

Article

VFD-Based Frequency Regulation and Surplus Utilization Framework for Standalone Micro-Hydro Power Plants

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Abstract. Standalone micro-hydro power plants commonly regulate excess generation through electronic load controllers, which dissipate surplus energy in ballast loads. This study evaluates a dual-inverter variable-frequency-drive framework that prioritizes domestic demand and directs the remaining DC-link power to a motor-pump system. The controller applies 6/4 kW hysteresis and a 0.7 kW/s pump-power ramp limit. A 24-hour energy-management analysis was combined with a short-duration switched-inverter assessment of DC-link and load-side power quality. For a 30kW generator, the system served 423.69 of 424.00 kWh/day of domestic demand and supplied 181.08 kWh/day to the pump drive, recovering 95.95% of the available DC-side surplus. Relative to a conventional electronic load controller, useful end-use utilization increased from 65.75% to 84.66%. The regulated output had a mean phase voltage of 225.85 V, a mean frequency of 49.982 Hz, a maximum frequency deviation of 0.0346 Hz, and a voltage total harmonic distortion of 3.996%. The results indicate that the proposed configuration can reduce dissipative surplus handling while maintaining domestic energy service and acceptable load-side power quality.

Keywords: Renewable energy, microgrid, micro-hydro power, variable frequency drive (VFD), frequency stabilization

ENGINEERING JOURNAL Volume 30 Issue 8

Received 29 November 2025

Accepted 27 July 2026

Published 31 August 2026

Online at <https://engj.org/>

DOI:10.4186/ej.2026.30.8.19

1. Introduction

Affordable and reliable electricity remains inaccessible to many rural and remote communities [1]. Extending centralized grids to these areas is often impractical because of high infrastructure costs, transmission losses, and difficult terrain [2]. Decentralized renewable-energy systems therefore offer a practical alternative for rural electrification [3], [4].

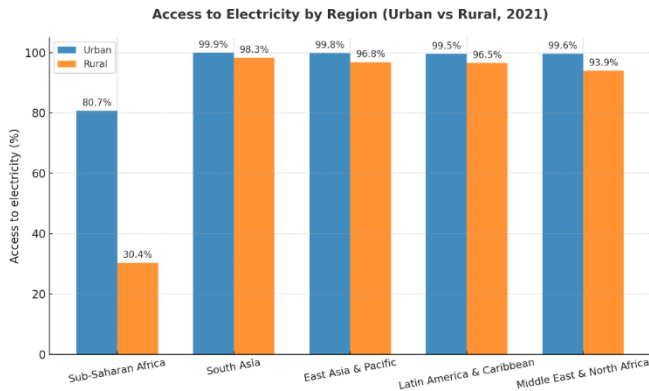


Fig. 1. Global access to electricity, highlighting disparities between regions [1].

Among these options, micro-hydro power plants (MHPPs) are particularly attractive because they can provide relatively continuous generation where adequate water resources are available, with favorable performance and cost characteristics [5]. Figures 1 and 2 highlight the electricity-access gap and the relative suitability of major renewable-energy technologies for rural applications.

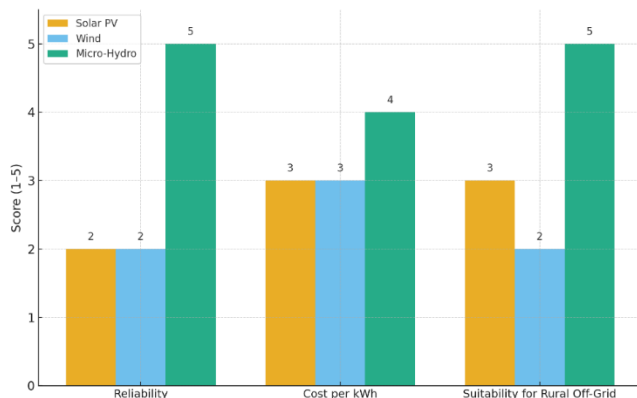


Fig. 2. Comparative reliability of solar, wind, and micro-hydro for rural electrification.

