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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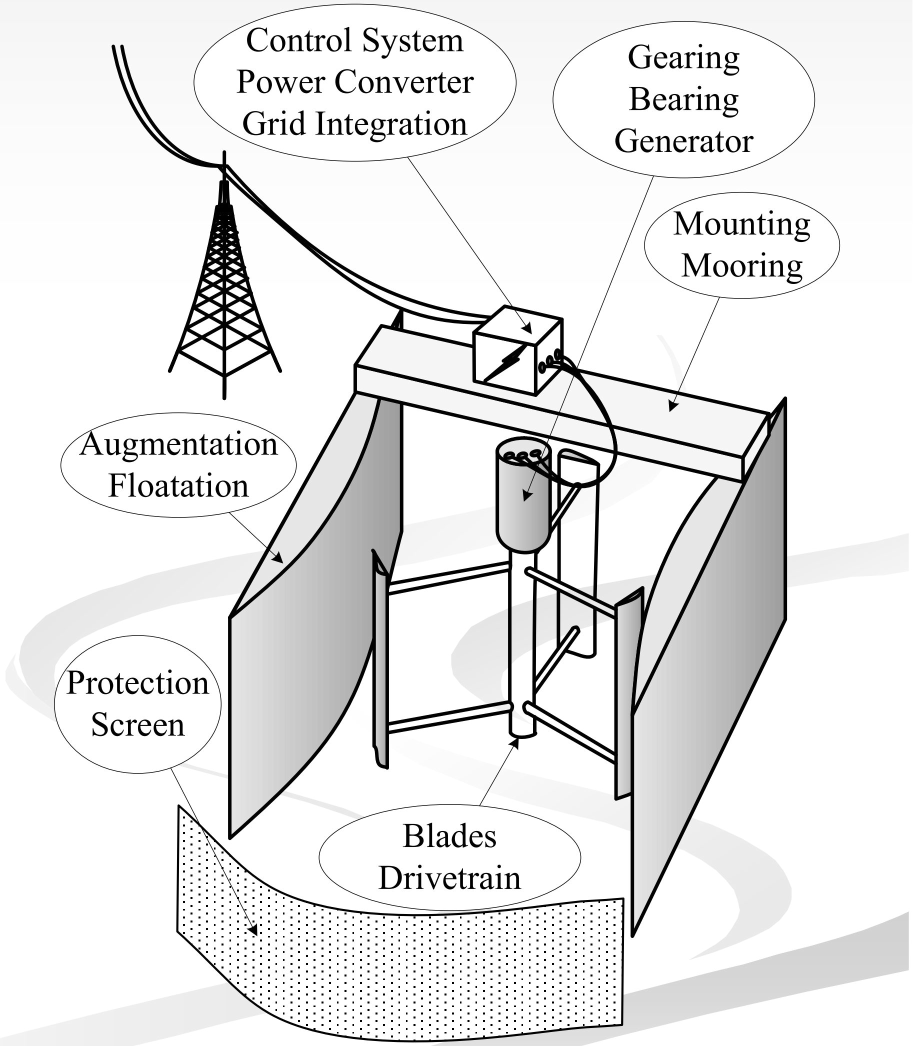
Outline

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

- **Introduction**
- Review & Critique
- Modeling & Validation
- Controller Evaluation
- Adaptive Controller Synthesis
- Conclusion

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*

Introduction

Research Scope

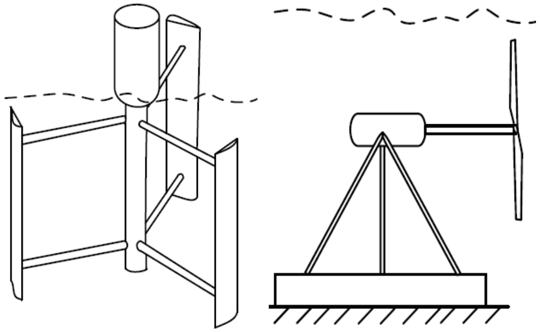
- Considerations for broader spectrum of hydrokinetic technologies
- Focus on test, modeling and experiments on a small-scale vertical axis turbine containing
    - *multi-pole outer rotor permanent magnet alternator*
    - *single-phase utility grid with a power electronic (ac-dc-ac) link*
- Design,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

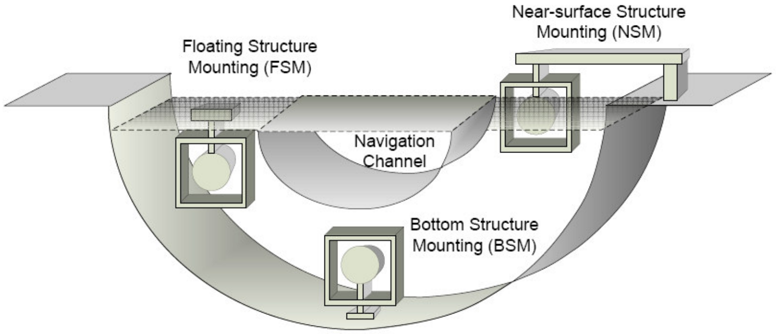
- Introduction
- **Review & Critique**
- Modeling & Validation
- Controller Evaluation
- Adaptive Controller Synthesis
- Conclusion

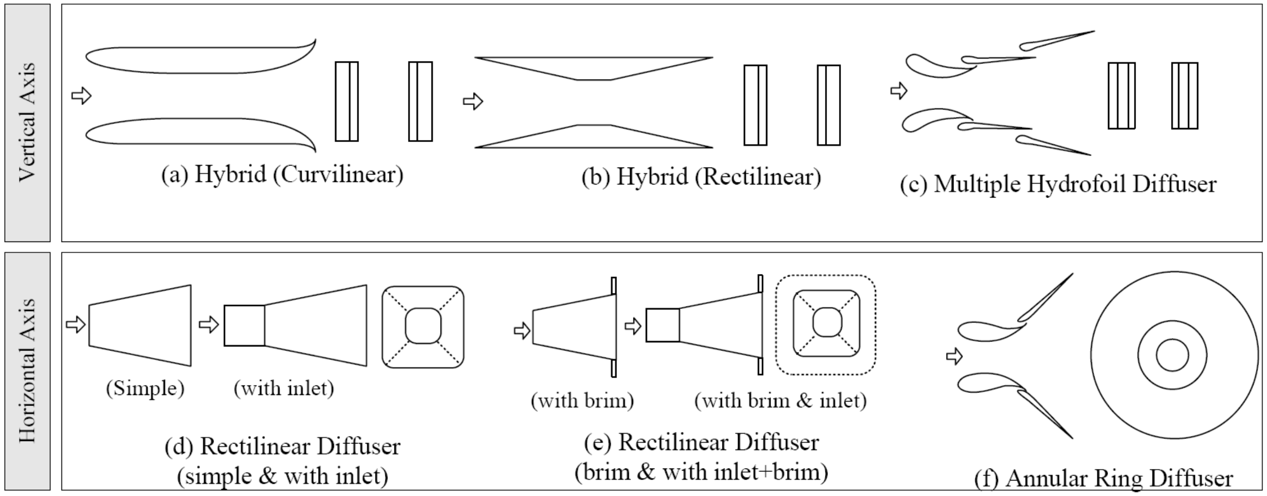
Review & Critique

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







Review & Critique

Control of Hydrokinetic Turbines

- **Recent work:** Robust gain scheduling controller (H_∞ 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**
- Controller Evaluation
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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.

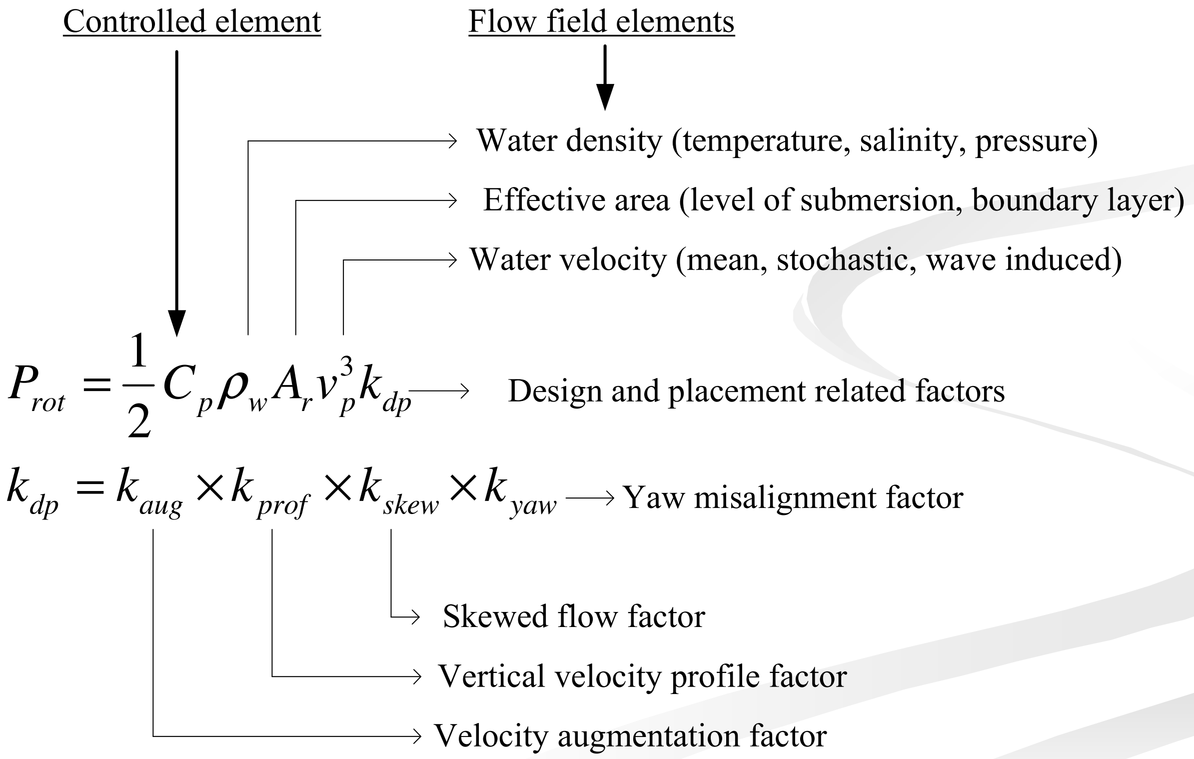
Modeling & Validation

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)

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

Design and placement related factors

$$k_{dp} = k_{aug} \times k_{prof} \times k_{skew} \times k_{yaw} \longrightarrow$$

Yaw misalignment factor

Skewed flow factor

Vertical velocity profile factor

Velocity augmentation factor

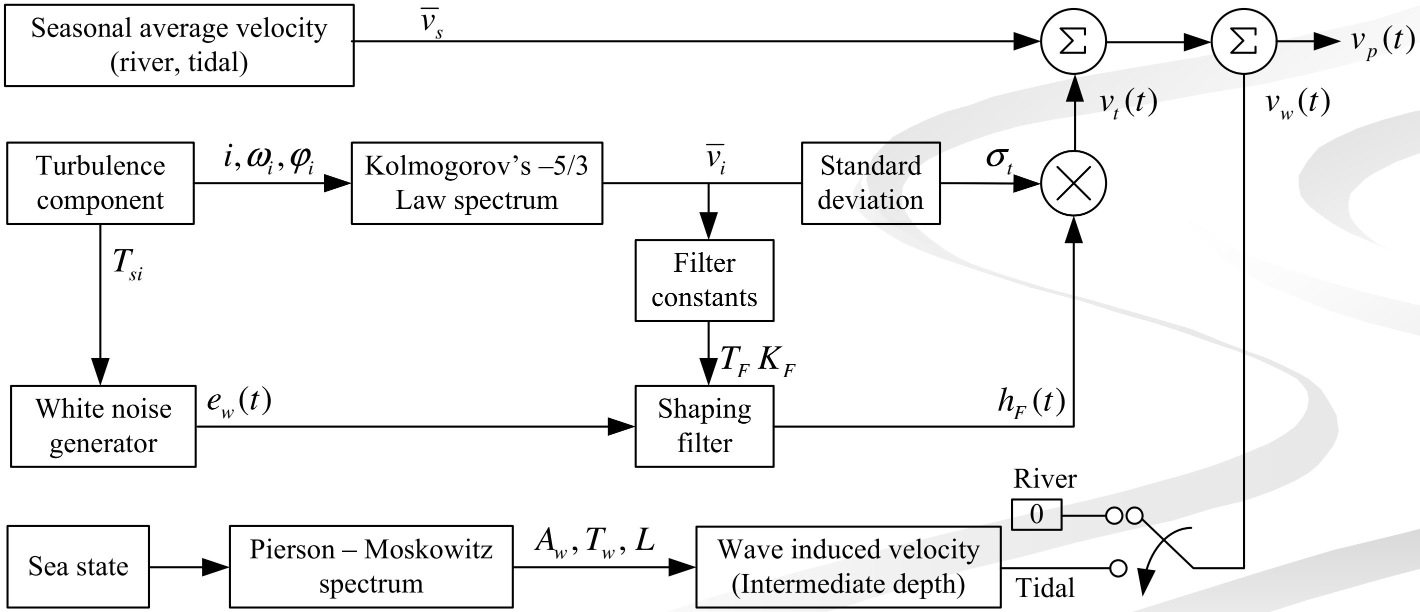
Modeling & Validation

Flow Field Representation (cont'd)

- Water velocity components:

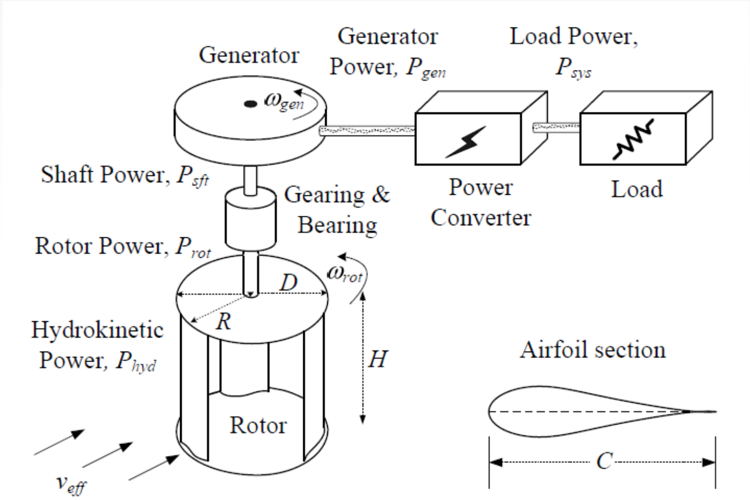
$$v_p(t) = \overline{v_s} + v_t(t) + v_w(t)$$
$$\overline{v_s} = \begin{cases} v_R, & \text{River seasonal mean} \\ v_T, & \text{Tidal hourly mean} \end{cases}$$

- Synthesis of the water velocity model:

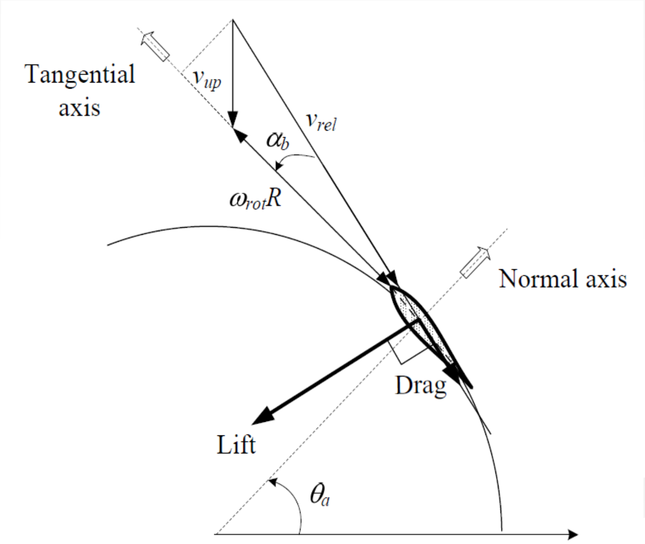


Darrieus Rotor Performance Analysis

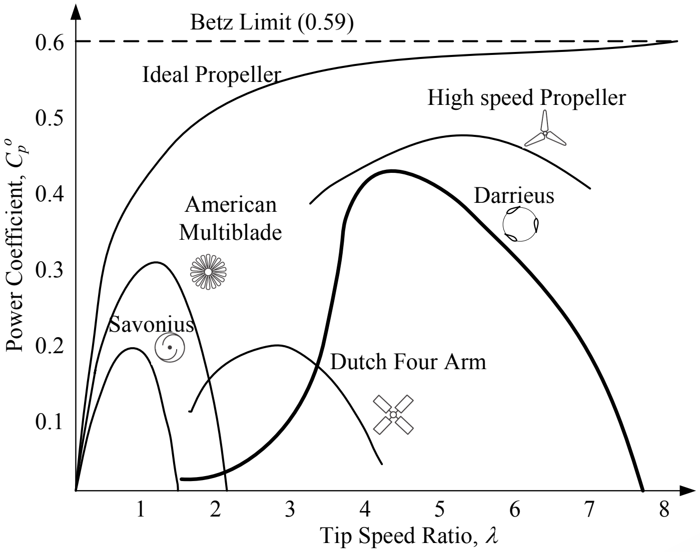
- Darrieus Rotor



- General principle



- Performance curve



- Relevant terms

Incident hydraulic power - $P_{hyd} = \frac{1}{2}\rho_w A_r v_{up}^3$

Captured rotor power - $P_{rot} = C_p^o \frac{1}{2}\rho_w A_r v_{eff}^3$

Power coefficient (ideal) - $C_p^o = \frac{P_{rot}}{P_{hyd}}$

Torque coefficient (ideal) - $C_T^o = \frac{C_p^o}{\lambda}$

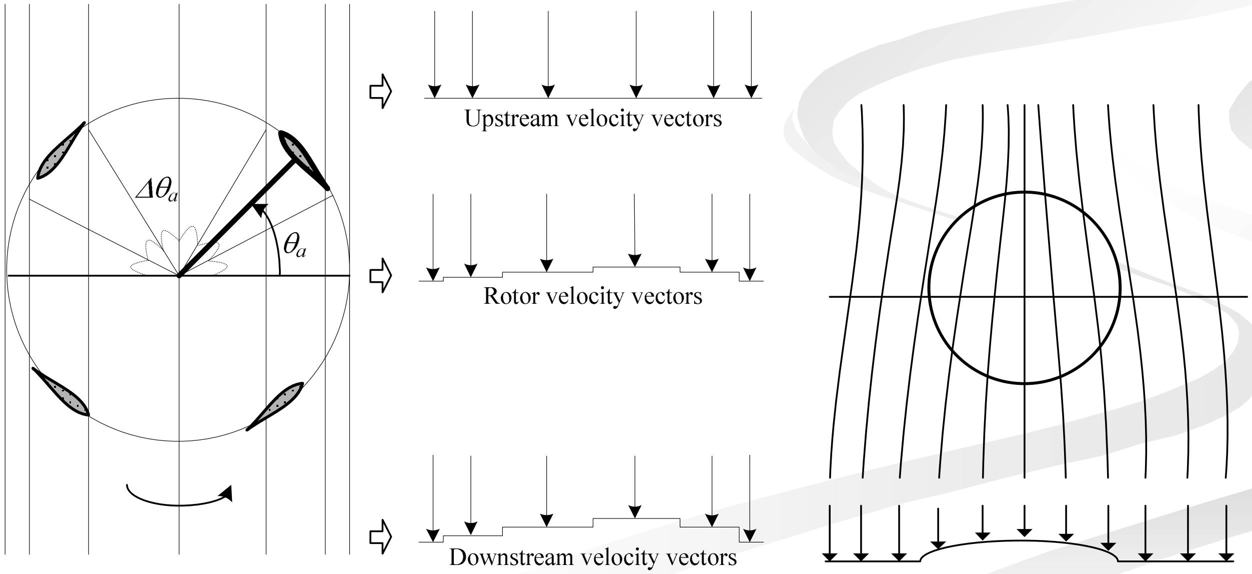
Tip speed ratio (TSR) - $\lambda = \frac{\omega_{rot} R}{v_{eff}}$

