Optimal Aerodynamic Energy Capture Strategies for Hydrostatic Transmission Wind Turbine

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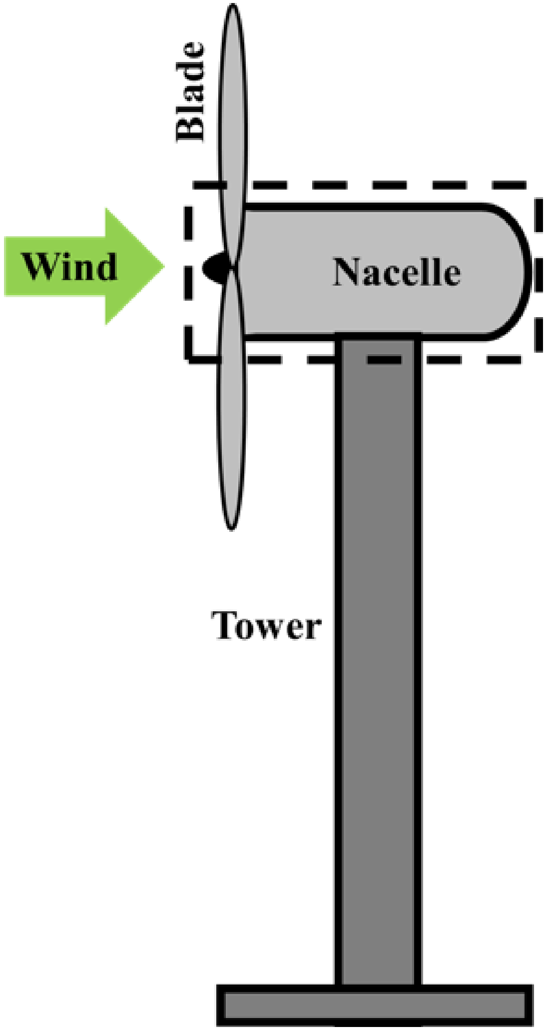
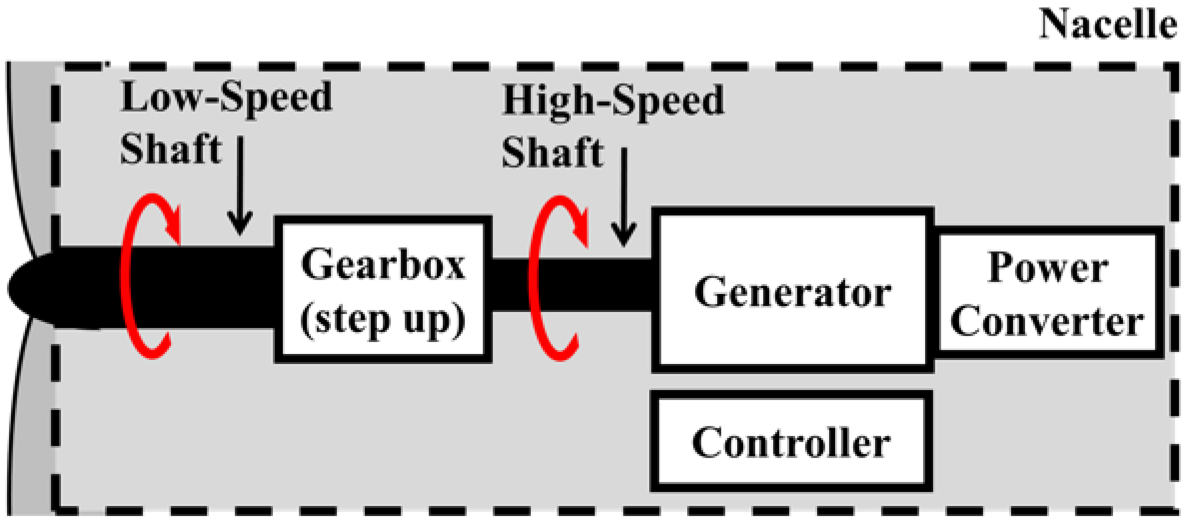
Background