Standalone MHPPs, however, must maintain voltage and frequency under variations in water flow and consumer demand. Mechanical governors are costly and require substantial maintenance. In contrast, electronic load controllers (ELCs) regulate frequency by diverting surplus power to ballast loads [6], [7]. Although effective, ELCs dissipate surplus energy as heat rather than converting it into productive use.

Recent studies have investigated fuzzy-logic and AI-based approaches for improving hydro and MHPP frequency regulation [8]-[12], while power-electronic

converter-based architectures have also received increasing attention [13], [14]. Variable-frequency-drive-based systems can decouple load-side voltage and frequency from generator-side variations while supporting motor-driven applications. Nevertheless, existing studies rarely integrate domestic-load prioritization, productive surplus allocation, and residual-surplus management. They also seldom assess load-side power quality or directly compare the proposed approach with a conventional ELC under identical operating conditions.

To address this gap, this study develops a dual-inverter VFD framework in which a primary inverter regulates the domestic supply and a secondary inverter directs available DC-link surplus to a motor-pump system. The novelty lies in the integrated control and quantitative evaluation of these functions rather than in the individual use of a VFD, inverter, or pump. The controller incorporates domestic-load priority, hysteresis-based pump control, ramp-limited power dispatch, and explicit residual-surplus handling. Performance is assessed through a daily energy-management analysis and a matched conventional-ELC baseline. A separate switched-inverter evaluation is also conducted to assess DC-link and load-side power quality. The framework also draws on recent developments in hybrid renewable operation [15], synchronization under non-ideal conditions [16], and community-oriented MHPP planning [17].

The remainder of the paper is organized as follows. Section 2 reviews existing MHPP control and surplus-utilization methods. Section 3 presents the system architecture, models, and simulation procedure. Section 4 discusses the results, and Section 5 concludes the study.

2. Literature Review

MHPP control has evolved from mechanical governors to electronic, intelligent, hybrid, and converter-based approaches [6], [8], [13]. As illustrated in Fig. 3, this progression reflects growing emphasis on regulation accuracy, system efficiency, and productive surplus-energy utilization.

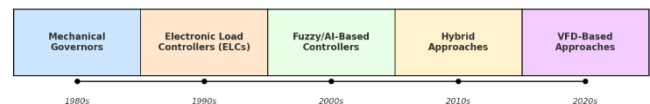


Fig. 3. Evolution of MHPP frequency control methods from governors to modern VFD-based strategies.

2.1. Mechanical Governors and Classical Controls

Mechanical governors regulate turbine speed by adjusting water flow in response to load variations [18]-[20]. These systems are robust and well established in large hydropower plants. Their cost, mechanical complexity, and maintenance requirements limit their suitability for rural mini-grids. This has encouraged the adoption of simpler electronic alternatives [6], [21].

2.2. Electronic Load Controllers (ELCs)

Electronic load controllers are widely used in standalone micro-hydro systems as a low-cost alternative to mechanical governors [6], [7], [21]. They regulate voltage and frequency by diverting surplus generation to resistive dump loads as consumer demand decreases [6], [7], [21]. Although effective, conventional ELCs dissipate usable energy and impose continuous electrical and thermal stress on system components [21]. Distributed ELCs can redirect excess power to household applications [22], while zero-crossing switching can reduce transients and harmonic distortion [23].

2.3. Fuzzy Logic and AI-Based Controllers

Fuzzy-logic and AI-based controllers improve the transient response of isolated MHPPs under nonlinear and variable loads [8]-[12]. Fuzzy control can improve frequency regulation [24], while AI-based methods have been applied to load-frequency control and oscillation damping [25], [26]. However, some MHPP implementations still rely on ELC/ballast-based regulation [9], [12]. Advanced fuzzy, neural-network, and optimization-based approaches can also increase controller tuning and implementation complexity [8]-[12].

2.4. Hybrid Renewable Systems

Hybrid systems combine MHPPs with solar PV, wind generation, or energy storage to improve reliability and mitigate seasonal resource variation [27]-[29]. PV-hydro coordination can enhance resource utilization [15], [27],

while wind-hydro systems have been studied for applications such as water treatment [30]. Nevertheless, hybridization increases capital cost and operational complexity, particularly when batteries are required [28]. It also does not inherently resolve surplus-energy management in standalone MHPPs.