Darrieus Rotor Performance Analysis (cont’d)

- Performance analysis of Darrieus rotors

Fluid mechanic analysis of Darrieus-type rotors
- Momentum Method
  - Single-disk single-streamtube
  - Single-disk multiple-streamtube
  - Double-disk multiple-streamtube
- Vortex Method
- CFD Method

- Single-disk multiple-streamtube analysis:



Streamtubes uniformly divided by a separation of $\Delta\theta_a$
(a)

Velocity vectors
(b)

Uniformly distributed flow tubes
(c)

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

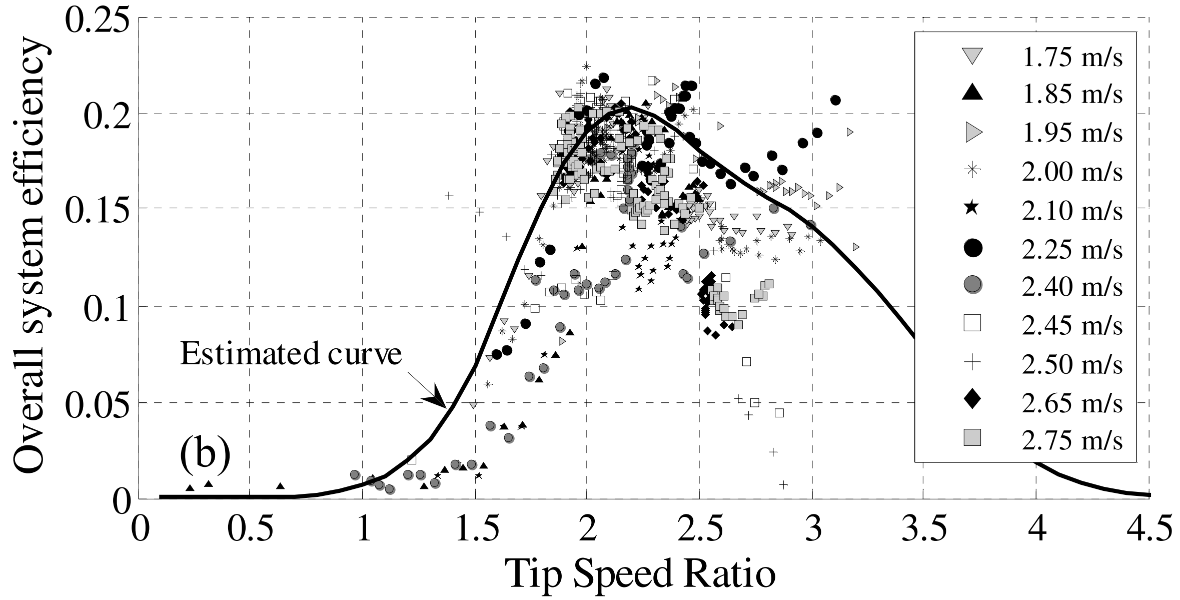
$$C_T^o = \sigma_r \frac{\sum_{i=1}^{m} \left(\frac{v_{rel}}{v_{up}}\right)^2 C_{tang}}{m}$$

- 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)

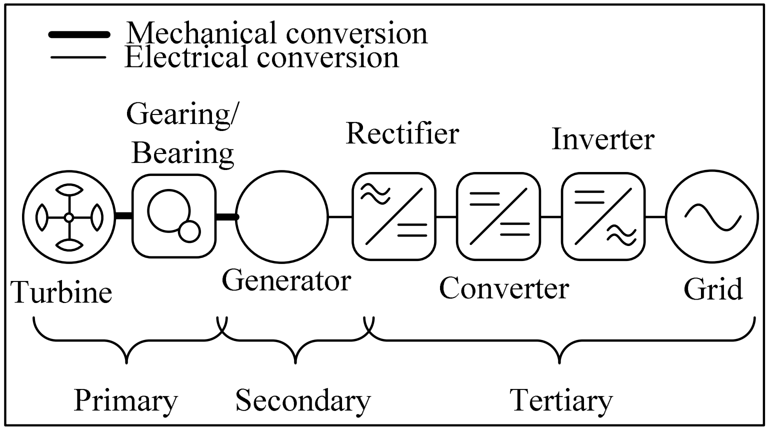
- Performance curve of a test system (NECI – 4 bladed)
- Emphasis on overall system efficiency
- Estimates are particularly successful in identifying the optimum TSR point

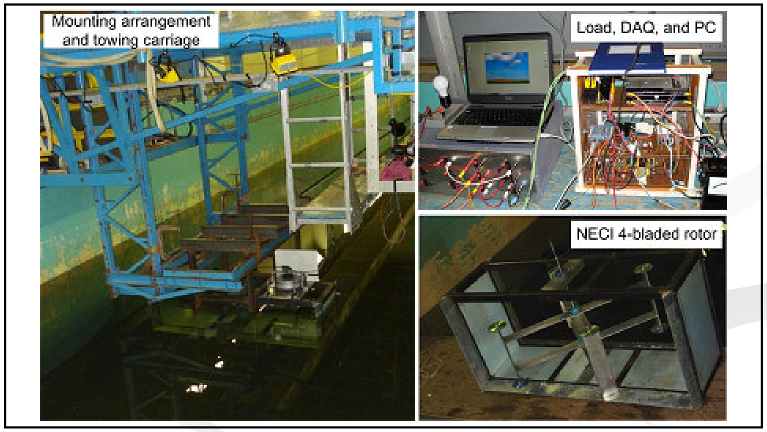


- Divergence high on post-optimum TSR region
- Contrary to expectations, multiple performance curves (at various water speeds) can be observed

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)



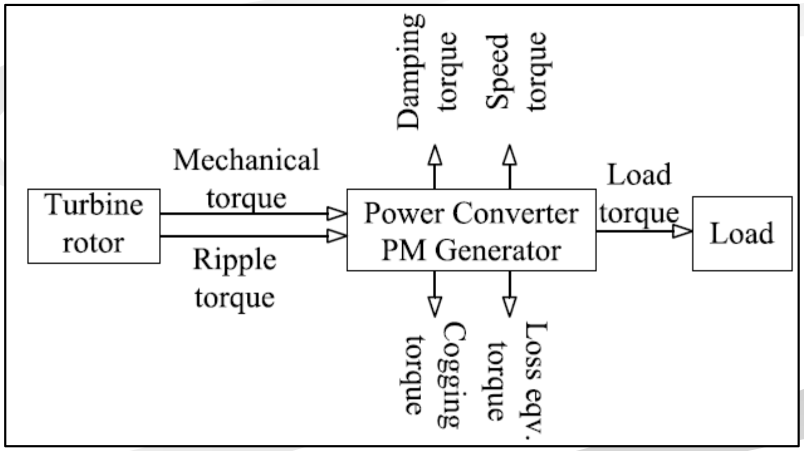


- Detailed synthesis of torque components
- Permanent magnet alternator (PMA) with ac-dc-ac (grid-connected) topology
- Assessment of start-up, torque ripple, and nonlinear efficiency issues

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: $\theta_b = \int N_b \omega_{rot} dt$



Damping torque

Speed torque

Mechanical torque

Turbine rotor

Power Converter PM Generator

Load torque

Load

Ripple torque

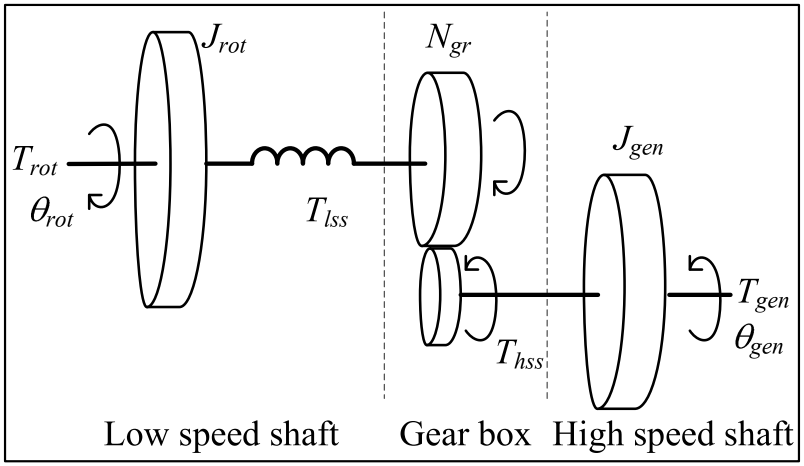
Cogging torque

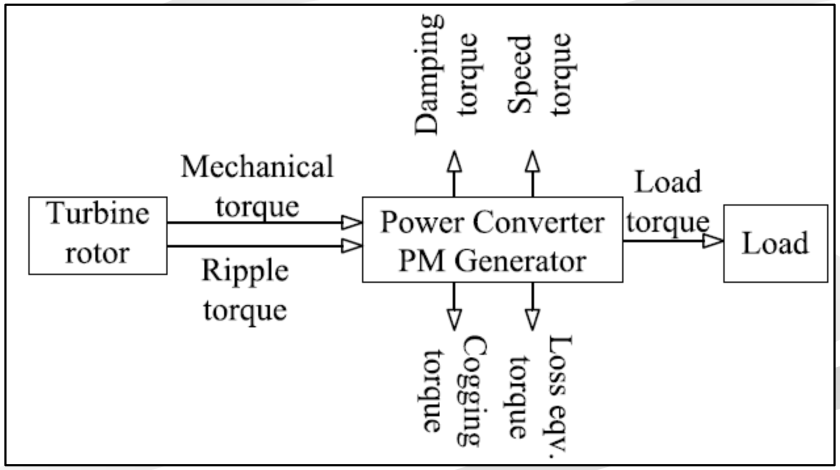
Loss eqv. torque

Dynamic Modeling of Hydrokinetic System (Cont’d)

Drive-train

- Rotor torque: $T_{rot} = J_{rot}\frac{d\omega_{rot}}{dt} + T_{lss} + B_{rot}\omega_{rot}$
- Generator torque: $T_{gen} = \eta_{tran}\frac{T_{lss}}{N_{gen}}, N_{gr} = \frac{\omega_{gen}}{\omega_{rot}}\ (N_{gr} > 1)$
- Low-speed shaft torque: $T_{lss} = k_{spr}\int(\omega_{rot} - \frac{\omega_{gen}}{N_{gen}})dt$

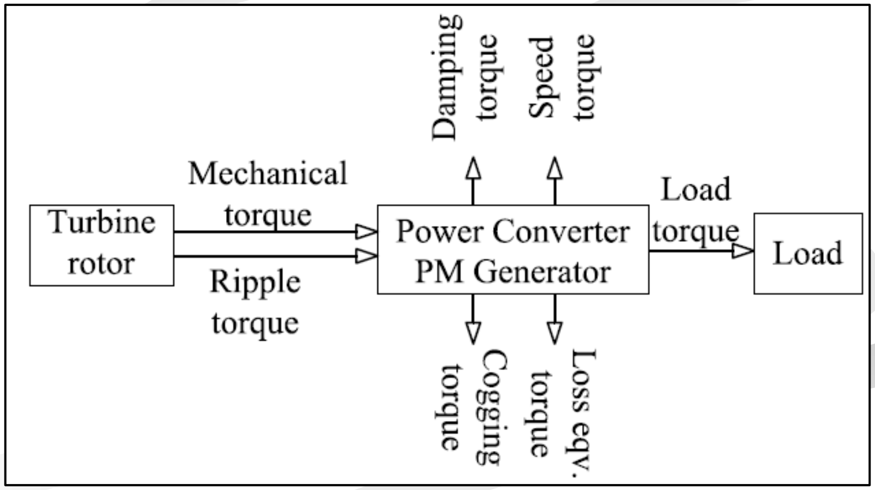




Dynamic Modeling of Hydrokinetic System (Cont’d)

Permanent magnet alternator

- Overall torque balance: $T_{gen} = J_{gen} p \omega_{gen} + B_{gen}\omega_{gen} + T_{cog} + T_{load} + T_{loss}$
- Cogging torque: $T_{cog} = \hat{T}_{cog} \sin\theta_g \times f_h(-I_{gr})$
- Load torque: $T_{load} = \frac{3}{2}\frac{N_P}{2}\lambda_m I_g$
- Loss torque: $T_{loss} = \frac{P_{nll}+P_{ll}}{\omega_{gen}} - B_{gen}\omega_{gen}$

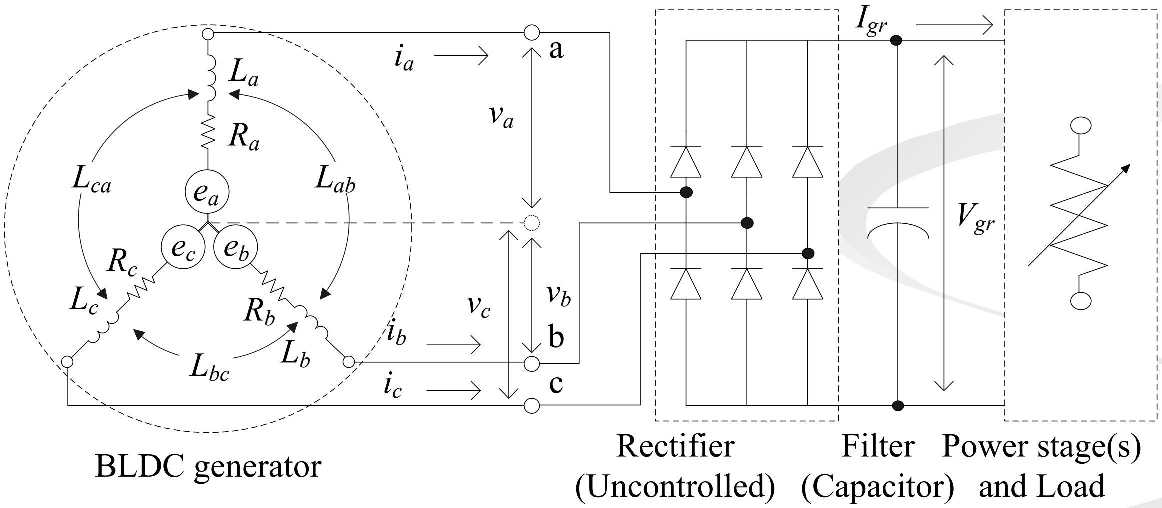


Modeling & Validation

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): $\frac{V_{gr}}{V_{gr}^{o}} = \frac{1}{L_{fg}C_{fg}s^2 + R_{fg}C_{fg}s + 1}$

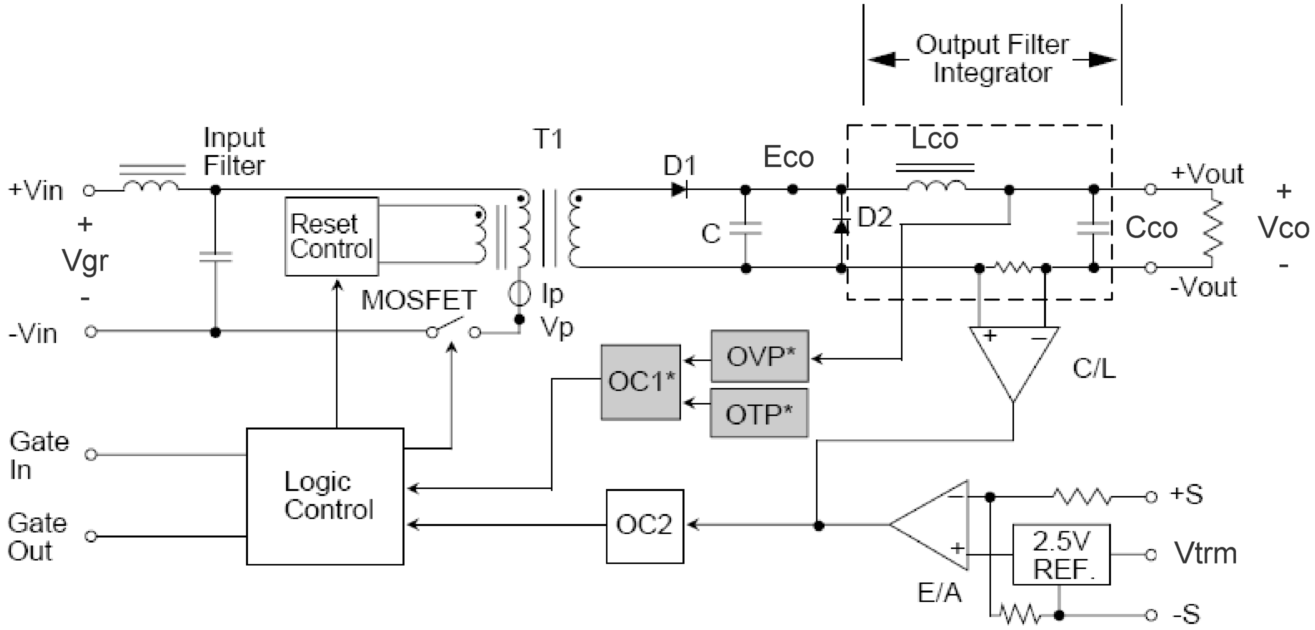


Dynamic Modeling of Hydrokinetic System (Cont’d)

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

- Open circuit voltage (steady-state): $E_{co}^{o} = \frac{V_{trm}}{2.5} V_{cnom}$
- 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: $I_{Lco} = \frac{1}{L_{co}} \int (E_{co} - V_{co}) dt$

$$V_{co} = \frac{1}{C_{co}} \int (I_{Lco} - I_{c}) dt$$

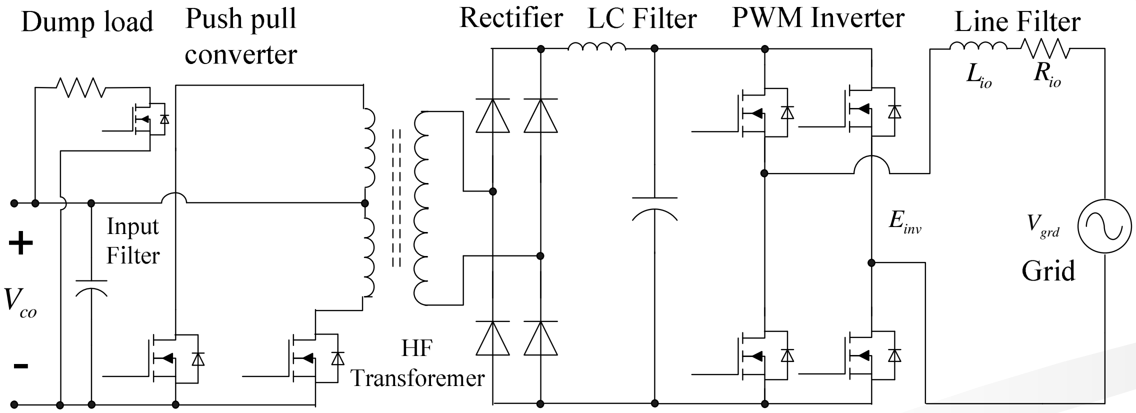


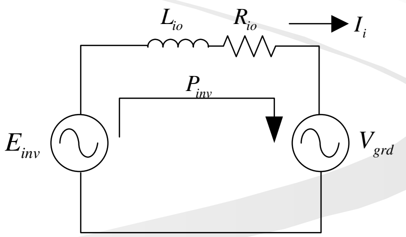
Dynamic Modeling of Hydrokinetic System (Cont'd)

