Adaptive Power Tracking Control of Hydrokinetic Energy Conversion Systems

A thesis submitted to the School of Graduate Studies in partial fulfillment of the requirements for the degree of Doctor of Philosophy

By

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Outline

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  - Hydrokinetic systems, research objective & scope
- Review & Critique
  - Technology status, applied & basic Research
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  - Numerical models, test & validation initiatives
- Controller Evaluation
  - Power tracking control challenges, methods & solutions
- Adaptive Controller Synthesis
  - Extremum Seeking Controller design for hydrokinetic systems
- Conclusion
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• **Introduction**
• Review & Critique
• Modeling & Validation
• Controller Evaluation
• Adaptive Controller Synthesis
• Conclusion
Introduction

Hydrokinetic Energy Conversion Systems

- Electromechanical device that generates electricity by harnessing the kinetic energy of flowing water

- Areas of application: tidal/marine current, river streams, artificial waterways, irrigation canals, dam head/tailrace etc.

- Could be built as a free-rotor or duct augmented system, and deployed as modular multi-unit arrays

- Potentially requires little or no civil work, unlike large hydro power plants
Research Objectives

- Identify the current state of hydrokinetic technologies
  … in the context of associated control challenges

- Develop direct knowledge of a turbine's operational characteristics
  … by undertaking relevant design, develop & test activities

- Identify the power tracking control challenges
  … that are unique to the broader class of hydrokinetic systems

- Investigate on a set of possible alternative solutions
  … through simulation & qualitative evaluation on existing methods

- Formulate an advanced power tracking algorithm
  … that may suit the unique needs of hydrokinetic technologies
Research Scope

- Considerations for broader spectrum of hydrokinetic technologies
- Focus on test, modeling and experiments on a small-scale vertical axis turbine containing
  - multi-pole outer rotor permanent magnet alternator
  - single-phase utility grid with a power electronic (ac-dc-ac) link
- Design, development & laboratory scale testing
- Validated dynamic numerical models in Matlab-Simulink™
- In-depth maximum power tracking controller analysis/synthesis using the models
- Introduction
- **Review & Critique**
- Modeling & Validation
- Controller Evaluation
- Adaptive Controller Synthesis
- Conclusion
Review & Critique

Hydrokinetic Systems: Technology Status

- Primarily a nascent technology (demonstration & pre-commercial)
- Both horizontal and vertical axis turbines can be used
- Free-flowing or ducted turbines are being investigated
- Multitude of placement options can be opted

![Diagram of hydrokinetic systems]

<table>
<thead>
<tr>
<th>Vertical Axis</th>
<th>Horizontal Axis</th>
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</thead>
<tbody>
<tr>
<td>(a) Hybrid (Curvilinear)</td>
<td>(d) Rectilinear Diffuser</td>
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<tr>
<td>(b) Hybrid (Rectilinear)</td>
<td>(e) Rectilinear Diffuser</td>
</tr>
<tr>
<td>(c) Multiple Hydrofoil Diffuser</td>
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</table>
Review & Critique

Control of Hydrokinetic Turbines

- **Recent work**: Robust gain scheduling controller ($H_\infty$ linear parameter varying) [Ginter, 2009]

- **Early work**: PID type tips speed ratio controller (horizontal axis turbine) [Tuckey et. al., 1997]

- **Other works**: High-level wind oriented [Ben Elghali et. al. 2008] & applied work [Mattarolo et. al. 2006, MCT 2008]

- **Supporting knowledge-base**: Wind energy and solar photovoltaic maximum power point tracking control literature [various publications]
Introduction

Review & Critique

Modeling & Validation

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Modeling & Validation

Flow Field Representation

- To identify various flow field components affecting a hydrokinetic system and assess their possible impacts on the overall power extraction.

- To analyze the time scale of variation reflecting the dynamics of relevant flow field components.

- To establish the magnitude and range of various flow field parameters that are of interest to the power tracking control problem.
Modeling & Validation

Flow Field Representation (cont’d)

- Power captured by a hydrokinetic turbine rotor:

\[
P_{rot} = \frac{1}{2} C_p \rho_w A_r v_p^3 k_{dp}
\]
\[
k_{dp} = k_{aug} \times k_{prof} \times k_{skew} \times k_{yaw}
\]

- Elements of the flow field

Controlled element  
Flow field elements  

→ Water density (temperature, salinity, pressure)  
→ Effective area (level of submersion, boundary layer)  
→ Water velocity (mean, stochastic, wave induced)  

\[
P_{rot} = \frac{1}{2} C_p \rho_w A_r v_p^3 k_{dp}  
\]

Design and placement related factors  

→ Skewed flow factor  
→ Vertical velocity profile factor  
→ Velocity augmentation factor  

→ Yaw misalignment factor
Flow Field Representation (cont’d)

- Water velocity components:

\[ v_p(t) = \bar{v}_s + v_t(t) + v_w(t) \]

\[ \bar{v}_s = \begin{cases} v_{R}, \text{ River seasonal mean} \\ v_{T}, \text{ Tidal hourly mean} \end{cases} \]

- Synthesis of the water velocity model:
Modeling & Validation

Darrieus Rotor Performance Analysis

- **Darrieus Rotor**

![Darrieus Rotor Diagram](image)