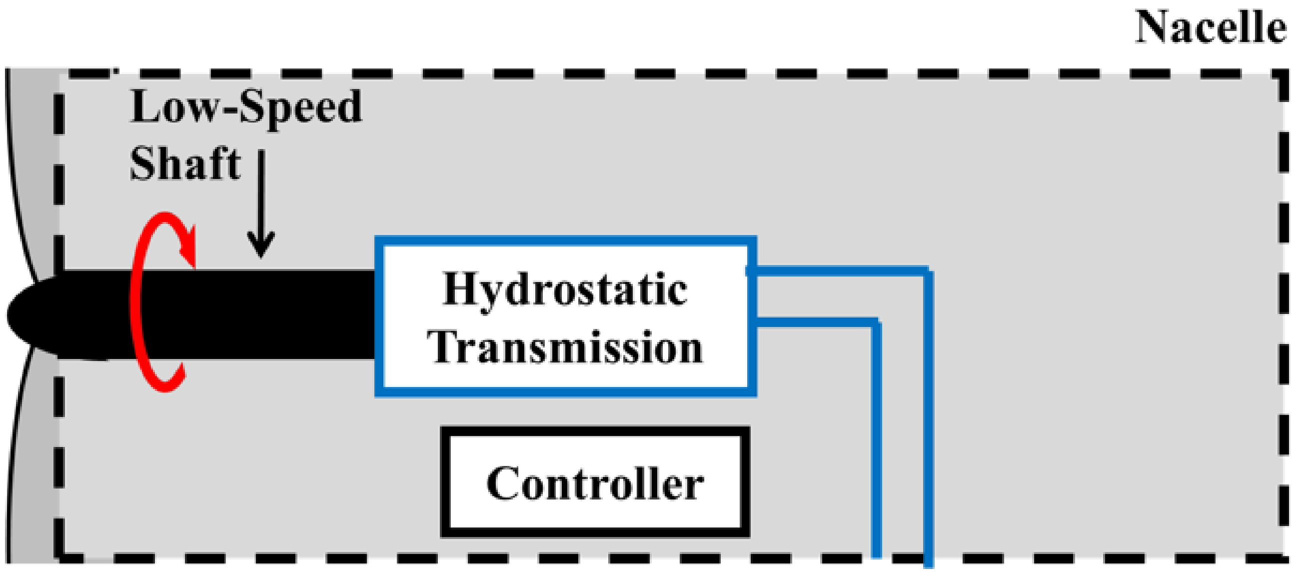


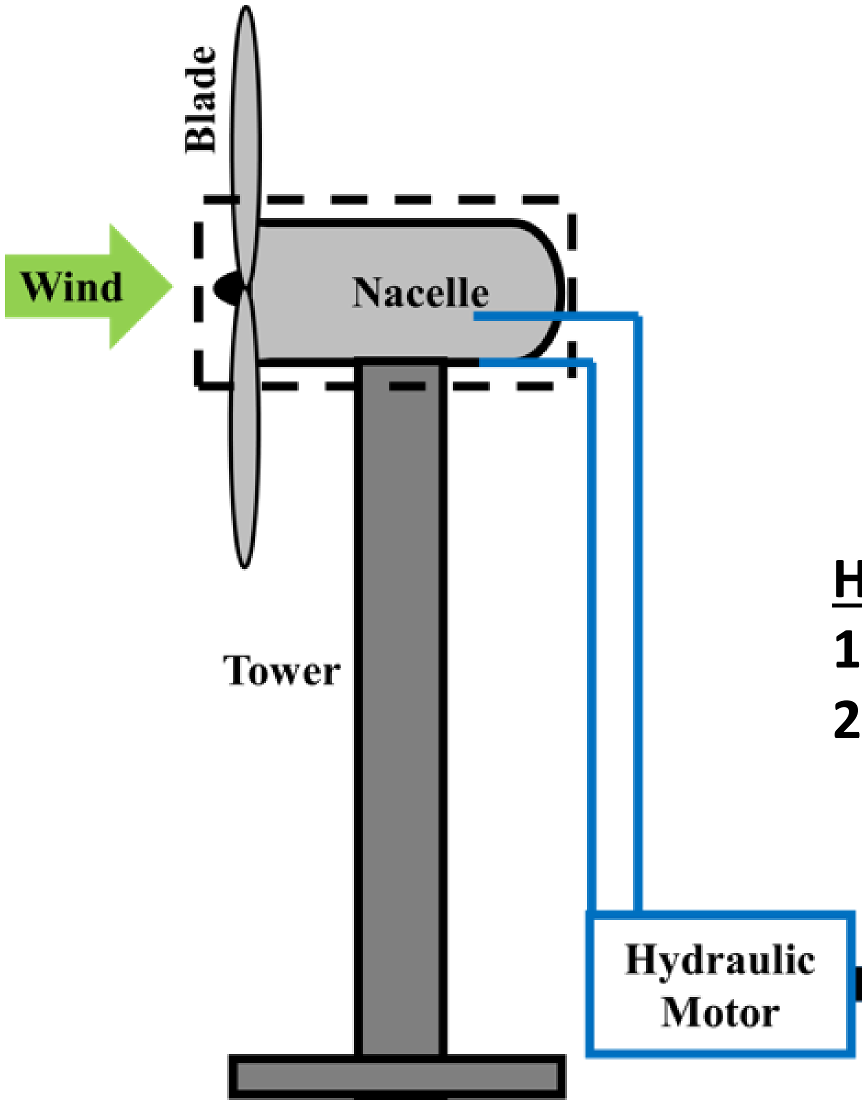


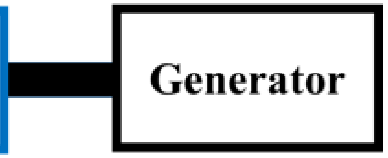
<u>Shortcomings for Conventional Wind Turbine</u>:

1. **Gearbox (step up) reliability issue (failed every 5 years).**
2. **Weight of gearbox and generator in the nacelle increases production, transportation, installation, and maintenance costs. If the weight can be lowered, the costs can be decreased.**

Background







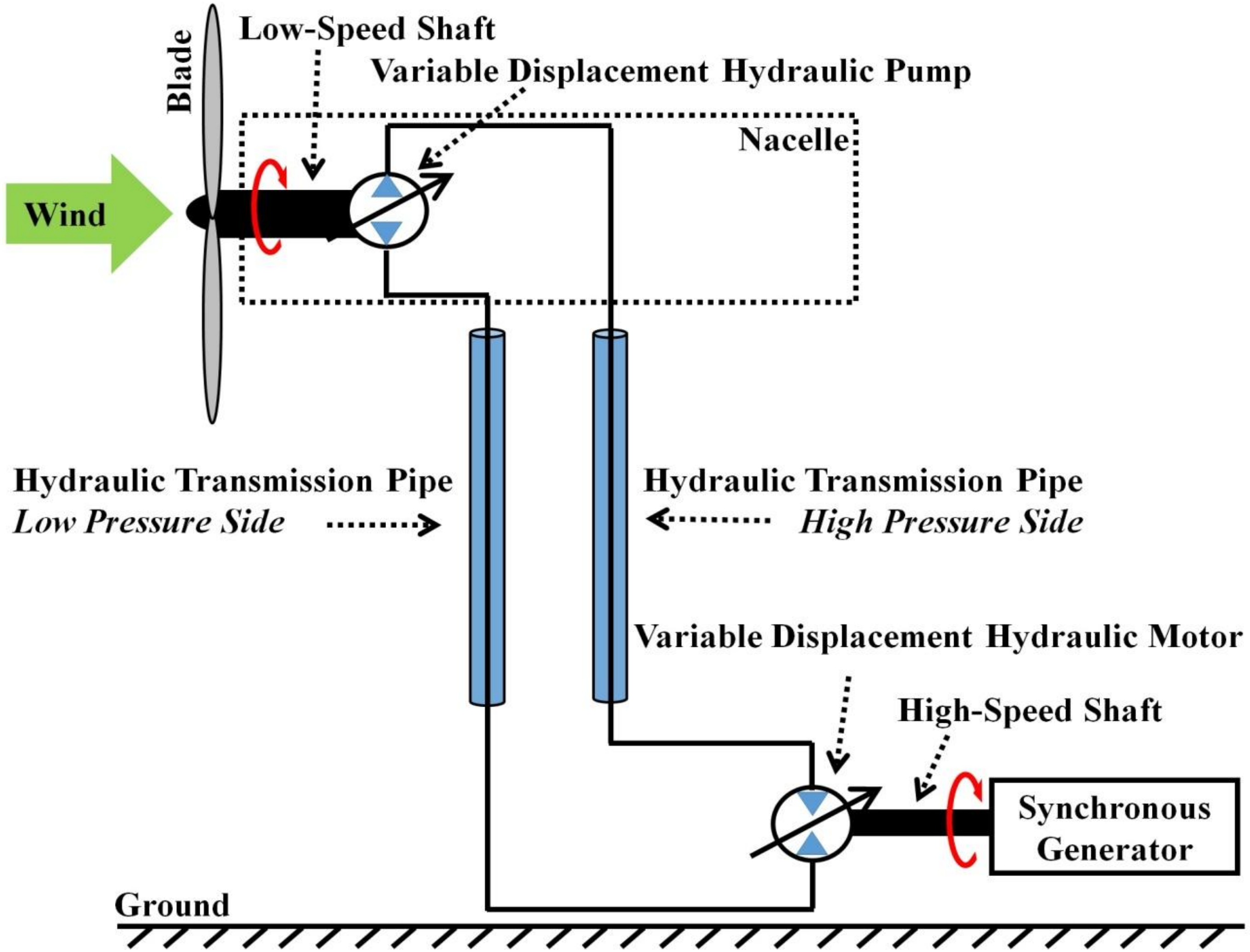
<u>Hydrostatic Transmission Wind Turbine</u>:

1. Gearbox is removed
2. Weight of the nacelle can be reduced by moving generator to ground, potentially reduce production, transportation, installation, and maintenance costs.

