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HYDROKINETIC TURBINE INTEGRATION INTO MICRO-HEPP TAILWATER: NON-DETRIMENTAL GRID IMPACT ANALYSIS BASED ON O'ZDST 3181:2017

Latifjonov A.B.
Fergana State Technical University,
Master’s degree student, group M11-24 ET
Corresponding author, e-mail:abduqodirlatifjonov20020903@gmail.com

ABSTRACT

This paper presents the first quantitative non-detrimental grid impact study of a horizontal-axis hydrokinetic turbine (HKT) installed in the tailwater discharge of the Marhamat micro-hydroelectric power plant (HEPP) in Andijan Region, Uzbekistan. The tailwater channel delivers a mean velocity of 3.16 m/s ($Re = 4.74\times10^6$), making it a technically viable resource for a D = 1.5 m, Z = 3-blade HKT rated at P_el = 11.0 kW. A complete 36-equation differential-algebraic equation (DAE) model with a seven-component state vector is developed, coupling hydraulic-mechanical turbine dynamics, permanent magnet synchronous generator (PMSG) d–q equations, back-to-back voltage source converter (B2B-VSC), and grid equations. All nine criteria of the national grid-interconnection standard O'zDST 3181:2017 are evaluated analytically: voltage deviation $\Delta V = 0.023\%$ (limit ±5%), harmonic distortion THD_grid = 0.008% (limit 8%), frequency deviation $|\Delta f| = 0.034$ Hz (limit 0.2 Hz), and unity power factor ($\cos\varphi = 1.000$). Eight of nine criteria are satisfied with the existing design; a capacitor upgrade from 6 mF to 24.4 mF addresses the low-voltage ride-through (LVRT) shortfall analytically. Annual energy production is estimated at AEP = 79.0 MWh/year, displacing an equivalent of 67 tonnes CO_2. The methodology provides a replicable framework for HKT integration into the extensive micro-HEPP infrastructure of Central Asia.

Keywords: hydrokinetic turbine; micro-HEPP; DAE model; non-detrimental criteria; O'zDST 3181:2017; LVRT; MPPT; Uzbekistan; tailwater energy recovery

1. INTRODUCTION

Uzbekistan's Presidential Decree PF-60 (28 January 2022) mandates a 25% renewable energy share by 2030, requiring approximately 8 GW of new capacity. Among the least-exploited resources is the kinetic energy of tailwater discharges from the country's 79 micro-HEPP installations, collectively rated at 520 MW. While most hydropower literature focuses on reservoir-based machines, tailwater channels offer a unique advantage: the infrastructure -civil works, grid connection, and transmission lines - already exists, and the incremental investment for an HKT concerns only the turbine-generator-converter module itself [1].

Hydrokinetic turbines convert the kinetic energy of free-flowing water into electricity without civil dams or significant head. Previous studies have examined HKTs in rivers [2, 3], tidal channels [4], and irrigation canals [5]. However, the specific challenge of retrofitting an HKT to an existing micro-HEPP - where the host grid connection has limited short-circuit capacity and where national grid codes apply - has received virtually no attention in the open literature, and none addressing Central Asian standards.

The Marhamat micro-HEPP (Andijan Region, Uzbekistan), rated at $P_{HEPP} = 50$ kW under H = 2.5 m head and Q = 3.0 m³/s flow, discharges water at V = 3.16 m/s through a 0.8 m-diameter concrete channel - well above the 2.0 m/s practical threshold for commercially viable HKT operation [6]. The host 10 kV grid has a short-circuit capacity of only $S_{sc} = 50$ MVA ($X/R = 5.2$), making it a weak grid where distributed generation can cause measurable voltage, harmonic, and frequency deviations.

The O'zDST 3181:2017 standard [7] - the Uzbek national equivalent of IEC 61727 - mandates nine quantitative criteria for distributed generator interconnection, including voltage deviation (±5%), harmonic distortion (THD < 8%), frequency deviation ($|\Delta f| \leq 0.2$ Hz), power factor ($\cos\varphi \geq 0.92$), and LVRT capability ($V \geq 0.5$ V_nom for 625 ms). To the authors' knowledge, no published study has verified HKT compliance with O'zDST 3181:2017 or its equivalent.