**General principle**

- **Performance curve**

![Performance Curve](image)

- **Relevant terms**

\[
P_{\text{hyd}} = \frac{1}{2} \rho w A_r v_{up}^3
\]

\[
P_{\text{rot}} = C_p \frac{1}{2} \rho w A_r v_{eff}^3
\]

\[
C_p^o = \frac{P_{\text{rot}}}{P_{\text{hyd}}}
\]

\[
C_T^o = \frac{C_p^o}{\lambda}
\]

\[
\lambda = \frac{\omega_{rot} R}{v_{eff}}
\]
Modeling & Validation

**Darrieus Rotor Performance Analysis (cont’d)**

- Performance analysis of Darrieus rotors

- Single-disk multiple-streamtube analysis:

![Diagram](image_url)

(a) Streamtubes uniformly divided by a separation of \( \Delta \theta \)

(b) Velocity vectors

(c) Uniformly distributed flow tubes
Modeling & Validation

Darrieus Rotor Performance Analysis (cont’d)

- Mechanical torque & torque coefficient:
  - With \( m \) number of streamtubes and \( C_{tang} = C_L \sin \alpha_b - C_D \cos \alpha_b \), the mechanical torque is
    \[
    T_{mec} = N_b \frac{\sum_{i=1}^{m} \frac{1}{2} \rho w v_{rel}^2 (CH) C_{tang} R}{m}
    \]
  - Using the normalizing torque \( \frac{1}{2} \rho w v_{eff}^2 DHR \) and solidity \( \sigma_r = \frac{N_b C}{D} \), the torque coefficient (ideal) is
    \[
    C_{T_I}^o = \sigma_r \frac{\sum_{i=1}^{m} \left( \frac{v_{rel}}{v_{up}} \right)^2 C_{tang}}{m}
    \]

- Considerations embedded within the streamtube analysis:
  - Gluert's empirical formula
  - Lift and drag data correction (Reynold's number, Aspect ratio, Angle of attack)
Modeling & Validation

**Darrieus Rotor Performance Analysis (cont’d)**

- Performance curve of a test system (NECI – 4 bladed)
- Emphasis on overall system efficiency
- Estimates are particularly successful in identifying the optimum TSR point

- Divergence high on post-optimum TSR region
- Contrary to expectations, multiple performance curves (at various water speeds) can be observed
Modeling & Validation

Dynamic Modeling of Hydrokinetic System

- Large-signal non-linear model formulations
- Considerations for losses within all the subsystems
- Focus on electromechanical transients (as against electromagnetic transients)

- Detailed synthesis of torque components
- Permanent magnet alternator (PMA) with ac-dc-ac (grid-connected) topology
- Assessment of start-up, torque ripple, and nonlinear efficiency issues
Dynamic Modeling of Hydrokinetic System (Cont’d)

Vertical axis rotor

- **Total rotor torque:** \( T_{rot} = T_{mec} + T_{osc} \)

- **Mechanical input torque:** \( T_{mec} = \frac{1}{2} \rho_w A_r C_T v_{eff}^2 R \)
  - Effective torque coefficient: \( C_T = \frac{C_p}{\lambda} \)
  - Effective power coefficient: \( C_p = \eta_{asw} C_p^o \)
  - Ideal power coefficient: \( C_p^o = f_r(\lambda) \)

- **Oscillating torque:** \( T_{osc} = \hat{T}_{osc} \sin \theta_b \times f_h(I_{gr}) \)
  - Peak ripple torque: \( \hat{T}_{osc} = \frac{T_{mec}}{k_{osc} \lambda} \)
  - Azimuth position: \( \theta_b = \int N_b \omega_{rot} dt \)
Modeling & Validation

Dynamic Modeling of Hydrokinetic System (Cont’d)

Drive-train

- **Rotor torque:** \( T_{\text{rot}} = J_{\text{rot}} \frac{d\omega_{\text{rot}}}{dt} + T_{\text{lss}} + B_{\text{rot}}\omega_{\text{rot}} \)

- **Generator torque:** \( T_{\text{gen}} = \eta_{\text{tran}} \frac{T_{\text{lss}}}{N_{\text{gen}}} \), \( N_{\text{gr}} = \frac{\omega_{\text{gen}}}{\omega_{\text{rot}}} \) (\( N_{\text{gr}} > 1 \))

- **Low-speed shaft torque:** \( T_{\text{lss}} = k_{\text{spr}} \int (\omega_{\text{rot}} - \frac{\omega_{\text{gen}}}{N_{\text{gen}}}) dt \)
Modeling & Validation

Dynamic Modeling of Hydrokinetic System (Cont’d)

Permanent magnet alternator

- Overall torque balance: \[ T_{\text{gen}} = J_{\text{gen}}\omega_{\text{gen}} + B_{\text{gen}}\omega_{\text{gen}} + T_{\text{cog}} + T_{\text{load}} + T_{\text{loss}} \]

- Cogging torque: \[ T_{\text{cog}} = \hat{T}_{\text{cog}} \sin \theta_g \times f_h(-I_{gr}) \]

- Load torque: \[ T_{\text{load}} = \frac{3}{2} \frac{N_P}{2} \lambda_m I_g \]