Objective

- The objective of this study is to develop a control strategy to maximize aerodynamic energy capture for the hydrostatic transmission wind turbine taking into account the hydraulic motor and generator on the ground level.
  - A single turbine
  - A double turbine

System Model



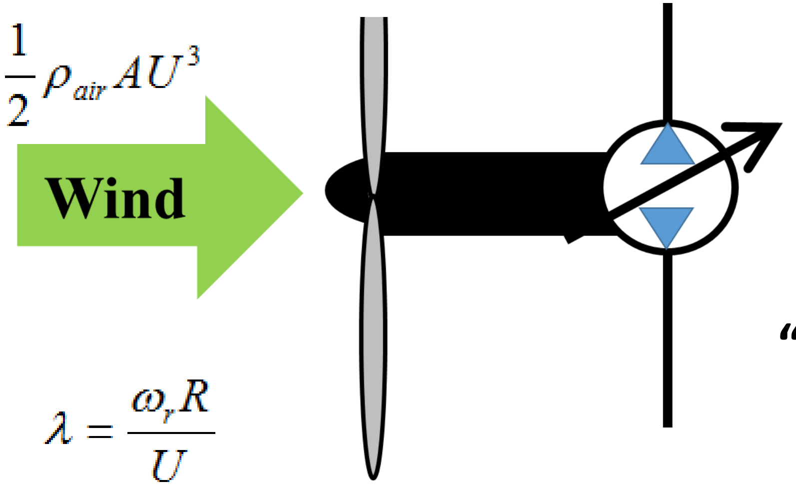
System Model

P_{wind}: Raw power from wind
P_{rotor}: Power available at rotor
τ_{rotor}: Torque asserted at rotor
C_p: Power coefficient
U: Wind speed
A: Swept area
R: Blade radius
ρ_{air}:Air density
λ: Tip-speed ratio
ω_r:Rotor speed
J_r: Rotor inertia
V_p: Pump displacement
ΔP_p: Differential pressure at pump
$\eta_{mech,p}$: Pump mechanical efficiency
β:pitch angle

$$P_{rotor} = P_{wind} C_p(\lambda, \beta)$$

$$\tau_{rotor} = \frac{1}{2}\rho_{air} A R \frac{C_p}{\lambda}(\lambda, \beta) U^2$$

$$P_{wind} = \frac{1}{2}\rho_{air} A U^3$$



$$\dot{\omega}_r = \frac{1}{J_r}\left(\tau_{rotor} - \frac{V_p \Delta p_p}{\eta_{mech,p}}\right)$$

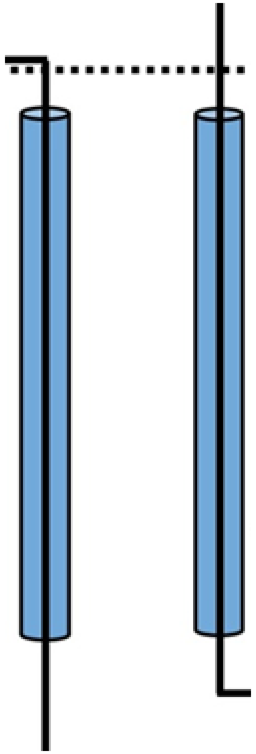
“Newton’s Second Law”

$$\lambda = \frac{\omega_r R}{U}$$

System Model

Δp_x: Differential pressure at pipe center
Δp_p: Differential pressure at pump
Δp_m: Differential pressure at motor
δp: Pressure drop along pipe
β_{fluid}: Fluid bulk modulus
V_{fluid}: Total fluid volume in pipe
V_p: Pump displacement
V_m: Motor displacement
$k_{leak,(p\ or\ m)}$: pump/motor leakage coefficient
L_{pipe}: Pipe length
D_{pipe}: Pipe diameter
A_{pipe}: Pipe cross-sectional area
ρ_{fluid}:Fluid density
Q, Q_{pipe}: Fluid flow rate in pipe
f: Friction factor
ν_{fluid}: Fluid kinematic viscosity
r_{pipe}: Roughness of pipe
Re: Reynold number

$$\Delta p_p = \Delta p_x + \frac{\delta p}{2}$$



$$\Delta p_m = \Delta p_x - \frac{\delta p}{2}$$

"Continuity Equation"

$$\Delta \dot{p}_x = \frac{\beta_{fluid}}{V_{fluid}}\left(V_p \omega_r - V_m \omega_m - k_{leak,p}\Delta p_p - k_{leak,m}\Delta p_m\right)$$

$$\delta p = f\,\frac{L_{pipe}}{D_{pipe}}\,\frac{\rho_{fluid}}{2A_{pipe}^2}\,Q_{pipe}^2$$

$$f\left(Q_{pipe}\right) = \frac{1}{\left(-1.8\log_{10}\left(\frac{6.9}{\mathrm{Re}} + \left(\frac{r_{pipe}/D_{pipe}}{3.7}\right)^{1.11}\right)\right)^2}$$

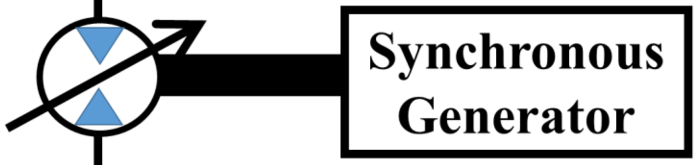
$$\mathrm{Re} = \frac{Q_{pipe}D_{pipe}}{A_{pipe}\nu_{fluid}}.$$

System Model

ω_m:Motor speed
ω_{sync}:Synchronous speed
K_s: Synchronizing torque coefficient
K_d: Damping torque coefficient
θ_{grid}: Phase of the grid voltage
θ_m: Synchronous generator mechanical angle
J_m: Rotor inertia
V_m: Motor displacement
ΔP_m: Differential pressure at motor
$\eta_{mech,m}$: Pump mechanical efficiency
τ_{load}:Torque load from synchronous generator

"Newton's Second Law"

$$\dot{\omega}_m = \frac{1}{J_m}(\eta_{mech,m} V_m \Delta p_m - \tau_{load})$$



$$\varepsilon_{angle} = \theta_{grid} - \theta_m$$

$$\tau_{load} = K_s \varepsilon_{angle} + K_d \dot{\varepsilon}_{angle}$$

Control Strategy

Power Coefficient	Pump Loss	Motor Loss	Friction Loss
$C_p(\lambda,\beta)$	$Loss_{leak,pump} = k_{leak,p}\Delta p_p^2$	$Loss_{mech,motor} = (1-\eta_{mech,m})V_m\omega_m\Delta p_m$	$Loss_{fric} = f\dfrac{L_{pipe}}{D_{pipe}}\dfrac{\rho_{fluid}}{2A_{pipe}^2}Q^3$
	$Loss_{mech,pump} = (1-\eta_{mech,p})\dfrac{V_p\Delta p_p}{\eta_{mech,p}}\omega_r$	$Loss_{leak,motor} = k_{leak,m}\Delta p_m^2$	

$$Loss_{total} = Loss_{mech,pump} + Loss_{leak,pump} + \ldots$$
$$\ldots Loss_{mech,motor} + Loss_{leak,motor} + Loss_{fric}.$$