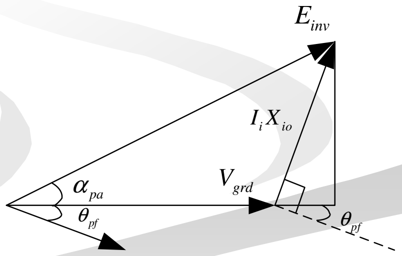
Inverter (grid-connected dc-ac architecture)

- Design power output: $P^*_{inv} = 10V_{co} - 250;\ \text{for } 24 < V_{co} < 48$

  $P^*_{inv} = 0;\ \text{for} V_{co} < 24 \text{ and } V_{co} > 48$
- 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: $L_{io}\frac{dI_i}{dt} + R_{io}I_i = V_{ilf}$



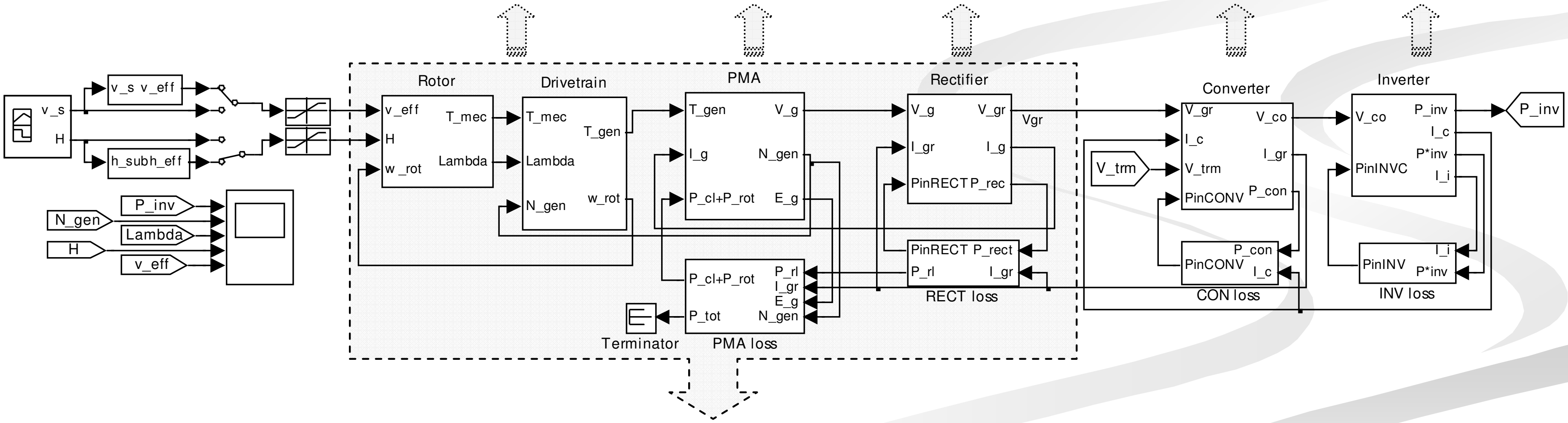




Dynamic Modeling of Hydrokinetic System (Cont'd)

Overall model

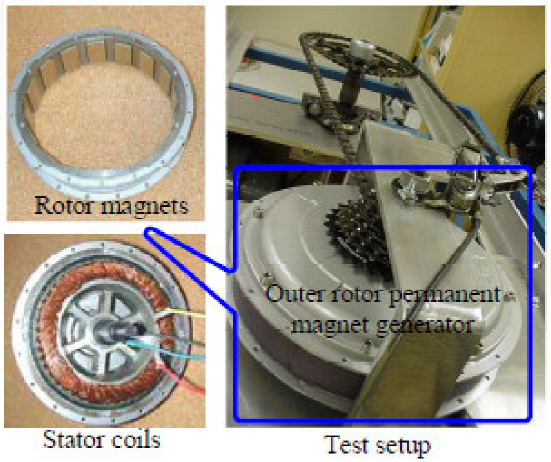
- Implemented in Matlab-Simulink^{TM}
- Model strength: *readily usable & numerically stable*
- Disturbance inputs are: *water flow & velocity variation*
- Control variable is: *converter trimming voltage*
- Output variables are: *rotational speed & electrical power*
- Component validation: *rotor, generator,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



- Part-system validation: *rotor, generator, rectifier + load*

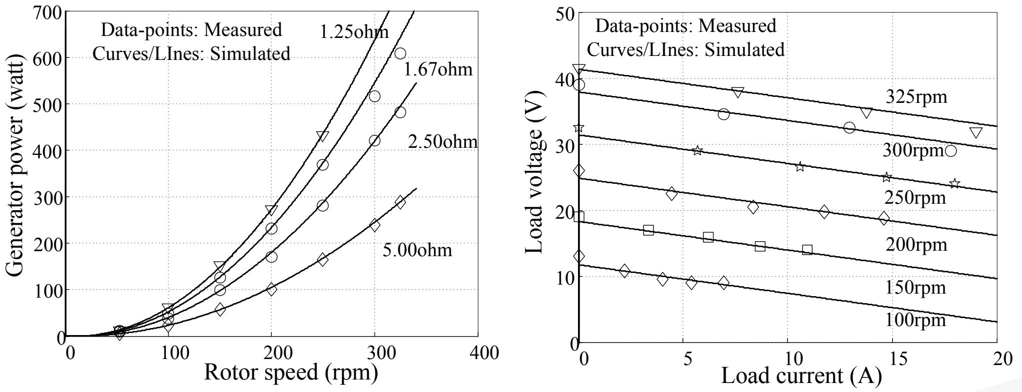
Test Apparatus and Model Validation

Permanent magnet alternator (with rectifier)

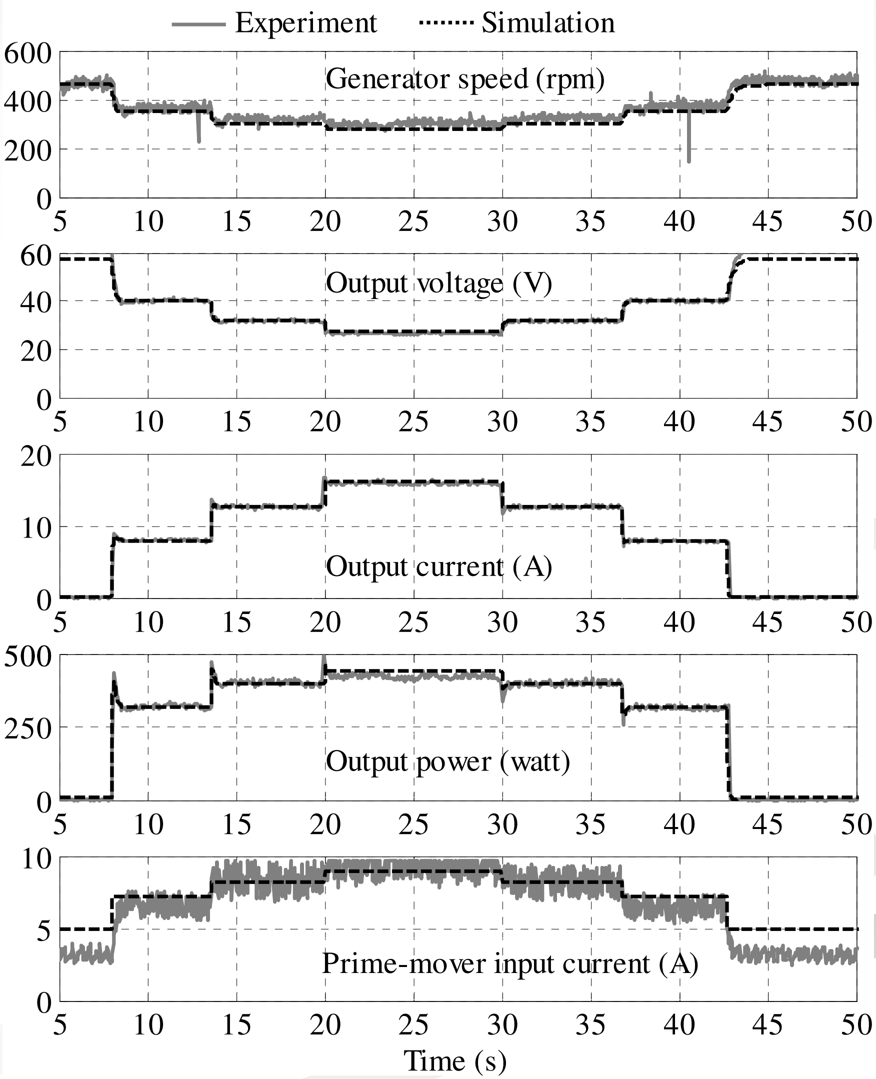


Dynamic

Steady state



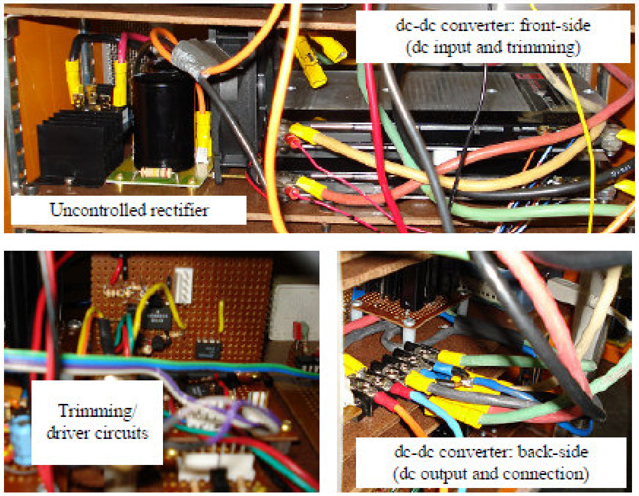
(a) (b)



Modeling & Validation

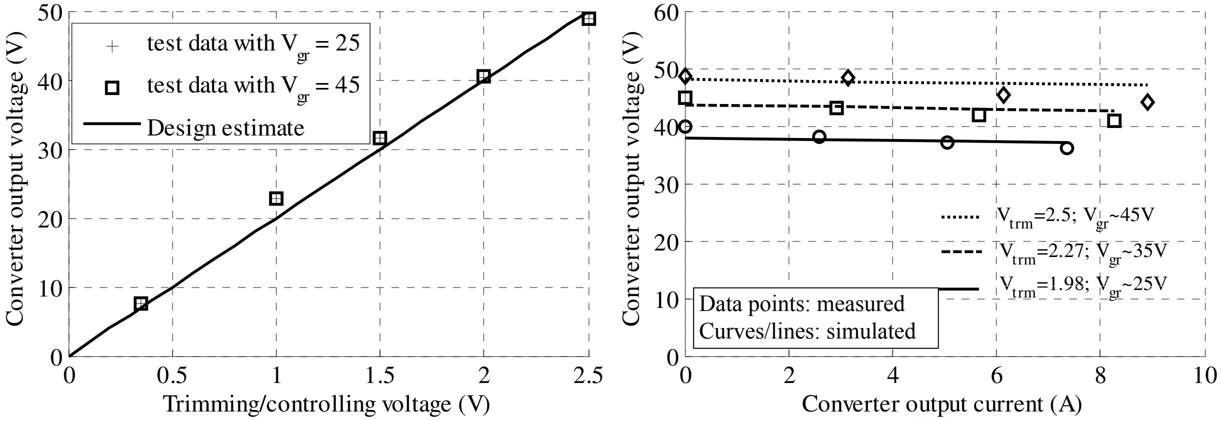
Test Apparatus and Model Validation (cont'd)

dc-dc converter



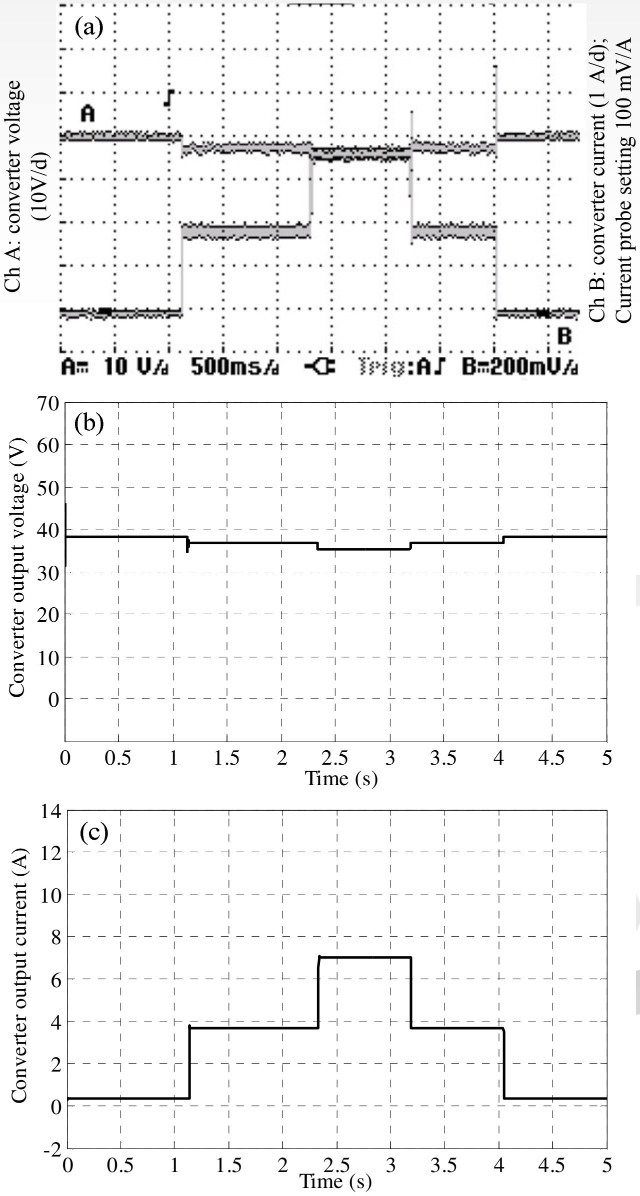
Dynamic

Steady state



(a)

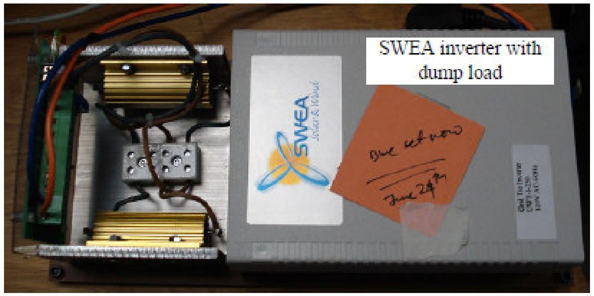
(b)

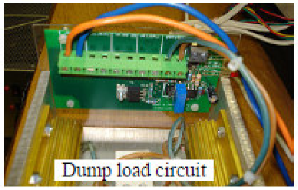


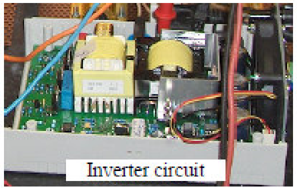
Modeling & Validation

Test Apparatus and Model Validation (cont'd)

dc-ac inverter

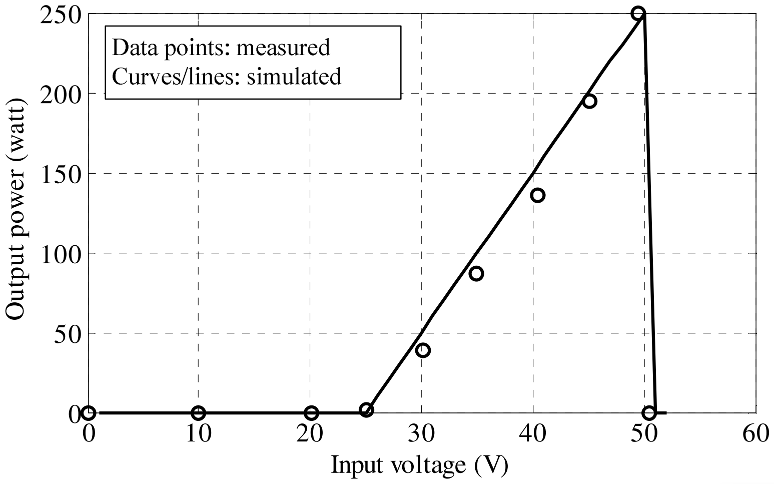


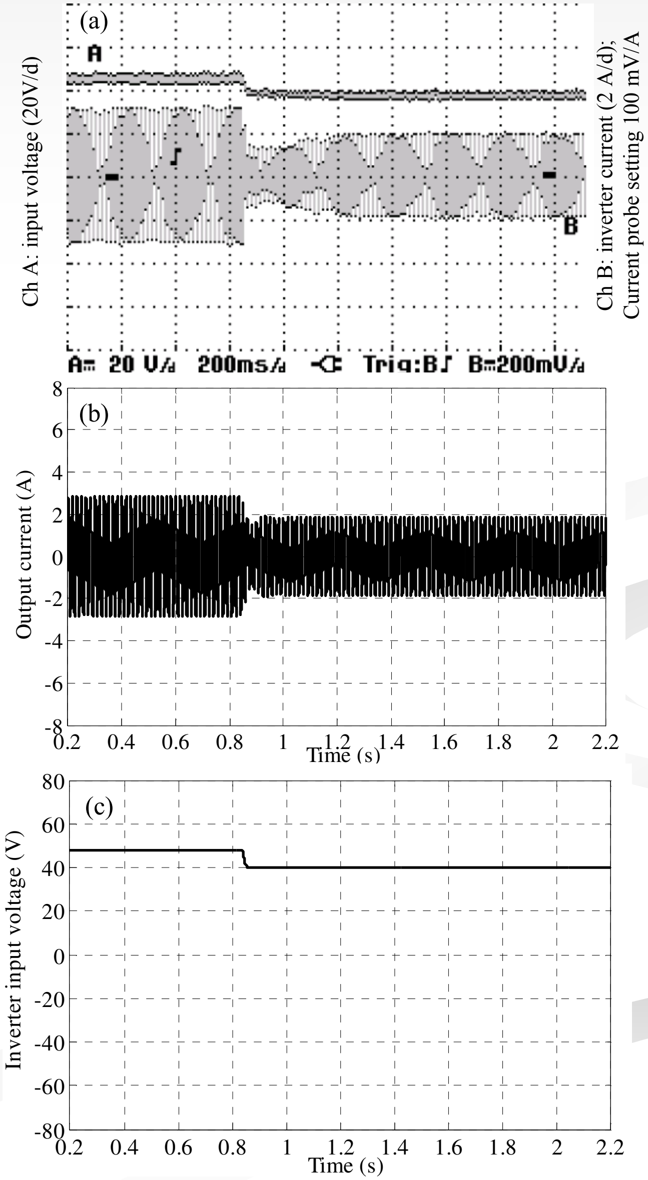




Dynamic

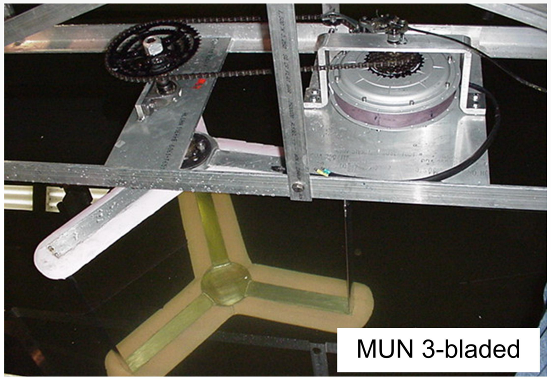
Steady state

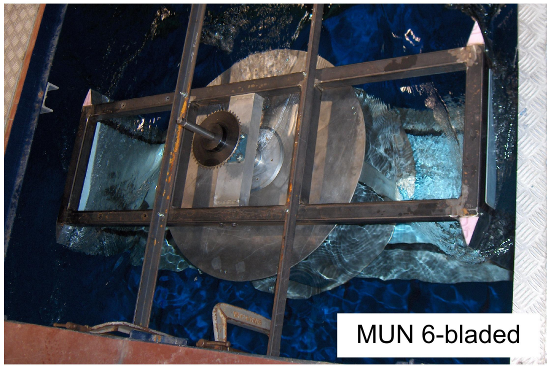




Test Apparatus and Model Validation (cont'd)