- Loss torque: \[ T_{\text{loss}} = \frac{P_{\text{nll}} + P_{\text{ll}}}{\omega_{\text{gen}}} - B_{\text{gen}}\omega_{\text{gen}} \]
Dynamic Modeling of Hydrokinetic System (Cont’d)
Rectifier (with capacitive filter)

- Output voltage (before filter): \[ V_{gr}^o = \frac{3\sqrt{3}}{\pi}V_g - 2V_f \]
- Output voltage (after filter): \[ \frac{V_{gr}}{V_{gr}^o} = \frac{1}{L_{fg}C_{fg}s^2 + R_{fg}C_{fg}s + 1} \]
Modeling & Validation

Dynamic Modeling of Hydrokinetic System (Cont’d)

Converter (zero-current-switching dc-dc architecture)

- Open circuit voltage (steady-state): \( E_{co}^o = \frac{V_{trm}}{2.5} V_{enom} \)
- Terminal voltage under load (steady-state): \( E_{co} = E_{co}^o - \Delta E_{co} \)
- Converter voltage regulation: \( R_{cvr} = \frac{\Delta E_{co}}{E_{co}^o} = \frac{E_{co}^o - E_{co}}{E_{co}^o} \)
- LC filter dynamics & output voltage: \( I_{Lco} = \frac{1}{L_{co}} \int (E_{co} - V_{co}) dt \)
  \[ V_{co} = \frac{1}{C_{co}} \int (I_{Lco} - I_c) dt \]
Modeling & Validation

Dynamic Modeling of Hydrokinetic System (Cont’d)

Inverter (grid-connected dc-ac architecture)

- Design power output: \( P_{inv}^* = 10V_{co} - 250; \) for \( 24 < V_{co} < 48 \)
  \[ P_{inv}^* = 0; \] for \( V_{co} < 24 \) and \( V_{co} > 48 \)

- Inverter output power: \( P_{inv} = \frac{E_{inv}V_{grd}}{X_{io}} \sin \alpha_{pa} \)

- Grid power injection: \( P_{out} = V_{grd}I_i \cos \theta_{pf} \)

- Power angle control: \( \alpha_{pa} = K_{pinv}(P_{inv}^* - P_{out}) + K_{iinv} \int (P_{inv}^* - P_{out})dt \)

- Line filter dynamics: \( L_{io} \frac{dI_i}{dt} + R_{io}I_i = V_{ilf} \)
Modeling & Validation

Dynamic Modeling of Hydrokinetic System (Cont’d)

Overall model

- Implemented in Matlab-Simulink™
- Model strength: readily usable & numerically stable
- Disturbance inputs are: water flow & velocity variation
- Control variable is: converter trimming voltage
- Output variables are: rotational speed & electrical power
- Component validation: rotor, generator, rectifier, converter, inverter

Part-system validation: rotor, generator, rectifier + load
Modeling & Validation

Test Apparatus and Model Validation

Permanent magnet alternator (with rectifier)

(a) (b)

Steady state

Dynamic

Rotor magnets

Stator coils

Rotor magnets

Outer rotor permanent magnet generator

Test setup
Modeling & Validation

Test Apparatus and Model Validation (cont’d)

dc-dc converter

![Image showing test apparatus and model validation]

Dynamic

Steady state

- Test data with $V_{gr} = 25$
- Test data with $V_{gr} = 45$
- Design estimate

- Data points: measured
- Curves/lines: simulated

- $V_{trm} = 2.5; V_{gr} = 45$
- $V_{trm} = 2.27; V_{gr} = 35$
- $V_{trm} = 1.98; V_{gr} = 25$

Ch A: converter voltage (10V/d)
Ch B: converter current (1 A/d), Current probe setting 100 mV/A

Converter output voltage (V)
Converter output current (A)
Modeling & Validation

Test Apparatus and Model Validation (cont’d)

dc-ac inverter

Steady state

Dynamic

Data points: measured
Curves/lines: simulated

Output power (watt)

Output current (A)

Inverter input voltage (V)

Input voltage (V)

Ch A: input voltage (20V/d)
Ch B: inverter current (2A/d);
Current probes setting 100 mV/A

Steady state
MUN 3-bladed
- NACA 63-018 blades, chord 6.25 cm, height 0.75 m, diameter 0.75 m, solidity 25%.
- Poor start-up due to low blade count & weak structure.

MUN 6-bladed
- NACA 0012 blades, chord 6.75 cm, height 0.4 m and diameter 0.8 m, solidity 50%.
- Poor start-up due to heavy mass, poor efficiency.

