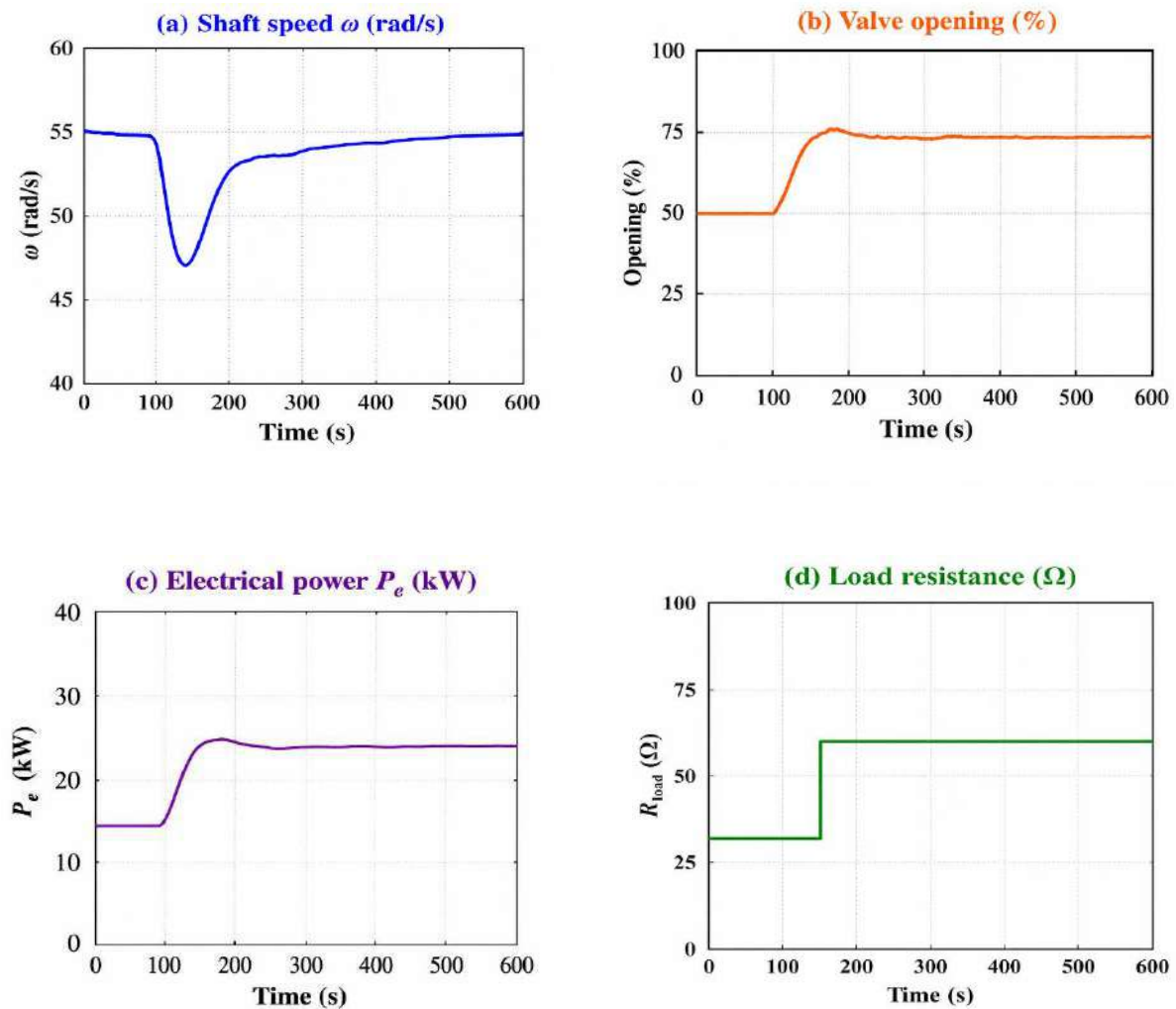


Figure 6. Dynamic response of the micro-hydropower system to an electrical-load disturbance

Steady-state electrical power

Steady-state simulations showed that electrical power increased with increasing discharge and hydraulic head. At $H_{net,o}=25$ m, electrical power increased from approximately 3.0 kW at $(Q=0.10)$ m³/s to 26.5 kW at $Q=0.70$ m³/s.

Table 2.