Tow-tank test apparatus (turbine rotors)


MUN 3-bladed


MUN 6-bladed

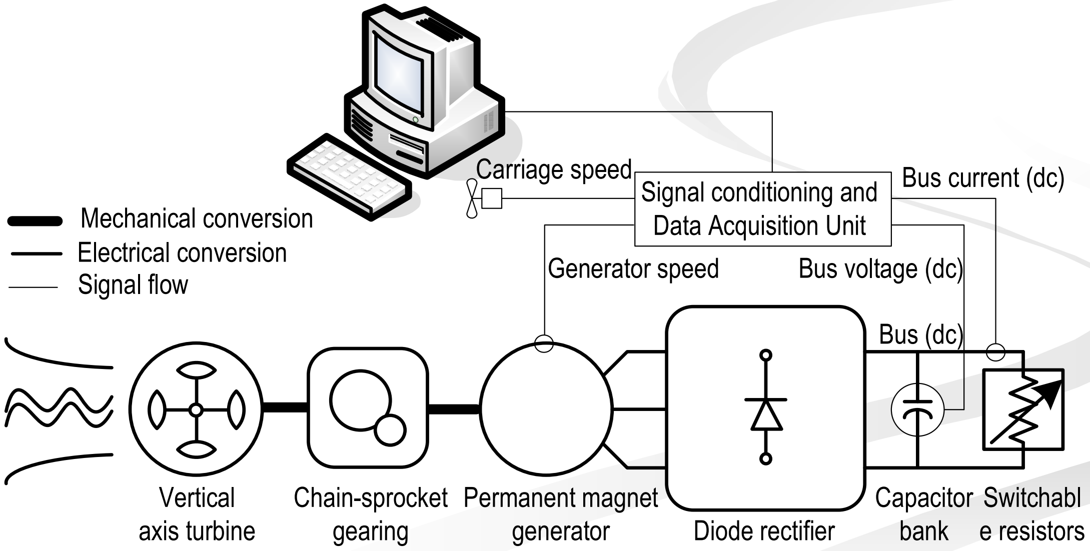

NECI 4-bladed

- **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)

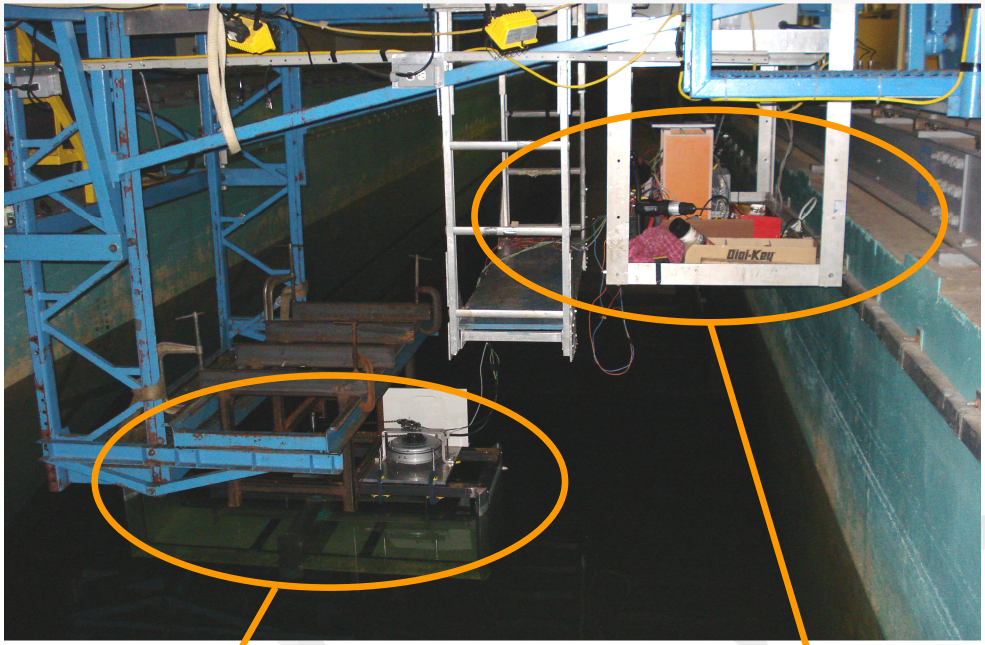
- NECI 4-bladed rotor coupled to a multi-pole outer rotor PMG
- Chain-sprocket gear coupling between rotor shaft and generator
- Diode bridge at the generator output coupled to a capacitor bank and switchable load
- Customized DAQ unit with 4 sensed signals (rotor speed, flow velocity, load voltage,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

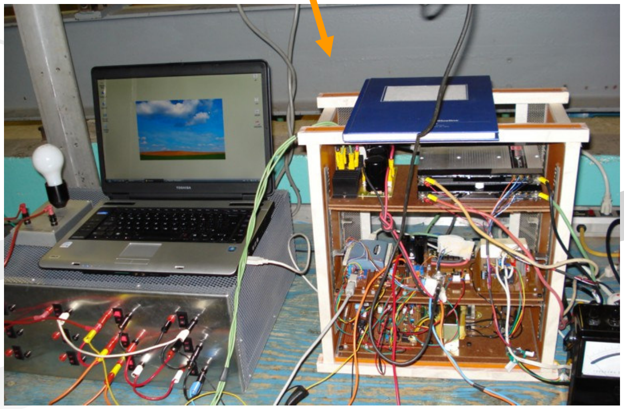


Test Apparatus and Model Validation (cont'd)

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.



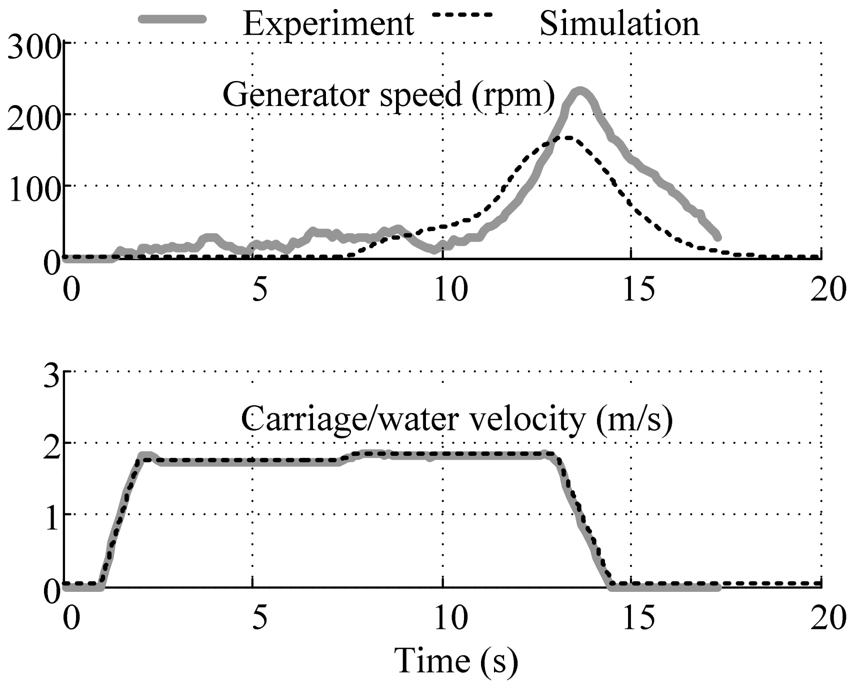


Modeling & Validation

Test Apparatus and Model Validation (cont'd)

Tow-tank test apparatus (model validation – start-up)

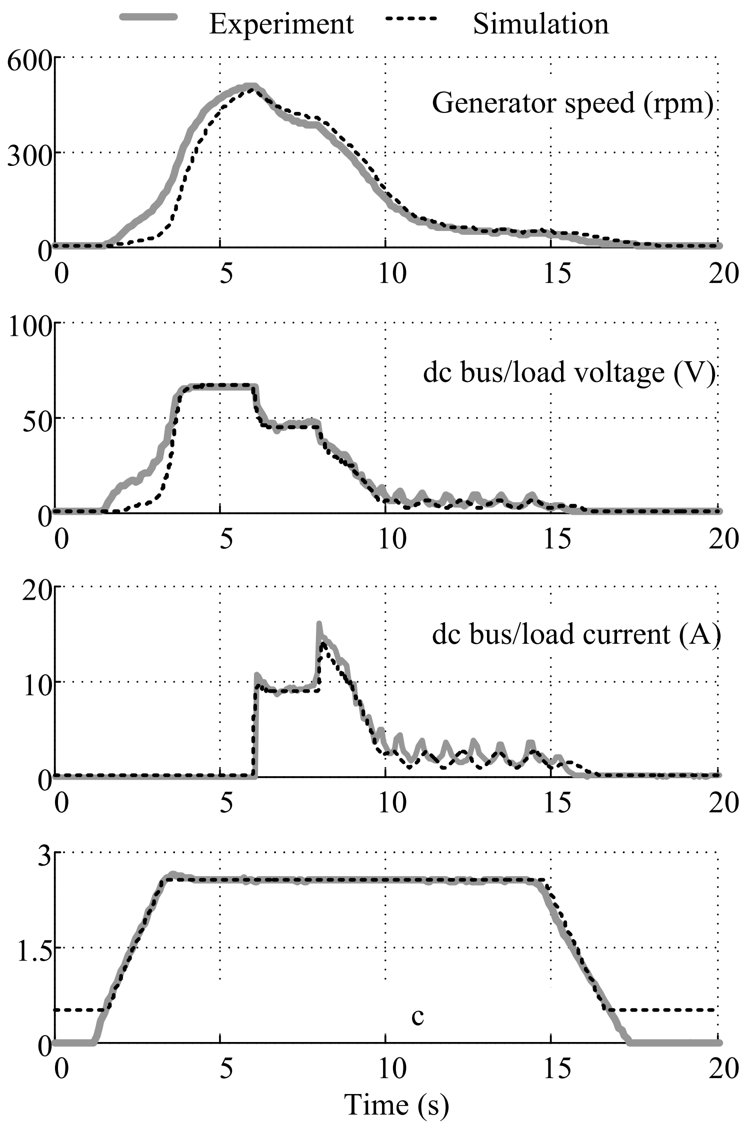
- Cogging in PMG directly affects start-up behavior
- Unloaded rotor self-starts at 0.65 ~ 0.75 m/s
- Test prototype with load self-starts at 1.75 ~ 1.85 m/s
- Simulations successfully exhibit similar behavior



Test Apparatus and Model Validation (cont’d)

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

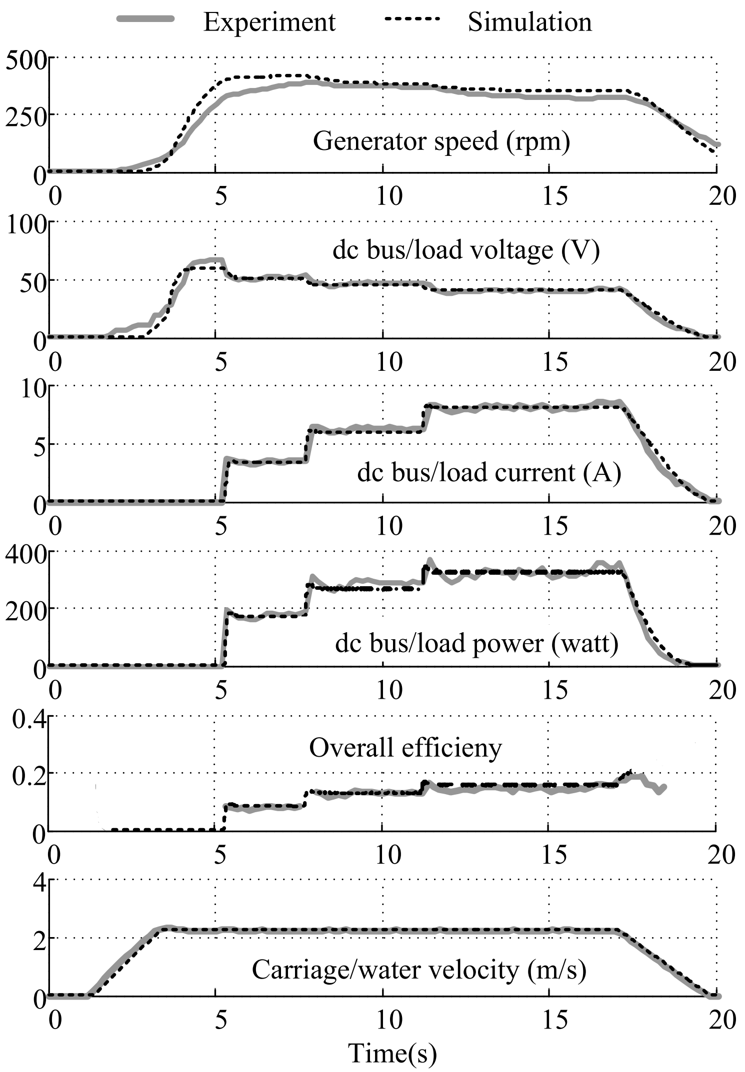
- Torque ripple is reflected on load current
- System inertia and capacitor bank reduce low frequency ripple
- Ripple magnitude is dominant in low TSR conditions
- Ripple frequency directly relates to rotor speed
- Exact instance of ripple occurrence is time-shifted in simulation.



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
- Review & Critique
- Modeling & Validation
- **Controller Evaluation**
- Adaptive Controller Synthesis
- Conclusion

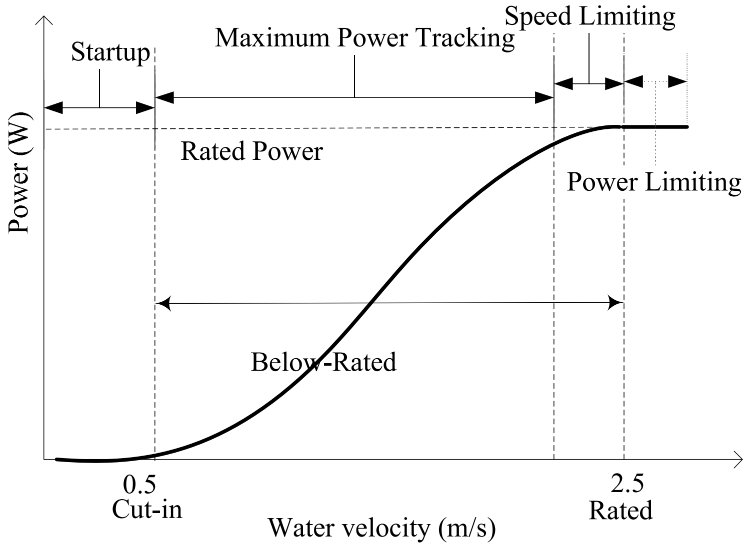
Control Objectives & Regions

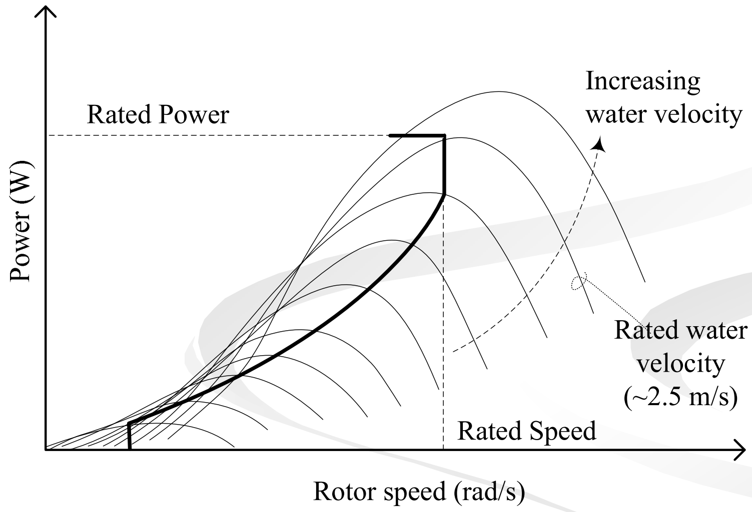
- **General objective:**

  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)