NECI 4-bladed
- NACA 0015 blades, chord 10.1 cm, height 0.4 m, diameter 1 m, solidity 40%.
- Promising overall performance.
Test Apparatus and Model Validation (cont’d)

Tow-tank test apparatus (instrumentations)

- NECI 4-bladed rotor coupled to a multi-pole outer rotor PMG
- Chain-sprocket gear coupling between rotor shaft and generator
- Diode bridge at the generator output coupled to a capacitor bank and switchable load
- Customized DAQ unit with 4 sensed signals (rotor speed, flow velocity, load voltage, load current)
Test Apparatus and Model Validation (cont’d)

Tow-tank test apparatus (test conditions)

- Tested at MUN OERC tow tank (~55 m length)
- Each run was limited to 15-25 seconds
- Rotor mounting required special arrangements
- Start-up and loading manually adjusted.
Cogging in PMG directly affects start-up behavior

- Unloaded rotor self-starts at 0.65 ~ 0.75 m/s
- Test prototype with load self-starts at 1.75 ~ 1.85 m/s
- Simulations successfully exhibit similar behavior
Test Apparatus and Model Validation (cont’d)

Tow-tank test apparatus (model validation – torque ripple)

- Torque ripple is reflected on load current
- System inertia and capacitor bank reduce low frequency ripple
- Ripple magnitude is dominant in low TSR conditions
- Ripple frequency directly relates to rotor speed
- Exact instance of ripple occurrence is time-shifted in simulation.
Test Apparatus and Model Validation (cont’d)

Tow-tank apparatus (model validation – overall performance)

- Incorporation of non-linearity directly affects representation of overall power output and efficiency
- Subtle improvements can be made (e.g., efficiency calculations)
- Overall peak efficiency is ~ 20% and optimum TSR is ~ 2.15 for this system
- Simulation time is short and tests conform to simulations.
Introduction
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Controller Evaluation
Adaptive Controller Synthesis
Conclusion
Controller Evaluation

Control Objectives & Regions

- **General objective:**
  To achieve acceptable steady-state and transient performance

- **Specific objective:**
  To adjust the rotor speed such that the maximum power point can be tracked

- **Control Regions:**
  - Start-up, maximum power tracking (MPT) and speed-limiting
  - Hydrokinetic systems exhibits wide MPT region
Controller Evaluation

Control Objectives & Regions (cont’d)

- **Technological diversity:**
  
  *Which MPT method would suit horizontal/vertical, ducted/free-flowing, partial/full submersion, if at all possible?*

- **State of the technology:**
  
  *How to gain confidence in a particular MPT method, given little operational experience exists?*

- **Resource conditions:**
  
  *How to adjust a turbine’s operational parameters against variations in water velocity, level, density, etc.?*

- **Turbine design and operation:**
  
  *To what extent the Cp vs. TSR curve can be relied upon toward MPT controller synthesis (uncertain curve profile, over-time drifts/degradation, and possible local maxima/minima)*

- **Underwater instrumentation:**
  
  *How to avoid reliance upon flow measuring instruments in implementing a MPT controller?*
Controller Evaluation

Effects of Efficiency Nonlinearity

- Noticeable nonlinearity within various subsystems’ efficiency characteristics can be observed.
- In addition to achieving optimum TSR, other control requirements are present.
Controller Evaluation

Effects of Efficiency Nonlinearity (cont’d)

- Method to realize the true shape of the performance curve & power curve needs to be developed

- An iterative method using a-priori knowledge of all the subsystems’ efficiency profile (after normalization to a base quantity) is proposed
Controller Evaluation

Effects of Efficiency Nonlinearity (cont’d)

- **System A**: Typical system with nonlinearity in the front-end (rotor performance) only
- **System B**: Physical system (test hardware) with true nonlinearity in all subsystems
- **System C**: Fictive system with significant nonlinearity in more than one subsystems

![Diagram](image)

- **Estimated curve**
  - **System A**: Typical system with nonlinearity in the front-end (rotor performance) only
  - **System B**: Physical system (test hardware) with true nonlinearity in all subsystems
  - **System C**: Fictive system with significant nonlinearity in more than one subsystems
Controller Evaluation

Candidate Control Methods

- Power tracking methods applied in wind & photovoltaic systems

- Three basic control methods in wind energy systems can be identified (based on parameters being measured/controlled):
  - Tip speed ratio (TSR) method
  - Power signal feedback (PSF) method
  - Hill climbing search (HCS) method

- Other methods (such as, torque control, velocity estimation, etc.) can be shown to be variants of these methods.
Candidate Control Methods (cont’d)

Tip speed ratio (TSR) method:

- Most fundamental and the most direct method
- Seldom used due to high reliance on flow measurement
- Depends entirely on the prior knowledge of the normalized performance curve
- Simulation with a P-type controller: $V_{trim}^* = k_{ptsr} (\hat{\lambda} - \lambda)$
- Block representation:
Candidate Control Methods (cont’d)

Power signal feedback (PSF) method:

- Needs dimensional performance curves (‘power vs. speed’ or ‘torque vs. speed’ curve)
- Simulation with a P-type controller: \( V_{trm}^* = k_{ppsf} (\omega_{rot}^* - \omega_{rot}) \)
- Optimum/reference speed: \( \omega_{rot}^* = \left( \frac{P_{sys}^*}{k_{nch_{eff}}} \right)^{\frac{1}{3}} \)

where \( \hat{\lambda} = \frac{\omega_{rot}^* R}{v_{eff}} \) and \( k_{ncc} = \rho w R^4 \frac{C_p}{\lambda^3} k_{cf} \)

- Block representation:
Candidate Control Methods (cont’d)