2.5. VFD-Based Approaches

Variable-frequency-drive interfaces employ controlled power-electronic conversion to regulate electrical output [13], [14], [31] and can support motor-driven applications such as water pumping [32]. Such arrangements provide a pathway for productive utilization of hydroelectric power in pumping applications. Practical implementation requires additional converter hardware and appropriate protection coordination [14], [33].

2.6. Resource Assessment and Community Perspectives

Successful MHPP deployment depends not only on technical performance but also on resource assessment, site selection, and community participation. Hydro-resource and GIS-based studies support capacity planning and site selection [34]-[36], while community-oriented planning supports local engagement [17]. Prototype and component-level studies also support technical training and practical evaluation [37], [38]. Accordingly, such systems should be considered within broader techno-economic, infrastructure, and clean-energy planning contexts [39]-[43].

Table 1. Comparative overview of MHPP control approaches in prior literature

Approach	Control principle	Main advantage	Main limitation
Mechanical governors [18]-[20]	Hydraulic speed and flow control	Robust and established	Costly and maintenance-intensive
ELCs [6], [7], [21]-[23]	Divert surplus to ballast loads	Simple and low-cost	Dissipates usable surplus energy
Fuzzy/AI control [8]-[12], [24]-[26]	Adaptive control, often combined with ELCs	Improved transient regulation	Computational burden; may retain ballast loading
Hybrid systems [15], [27]-[30]	Combine hydro with PV, wind, or storage	Improved reliability and seasonal balance	Higher cost and operational complexity
VFD-based control [13], [14], [31], [32]	Regulates output and supplies motor loads	Enables productive surplus utilization	Higher converter cost and expertise requirements

As summarized in Table 1, the reviewed approaches involve trade-offs among regulation performance, implementation complexity, and energy utilization. Conventional, intelligent, and hybrid methods can improve system regulation, but their ability to support productive surplus-energy utilization remains limited. The unresolved gap is the absence of an integrated standalone MHPP framework that prioritizes domestic demand and directs surplus power to a controllable pump load. It should quantify residual unused energy and evaluate load-side power quality. It should also compare performance

with a conventional ELC using the same operating profiles. The proposed dual-inverter framework is developed to address this gap.

3. Methodology

This section presents the system architecture, control strategy, mathematical models, simulation parameters, and principal assumptions.

3.1. System Architecture

The proposed standalone MHPP supplies regulated electricity to domestic loads and directs surplus generation to a motor-pump system. As shown in Fig. 4, a Pelton turbine drives a synchronous generator whose output is converted through a rectifier, DC link, and inverter. This AC-DC-AC conversion stage regulates the load-side voltage and frequency, while a second inverter controls the induction motor pump.

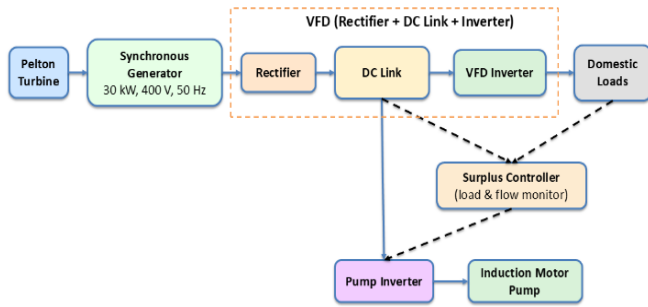


Fig. 4. Framework of the proposed MHPP with VFD and motor pump.

The supervisory controller prioritizes domestic demand and enables pump operation only when sufficient DC-side surplus is available. The pump therefore functions as a controllable productive load rather than a conventional ballast load. Surplus power beyond the pump capacity is assigned to a residual curtailment or protection path.