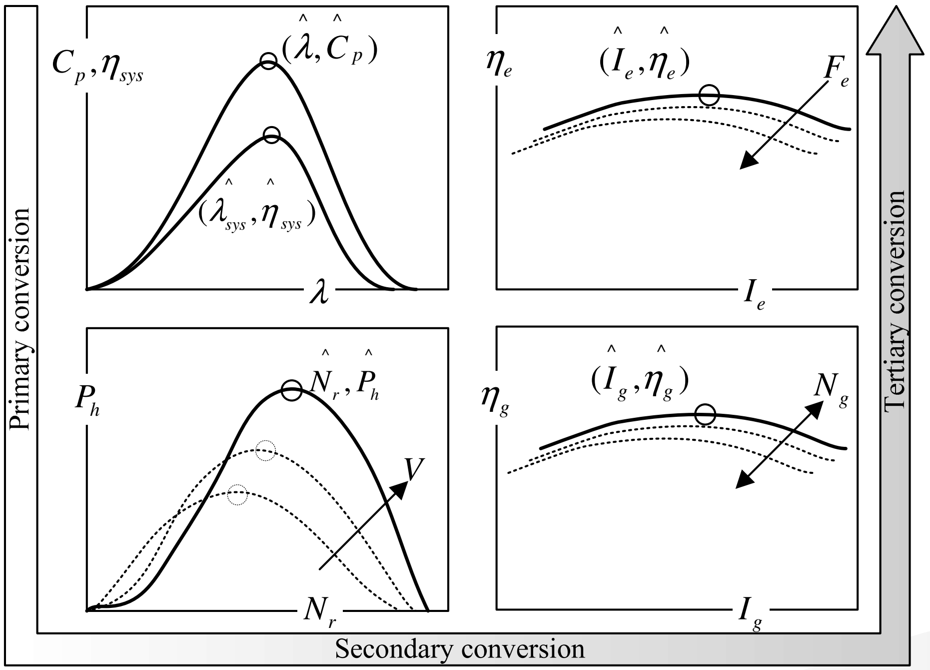
- **Underwater instrumentation:**

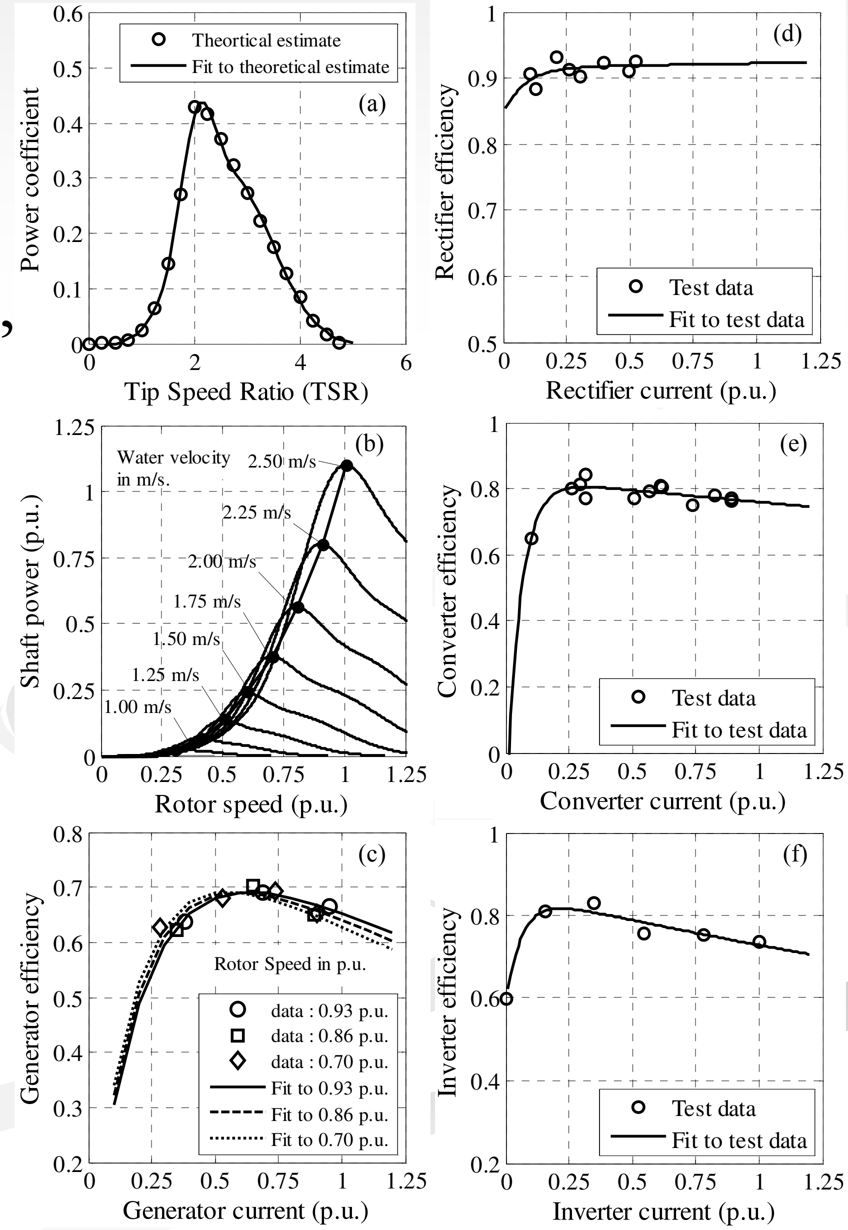
  How to avoid reliance upon flow measuring instruments in implementing a MPT controller ?

Controller Evaluation

Effects of Efficiency Nonlinearity

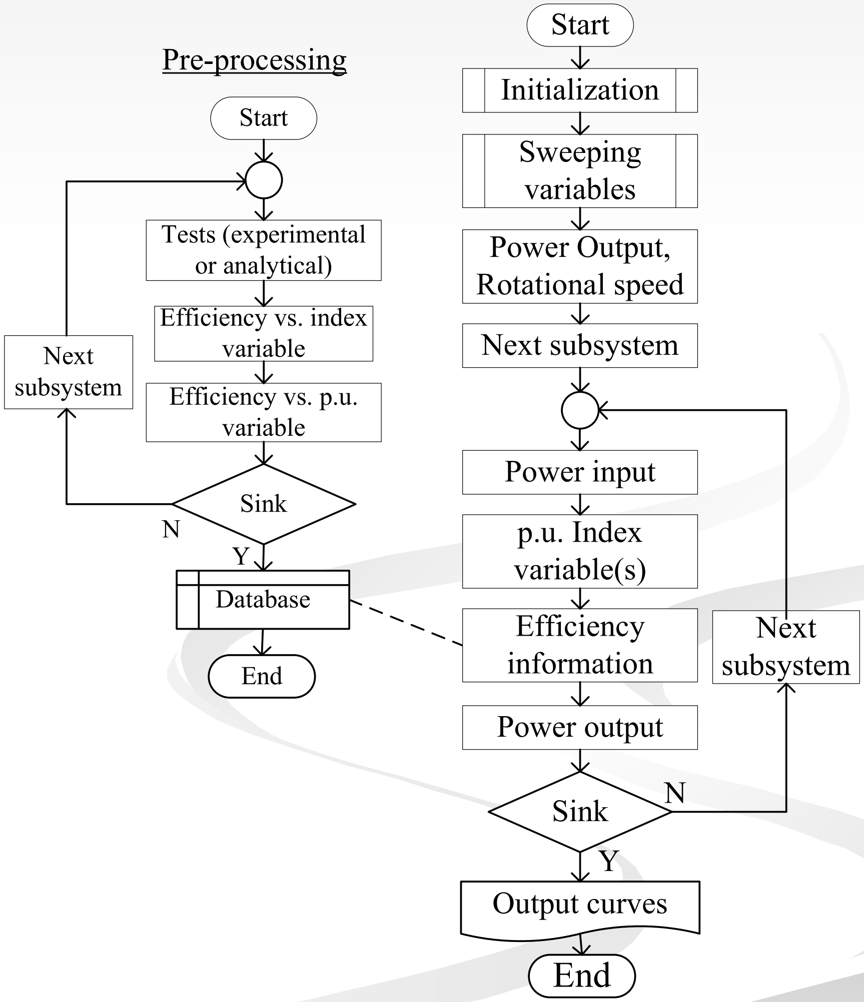
- Noticeable nonlinearity within various subsystems' efficiency characteristics can be observed
- In addition to achieving optimum TSR, other control requirements are present





Effects of Efficiency Nonlinearity (cont'd)

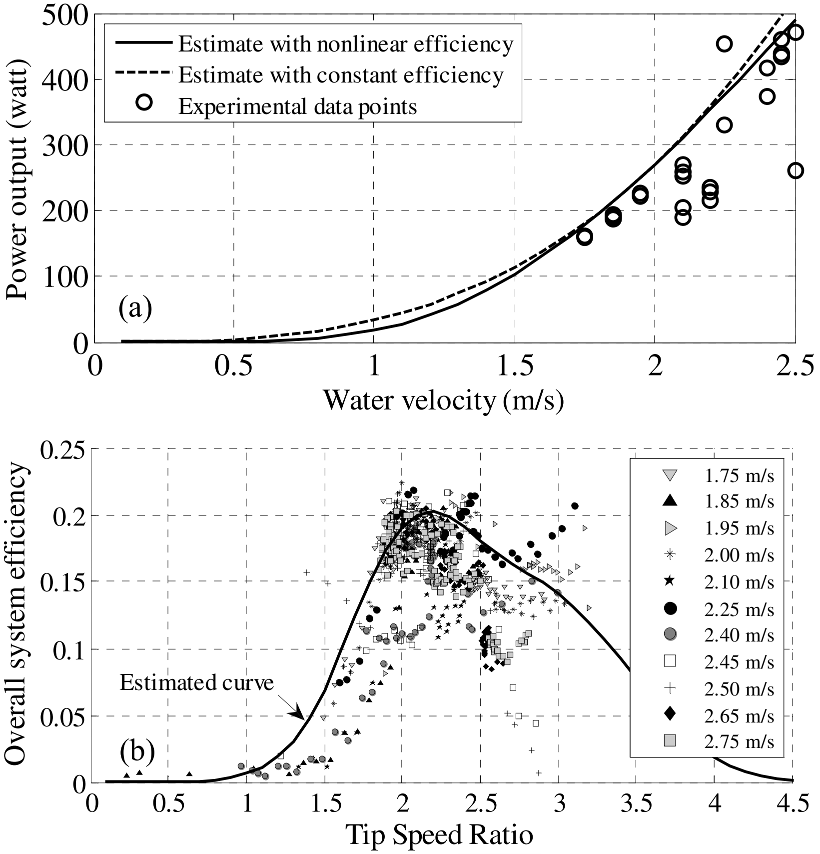
- Method to realize the true shape of the performance curve & power curve needs to be developed
- An iterative method using a-priori knowledge of all the subsystems' efficiency profile (after normalization to a base quantity) is proposed

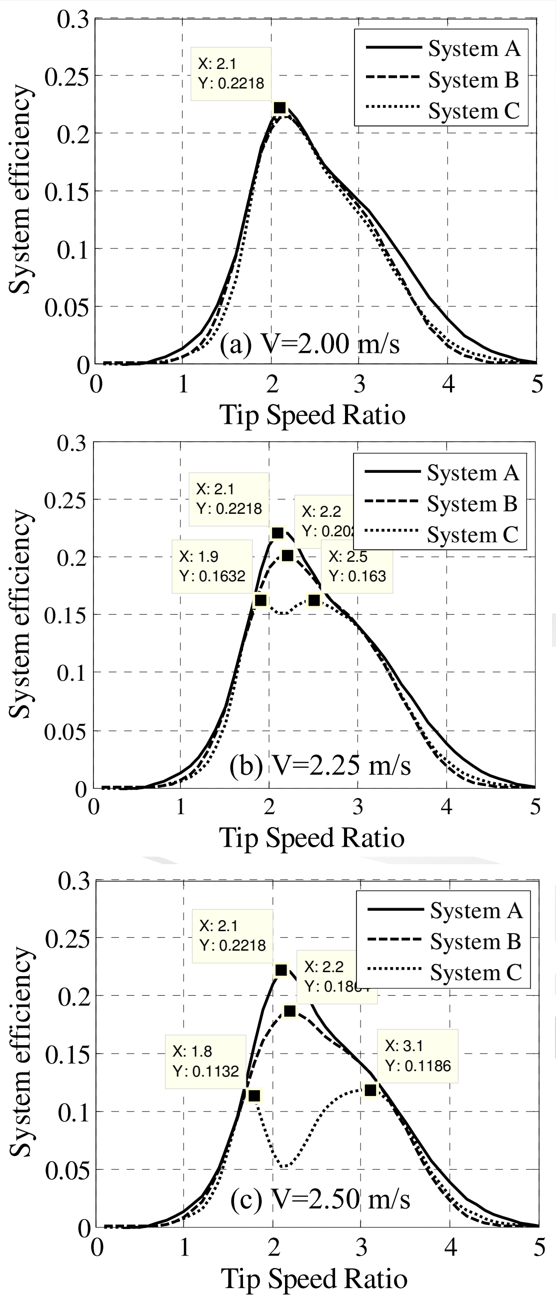


Controller Evaluation

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





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):

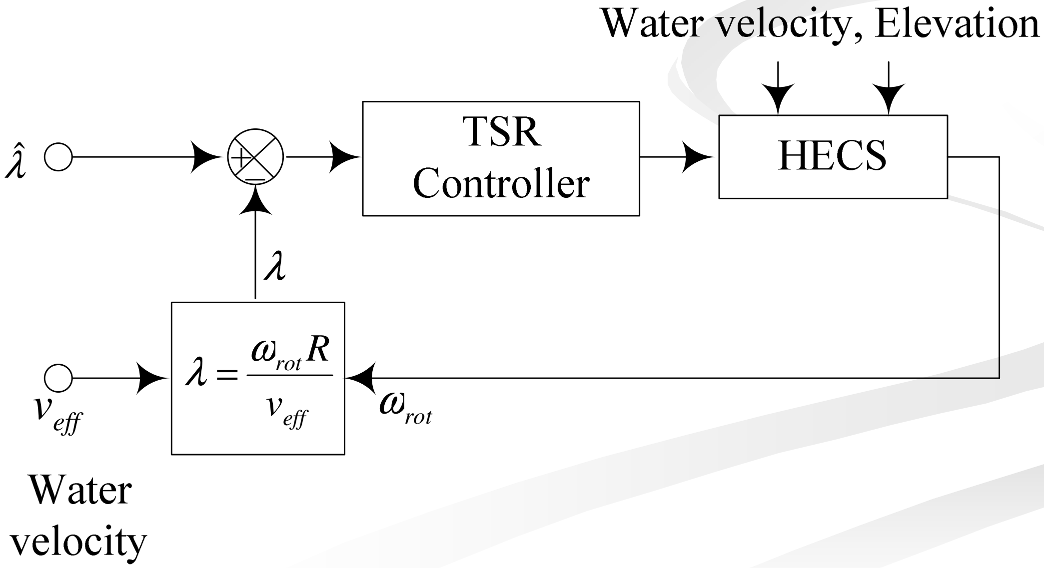
    - *Tip speed ratio (TSR) method*
    - *Power signal feedback (PSF) method*
    - *Hill climbing search (HCS) method*

- 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: $V^*_{trm} = k_{ptsr}(\hat{\lambda} - \lambda)$
- Block representation:



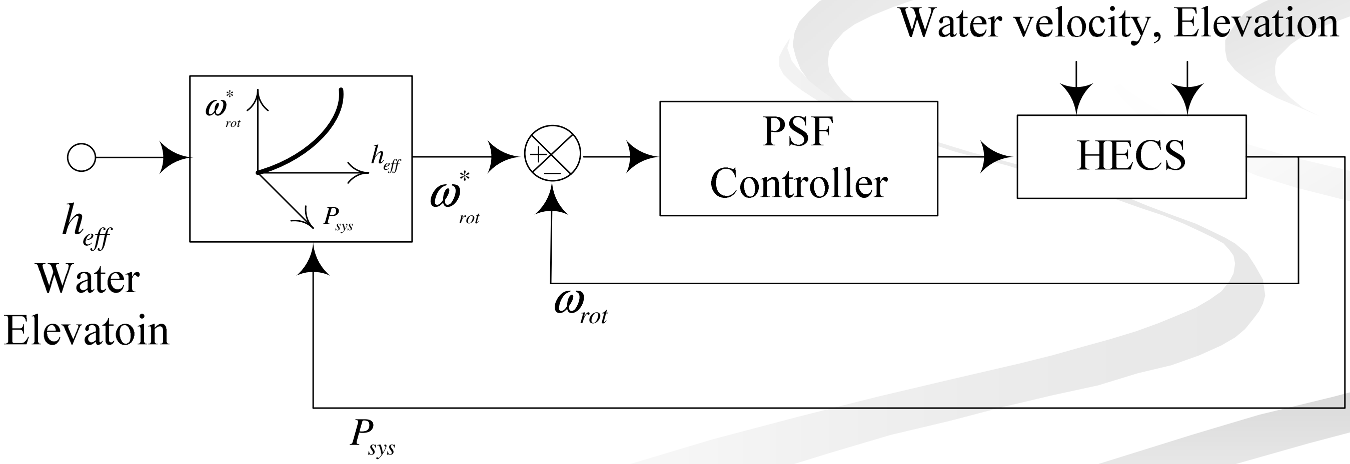
Controller Evaluation

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: $\omega^*_{rot} = \left(\frac{P^*_{sys}}{k_{ncc} h_{eff}}\right)^{\frac{1}{3}}$

  where $\hat{\lambda} = \frac{\omega^*_{rot} R}{v_{eff}}$ and $k_{ncc} = \rho_w R^4 \frac{\hat{C}_p}{\hat{\lambda}^3} k_{cf}$
- 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

$$\omega^*_{rot}(k+1) = \omega^*_{rot}(k) + \Delta\omega^*_{rot}$$

$$\Delta\omega^*_{rot} = sign(\Delta\omega_{rot}, \Delta P_{sys}) \times \left|\Delta\omega^*_{rot}\right|$$

- Sign and magnitude of incremental tracking reference can be found by

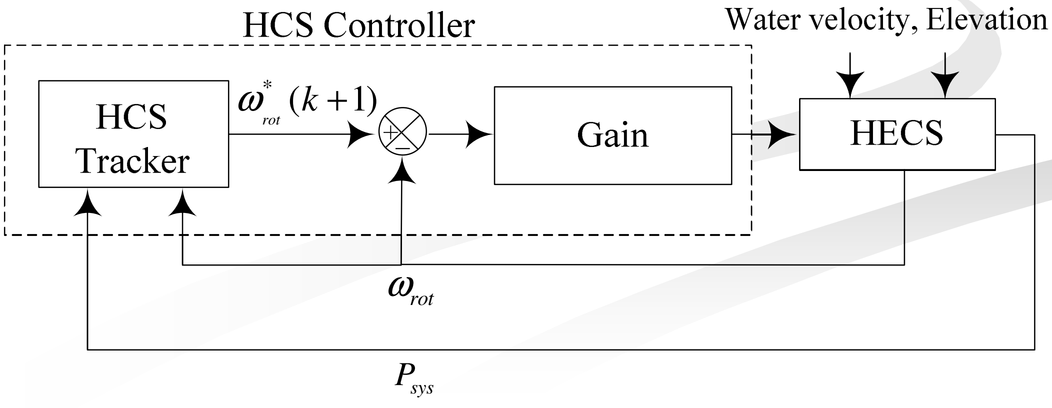
$$\left|\Delta\omega^*_{rot}\right| = k_{phcs}\left|\Delta P_{sys}\right|$$

$$sign(\Delta\omega_{rot}, \Delta P_{sys}) = sign(\Delta\omega_{rot}) \times sign(\Delta P_{sys})$$

- Rotor speed is controlled around the new tracking information

$$V^*_{trm} = k_{phcs}(\omega^*_{rot}(k+1) - \omega^*_{rot})$$

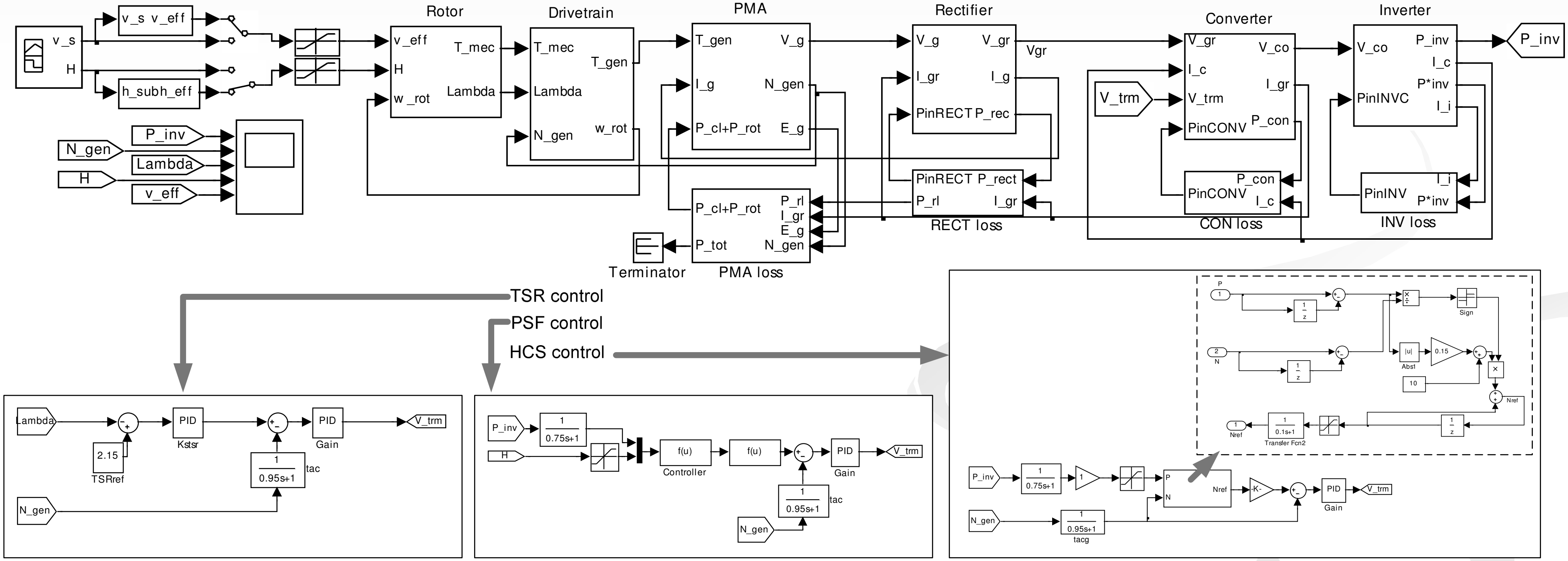
- Block representation:



Controller Evaluation

Candidate Control Methods (cont’d)

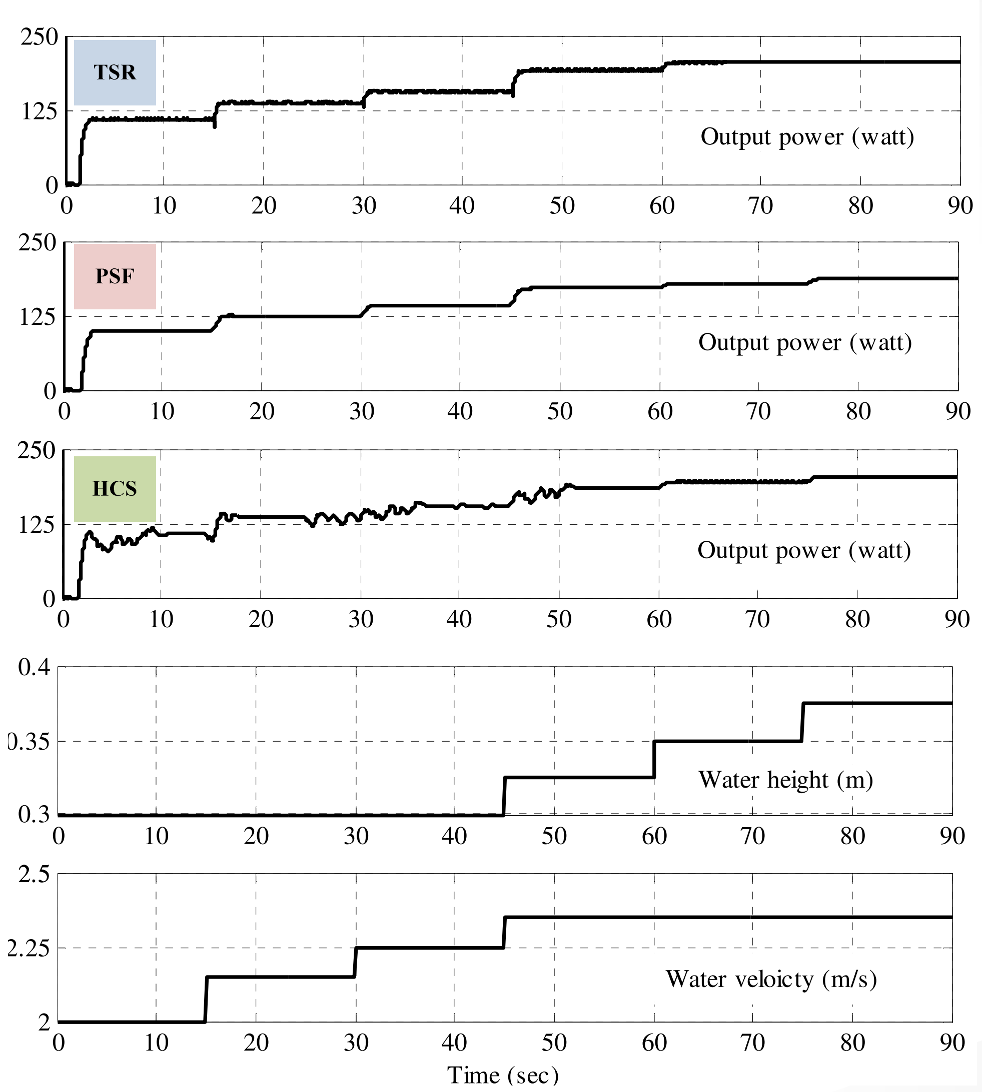
Implementation in Matlab-Simulink^{TM}:

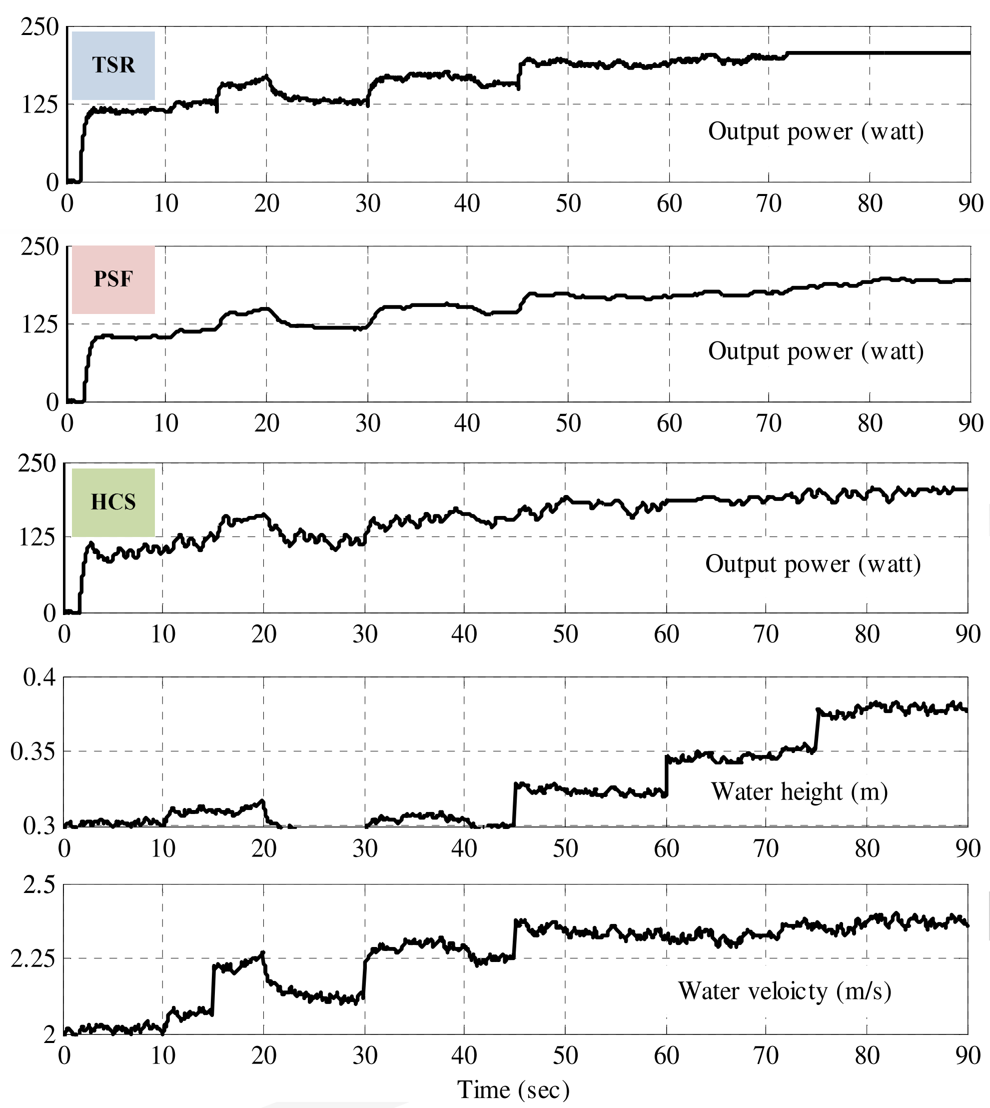


Controller Evaluation

Candidate Control Methods (cont’d)

Simulation results:





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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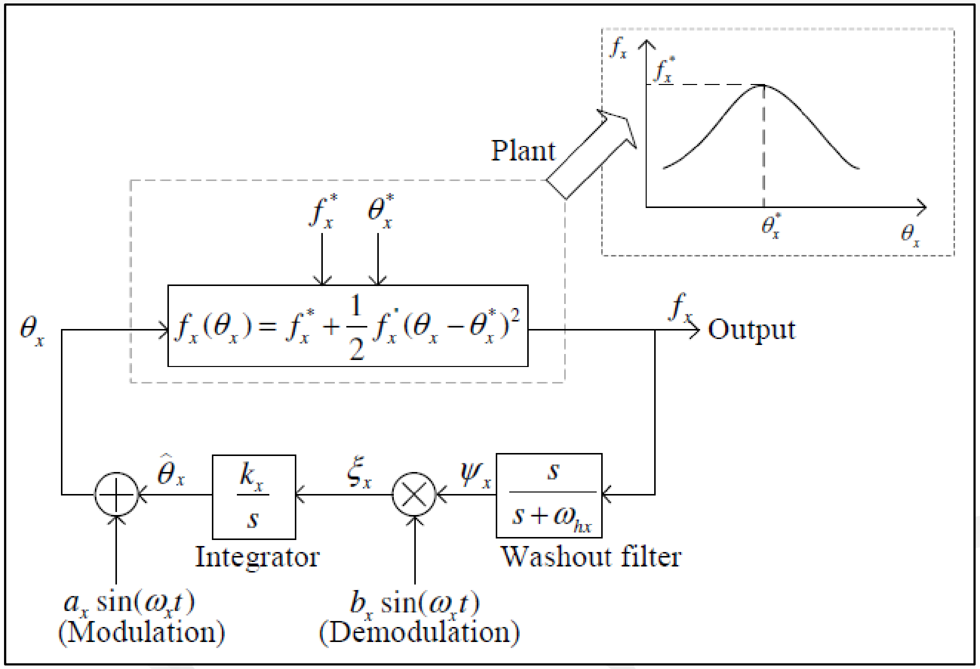
Adaptive Controller Synthesis

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

Extremum Seeking Control (cont'd)

Principles of ESC, plants with static nonlinearity:

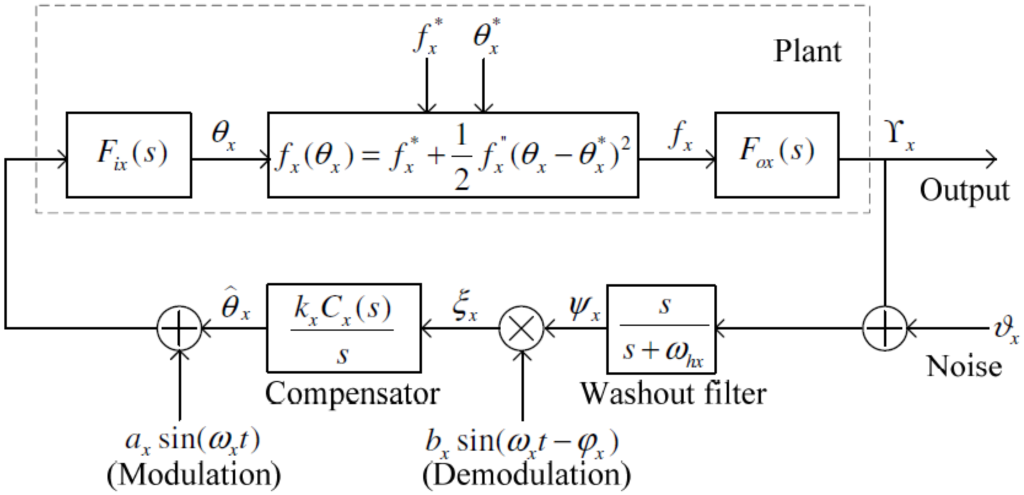


- Plant model: $f_x(\theta_x) = f_x^* + \frac{1}{2} f_x''(\theta_x - \theta_x^*)^2$
- Unknown setpoint (maxima): θ_x^*
- Plant input: $\theta_x = a_x \sin(\omega_x t) + \hat{\theta}_x$
- Estimate of the setpoint: $\hat{\theta}_x$
- Estimation error: $\tilde{\theta}_x = \theta_x^* - \hat{\theta}_x$
- 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): $\dot{\tilde{\theta}}_x \approx \frac{1}{2} k_x a_x b_x f_x'' \tilde{\theta}_x$
- With $f_x'' < 0$, $k_x a_x b_x > 0$, $sign(\dot{\tilde{\theta}}_x) = sign(\tilde{\theta}_x)$ it is guaranteed that estimation error will always approach zero
- Frequencies of interest ($\omega_{hx} < \omega_x < \omega_{pa}$):
  - **Fastest:** Plant dynamics, ω_{pa}
  - **Medium:** Perturbation signal frequency, ω_x
  - **Slowest:** Washout filter cut-off frequency, ω_{hx}

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



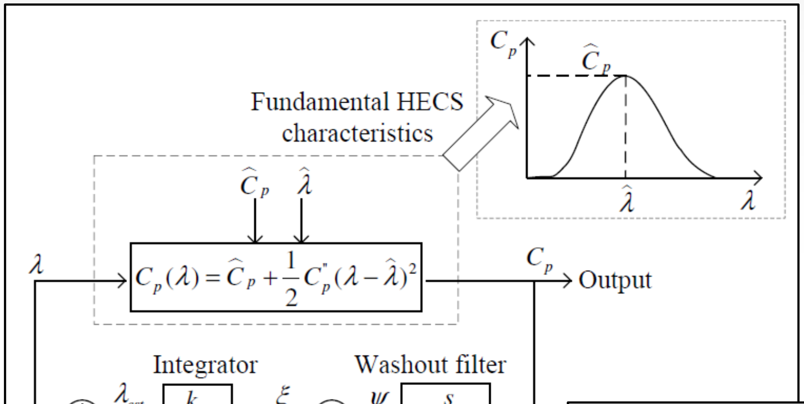
- Average linearized relationship between error in estimated & actual optimum point: $\frac{\tilde{\theta}_x}{\theta_x^*} = \frac{1}{1+L_x(s)}$
- Average linearized relationship between output error & system noise:

$$\frac{\tilde{\Upsilon}_x}{F_{ox}(s)[f_x^*]+\vartheta_x} = -\frac{M_x(s)}{1+M_x(s)}$$

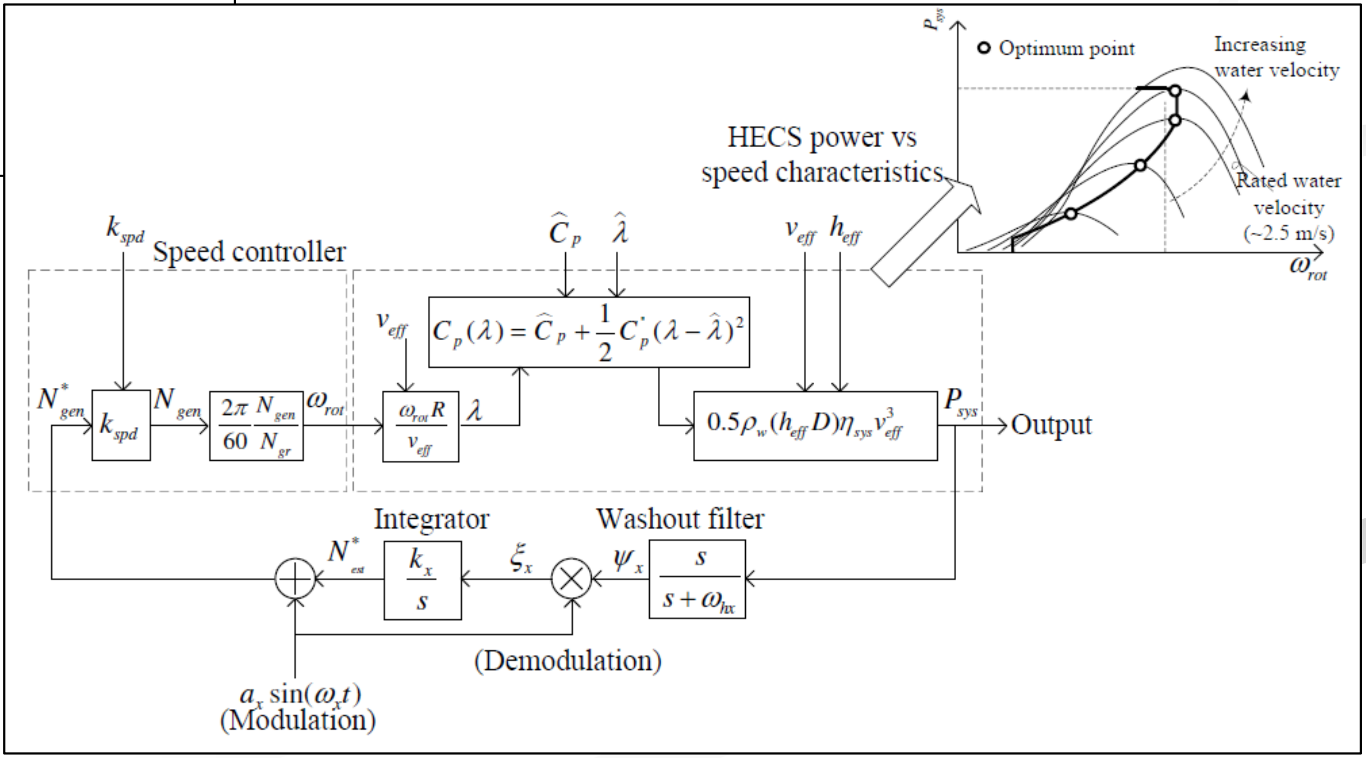
Adaptive Controller Synthesis

ESC in Hydrokinetic Systems

- Hydrokinetic systems with static plant model

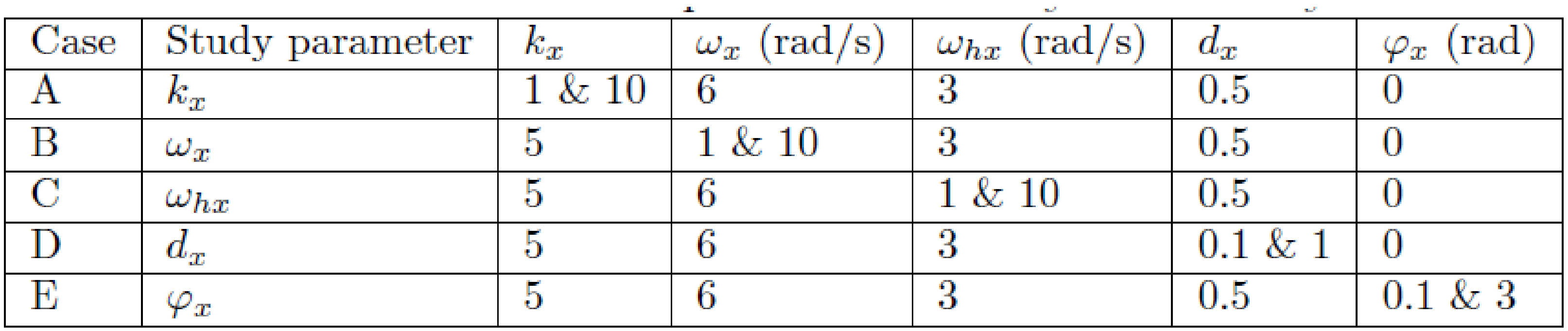


- Assessment of dominant nonlinear plant characteristics



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



Case	Study parameter	k_x	ω_x (rad/s)	ω_{hx} (rad/s)	d_x	φ_x (rad)
A	k_x	1 & 10	6	3	0.5	0
B	ω_x	5	1 & 10	3	0.5	0
C	ω_{hx}	5	6	1 & 10	0.5	0
D	d_x	5	6	3	0.1 & 1	0
E	φ_x	5	6	3	0.5	0.1 & 3