Hill climbing search (HCS) method:
- Changes in rotor speed and variations in power output are measured
- Tracking reference is generated in an iterative manner
  \[
  \omega^*_{rot}(k + 1) = \omega^*_{rot}(k) + \Delta \omega^*_{rot}
  \]
  \[
  \Delta \omega^*_{rot} = \text{sign}(\Delta \omega_{rot}, \Delta P_{sys}) \times |\Delta \omega^*_{rot}|
  \]
- Sign and magnitude of incremental tracking reference can be found by
  \[
  |\Delta \omega^*_{rot}| = k_{phcs} |\Delta P_{sys}|
  \]
  \[
  \text{sign}(\Delta \omega_{rot}, \Delta P_{sys}) = \text{sign}(\Delta \omega_{rot}) \times \text{sign}(\Delta P_{sys})
  \]
- Rotor speed is controlled around the new tracking information
  \[
  V^*_{trm} = k_{phcs} (\omega^*_{rot}(k + 1) - \omega^*_{rot})
  \]
- Block representation:
Controller Evaluation

Candidate Control Methods (cont’d)

Implementation in Matlab-Simulink™:
Controller Evaluation

Candidate Control Methods (cont’d)

Simulation results:

- **TSR**
- **PSF**
- **HCS**

Output power (watt)

Water height (m)

Water velocity (m/s)
Controller Evaluation

Candidate Control Methods (cont’d)

- **Tip speed ratio (TSR) method:**
  - Superior steady-state and dynamic characteristics
  - Conceptually simple
  - Absolute reliance on a-priori knowledge of the optimum operating point
  - Velocity measurement is required, which is prone to reliability and accuracy issues

- **Power signal feedback (PSF) method:**
  - Moderate steady-state and dynamic characteristics
  - Conceptually simple & less dependent on a-priori knowledge
  - Possibilities of sub-optimal operation
  - Controller design process is often subject to device specific parameter tuning
  - Water level measurement is required, which is prone to reliability and accuracy issues

- **Hill climbing search (HCS) method:**
  - Model/device independent and exhibits adaptive performance
  - Can be implemented without using underwater sensors
  - System output can be oscillatory in nature and no guarantee of system stability
  - Step size needs to be properly tuned considering the turbine dynamics and settling time
Candidate Control Methods (cont’d)

Attributes of a more suitable power tracking controller for hydrokinetic systems:

- **Adaptive**
  ... *adapts to variations in internal and external parameters & disturbances*

- **Sensorless**
  ... *does not require underwater instrumentation (i.e, flow/speed sensors)*

- **Model independent**
  … *can be tuned without relying on the performance curve & model details*
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Adaptive Controller Synthesis

**Extremum Seeking Control (ESC)**

- A special class of non-linear adaptive control method
- Model-independent and self-regulating to an unknown setpoint
- Particularly suitable where a single maximum or minimum characterizes the non-linearity
- Primary difference with mainstream adaptive control methods: ESC is capable of working under unknown reference
- Early research dates back to 1922, significant work done during 1940-1970 through Soviet-era activities
- Series of fundamental works by Krsti´c et. al. has caused a noticeable resurgence
- Application in wind, solar photovoltaic & fuel-cell systems being reported
Adaptive Controller Synthesis

Extremum Seeking Control (cont’d)

Principles of ESC, plants with static nonlinearity:

- Plant model: \( f_x(\theta_x) = f_x^* + \frac{1}{2} f_x''(\theta_x - \theta_x^*)^2 \)
- Unknown setpoint (maxima): \( \theta_x^* \)
- Plant input: \( \theta_x = a_x \sin(\omega_x t) + \hat{\theta}_x \)
- Estimate of the setpoint: \( \hat{\theta}_x \)
- Estimation error: \( \tilde{\theta}_x = \theta_x^* - \hat{\theta}_x \)
- By entering \( \theta_x - \theta_x^* = a_x \sin(\omega_x t) - \tilde{\theta}_x \) in the plant model, it can be shown that (after reductions): \( \tilde{\theta}_x \approx \frac{1}{2} k_x a_x b_x f_x''(\tilde{\theta}_x) \)
- With \( f_x'' < 0, k_x a_x b_x > 0 \), \( \text{sign}(\tilde{\theta}_x) = \text{sign}(\hat{\theta}_x) \) it is guaranteed that estimation error will always approach zero
- Frequencies of interest (\( \omega_{hx} < \omega_x < \omega_{pa} \)):
  - **Fastest**: Plant dynamics, \( \omega_{pa} \)
  - **Medium**: Perturbation signal frequency, \( \omega_x \)
  - **Slowest**: Washout filter cut-off frequency, \( \omega_{hx} \)
Adaptive Controller Synthesis

Extremum Seeking Control (cont’d)

Considerations for ESC in plants with nonlinear dynamics:

- Use of Wiener-Hammerstein model
- Setpoint may drift during prolonged operation or may be unknown due to modeling uncertainty
- Internal and external noise may impact the success of convergence

Average linearized relationship between error in estimated & actual optimum point:

\[ \frac{\tilde{\theta}_x}{\theta_x^*} = \frac{1}{1 + L_x(s)} \]