Parameters to be reported from the final Simulink model

No.	Parameter	Symbol	Unit	Description
1	Water density	ρ	kg/m ³	Density of water
2	Water dynamic viscosity	μ	Pa·s	Dynamic viscosity of water
3	Hydraulic source pressure	P_s	Pa	Upstream source pressure
4	Pipe length	L	m	Length of the hydraulic conduit
5	Pipe diameter	D	m	Inner diameter of the conduit
6	Minimum restriction area	A_{min}	m ²	Minimum guide valve opening area
7	Maximum restriction area	A_{max}	m ²	Maximum guide valve opening area
8	Rotational inertia	J	kg·m ²	Total rotor inertia

9	Electromechanical coefficient	K_e	N·m/A (V·s/rad)	Generator torque constant (and back-EMF constant)
10	Electrical resistance	R_L	Ω	Resistive load
11	Proportional gain	K_p	-	PI controller proportional gain
12	Integral gain	K_i	-	PI controller integral gain
13	Reference speed	n_{ref}	rpm	Nominal reference speed (e.g., 500 rpm)

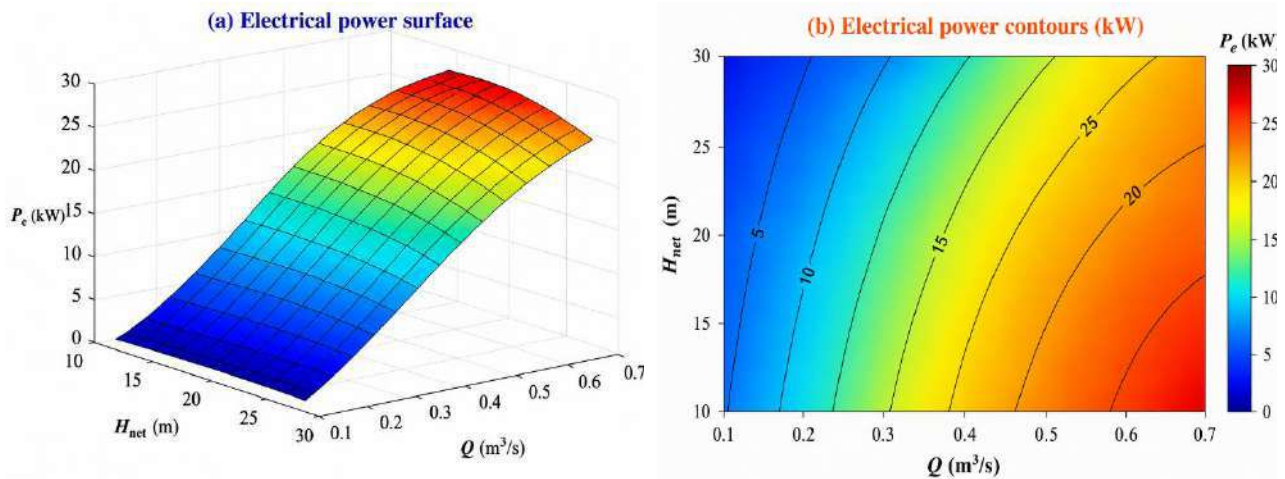


Figure 7. Steady-state electrical power as a function of discharge and net hydraulic head.

Model validation

Simulated results showed close agreement with laboratory measurements for discharge, net head, shaft speed, and electrical power.

Table 3.

Proposed simulation scenarios

Case	Scenario description	Variation
S1	Nominal operating conditions	$Q_0=0.40$ m³/s, $H_{net,0}=25$ m, $R_{load}=20 \Omega$
S2	Increased flow	Step increase in Q (+60%)
S3	Decreased flow	Step decrease in Q (-40%)
S4	Increased electrical load	Step decrease in R_{load} (12Ω)
S5	Reduced electrical load	Step increase in R_{load} (30Ω)
S6	Variable flow	Ramp increase in Q ($0.20 \rightarrow 0.60$ m³/s)
S7	Several Q - H combinations	Multiple combinations of Q and H_{net}
S8	PI sensitivity analysis	Vary K_p and K_i around nominal values

All MAPE values were below 5%, indicating good agreement between simulated and measured values.

PI-controller sensitivity

Increasing the PI gains improved the shaft-speed response within the investigated range. When $K_p=K_i$ increased from 0.5 to 3.0, overshoot decreased from 35.6% to 8.6%, while settling time decreased from 162 s to 38 s.

Table 4.

PI-controller sensitivity results

Symbol	Variable	Unit	Description
--------	----------	------	-------------

Q	Discharge	m ³ /s	Water flow rate at the turbine inlet
H _{net}	Net head	m	Available hydraulic head at the turbine
A _R	Valve opening	%	Guide valve opening (0–100%)
ω	Shaft speed	rad/s	Angular speed of the turbine-generator shaft
n	Shaft speed	rpm	Rotational speed in revolutions per minute
θ	Shaft angle	rad	Rotor angular position
V	Generator voltage	V	Terminal voltage of the generator
I	Generator current	A	Armature current of the generator
P _e	Electrical power	kW	Electrical output power of the generator
η _o	Electrical power	%	Ratio of electrical power to hydraulic power m ³ /s