Adaptive Controller Synthesis

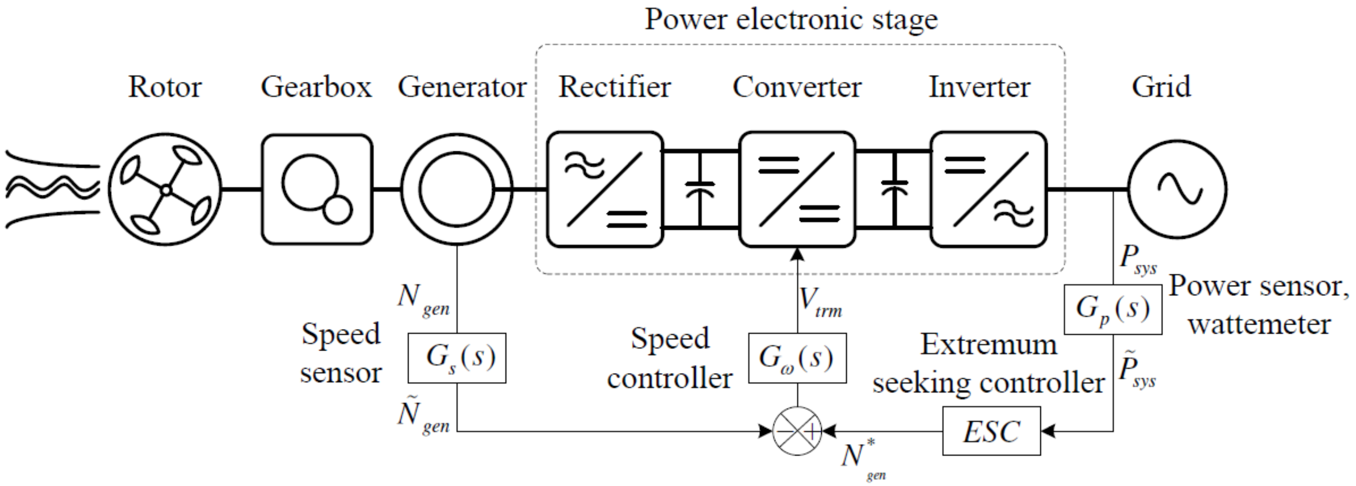
ESC in Hydrokinetic Systems (cont'd)

- **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

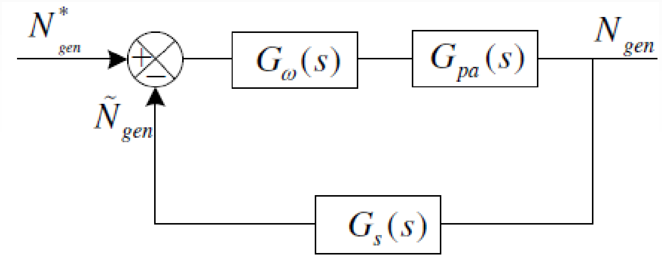


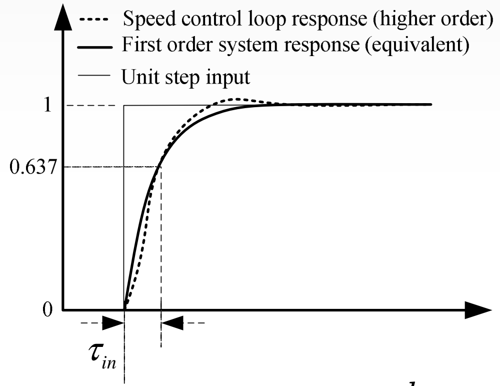
- Internal controller adjusts the set point of the power electronic stage such that the speed reference (as generated by the extremum-seeking controller) can be tracked
- Two measured parameters (rotational speed & output power) and one control variable (power converter settings)

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 $k_{pa} = \frac{N_{gr}}{k_{tsc}}$, $k_{tsc} = -\frac{1}{2}\rho_w A_r v_{eff} R^2 C'_{TO}$, $C'_{TO} = \left.\frac{\partial C_T(\lambda)}{\partial \lambda}\right|_{\widehat{\lambda}_{sys}}$

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):

$$F_{ix}(s) = \frac{k_{pa}(k_{p\omega}\tau_1 s^2+(k_{p\omega}\tau_1+k_{p\omega})s+k_{i\omega})}{\tau_{pa}\tau_1 s^3+(\tau_{pa}+\tau_1)s^2+k_{pa}k_{p\omega}s+k_{pa}k_{i\omega}} \approx \frac{1}{\tau_{in}s+1}$$

ESC Synthesis & Implementation (cont'd)

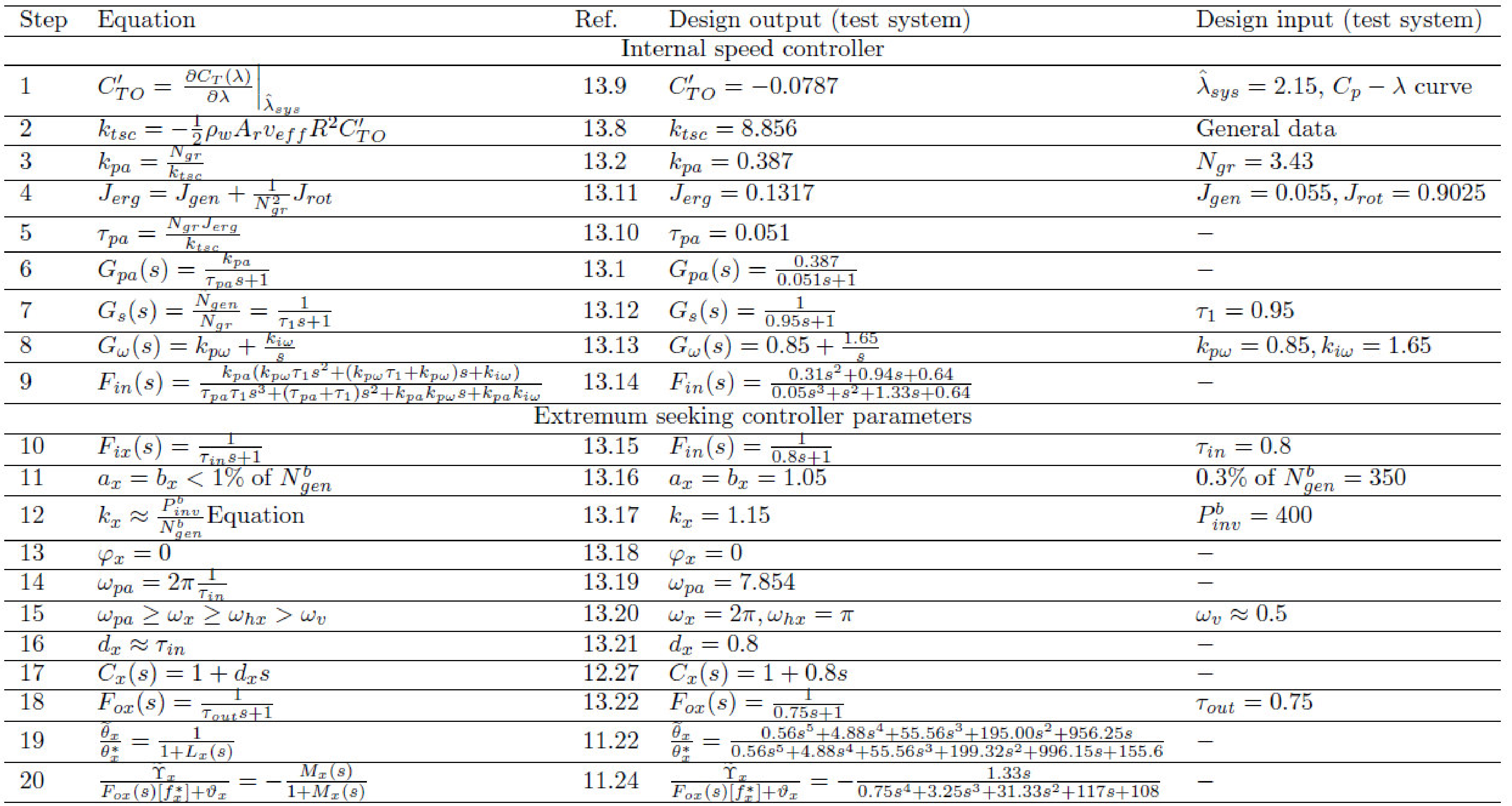
ESC parameter tuning considerations:

- 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^b_{gen}
- Controller gain: $k_x \approx \frac{P^b_{inv}}{N^b_{gen}}$
- 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: $F_{ox}(s) = \frac{1}{\tau_{out}s+1}$

Controller Evaluation

ESC Synthesis & Implementation (cont’d)

ESC design steps for test hydrokinetic systems:

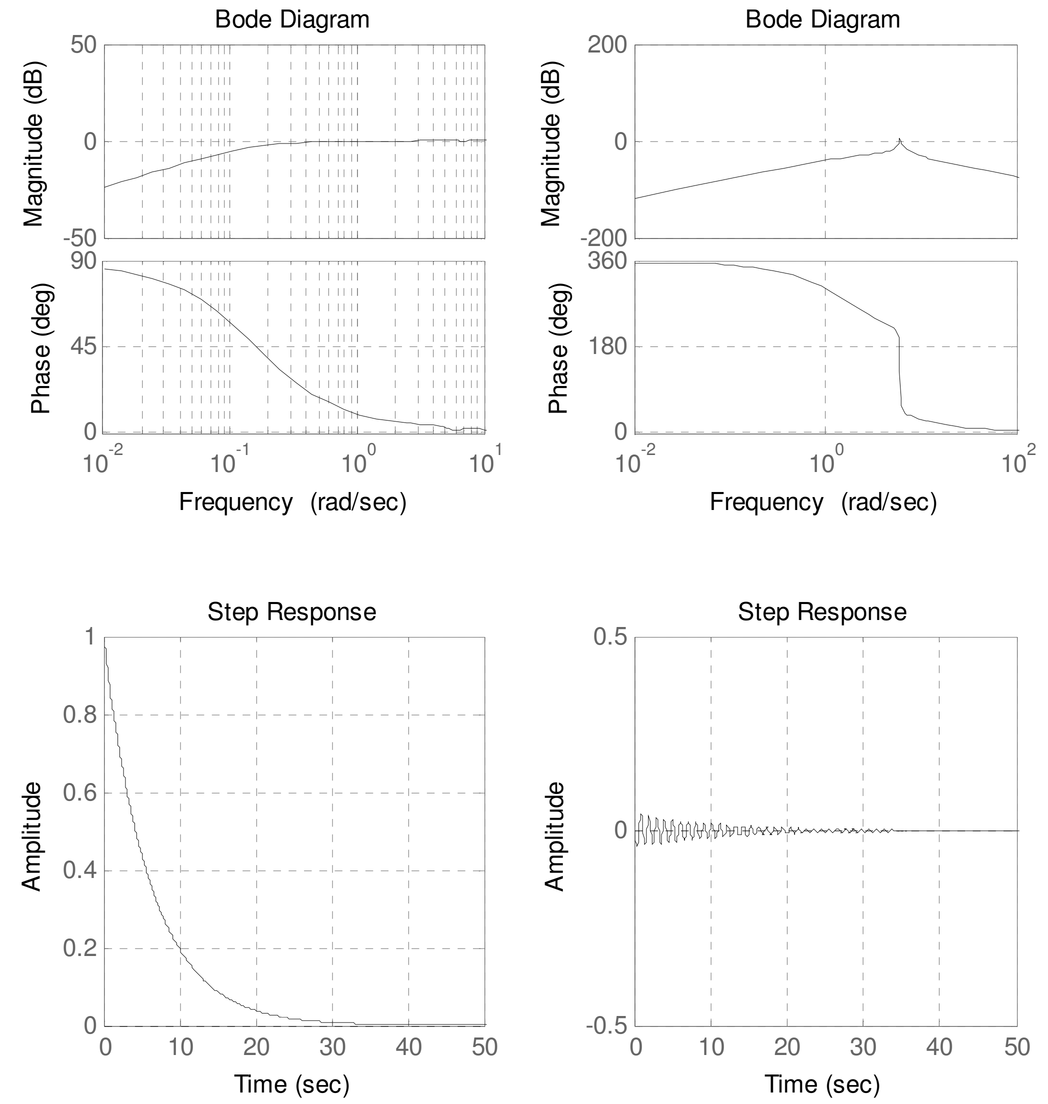


Step	Equation	Ref.	Design output (test system)	Design input (test system)
Internal speed controller				
1	$C'_{TO} = \left.\frac{\partial C_T(\lambda)}{\partial \lambda}\right\vert_{\hat{\lambda}_{sys}}$	13.9	$C'_{TO} = -0.0787$	$\hat{\lambda}_{sys} = 2.15$, $C_p - \lambda$ curve
2	$k_{tsc} = -\frac{1}{2}\rho_w A_r v_{eff} R^2 C'_{TO}$	13.8	$k_{tsc} = 8.856$	General data
3	$k_{pa} = \frac{N_{gr}}{k_{tsc}}$	13.2	$k_{pa} = 0.387$	$N_{gr} = 3.43$
4	$J_{erg} = J_{gen} + \frac{1}{N_{gr}^2} J_{rot}$	13.11	$J_{erg} = 0.1317$	$J_{gen} = 0.055, J_{rot} = 0.9025$
5	$\tau_{pa} = \frac{N_{gr} J_{erg}}{k_{tsc}}$	13.10	$\tau_{pa} = 0.051$	–
6	$G_{pa}(s) = \frac{k_{pa}}{\tau_{pa} s + 1}$	13.1	$G_{pa}(s) = \frac{0.387}{0.051s+1}$	–
7	$G_s(s) = \frac{N_{gen}}{N_{gr}} = \frac{1}{\tau_1 s + 1}$	13.12	$G_s(s) = \frac{1}{0.95s+1}$	$\tau_1 = 0.95$
8	$G_\omega(s) = k_{p\omega} + \frac{k_{i\omega}}{s}$	13.13	$G_\omega(s) = 0.85 + \frac{1.65}{s}$	$k_{p\omega} = 0.85, k_{i\omega} = 1.65$
9	$F_{in}(s) = \frac{k_{pa}(k_{p\omega}\tau_1 s^2 + (k_{p\omega}\tau_1 + k_{p\omega})s + k_{i\omega})}{\tau_{pa}\tau_1 s^3 + (\tau_{pa}+\tau_1)s^2 + k_{pa}k_{p\omega}s + k_{pa}k_{i\omega}}$	13.14	$F_{in}(s) = \frac{0.31s^2+0.94s+0.64}{0.05s^3+s^2+1.33s+0.64}$	–
Extremum seeking controller parameters				
10	$F_{ix}(s) = \frac{1}{\tau_{in} s + 1}$	13.15	$F_{in}(s) = \frac{1}{0.8s+1}$	$\tau_{in} = 0.8$
11	$a_x = b_x <$ 1% of N_{gen}^b	13.16	$a_x = b_x = 1.05$	0.3% of $N_{gen}^b = 350$
12	$k_x \approx \frac{P_{inv}^b}{N_{gen}^b}$ Equation	13.17	$k_x = 1.15$	$P_{inv}^b = 400$
13	$\varphi_x = 0$	13.18	$\varphi_x = 0$	–
14	$\omega_{pa} = 2\pi \frac{1}{\tau_{in}}$	13.19	$\omega_{pa} = 7.854$	–
15	$\omega_{pa} \geq \omega_x \geq \omega_{hx} > \omega_v$	13.20	$\omega_x = 2\pi, \omega_{hx} = \pi$	$\omega_v \approx 0.5$
16	$d_x \approx \tau_{in}$	13.21	$d_x = 0.8$	–
17	$C_x(s) = 1 + d_x s$	12.27	$C_x(s) = 1 + 0.8s$	–
18	$F_{ox}(s) = \frac{1}{\tau_{out} s + 1}$	13.22	$F_{ox}(s) = \frac{1}{0.75s+1}$	$\tau_{out} = 0.75$
19	$\frac{\tilde{\theta}_x}{\theta_x^*} = \frac{1}{1+L_x(s)}$	11.22	$\frac{\tilde{\theta}_x}{\theta_x^*} = \frac{0.56s^5+4.88s^4+55.56s^3+195.00s^2+956.25s}{0.56s^5+4.88s^4+55.56s^3+199.32s^2+996.15s+155.6}$	–
20	$\frac{\tilde{\Upsilon}_x}{F_{ox}(s)[f_x^*]+\vartheta_x} = -\frac{M_x(s)}{1+M_x(s)}$	11.24	$\frac{\tilde{\Upsilon}_x}{F_{ox}(s)[f_x^*]+\vartheta_x} = -\frac{1.33s}{0.75s^4+3.25s^3+31.33s^2+117s+108}$	–

Adaptive Controller Synthesis

ESC Synthesis & Implementation (cont’d)

Test of stability, tracking capability & sensitivity to noise:

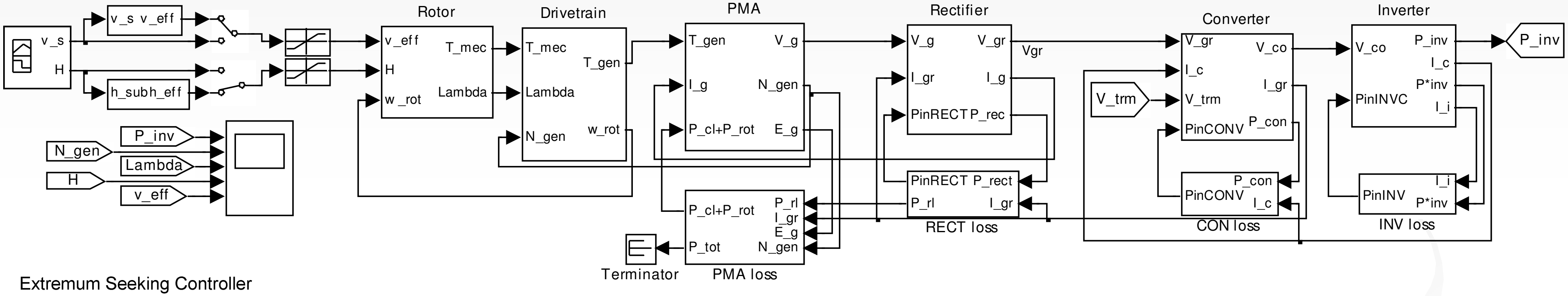


Drift in setpoint Sensitivity to noise

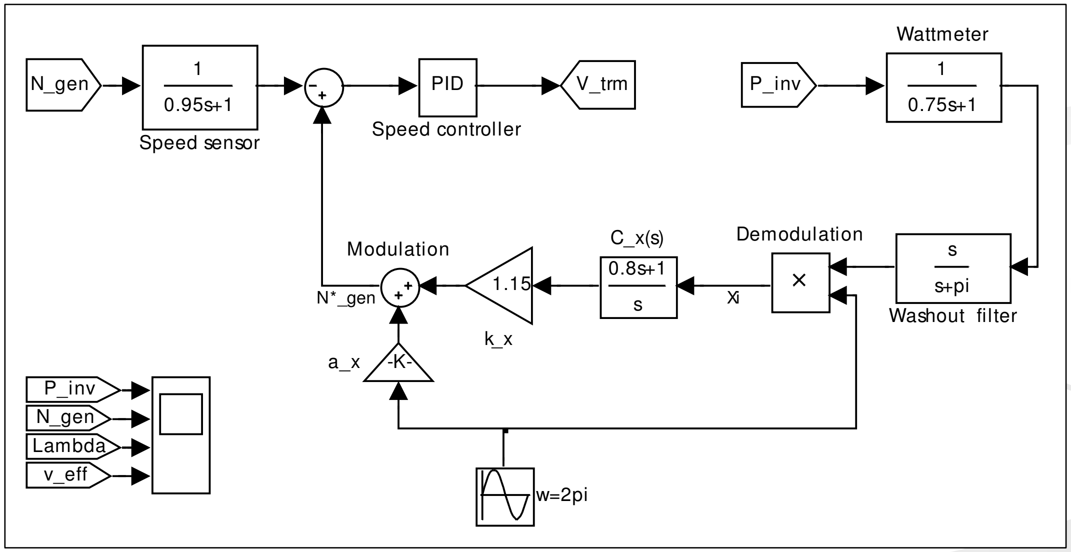
Adaptive Controller Synthesis

ESC Synthesis & Implementation (cont'd)

Implementation in simulation model:

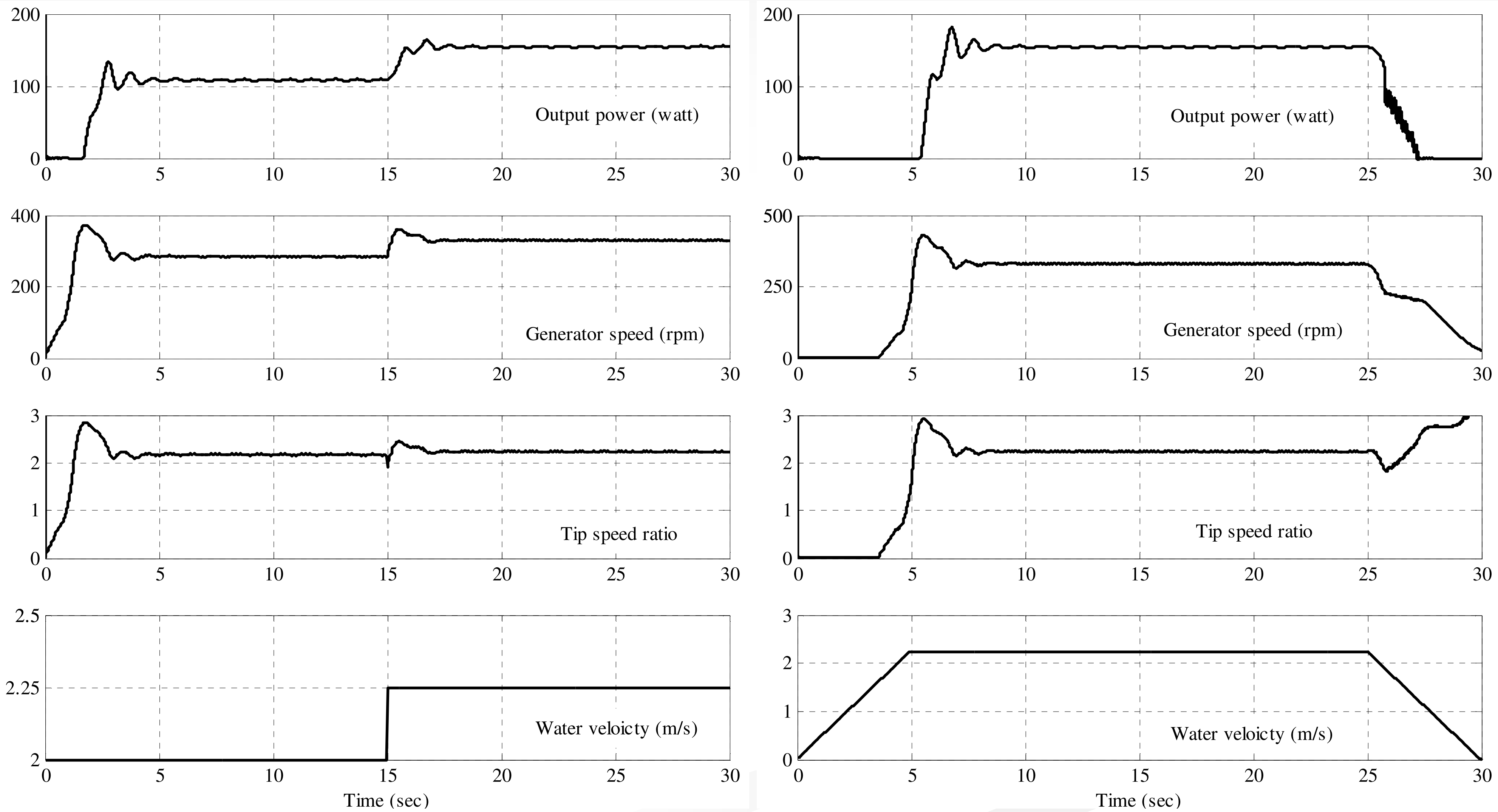


Extremum Seeking Controller



ESC Synthesis & Implementation (cont'd)

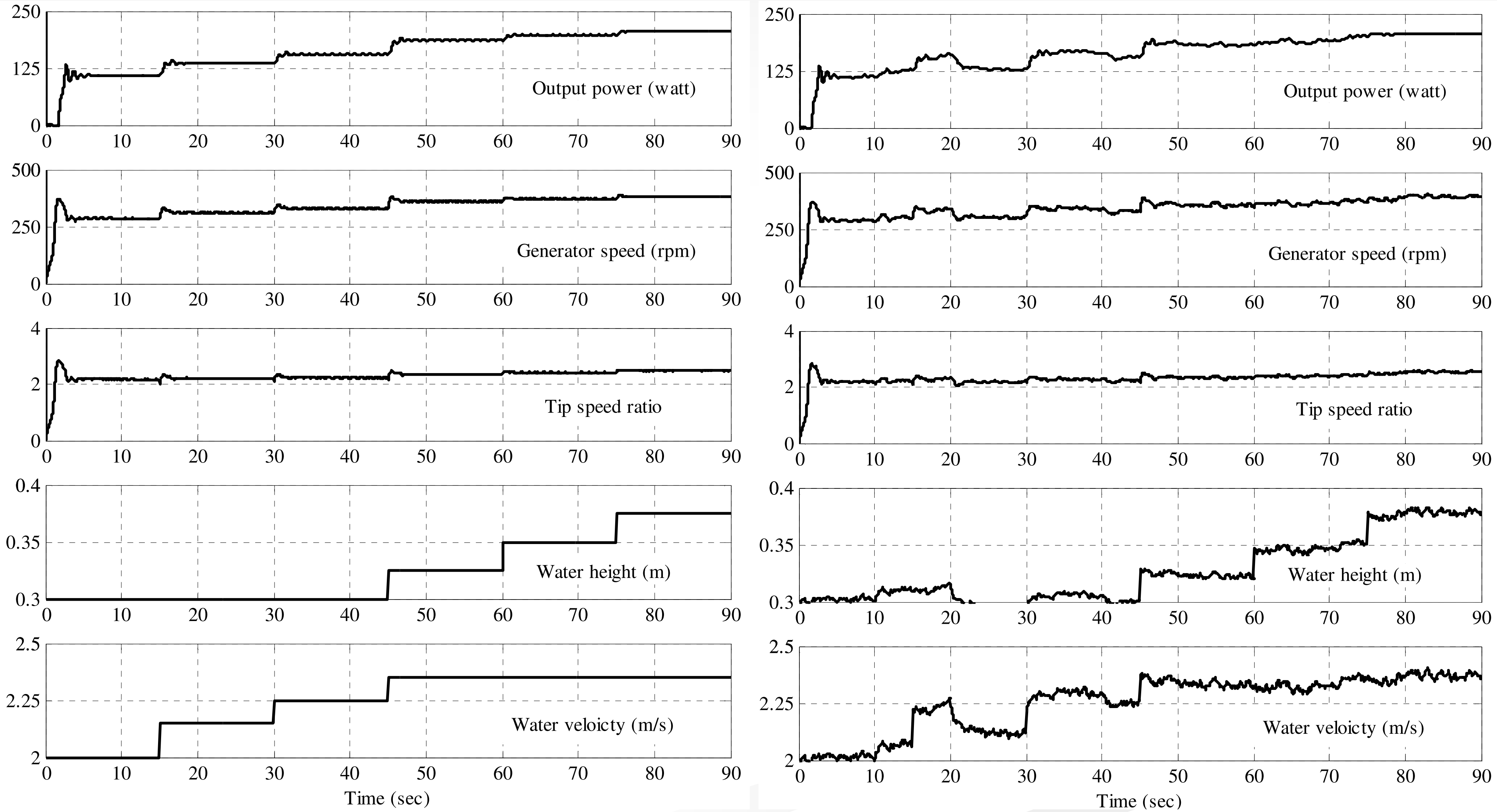
Simulation results (single-step & dual-ramp variations):



Adaptive Controller Synthesis

ESC Synthesis & Implementation (cont’d)

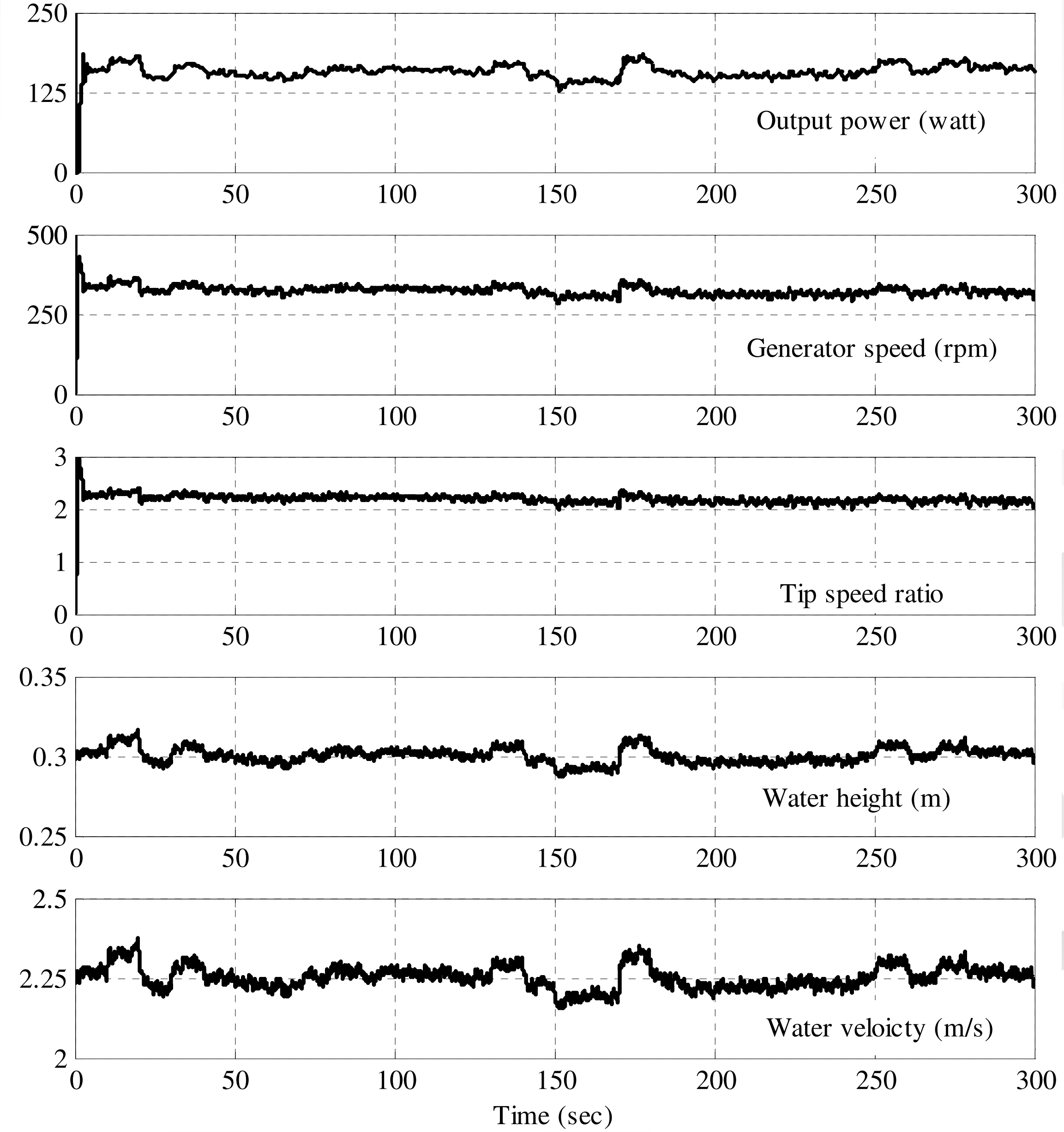
Simulation results (multiple-step & stochastic variations):



Adaptive Controller Synthesis

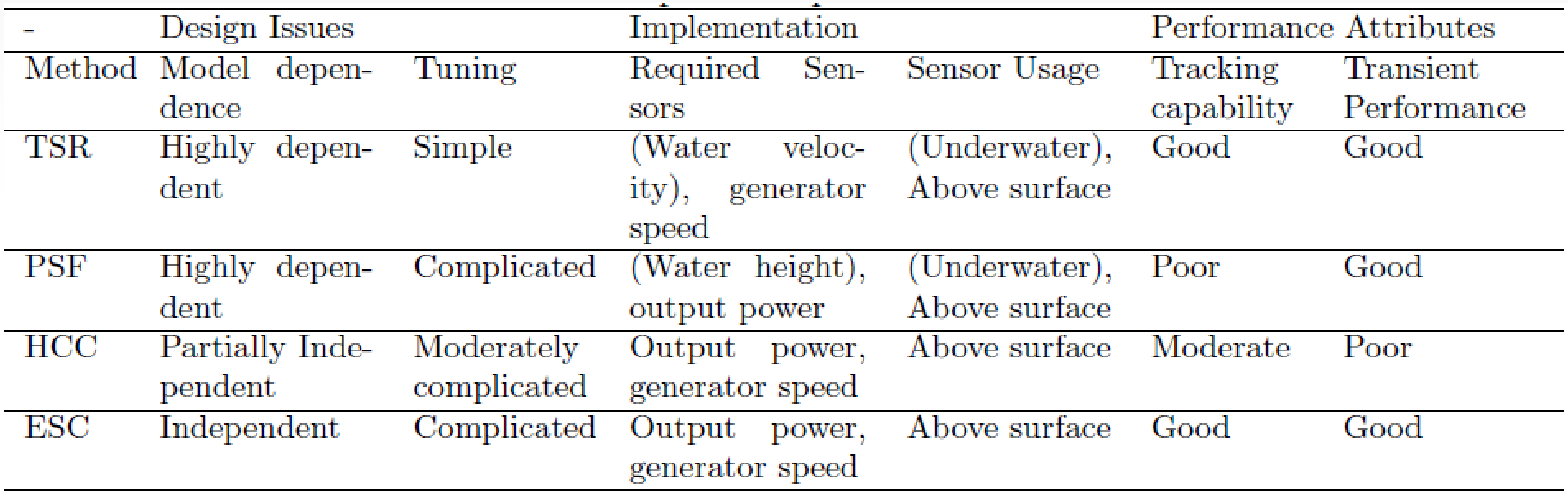
ESC Synthesis & Implementation (cont'd)

Simulation results (stochastic variations):



ESC Synthesis & Implementation (cont’d)

Comparative (subjective) evaluation:



-	Design Issues		Implementation		Performance Attributes	
Method	Model dependence	Tuning	Required Sensors	Sensor Usage	Tracking capability	Transient Performance
TSR	Highly dependent	Simple	(Water velocity), generator speed	(Underwater), Above surface	Good	Good
PSF	Highly dependent	Complicated	(Water height), output power	(Underwater), Above surface	Poor	Good
HCC	Partially Independent	Moderately complicated	Output power, generator speed	Above surface	Moderate	Poor
ESC	Independent	Complicated	Output power, generator speed	Above surface	Good	Good

- Introduction
- Review & Critique
- Modeling & Validation
- Controller Evaluation
- Adaptive Controller Synthesis
- **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

- M.J. Khan, M.T. Iqbal, J.E. Quaicoe; *Dynamics of a Vertical Axis Hydrokinetic Energy Conversion System with a Rectifier Coupled Multi-pole Permanent Magnet Generator*; IET Renewable Power Generation, Vol. 4, Iss. 2, pp. 116–1272010, 2010

- M. J. Khan, M. T. Iqbal and J. E. Quaicoe, *Tow tank testing and performance evaluation of a permanent magnet generator based small vertical axis hydrokinetic turbine*, Journal of Ocean Technology, Vol,. 4, No. 1, pp. 66-84, 2009.

- M.J. Khan, G. Bhuyan, M.T. Iqbal, J.E. Quaicoe; *Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review;* Applied Energy, Volume 86, Issue 10, October 2009, Pages 1823-1835

- M.J. Khan, M.T. Iqbal, J.E. Quaicoe; *River current energy conversion systems: Progress, prospects and challenges; Renewable and Sustainable Energy Reviews*; 12 (2008) 2177–2193

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
- Jahangir Khan, Ali Moshref, Gouri Bhuyan; *A Generic Outline for Dynamic Modeling of Ocean Wave and Tidal Current Energy Conversion Systems*; Presented at IEEE PES General Meeting, 26-30 July, 2009, Calgary, Alberta, Canada
- 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
- Jahangir Khan, Gouri Bhuyan, Ali Moshref, Kip Morison, John H. Pease Jr., and Jim Gurney, '*Ocean Wave and Tidal Current Conversion Technologies and their Interaction with Electrical Networks*', IEEE PES General Meeting, 20-24 July 2008, Pittsburgh, PA, USA
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- M. J. A. Khan, M. T. Iqbal, *Simplified modeling of rectifier coupled brush-less DC generators*, Presented at IEEE 4th international conference on electrical and computer engineering conference, Dhaka Bangladesh, December 18-21, 2006.
- M. J. A. Khan, M. T. Iqbal, and J. E. Quaicoe, *Design Considerations of a Straight Bladed Darrieus Rotor for River Current Turbines*, Presented at IEEE International Symposium on Industrial Electronics ISIE06, Montreal, Canada, July 9-13, 2006.
- M. J. A. Khan, M. T. Iqbal, and J. E. Quaicoe, *A technology review and simulation based performance analysis of river current turbine*, CCECE 2006: Canadian Conference on Electrical and Computer Engineering Ottawa 7-10 May, 2006.

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Thank You