3.2. Control Architecture and Operating Logic

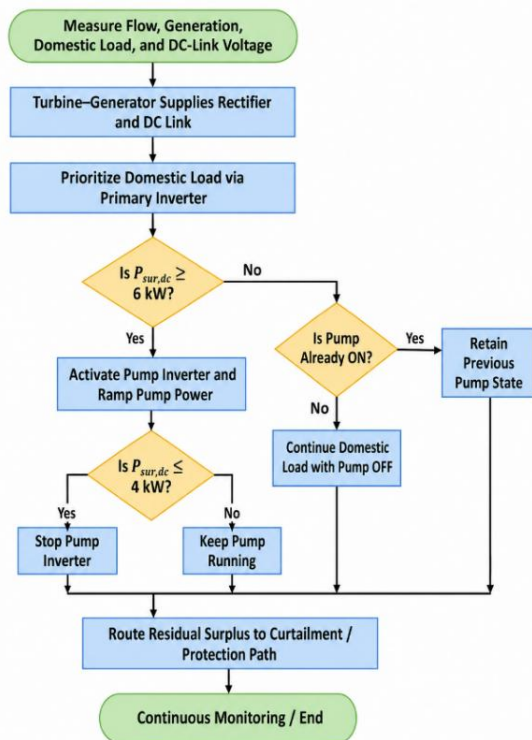


Fig. 5. Supervisory control logic for domestic-load prioritization.

The controller determines the available surplus on a common DC-side basis by converting the domestic AC demand to its equivalent inverter input:

$$P_{sur,dc} = \max(P_{rect,dc} - P_{dom,ac} / \eta_{inv}, 0) \quad (1)$$

where $P_{sur,dc}$ is the available DC surplus, $P_{rect,dc}$ is the rectifier output power, $P_{dom,ac}$ is the domestic AC demand, and η_{inv} is the domestic-inverter efficiency.

Domestic demand is allocated before the pump command is determined. As illustrated in Fig. 5, the controller first supplies the domestic load and then assigns the remaining DC-side power to the pump drive. Any surplus beyond the pump requirement is directed to the curtailment or protection path.

3.3. Simulation Modeling

Two complementary MATLAB models were used. The first was a 24-hour average-value energy-management model with a 1 s time step. It represented river-flow variation, turbine-generator conversion, the 30kW generator limit, domestic-load priority, pump dispatch, conversion losses, and the conventional ELC baseline.

The second was a short-duration switched-inverter model for DC-link and load-side power-quality assessment. It included an average-value source-rectifier representation, DC-link dynamics, a three-phase two-level inverter, 5 kHz third-harmonic-injection PWM, an LC output filter, and a variable three-phase load. Separating the models prevents switching-level quantities, such as voltage THD, from being inferred from the daily analysis.

3.3.1. Hydro Turbine Model

The turbine-shaft mechanical power is expressed as:

$$P_t = \rho g Q H \eta_t \quad (2)$$

where ρ is water density, g is gravitational acceleration, Q is flow rate, H is net head, and η_t is turbine efficiency. This power corresponds to the mechanical torque applied to the generator shaft. The resulting shaft power provides the mechanical input to the generator and is distinct from its electrical output.

3.3.2. Synchronous Generator Model

The electrical power available from the generator before applying its rating limit is calculated as:

$$P_{gen,avail} = \eta_g P_t \quad (3)$$

where η_g is the generator efficiency.

The delivered generator AC power is constrained by the 30kW nameplate rating:

$$P_{gen,ac} = \min(P_{gen,avail}, P_{gen,rated}) \quad (4)$$

When the available electrical power exceeds 30kW, the generator output remains at its rated value. In practice, the additional hydraulic input would require flow regulation, bypass, or source-side curtailment.

The general electromechanical rotor relationship is:

$$J(d\Delta\omega/dt) = T_m - T_e - D\Delta\omega \quad (5)$$

where J is the rotor inertia, $\Delta\omega = \omega - \omega_s$ is the rotor-speed deviation from synchronous speed, T_m is turbine torque, T_e is electromagnetic torque, and D is the damping coefficient. Equation (5) describes the general rotor dynamics, whereas the 24-hour analysis uses the average-value power relations in Eqs. (2)-(4).

3.3.3. DC Link Dynamics

The rectifier supplies a capacitor-supported DC link shared by the domestic-load and pump inverters. Its power balance is expressed as

$$CV_{dc} dV_{dc}/dt = P_{rect,dc} - P_{dom,dc} - P_{pump,dc} - P_{res,dc} \quad (6)$$

where C is the DC-link capacitance, $P_{rect,dc}$ is the rectifier output, $P_{dom,dc}$ is the domestic-inverter input, $P_{pump,dc}$ is the pump-drive input, and $P_{res,dc}$ is the residual power assigned to the curtailment or protection path.