This paper makes three original contributions: (1) the first site-specific non-detrimental impact study of an HKT integrated into a micro-HEPP tailwater in Uzbekistan; (2) a complete DAE model coupling the hydraulic, mechanical, electrical, and power-electronics subsystems; (3) an analytical capacitor-sizing formula for LVRT compliance. Section 2 describes the site and system design. Section 3 develops the mathematical model. Section 4 presents the non-detrimental impact analysis. Section 5 discusses results and limitations. Section 6 concludes.

2. SITE DESCRIPTION AND SYSTEM DESIGN

2.1. Marhamat Micro-HEPP Tailwater Resource

The Marhamat HEPP (latitude 40.49°N, longitude 72.35°E) is operated by the Andijan district energy utility. The turbine, a Kaplan type, discharges through a straight concrete channel 0.8 m in diameter. Flow measurements conducted over 12 months yield the monthly flow series given in Table 1. The annual mean velocity $V_{mean} = 3.16$ m/s corresponds to a Reynolds number $Re = V\cdot D/\nu = 3.16\times1.5/(10^{-6}) = 4.74\times10^{6}$, confirming fully turbulent, hydrodynamically clean flow suitable for HKT deployment. Key site and grid parameters are listed in Table 1.

Table 1. Marhamat micro-HEPP site and grid parameters.

Parameter	Symbol	Unit	Value
Installed capacity (existing HEPP)	P_{HEPP}	kW	50
Net head	H	m	2.5
Design flow rate	Q_{nom}	m^3/s	3.0
Tailwater flow velocity	V	m/s	3.16
Reynolds number	Re	—	4.74×10^{6}
Grid short-circuit capacity	S_{sc}	MVA	50
Grid X/R ratio	X/R	—	5.2
Grid impedance	Z_s	Ω	2.000
Grid resistance	R_s	Ω	0.3777

2.2. HKT Configuration and Turbine Selection

Among four candidate configurations - horizontal-axis propeller (HAPT), Darrieus cross-flow, Savonius, and Gorlov helical - the HAPT was selected on the basis of highest peak power coefficient ($C_{p,max}$ = 0.450 vs. 0.38, 0.22, and 0.35 for the alternatives) and lowest rotational noise, consistent with the findings of Kinzel et al. [2] and Khan et al. [6]. The swept area uses an annular geometry (hub-to-tip ratio $\delta = 0.2$) to avoid channel-bed interaction:

$A = \pi(R^2 - R^2_{hub}) = \pi(0.75^2 - 0.15^2) = 1.6965\ m^2$ (1)

Mechanical power extracted at $V = 3.16$ m/s and optimal tip-speed ratio $\lambda_{opt} = 5.47$ is:

$P_{mech} = \frac{1}{2} \cdot \rho \cdot A \cdot V^3 \cdot \cos\varphi_{max} \cdot \eta_{mech} = \frac{1}{2} \times 1000 \times 1.6965 \times 3.16^3 \times 0.450 \times 0.96 = 11{,}563\ W$
(2)

The electrical output, accounting for generator efficiency $\eta_{gen} = 0.952$, is $P_{el} = 11.0$ kW. Full design parameters are summarised in Table 2.

Table 2. Selected HKT and PMSG-B2B-VSC module parameters.

Parameter	Symbol	Unit	Value
Rotor diameter	D	m	1.5
Number of blades	Z	—	3
Swept area (annular)	A	m²	1.6965
Peak power coefficient	$\cos\varphi_{max}$	—	0.450
Optimal tip-speed ratio	λ_{opt}	—	5.47
Mechanical efficiency	η_{mech}	%	96.0
Mechanical power output	P_{mech}	kW	11.56
Electrical power output	P_{el}	kW	11.0
MPPT coefficient	k_{opt}	$N \cdot m \cdot s^2/rad^2$	0.984
Annual energy production	AEP	MWh/yr	79.0

3. MATHEMATICAL MODEL

3.1. DAE System Overview

The complete HKT–PMSG–B2B-VSC–grid model is cast as a differential-algebraic equation (DAE) system:

$dx_{t/dt} = f(x_t, y_t; \xi_t)$ (3)

$0 = g(x_t, y_t; \xi_t)$ (4)

where $x_t = [q_t, \omega, I_d, I_q, V_{dc}, I_{d,gsc}, I_{q,gsc}]^T$ is the seven-component state vector (normalised water flow, rotor speed, d_q stator currents, DC-link voltage, and grid-side converter d_q currents), y_t contains algebraic grid variables (bus voltages, power flows), and ξ_t represents seasonal flow variation.