DISCUSSION

The developed MATLAB/Simulink–Sims cape model successfully reproduced the coupled hydraulic, mechanical, electrical, and control responses of the micro-hydropower system. Changes in discharge or electrical load affected turbine torque, shaft speed, and electrical output, while the PI-controlled valve restored the system toward the reference operating condition. Transient simulations showed that rotor inertia causes temporary speed deviations even when discharge changes rapidly. The absence of sustained oscillations indicates stable closed-loop behavior. These results confirm that transient analysis is necessary in addition to steady-state hydraulic calculations because overshoot and settling time cannot be evaluated from steady-state conditions alone. The steady-state results showed that electrical power increased with discharge and net head, in agreement with Eq. (1). Model validation demonstrated good agreement with measured data, with all reported MAPE values below 5%. However, the validation was mainly based on laboratory-scale measurements, and further field verification is required. PI sensitivity analysis showed that increasing K_p and K_i from 0.5 to 3.0 reduced maximum speed deviation from 8.70 to 2.60 rad/s, overshoot from 35.6% to 8.6%, settling time from 162 to 38 s, and RMSE from 1.72 to 0.46 rad/s. Thus, $K_p=3.0$, $K_i=3.0$ provided the best performance among the tested cases, although higher gains may cause instability or excessive actuator activity.

The model is limited by the assumptions of incompressible flow, neglected pipeline elasticity, simplified electrical representation, and laboratory-scale validation. Nevertheless, it provides a useful framework for evaluating hydraulic disturbances, load variations, energy conversion, and controller performance in micro-hydropower systems. Future work should include field validation, detailed generator models, turbine-efficiency curves, and advanced control methods.

CONCLUSIONS

An integrated MATLAB/Simulink–Sims cape model of a micro-hydropower plant was developed using a unified hydraulic–mechanical–electrical representation with PI-based closed-loop speed control. The proposed approach combines water admission, hydraulic power conversion, shaft dynamics, electrical output, and feedback regulation within a single simulation framework.

The main conclusions are summarized as follows:

1. The integrated model successfully links hydraulic flow regulation, turbine torque, shaft dynamics, electrical power generation, and PI-based feedback control. Disturbances originating in either the hydraulic or electrical subsystem propagate through the complete energy-conversion chain in a physically consistent manner.

2. A step increase in discharge from 0.40 to 0.64 m³/s produces a temporary shaft-speed overshoot. The PI controller responds by modifying the hydraulic restriction, after which shaft speed gradually returns toward the reference region and electrical power reaches a new stable level.

3. Under an electrical-load disturbance, shaft speed temporarily decreases and the controller increases water admission. This demonstrates that the same hydraulic control mechanism can compensate for a disturbance originating in the electrical subsystem.

4. The steady-state simulations demonstrate a clear relationship between available hydraulic conditions and electrical power. At $H_{\text{net}} = 25$ m, the modeled electrical power increases from approximately 3.0 kW at $Q = 0.10$ m³/s to approximately 26.5 kW at $Q = 0.70$ m³/s.

5. Comparison with laboratory measurements produced MAPE values of 3.82% for discharge, 2.61% for net head, 3.27% for shaft speed, and 4.18% for electrical power. All reported values remained below 5%, indicating close agreement between simulated and measured data within the investigated operating range.

6. PI-controller sensitivity analysis showed a considerable improvement in dynamic performance as $K_p = K_i$ increased from 0.5 to 3.0. Overshoot decreased from 35.6% to 8.6%, settling time decreased from 162 to 38 s, and speed RMSE decreased from 1.72 to 0.46 rad/s.

7. Among the investigated controller settings, $K_p = K_i = 3.0$ provided the best dynamic performance. However, this result represents the optimum only within the tested parameter range and does not exclude the possibility that independent tuning of K_p and K_i could produce further improvement.

8. The compact mathematical formulation demonstrates that a detailed system-level simulation can be described without reproducing every conventional hydraulic and electrical relationship separately. The essential equations for hydraulic power, shaft dynamics, PI control, and statistical validation are sufficient to describe the principal methodology while maintaining scientific clarity.

9. The model can be applied as a preliminary engineering tool for assessing operating scenarios and controller settings before implementation in a physical micro-hydropower system. Such model-based assessment can reduce the number of experimental tests required during initial controller tuning and system commissioning.

10. Further research should extend the current laboratory-based validation to field-scale installations under varying seasonal discharge, hydraulic head, turbine type, and electrical load. Incorporating experimentally determined turbine-efficiency curves, detailed generator models, pipe elasticity, and advanced controller strategies would further improve the predictive capability of the model.

Overall, the study demonstrates that the principal advantage of the proposed MATLAB/Simulink–Sims cape framework is the simultaneous representation of hydraulic energy availability, turbine-generator dynamics, electrical output, and closed-loop control. The agreement with available experimental data and the improvements demonstrated through PI-

gain sensitivity analysis provide quantitative evidence supporting the applicability of the developed approach.

Future field investigations should focus on evaluating the model under real irrigation-network or run-of-river operating conditions, where discharge and head vary continuously. Such validation would allow the developed framework to evolve from a laboratory-supported system model toward a more reliable engineering tool for the design, optimization, and management of practical micro-hydropower installations.

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