The daily model assumes a regulated DC-link voltage of 600 V. The switched-inverter model integrates Eq. (6) using a capacitance of 11.396 mF to evaluate deficit and surplus disturbances.

3.3.4. Induction Motor Pump Model

The pump is driven by a three-phase squirrel-cage induction motor. The centrifugal-pump load torque follows

$$T_{load} = K_T \omega_r^2 \quad (7)$$

where ω_r is the rotor speed and K_T is the pump torque coefficient.

Consequently, the mechanical pump power varies approximately with the cube of speed:

$$P_{shaft} = K_P \omega_r^3 \quad (8)$$

The electrical-to-hydraulic conversion is represented by

$$P_{shaft} = \eta_{md} P_{pump,dc}, P_{hyd} = \eta_p P_{shaft} \quad (9)$$

where η_{md} is the combined pump-inverter and motor efficiency, and η_p is the hydraulic pump efficiency.

For the specified pumping head H_p , the instantaneous water-flow rate is calculated as

$$Q_p = P_{hyd} / \rho g H_p \quad (10)$$

The model uses a motor-drive efficiency of 90%, a pump efficiency of 75%, and a pumping head of 20 m.

3.3.5. Surplus Power Controller

The supervisory controller uses the DC-side surplus defined in Eq. (1) to determine the pump operating state. The pump is enabled when $P_{sur,dc}$ reaches 6 kW and disabled when it falls to 4 kW. Within the 4-6 kW hysteresis band, the previous operating state is retained to prevent repeated switching. The resulting hysteresis logic is expressed as:

$$u_p(k) = \begin{cases} 1, & P_{sur,dc}(k) \geq 6 \text{ kW} \\ 0, & P_{sur,dc}(k) \leq 4 \text{ kW} \\ u_p(k-1), & 4 < P_{sur,dc}(k) < 6 \text{ kW} \end{cases} \quad (11)$$

where u_p is the pump-enable command.

When the pump is enabled, its target input power is limited to the smaller of the available DC-side surplus and the 20 kW drive rating:

$$P_{pump,target} = \min(P_{sur,dc}, 20 \text{ kW}) \quad (12)$$

The commanded pump power is subject to a ramp-rate constraint of

$$|d_{pump,dc} / dt| \leq 0.7 \text{ kW/s} \quad (13)$$

If the available surplus decreases faster than the permitted ramp-down rate, the pump input is immediately clamped to the available surplus to preserve domestic-load priority. The residual DC-side power is calculated as:

$$P_{res,dc} = \max(P_{sur,dc} - P_{pump,dc}, 0) \quad (14)$$

This residual quantity represents power that must be handled through source curtailment, storage, another controllable load, or a protection path.

3.4. Simulation Parameters

Table 2. Simulation parameters of the proposed MHPP system

Subsystem	Parameters	Values
Hydro turbine	Net head; flow range; efficiency	25 m; 0.10-0.20 m ³ /s; 85%
Synchronous generator	Rated power; efficiency; voltage; frequency	30 kW; 92%; 400 V L-L; 50 Hz
Conversion stage	Rectifier/inverter efficiency; DC-link voltage	97% / 97%; 600 V
Switched-inverter model	DC-link capacitance; switching frequency	11.396 mF; 5 kHz
Domestic load	Demand range; nominal output voltage	3-28 kW; 400 V L-L

Pump controller	Maximum input; 20 kW; 6/4 ON/OFF thresholds; ramp limit	20 kW; 0.7 kW/s
Motor-pump system	Motor-drive efficiency; pump efficiency; pumping head	90%; 75%; 20 m

The principal parameters of the daily energy-management and switched-inverter analyses are summarized in Table 2.

The daily simulation used a 1 s time step and a configured flow range of 0.10–0.20 m³/s. The generated profile remained within these limits and is presented in Section 4.1. Generator output was capped at 30 kW when the available hydraulic input could support greater electrical generation.

The 11.396 mF capacitance and 5 kHz switching frequency were applied only in the switched-inverter analysis. The daily model assumed a regulated 600 V DC link.