Average linearized relationship between output error & system noise:

\[ \frac{\tilde{\Gamma}_x}{F_{ox}(s)[f_x^*] + \hat{\theta}_x} = -\frac{M_x(s)}{1 + M_x(s)} \]
Adaptive Controller Synthesis

ESC in Hydrokinetic Systems

- Hydrokinetic systems with static plant model

- Assessment of dominant nonlinear plant characteristics
Adaptive Controller Synthesis

ESC in Hydrokinetic Systems (cont’d)

- Hydrokinetic systems with dynamic plant model studied with
  - Compensator: \( C_x(s) = 1 + d_x s \)
  - Input & output dynamics: \( F_{ix}(s) = F_{ox}(s) = \frac{1}{0.5s+1} \)

- Frequency domain analysis with multiple cases having variations in controller parameters

<table>
<thead>
<tr>
<th>Case</th>
<th>Study parameter</th>
<th>( k_x )</th>
<th>( \omega_x ) (rad/s)</th>
<th>( \omega_{hx} ) (rad/s)</th>
<th>( d_x )</th>
<th>( \varphi_x ) (rad)</th>
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<tbody>
<tr>
<td>A</td>
<td>( k_x )</td>
<td>1 &amp; 10</td>
<td>6</td>
<td>3</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>( \omega_x )</td>
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<td>1 &amp; 10</td>
<td>3</td>
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<td>0</td>
</tr>
<tr>
<td>C</td>
<td>( \omega_{hx} )</td>
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<td>1 &amp; 10</td>
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<td>0</td>
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<tr>
<td>D</td>
<td>( d_x )</td>
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<td>3</td>
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<td>E</td>
<td>( \varphi_x )</td>
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<td>6</td>
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<td>0.5</td>
<td>0.1 &amp; 3</td>
</tr>
</tbody>
</table>
Adaptive Controller Synthesis

ESC in Hydrokinetic Systems (cont’d)

- **Favorable features:**
  - Model independence
  - Robustness against drift
  - Stabilization near maxima

- **Challenge areas:**
  - High number of parameters to be tuned
  - Heuristic method of parameter tuning
Adaptive Controller Synthesis

ESC Synthesis & Implementation

- On a hierarchical viewpoint, there are two levels of control within the ESC design exercise:
  - Internal speed controller design (and development of input dynamics model)
  - Extremum seeking controller parameter selection (and development of output dynamics model).

- External extremum-seeking controller adaptively generates the speed reference

- Internal controller adjusts the set point of the power electronic stage such that the speed reference (as generated by the extremum-seeking controller) can be tracked

- Two measured parameters (rotational speed & output power) and one control variable (power converter settings)
Adaptive Controller Synthesis

ESC Synthesis & Implementation (cont’d)

Internal speed controller design:

- Represented using a reduced order linear averaged model

Plant-actuator transfer function: \( G_{pa}(s) = \frac{k_{pa}}{\tau_{pa}s+1} \)
where \( k_{pa} = \frac{N_{gr}}{k_{tsc}} \), \( k_{tsc} = -\frac{1}{2} \rho_w A_r v_{eff} R^2 C'_{TO} \), \( C'_{TO} = \frac{\partial C_T(\lambda)}{\partial \lambda} \bigg|_{\hat{\lambda}_{sys}} \)
and \( \tau_{pa} = \frac{N_{gr} J_{erg}}{k_{tsc}} \), \( J_{erg} = J_{gen} + \frac{1}{N_{gr}^2} J_{rot} \)

- Speed sensor transfer function: \( G_s(s) = \frac{\tilde{N}_{gen}}{N_{gr}} = \frac{1}{\tau_1 s+1} \)

- Speed controller (minimal overshoot & sufficiently damped):
  \[ G_\omega(s) = k_{p\omega} + \frac{k_{i\omega}}{s} \]

- Overall transfer function (input dynamics block):
  \[ F_{ix}(s) = \frac{k_{pa}(k_{p\omega} \tau_1 s^2 + (k_{p\omega} \tau_1 + k_{p\omega}) s + k_{i\omega})}{\tau_{pa} \tau_1 s^3 + (\tau_{pa} + \tau_1) s^2 + \frac{k_{pa} k_{p\omega}}{s} + k_{pa} k_{i\omega}} \approx \frac{1}{\tau_{in} s+1} \]
Adaptive Controller Synthesis

ESC Synthesis & Implementation (cont’d)

ESC parameter tuning considerations:

- Each parameter affects the performance (in various degrees) in terms of
  - convergence, overshoot, limit cycle amplitude,
  - sensitivity to noise, capability to override local maxima,
  - structural stress & overall stability

- Modulating and demodulating signal: \( a_x = b_x < 1\% \) of \( N_{\text{gen}}^b \)
- Controller gain: \( k_x \approx \frac{P_{\text{inv}}^b}{N_{\text{gen}}^b} \)
- Modulating signal frequency: \( \omega_{pa} = 2\pi \frac{1}{\tau_{in}} \)
- Washout filter cut-off frequency using: \( \omega_{pa} \geq \omega_x \geq \omega_{hx} > \omega_v \)
- Dynamic compensator: \( d_x \approx \tau_{in} \)
- Output dynamic block: \( F_{ox}(s) = \frac{1}{\tau_{out}s+1} \)
ESC Synthesis & Implementation (cont’d)