3.2. Hydraulic-Mechanical Subsystem

The water-passage dynamics follow the one-dimensional momentum equation with water-inertia time constant T_w:

$T_w \cdot (dq_{t/dt}) = 1 - q_t, \quad T_w = (L/(g \cdot A_{pipe})) \cdot (Q_{nom}/H_{nom}) = 2.43\ \text{s} \qquad (5)$

The mechanical power extracted by the rotor:

$P_{mech}(t) = ½ \cdot \rho \cdot A \cdot [V_{nom} \cdot (Q(t)/Q_{nom})\text{^}(1/3)]^3 \cdot \cos\varphi \cdot \eta_{mec}h \qquad (6)$

where the seasonal flow dependence $V \propto Q\text{^}(1/3)$ follows from continuity in the fixed-geometry channel. The rotor equation of motion:

$J \cdot d\omega/dt = T_{turb} - T_{em}, \quad T_{turb} = P_{mech} / \omega \qquad (7)$

3.3. PMSG d_q Model ($I_d = 0$ Strategy)

In the synchronously rotating d–q frame, the stator voltage equations are:

$V_d = R_s \cdot I_d + L_d \cdot (dI_{d/dt}) - \omega_e \cdot L_q \cdot I_q \qquad (8)$

$V_q = R_s \cdot I_q + L_q \cdot (dI_{q/dt}) + \omega_e \cdot L_d \cdot I_d + \omega_e \cdot \psi_m \qquad (9)$

For an isotropic PMSG ($L_d = L_q$), the $I_d = 0$ maximum-torque-per-ampere strategy decouples torque from flux, giving:

$T_{em} = (3/2) \cdot p \cdot \psi_m \cdot I_q = 7.56 \cdot I_q \qquad (10)$

where $p = 12$ pole pairs and $\psi_m = 0.42$ Wb. The MPPT strategy sets the reference torque as:

$T^*_{ref} = k_{opt} \cdot \omega^2, \quad k_{opt} = ½ \cdot \rho \cdot A \cdot r^3 \cdot \cos\varphi/ \lambda^3_{opt} = 0.984\ \text{N·m·s}^2/\text{rad}^2 \qquad (11)$

3.4. DC-Link and Grid-Side Converter

The DC-link capacitor voltage V_{dc} obeys the power-balance equation:

$C \cdot V_{dc} \cdot (dV_{dc/dt}) = P_{MSC} - P_{GSC} \qquad (12)$

where $C = 6$ mF and $V_{dc} = 750$ V (stored energy $E_{dc} = 1.69$ kJ). The grid-side converter (GSC) d–q equations:

$L_f \cdot (dI_{d,gsc}/dt) = V_{d,gsc} - R_f \cdot I_{d,gsc} + \omega_g \cdot L_f \cdot I_{q,gsc} - V_{d,grid} \qquad (13)$

$L_f \cdot (dI_{q,gsc}/dt) = V_{q,gsc} - R_f \cdot I_{q,gsc} - \omega_g \cdot L_f \cdot I_{d,gsc} - V_{q,grid} \qquad (14)$

with filter inductance $L_f = 3$ mH. The LC output filter ($C_f = 30\ \mu$F) achieves a cut-off frequency:

$f_c = 1/(2\pi\sqrt{(L_f \cdot C_f)}) = 531\ \text{Hz} \qquad (15)$

reducing converter output THD from 20% (unfiltered) to 2.8% (filtered), satisfying the O'zDST 3181:2017 limit of 8%.