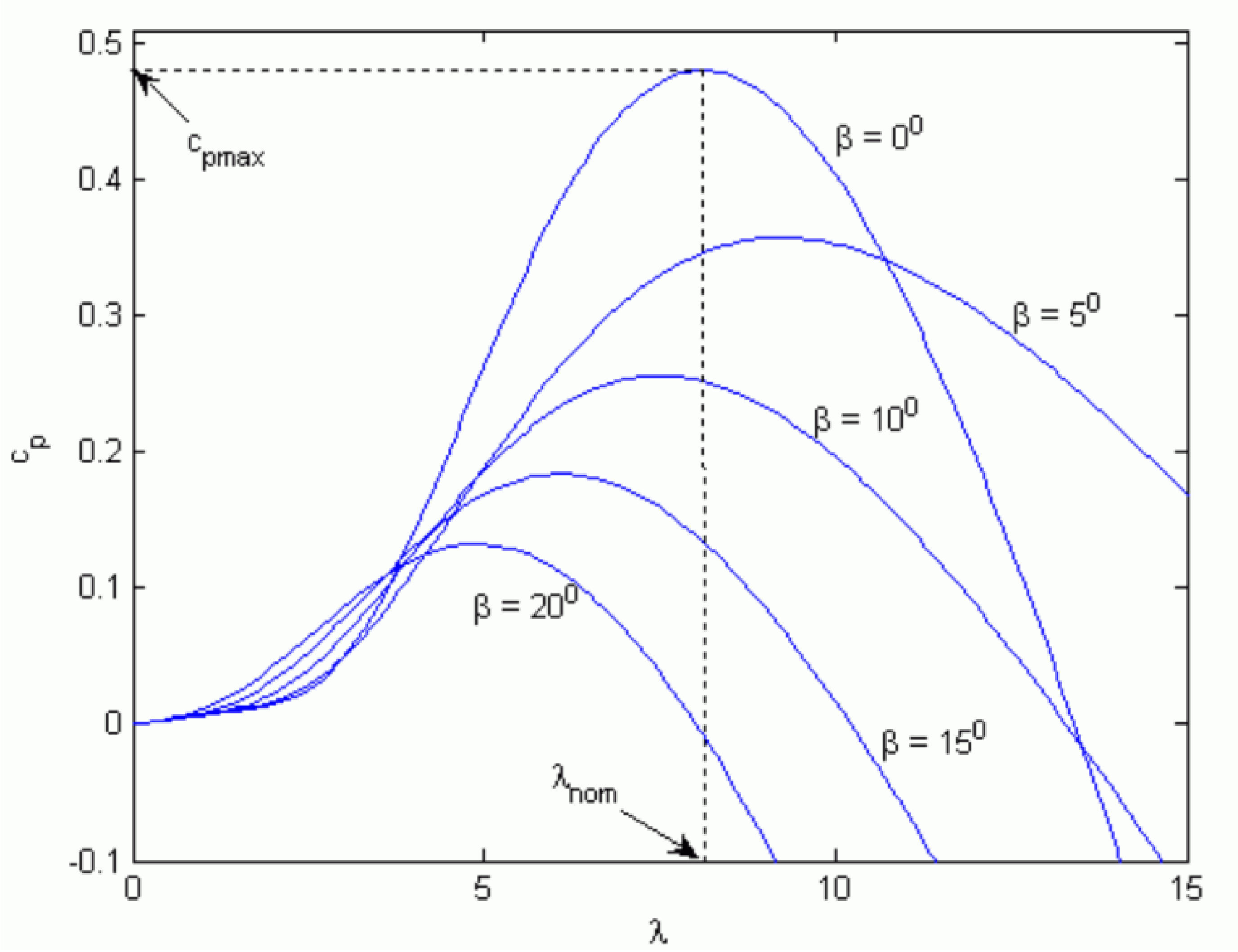
$$C_T = \frac{P_{out}}{P_{rotor}} = \frac{1 - Loss_{total}}{P_{rotor}}$$

Control Strategy:

1. Maximize power coefficient by controlling hydraulic pump displacement

2. Maximize transmission coefficient by controlling hydraulic motor displacement

Strategy 1: Maximize C_p



$$\dot{\omega}_r = \frac{1}{J_r}\left(\tau_{rotor} - \frac{V_p \Delta p_p}{\eta_{mech,p}}\right)$$

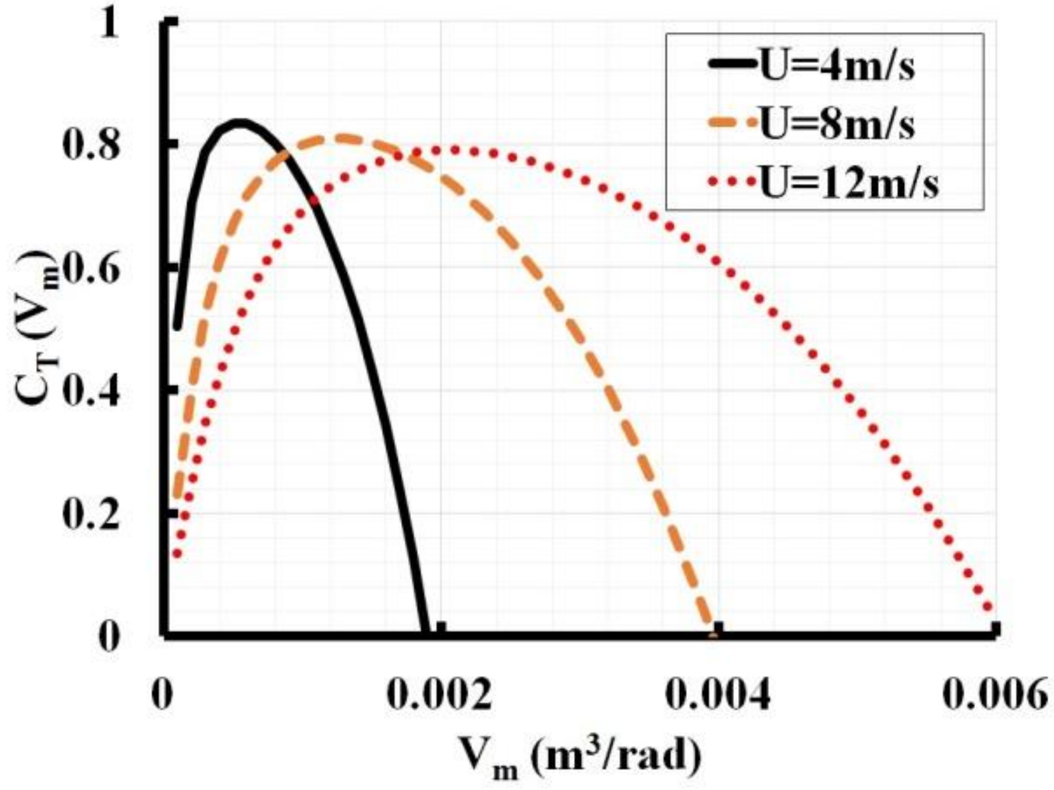
$$\tau_{rotor} = \frac{1}{2}\rho_{air} A R \frac{C_p}{\lambda}(\lambda, \beta) U^2$$