ESC design steps for test hydrokinetic systems:

<table>
<thead>
<tr>
<th>Step</th>
<th>Equation</th>
<th>Ref.</th>
<th>Design output (test system)</th>
<th>Design input (test system)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$C_{TO}^r = \frac{\partial C_T(\lambda)}{\partial \lambda} \tilde{\lambda}_{sys}$</td>
<td>13.9</td>
<td>$C_{TO}^r = -0.0787$</td>
<td>$\tilde{\lambda}_{sys} = 2.15$, $C_p - \lambda$ curve</td>
</tr>
<tr>
<td>2</td>
<td>$k_{lsc} = -\frac{1}{2} \rho_w A_r v_{eff} R^2 C_{r_{TO}}$</td>
<td>13.8</td>
<td>$k_{lsc} = 8.856$</td>
<td>General data</td>
</tr>
<tr>
<td>3</td>
<td>$k_{pa} = \frac{N_{gr}^i}{\tilde{N}_{gr}}$</td>
<td>13.2</td>
<td>$k_{pa} = 0.387$</td>
<td>$N_{gr} = 3.43$</td>
</tr>
<tr>
<td>4</td>
<td>$J_{erg} = J_{gen} + \frac{1}{2} N_{gr}^i \dot{J}_{rot}$</td>
<td>13.11</td>
<td>$J_{erg} = 0.1317$</td>
<td>$J_{gen} = 0.055$, $J_{rot} = 0.9025$</td>
</tr>
<tr>
<td>5</td>
<td>$\tau_{pa} = \frac{N_{gr} \cdot J_{erg}}{\tilde{N}_{gr}^i}$</td>
<td>13.10</td>
<td>$\tau_{pa} = 0.051$</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>$G_{pa}(s) = k_{pa} \frac{k_{pa}}{\tau_{pa} s + 1}$</td>
<td>13.1</td>
<td>$G_{pa}(s) = \frac{0.387}{0.051 s + 1}$</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>$G_{s}(s) = \frac{N_{gen}^i}{N_{gr}^i} = 1 \frac{1}{\tau_{1} s + 1}$</td>
<td>13.12</td>
<td>$G_{s}(s) = \frac{1}{0.95 s + 1}$</td>
<td>$\tau_1 = 0.95$</td>
</tr>
<tr>
<td>8</td>
<td>$G_{\omega}(s) = k_{pa} + \frac{k_{pa}}{\tau_{pa} s + 1}$</td>
<td>13.13</td>
<td>$G_{\omega}(s) = 0.85 + 1.65$</td>
<td>$k_{pa} = 0.85$, $k_{\omega} = 1.65$</td>
</tr>
<tr>
<td>9</td>
<td>$F_{in}(s) = \frac{k_{pa}(k_{pa} \tau_{1} s^2 + (k_{pa} \tau_{1} + k_{pa}) s + k_{\omega})}{\tau_{pa} \tau_{1} s^2 + (\tau_{pa} + \tau_{1}) s + k_{pa} k_{\omega}}$</td>
<td>13.14</td>
<td>$F_{in}(s) = \frac{0.31 s^2 + 0.94 s + 0.64}{0.05 s^2 + 1.33 s + 0.64}$</td>
<td></td>
</tr>
</tbody>
</table>

Extremum seeking controller parameters:

<table>
<thead>
<tr>
<th>Step</th>
<th>Equation</th>
<th>Ref.</th>
<th>Design output (test system)</th>
<th>Design input (test system)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>$F_{ix}(s) = \frac{1}{\tau_{in} s + 1}$</td>
<td>13.15</td>
<td>$F_{in}(s) = \frac{1}{0.8 s + 1}$</td>
<td>$\tau_{in} = 0.8$</td>
</tr>
<tr>
<td>11</td>
<td>$a_x = b_x &lt; 1%$ of $N_{gen}^b$</td>
<td>13.16</td>
<td>$a_x = b_x = 1.05$</td>
<td>$0.3%$ of $N_{gen}^b = 350$</td>
</tr>
<tr>
<td>12</td>
<td>$k_x \approx \frac{P_{inv}}{N_{gen}^b}$ Equation</td>
<td>13.17</td>
<td>$k_x = 1.15$</td>
<td>$P_{inv} = 400$</td>
</tr>
<tr>
<td>13</td>
<td>$\varphi_x = 0$</td>
<td>13.18</td>
<td>$\varphi_x = 0$</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>$\omega_{pa} = 2\pi \frac{1}{\tau_{in}}$</td>
<td>13.19</td>
<td>$\omega_{pa} = 7.854$</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>$\omega_{pa} \geq \omega_x \geq \omega_{hx} &gt; \omega_v$</td>
<td>13.20</td>
<td>$\omega_x = 2\pi$, $\omega_{hx} = \pi$</td>
<td>$\omega_v \approx 0.5$</td>
</tr>
<tr>
<td>16</td>
<td>$d_x \approx \tau_{in}$</td>
<td>13.21</td>
<td>$d_x = 0.8$</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>$C_x(s) = 1 + d_x s$</td>
<td>12.27</td>
<td>$C_x(s) = 1 + 0.8 s$</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>$F_{ox}(s) = \frac{1}{\tau_{ox} s + 1}$</td>
<td>13.22</td>
<td>$F_{ox}(s) = \frac{1}{0.75 s + 1}$</td>
<td>$\tau_{out} = 0.75$</td>
</tr>
<tr>
<td>19</td>
<td>$\theta_x = \frac{1}{1 + L_x(s)}$</td>
<td>11.22</td>
<td>$\theta_x = \frac{0.56 s^2 + 4.88 s^4 + 55.56 s^6}{0.56 s^2 + 1.488 s^4 + 55.56 s^6 + 199.32 s^2 + 956.25 s^4 + 155.6}$</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>$\frac{\tilde{\gamma}<em>x}{F</em>{ux}(s)} \frac{f_x^<em>}{f_x^</em>} + \varphi_x = \frac{-M_x(s)}{1 + M_x(s)}$</td>
<td>11.24</td>
<td>$\frac{\tilde{\gamma}<em>x}{F</em>{ux}(s)} \frac{f_x^<em>}{f_x^</em>} + \varphi_x = \frac{-0.75 s^4 + 3.25 s^3 + 31.39 s^2 + 117 s + 108}{1.33 s}$</td>
<td></td>
</tr>
</tbody>
</table>
Adaptive Controller Synthesis