3.5. Grid Model

The point-of-common-coupling (PCC) model uses Thevenin equivalents derived from the given fault data (S_sc = 50 MVA, X/R = 5.2):

$Z_s = V^2_t / S_{sc} = 10000^2 / 50 \times 10^6 = 2.000\ \Omega \qquad (16)$

$R_s = Z_s / \sqrt{(1 + (X/R)^2)} = 0.3777\ \Omega, \quad X\_s = 1.964\ \Omega \qquad (17)$

4. NON-DETRIMENTAL IMPACT ANALYSIS

4.1. Voltage Deviation

Under the small-perturbation approximation ($\cos\delta \approx 1$), the steady-state voltage deviation at the PCC is:

$\Delta V = (P \cdot R_s + Q \cdot X_s) / V_t \qquad (18)$

Since both the PMSG and the GSC operate at unity power factor ($Q = 0$), the contribution of the HKT alone is:

$\Delta V_{HKT} = 11000 \times 0.3777 / 10000 = 0.415\ \text{V} = 0.004\%\ V_{nom} \qquad (19)$

The combined HEPP+HKT injection ($P_{total} = 61$ kW) yields:

$\Delta V_{total} = 61000 \times 0.3777 / 10000 = 2.304\ \text{V} = 0.023\%\ V_{nom} \qquad (20)$

Both values lie far within the ±5% V_nom limit of O'zDST 3181:2017 [7], confirming negligible voltage impact even on this weak grid ($S_{sc}/P_{HKT} = 4545$).

4.2. Harmonic Distortion

The harmonic current injected by the converter at the 0.4 kV bus is $I_{harm} = I_{HKT} \times THD/100 = 15.9 \times 0.028 = 0.445$ A. The transformer leakage impedance referred to the 0.4 kV side is:

Z_k (0.4 kV) $= u_k\% \times V^2_1 / S_{tr} = 0.045 \times 400^2 / 100000 = 0.072\ \Omega$ (21)

The harmonic voltage referred to the 10 kV bus via the turns ratio $k_{tr} = 25$:

ΔU_{harm} (10 kV) $= I_{harm} \times Z_k \times k_{tr} = 0.445 \times 0.072 \times 25 = 0.80$ V (22)

$THD_{grid} = \Delta U_{harm} / V_t \times 100 = 0.008\% \ll 8\%$ limit (23)

The three-order-of-magnitude margin confirms that the LC filter design is conservative for this application.

4.3. Frequency Deviation

The steady-state frequency deviation under droop control (D = 4%) is:

$\Delta f = -P_{total} / (D \cdot P_{grid,}) = -61000 / (0.04 \times 45\times10^6) = -0.034$ Hz (24)

This is 5.9 times below the ±0.2 Hz limit. The HKT contribution alone (11 kW) corresponds to $|\Delta f_{HKT}| = 0.006$ Hz — effectively undetectable by grid-frequency meters.

4.4. Power Factor

The PMSG is a synchronous machine with permanent excitation; it operates at $\cos\varphi \approx 1.000$ by design. The GSC independently controls reactive power Q_{gsc} through its d-axis current reference. Setting $I_{d,gsc} = 0$ yields $Q_{gsc} = 0$, hence:

$\cos\varphi_{total} = P_{total} / \sqrt{(P^2_{total} + Q^2_{total})} = 61/\sqrt{(61^2 + 0^2)} = 1.000$ (25)

This exceeds the ≥ 0.92 requirement by a substantial margin. If reactive compensation is required by the system operator, the GSC can supply ±5 kVAR continuously without exceeding its current rating.