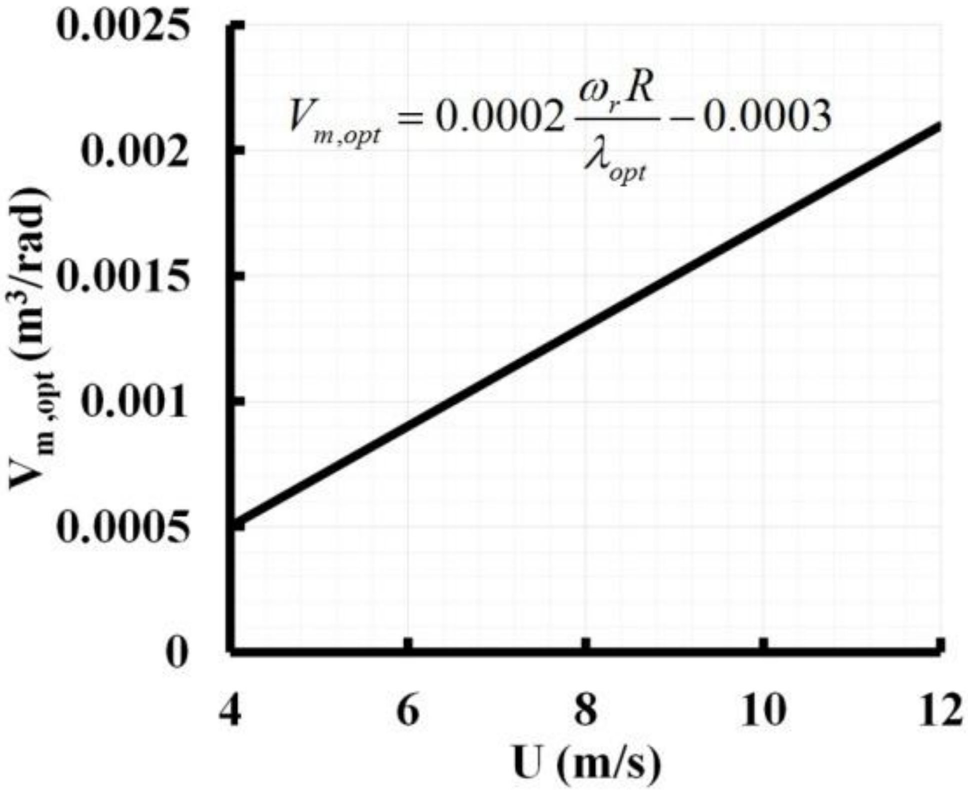
$$\frac{V_p \Delta p_p}{\eta_{mech,p}} = K\omega_r^2 \quad \Rightarrow \quad \boxed{V_p = \frac{K\omega_r^2 \eta_{mech,p}}{\Delta p_p}.}$$

$$K = \frac{1}{2}\rho_{air} A R^3 \frac{C_{p,\max}}{\lambda_{opt}^3}$$

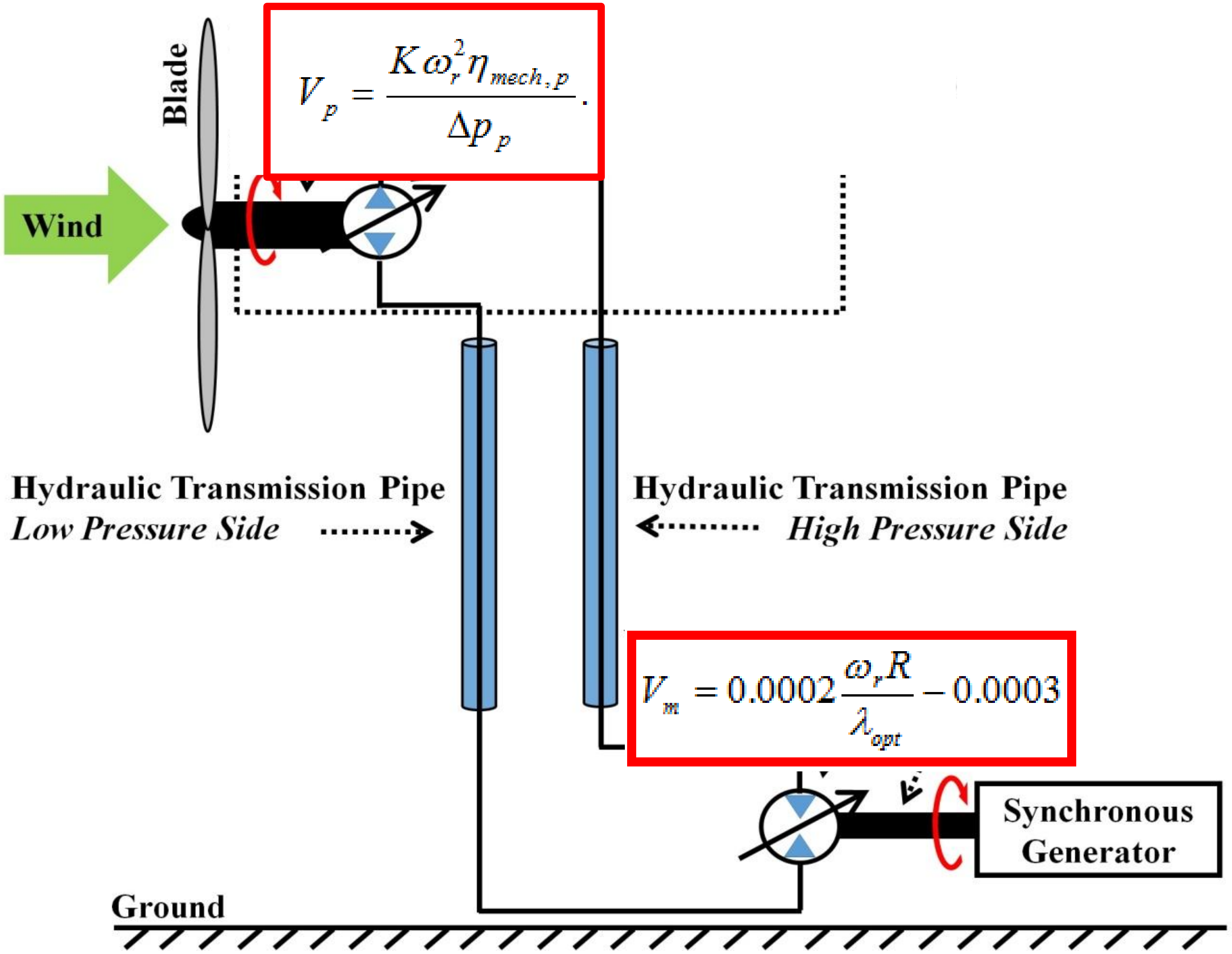
K. E. Johnson, L. Y. Pao, M. J. Balas, and L. J. Fingersh, "Control of Variable-Speed Wind Trubines: Standard and Adaptive Techniques for Maximizing Energy Capture," *IEEE Control Systems Magazine*, vol. 26, no. 3, pp. 70-81, Jun. 2006.