ESC Synthesis & Implementation (cont’d)

Test of stability, tracking capability & sensitivity to noise:

Drift in setpoint  Sensitivity to noise
Adaptive Controller Synthesis

ESC Synthesis & Implementation (cont’d)

Implementation in simulation model:

[Diagram of the simulation model with various components labeled and connected appropriately.]
Adaptive Controller Synthesis

ESC Synthesis & Implementation (cont’d)

Simulation results (single-step & dual-ramp variations):

![Graphs showing output power, generator speed, tip speed ratio, and water velocity over time for single-step and dual-ramp variations.](image)
Adaptive Controller Synthesis

ESC Synthesis & Implementation (cont’d)

Simulation results (multiple-step & stochastic variations):

- Output power (watt)
- Generator speed (rpm)
- Tip speed ratio
- Water height (m)
- Water velocity (m/s)

Time (sec)
Adaptive Controller Synthesis

ESC Synthesis & Implementation (cont’d)

Simulation results (stochastic variations):

- **Output power (watt)**
- **Generator speed (rpm)**
- **Tip speed ratio**
- **Water height (m)**
- **Water velocity (m/s)**

Time (sec)
Comparative (subjective) evaluation:

<table>
<thead>
<tr>
<th>Method</th>
<th>Design Issues</th>
<th>Implementation</th>
<th>Performance Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSR</td>
<td>Highly dependent</td>
<td>(Water velocity), generator speed</td>
<td>(Underwater), Above surface</td>
</tr>
<tr>
<td>PSF</td>
<td>Highly dependent</td>
<td>(Water height), output power</td>
<td>(Underwater), Above surface</td>
</tr>
<tr>
<td>HCC</td>
<td>Partially Independent</td>
<td>Output power, generator speed</td>
<td>Above surface</td>
</tr>
<tr>
<td>ESC</td>
<td>Independent</td>
<td>Complicated</td>
<td>Above surface</td>
</tr>
</tbody>
</table>
- Introduction
- Review & Critique
- Modeling & Validation
- Controller Evaluation
- Adaptive Controller Synthesis
- Conclusion
Conclusion

Summary

- Due emphasis given on identifying the problem of maximum power point tracking for hydrokinetic systems
- Efforts given to develop sufficient operational experience and multiple design, testing & performance evaluation activities undertaken
- Detailed modeling of systems/subsystems conducted and validated
- Comparative evaluation of various candidate power tracking methods conducted
- Suitability of extremum seeking control method investigated & systematic parameter tuning method developed
- The ESC method has been found to be of good promise
Conclusion

Future Work

- Open-ended initiative where further design & development activities are indispensable
- Future work along this topic needs to be directly linked to real-world trials
- Device sizes (physical dimensions as well as power ratings) need to be sufficiently large
- Considerations for economic aspects, environmental impacts, practical usage & sustainability factors need also be given
- Significant test & development program underway
Conclusion

Contributions


Conclusion

Contributions (cont’d)

- Jahangir Khan, Tariq Iqbal and John Quaicoe; Effects of Nonlinear Efficiency Characteristics on the Power-Tracking Control: A Case Study of Hydrokinetic Energy Conversion System, Presented at IEEE Energy Conversion Congress and Exposition (ECCE), San Jose, California, USA, September 20-24, 2009


- M. J. Khan, M.T. Iqbal, J.E. Quaicoe; Tow Tank Testing and Performance Evaluation of a Permanent Magnet Generator Based Small Vertical Axis Hydrokinetic Turbine; NAPS 2008; September 2008; Calgary; Canada


- M.J. Khan, M.T. Iqbal, J.E. Quaicoe; Dynamics of a Vertical Axis Hydrokinetic Energy Conversion System with Rectifier Coupled Multi-pole Permanent Magnet Generator, NECEC 2008; St. John s, NL, Canada; November 2008


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- School of Graduate Studies, MUN
- Technical Services, MUN

Thank You