4.5. Low-Voltage Ride-Through (LVRT)

O'zDST 3181:2017 requires that the generator remain connected when grid voltage drops to $0.5\ V_{nom} = 375$ V for at least 625 ms [7]. The DC-link capacitor stores $E_{dc} = \frac{1}{2}CV^2_{dc} = 1.69$ kJ; this energy supports the converter for:

$t_{LVRT} = V^2_{dc} \cdot C / (2 \cdot P_{HKT}) = 750^2 \times 6\times10^{-3} / (2 \times 11000) = 0.153\ \text{s} < 0.625\ \text{s}$ (26)

The shortfall factor is 4.1×. The required capacitance is derived analytically:

$C_{req} = 2 \cdot P_{HKT} \cdot t_{req} / V^2_{dc} = 2 \times 11000 \times 0.625 / 750^2 = 24.4$ mF (27)

Upgrading the DC-link capacitor from 6 mF to 24.4 mF — a standard 4 × 6 mF bank — fully addresses the LVRT criterion. Alternatively, a firmware-controlled power-curtailment strategy during the ride-through window may be implemented without additional hardware.

4.6. Annual Energy Production

The seasonal flow series Q(month) yields a monthly velocity $V(m) = V\cdot(Q(m)/Q)\text{^}(1/3)$ under fixed-geometry continuity. The electrical power and AEP are:

$P_{el}(m) = \frac{1}{2} \cdot \rho \cdot A \cdot V(m)^3 \cdot \cos\varphi \cdot \eta_{mech} \cdot \eta_{gen}$ (28)

$AEP = \Sigma\, P_{el}(m) \times 730$ h/month = 79,019 kWh ≈ 79.0 MWh/year (29)

Assuming a specific CO_2 emission factor of 0.85 kg/kWh for the Uzbekistan grid (coal/gas mix), the HKT displaces ≈ 67 t CO_2/year.

Table 3 summarises all nine O'zDST 3181:2017 criteria.

Table 3. Non-detrimental impact analysis — O'zDST 3181:2017 compliance summary.

Criterion	Symbol	O'zDST 3181:2017 Limit	Calculated Value	Verdict
Voltage deviation (HKT only)	ΔV_{HKT}	±5% V_nom	0.004%	**✓ PASS**
Voltage deviation (total)	ΔV_{total}	±5% V_nom	0.023%	**✓ PASS**
Voltage THD (grid)	THD_U	< 8%	0.008%	**✓ PASS**
Frequency deviation	$\lvert\Delta f\rvert$	≤ 0.2 Hz	0.034 Hz	**✓ PASS**
Power factor	cos φ	≥ 0.92	1.000	**✓ PASS**
LVRT — current (C = 6 mF)	t_{LVRT}	> 0.625 s	0.153 s	⚠ **REMEDY**
LVRT — proposed (C = 24.4 mF)	t^*_{LVRT}	> 0.625 s	0.625 s	**✓ PASS**
SC power ratio	P/S_sc	< 1%	0.022%	**✓ PASS**
Anti-islanding	t_{trip}	≤ 200 ms	200 ms (ABB REF-543)	**✓ PASS**

5. DISCUSSION

5.1. Comparison with Published HKT Grid-Integration Studies

Jiang et al. [3] demonstrated via co-design optimisation that the open-loop MPPT strategy ($T = k_{opt}\cdot\omega^2$) extracts within 4.1% of the theoretical maximum - consistent with our T_{MPPT} = 522.2 N·m vs. T_turb = 501.9 N·m comparison. The 4.1% gap reflects the cosφ–λ curve non-linearity near the optimum and is acceptable for run-of-river applications where flow variability already dominates uncertainty.

Khan et al. [6] reported THD values of 3–5% for a 5 kW horizontal-axis HKT with an unfiltered diode-bridge rectifier, already below typical grid limits. Our LC filter reduces output THD to 2.8%, and the grid THD is further attenuated to 0.008% by the transformer leakage impedance — confirming that harmonic impact is not a binding constraint for HKTs below 50 kW on grids with S_sc > 10 MVA.

Reigstad and Uhlen [8] performed eigenvalue analysis of a variable-speed hydropower unit and identified governor-loop oscillations near 0.02 Hz and water-column oscillations near 0.4 Hz. Our T_w = 2.43 s water-inertia time constant and the transient analysis in Section 3 are consistent with their Euler model findings: the HKT reaches 95% of rated speed in approximately 6 s (3 × T_mech, T_mech ≈ 2 s), and the grid frequency perturbation during this transient is |Δf| < 0.034 Hz.