Strategy 2: Maximize C_T

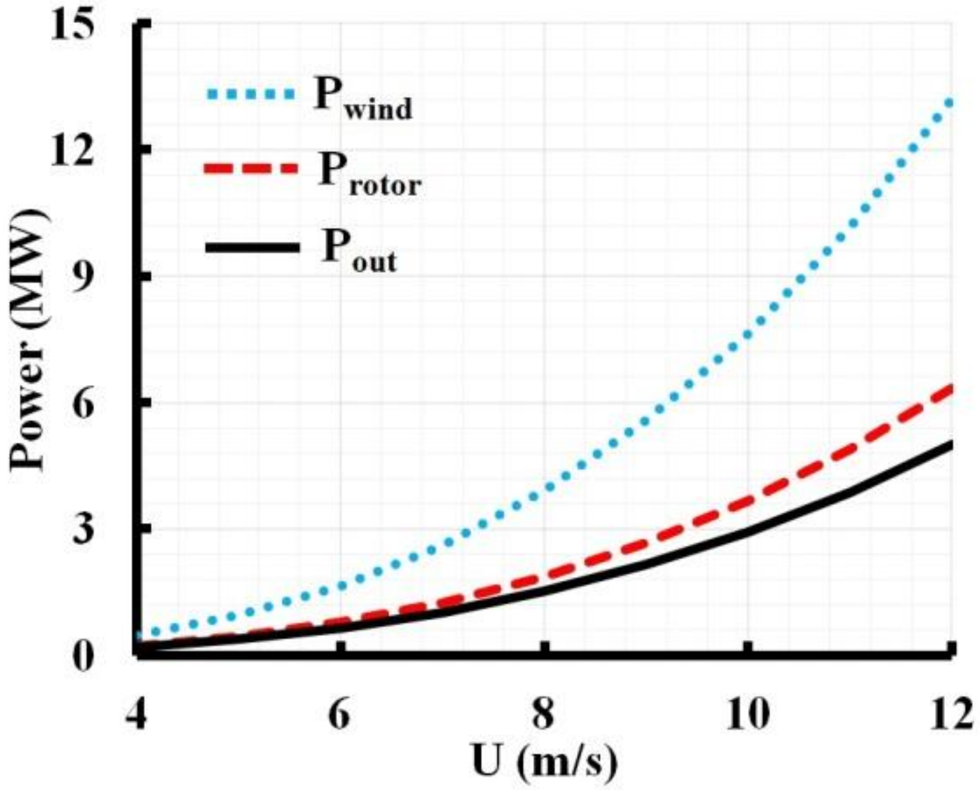


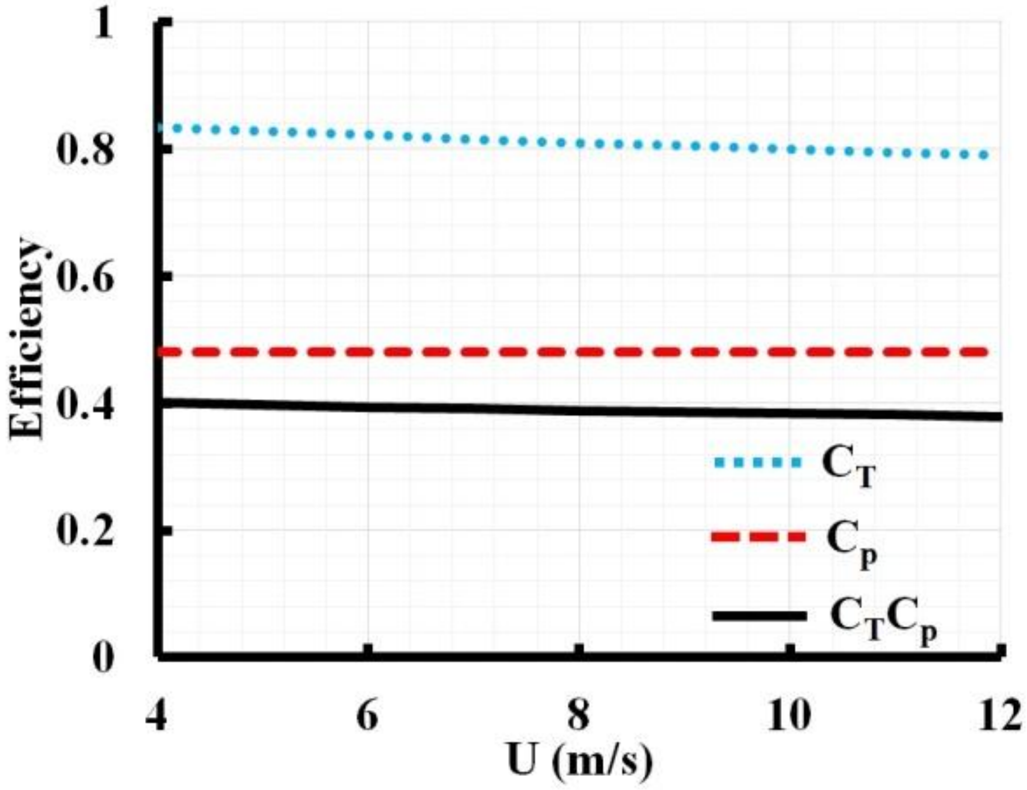


Control Realization

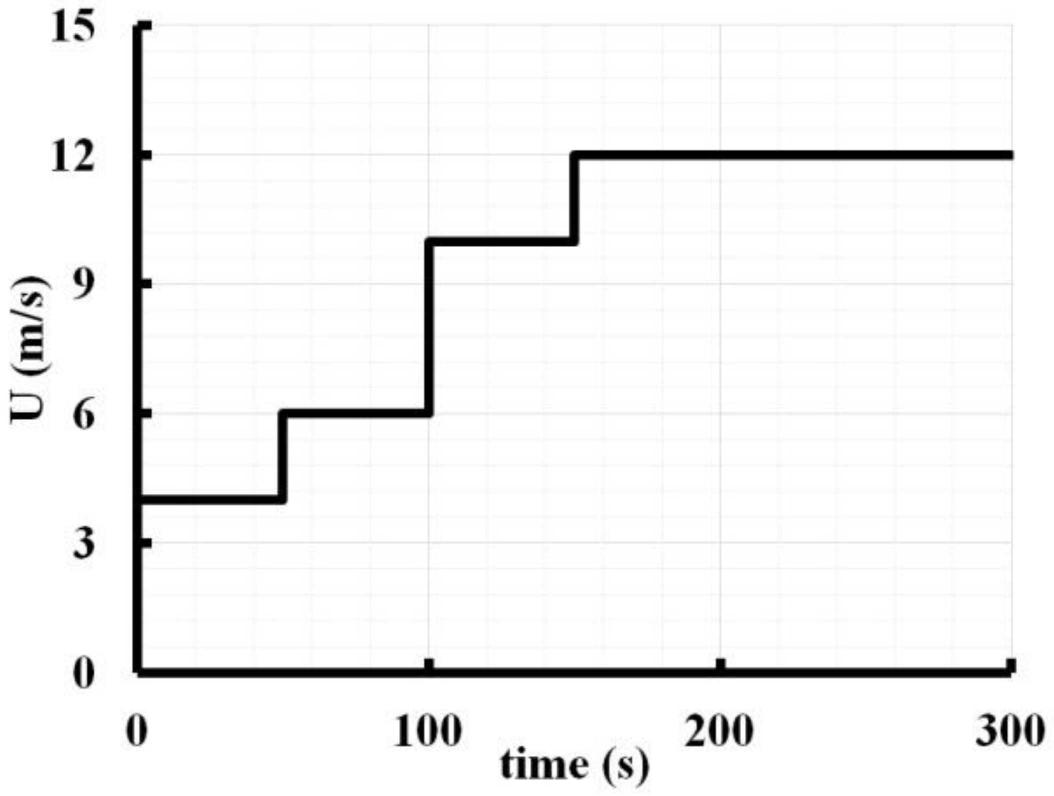