3.5. Assumptions and Simulation Scenarios

For the 24-hour analysis, identical river-flow and domestic-load profiles were applied to the proposed and conventional ELC configurations. In the conventional ELC baseline, domestic demand was supplied first, and the remaining generator AC power was diverted to the ballast load:

$$P_{ballast}(t) = \max[P_{gen,ac}(t) - P_{dom,ac}(t), 0] \quad (15)$$

During a generation deficit, the ballast command was zero, and the served domestic load was limited by the available generator output. Using the 1 s simulation time step, the daily ballast energy was calculated as:

$$E_{ballast} = \Delta t / 3600 \sum P_{ballast}[k], \Delta t = 1s \quad (16)$$

For comparison with the AC-side ballast energy of the conventional ELC, the proposed system's DC-side residual energy was converted to its source-equivalent value as:

$$E_{res,src} = E_{res,dc} / \eta_{rect} = 0.977.64 = 7.87 \text{ kW/h/day} \quad (17)$$

Fixed efficiencies were assumed for the turbine, generator, rectifier, inverters, motor drive, and pump. The daily analysis used average-value power-conversion models and did not include energy storage. Detailed generator electromagnetic dynamics, semiconductor thermal behavior, line and transformer losses, and site-specific hydraulic losses were excluded.

The switched-inverter scenario covered 0.5 s and included temporary deficit and surplus disturbances together with a 12–20 kW load transition. It incorporated 5 kHz PWM and an LC output filter. Ideal semiconductor switches were assumed; conduction losses, switching

losses, dead time, and thermal effects were neglected. Domestic demand retained priority throughout the evaluation, while pump operation was restricted to the available DC-side surplus.

4. Results and Discussion

This section evaluates resource-to-electrical-power conversion, DC-link and load-side power quality, domestic-load service, surplus utilization, and performance relative to a conventional ELC.

4.1. Resource Variability and Generator Output

The variation in river discharge and the resulting power outputs are presented in Figure 6. The river discharge ranged from 0.1119 to 0.1880 m³/s. At a net head of 25 m and a turbine efficiency of 85%, the corresponding turbine-shaft power ranged from 23.33 to 39.18 kW.

After applying the generator efficiency of 92%, the available electrical power ranged from 21.46 to 36.05 kW. Because the generator was rated at 30 kW, the delivered AC output was limited to 21.46–30.00 kW. When the available input exceeded this rating, the excess hydraulic resource was not converted into additional electrical output.

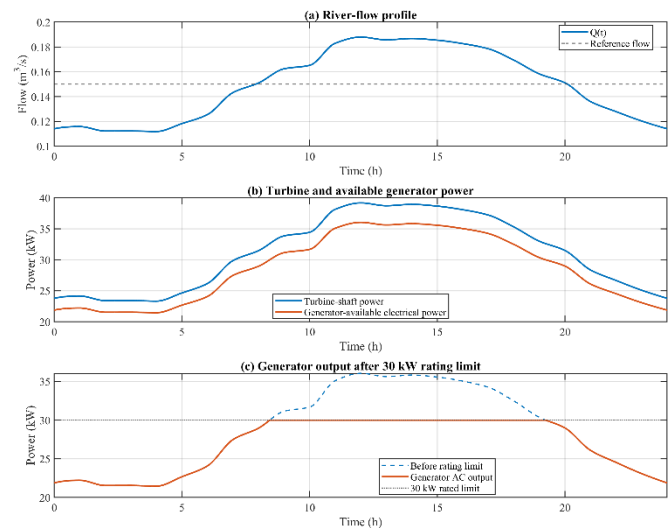


Fig. 6. Resource-to-electrical-power conversion during the 24-hour simulation: (a) river-flow profile, (b) turbine-shaft power and generator-available electrical power before rating limitation, and (c) generator AC output after application of the 30 kW rating limit.

4.2. Voltage Stability Through VFD Regulation

The DC-link response to temporary deficit and surplus disturbances is presented in Figure 7. The voltage remained between 577.74 and 604.25 V around the 600 V reference, with an RMS deviation of 3.19 V. It stayed within the selected $\pm 5\%$ band throughout the simulation and returned to the $\pm 1\%$ region within 11.31 ms after the deficit disturbance.