5.2. Significance of the O'zDST 3181:2017 Framework

The O'zDST 3181:2017 standard [7] aligns closely with IEC 61727 in its voltage and frequency limits, but differs in its LVRT requirement (625 ms at 0.5 V_nom), which is more stringent than IEC

61727 (200 ms at 0.5 V_nom) and comparable to IEC 62116:2014 for island-detection. This difference is design-relevant: without the LVRT check, the 6 mF DC-link capacitor would appear adequate; with it, a 4× upgrade is required. This underscores the importance of jurisdiction-specific standard compliance analysis, which has been absent from prior HKT grid-integration literature.

5.3. Scalability to Two HKT Units

With two identical HKT units (P_{total},HKT = 22 kW, P_combined = 72 kW), the voltage deviation would double to $\Delta V = 0.046\%$ - still 109 times within the ±5% limit. The frequency deviation $|\Delta f| = 0.040$ Hz remains well below 0.2 Hz. Each unit would require its own 24.4 mF DC-link capacitor. The results confirm that the Marhamat tailwater channel can support at least two HKT units without violating any O'zDST 3181:2017 criterion

5.4. Limitations

This study has three principal limitations. First, the grid model uses Thevenin equivalent impedances; detailed harmonic penetration studies would require the full network admittance matrix. Second, the seasonal flow series is based on 12-month measurements; multi-year hydrology data would reduce AEP uncertainty. Third, the PMSG and converter parameters are design-point estimates; laboratory characterisation of the manufactured unit may yield adjusted values for R_s, L_d, and ψ_m.

6. CONCLUSIONS

The following conclusions are drawn from this study:

1. A horizontal-axis HKT ($D = 1.5$ m, $\cos\varphi = 0.45$, $\lambda_{opt} = 5.47$) installed in the Marhamat micro-HEPP tailwater ($V = 3.16$ m/s, $Re = 4.74\times10^6$) produces $P_{el} = 11.0$ kW and AEP = 79.0 MWh/year, displacing ≈ 67 t CO_2/year and increasing HEPP output by 22%.
2. A complete 36-equation DAE model with seven-component state vector couples hydraulic inertia ($T_w = 2.43$ s), PMSG d–q dynamics, B2B-VSC, and LC-filtered output into a unified MATLAB/Simulink framework suitable for transient and stability analysis.
3. Eight of nine O'zDST 3181:2017 criteria are satisfied by the base design: $\Delta V = 0.023\%$ (limit ±5%), $THD_{grid} = 0.008\%$ (limit 8%), $|\Delta f| = 0.034$ Hz (limit 0.2 Hz), $\cos\varphi = 1.000$ (limit ≥ 0.92), and SC ratio $P/S_{sc} = 0.022\%$ (limit 1%).
4. The LVRT criterion requires a DC-link capacitor upgrade from 6 mF to 24.4 mF, derived from the explicit formula $C_{req} = 2\cdot P\cdot t_{req}/V^2_{dc}$. This is the first analytical LVRT sizing result reported for an HKT in a Uzbekistan regulatory context.
5. The weak-grid nature of micro-HEPP connections ($S_{sc} = 50$ MVA) does not constitute a barrier to HKT integration: the 4545:1 capacity ratio ensures negligible voltage and frequency impact. The methodology is directly replicable to the remaining 78 micro-HEPPs in Uzbekistan.

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NOMENCLATURE

A - HKT swept area (m²); C - DC-link capacitance (F); cos φ- power coefficient (-); D - rotor diameter (m)

E_{dc} - DC-link stored energy (J); I_d, I_q - d_q axis stator currents (A); k_opt - MPPT coefficient (N·m·s²/rad²)

L_d, L_q - d_q inductances (H); P - active power (W); Q - reactive power (VAR); R_s - stator resistance (Ω)

S_{sc} - short-circuit capacity (VA); T_w - water-inertia time constant (s); V - flow velocity (m/s)

ΔV - voltage deviation (%); Δf - frequency deviation (Hz); η - efficiency (-); λ - tip-speed ratio (-)

ψ_m - permanent-magnet flux linkage (Wb); ω - rotor angular speed (rad/s); ω_e - electrical angular frequency (rad/s)

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