The load-side power-quality results are summarized in Figure 8. The mean phase RMS voltage was 225.85 V, corresponding to a regulation error of -2.20% , while the maximum cycle-by-cycle deviation was 2.275% . Although the generator-side frequency varied from 48.211 to 52.896 Hz, the inverter output maintained a mean frequency of 49.982 Hz with a maximum deviation of 0.0346 Hz. The filtered output-voltage THD through the 40th harmonic was 3.996%. The principal metrics are listed in Table 3.

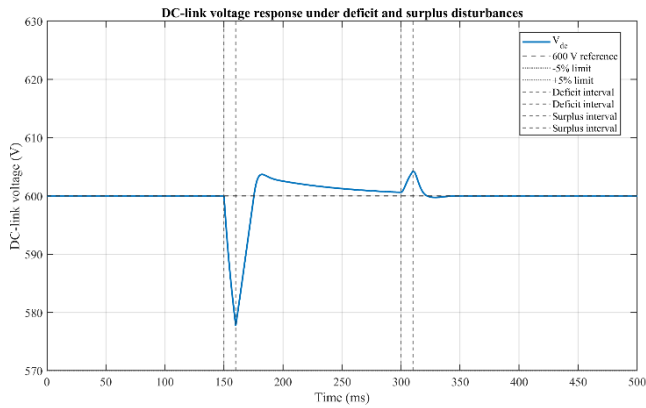


Fig. 7. DC-link voltage response under temporary deficit and surplus disturbances, showing the 600 V reference and selected $\pm 5\%$ tolerance limits.

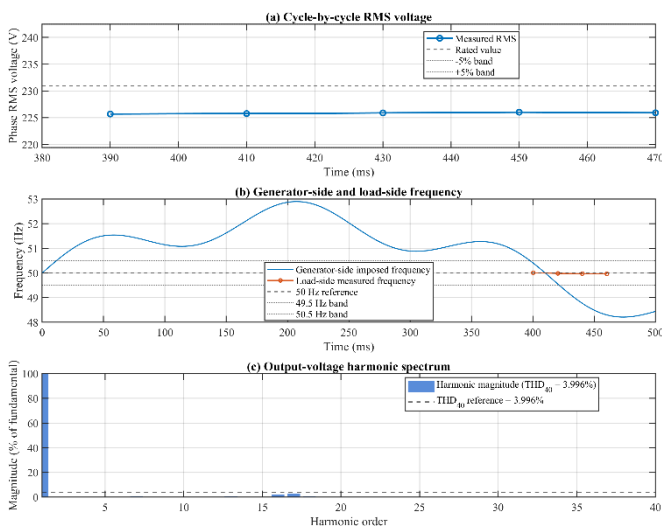


Fig. 8. Quantitative power-quality performance of the proposed VFD interface: (a) cycle-by-cycle RMS phase-voltage regulation, (b) generator-side and regulated load-side frequency responses, and (c) harmonic spectrum of the filtered output phase voltage.

Table 3. Quantitative DC-link and load-side power-quality performance.

Metric	Result
DC-link voltage range	577.74–604.25 V
DC-link RMS deviation	3.19 V
Time within $\pm 5\%$ DC-link band	100%
Mean phase RMS voltage	225.85 V
Voltage-regulation error	-2.20%
Mean output frequency	49.982 Hz
Maximum frequency deviation	0.0346 Hz
Voltage THD, 40th harmonic	3.996%

These results confirm that the proposed AC–DC–AC stage effectively decouples the domestic supply from generator-side variations while maintaining regulated load-side voltage and frequency.

4.3. Integrated Load and Surplus Utilization

Figure 9 shows the 24-hour power allocation and pump operation. The system served 423.69 kWh/day of the 424.00 kWh/day domestic demand, corresponding to an energy-service rate of 99.93%. After domestic-load prioritization, the pump drive absorbed 181.08 kWh/day and recovered 95.95% of the available DC-side surplus.

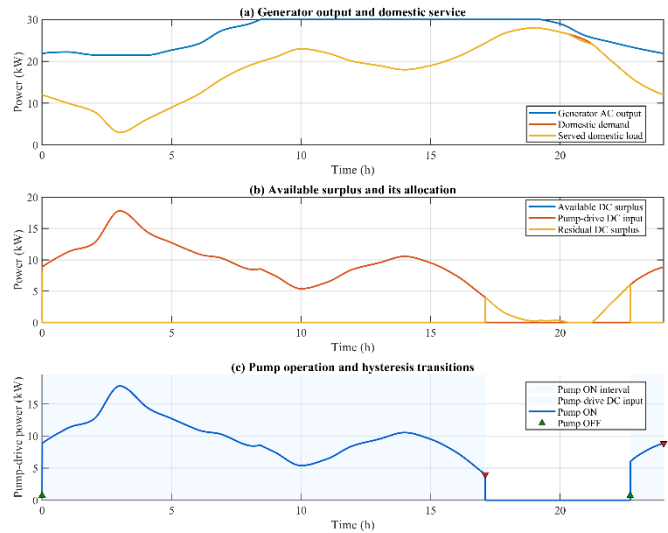


Fig. 9. 24-hour power allocation and pump operation: (a) generator output, domestic demand, and served domestic load; (b) available DC surplus, pump-drive input, and residual DC surplus; and (c) ramp-limited pump operation with hysteresis-controlled ON/OFF transitions.

The recovered energy produced 122.23 kWh/day of hydraulic output, corresponding to an estimated water delivery of 2242.7 m³/day at the modeled pumping head of 20 m. The complete energy balance is summarized in Table 4.

Table 4. Corrected 24-hour energy balance of the proposed system.

Metric	Value
Generator AC energy	644.86 kWh/day
Domestic demand / served	424.00 / 423.69 kWh/day
Unserved energy	0.310 kWh/day
Maximum unserved load	0.518 kW
Available DC surplus	188.72 kWh/day
Pump-drive energy	181.08 kWh/day
Hydraulic energy	122.23 kWh/day
Residual DC surplus	7.64 kWh/day
Surplus recovered	95.95%
Pump operating duration	18.40 h/day

4.4. Comparative Assessment

Under identical river-flow and domestic-load profiles, useful end-use utilization increased from 65.75% with the conventional ELC to 84.66% with the proposed framework. The source-equivalent ballast or residual-surplus energy decreased from 220.86 to 7.87 kWh/day. Domestic energy service remained essentially unchanged at 424.00 and 423.69 kWh/day, respectively, indicating that productive surplus utilization did not materially compromise the priority load. The complete comparison is presented in Table 5.

Table 5. Comparative performance of the conventional ELC and proposed VFD-pump systems.

Metric	Conventional ELC	Proposed VFD-pump
Domestic energy served (kWh/day)	424.00	423.69
Productive pump-drive energy (kWh/day)	0	181.08
Hydraulic energy output (kWh/day)	0	122.23
Ballast/residual surplus (kWh/day)	220.86	7.87
Useful end-use utilization	65.75%	84.66%
Surplus recovery	0%	95.95%

Note: Ballast and residual-surplus energies are compared on a source-equivalent basis.

These findings are subject to the adopted modeling assumptions. The daily analysis uses average-value conversion stages and fixed component efficiencies, while the switched-inverter analysis uses an average-value source-rectifier representation. Detailed generator electromagnetic dynamics, semiconductor thermal losses, field-measured flow and load profiles, and site-specific hydraulic pipe losses were not included. These aspects require hardware and site-based validation.

5. Conclusion

This study developed and evaluated a dual-inverter VFD framework for regulating domestic supply and productively utilizing surplus generation in a standalone MHPP. Under identical 24-hour resource and demand profiles, the proposed system maintained 99.93% domestic energy service while recovering 95.95% of the available DC-side surplus through pump operation. Compared with the conventional ELC, useful end-use utilization increased by 18.91 percentage points, and the source-equivalent ballast or residual-surplus energy decreased from 220.86 to 7.87 kWh/day. The switched-inverter assessment also demonstrated satisfactory DC-link and load-side regulation, with an output-voltage THD of 3.996%. These findings indicate that productive surplus allocation can substantially reduce dissipative ballast

loading without materially compromising priority-load service. Future work should include experimental validation, measured seasonal flow and demand profiles, detailed converter-loss modeling, and site-specific hydraulic assessment.

Acknowledgement

This research project is supported by the Second Century Fund (C2F), Chulalongkorn University.

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