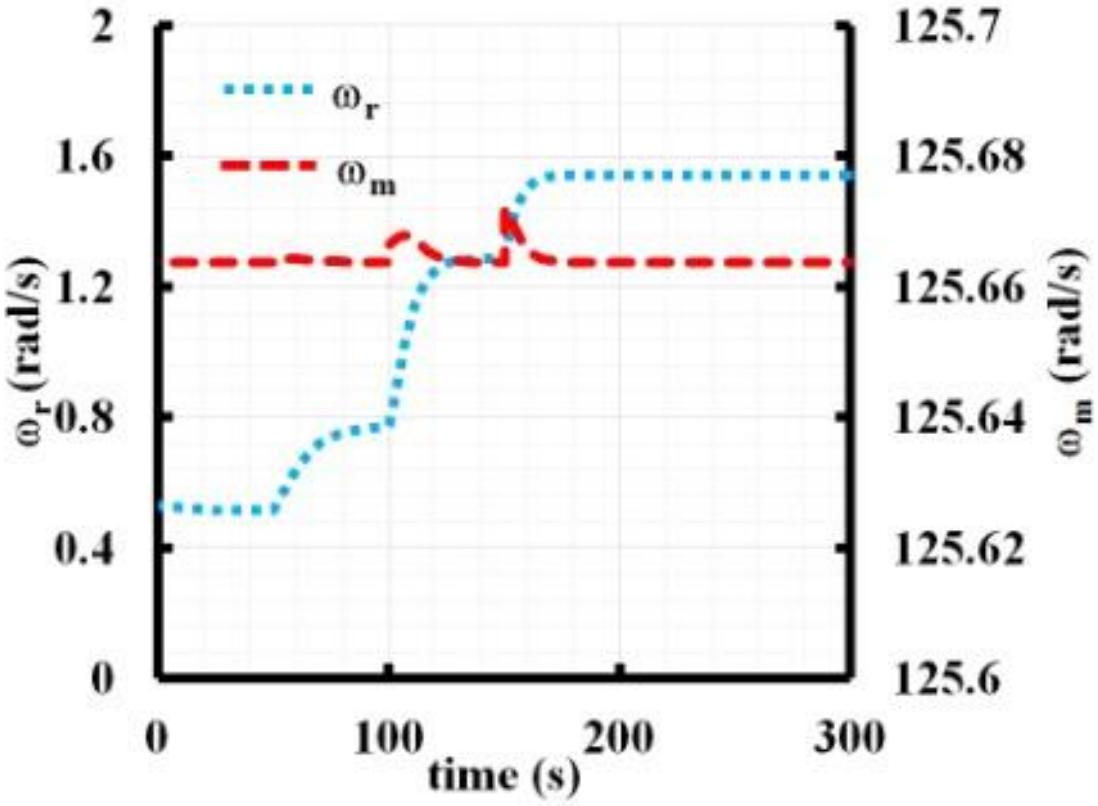
Steady State Operating Point



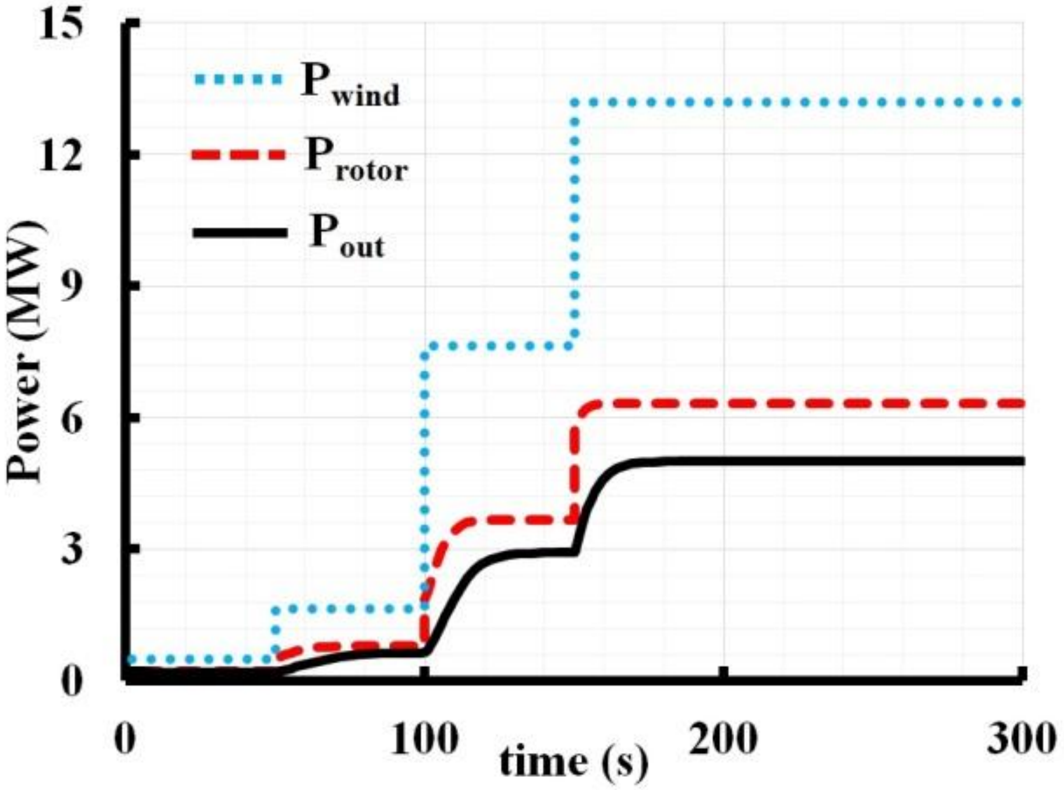


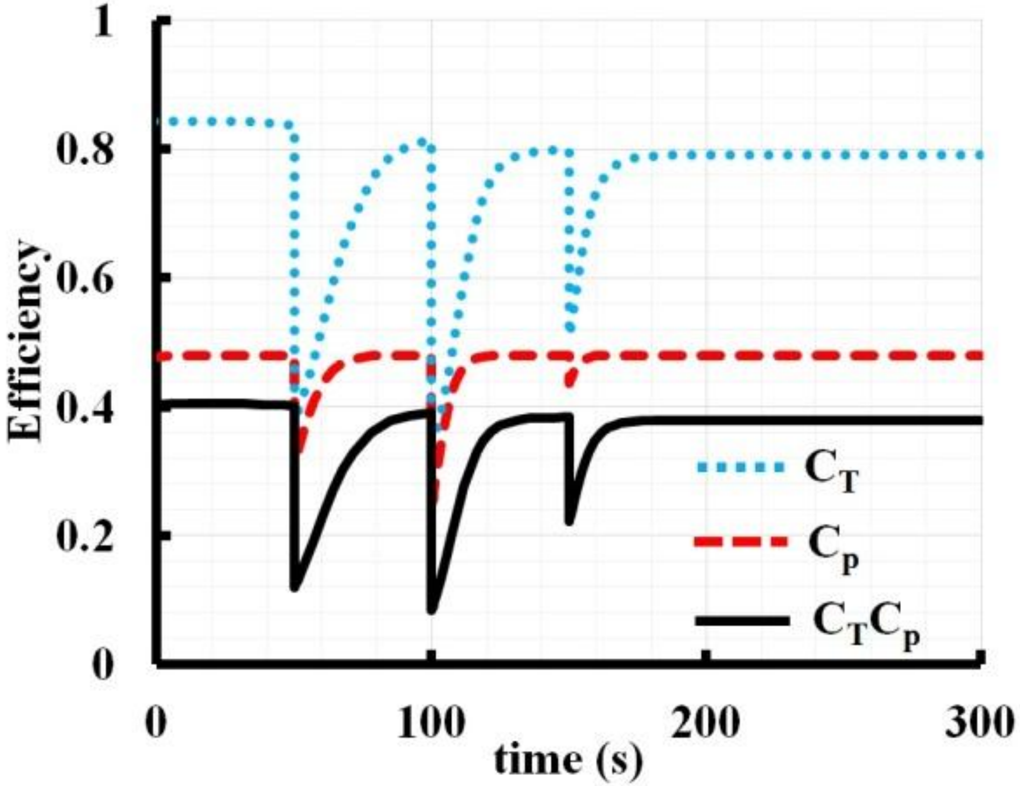
System Dynamics



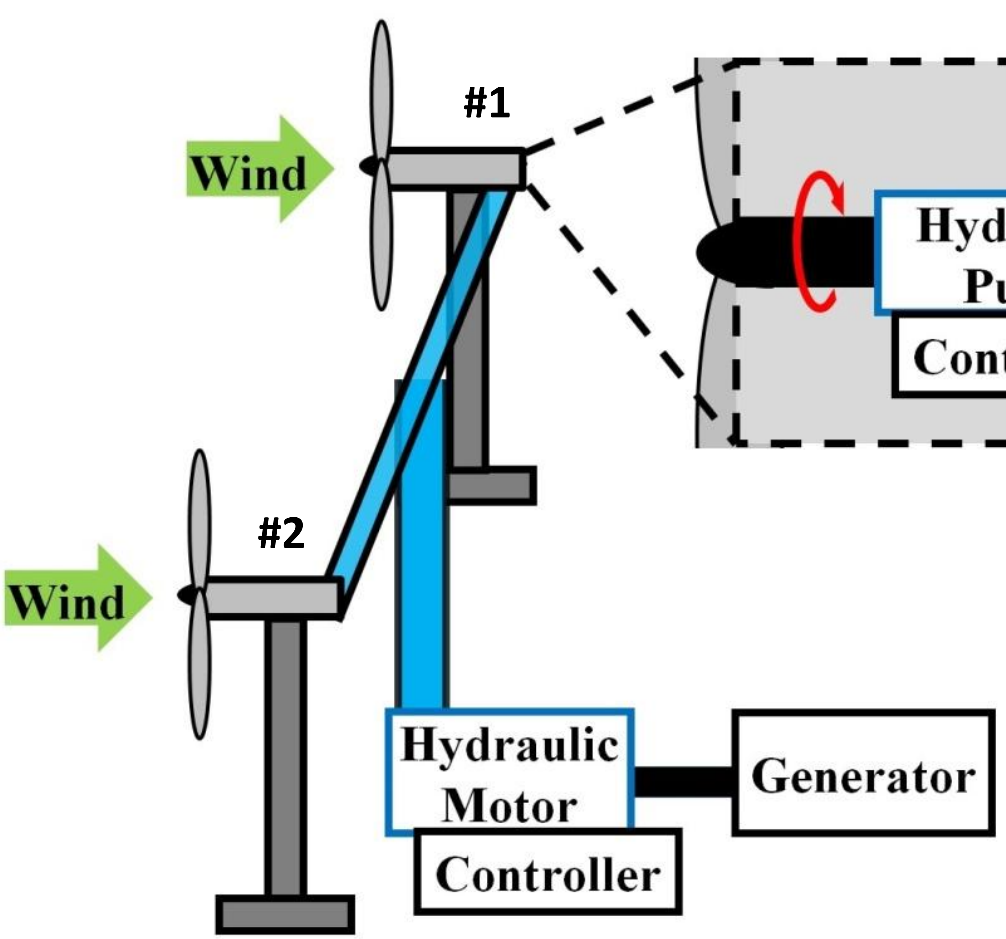


System Dynamics





Two Turbines Configuration



Control Strategy 1

$$V_{p1} = \frac{K_1 \omega_{r1}^2 \eta_{mech,p1}}{\Delta p_{p1}}.$$

$$V_{p2} = \frac{K_2 \omega_{r2}^2 \eta_{mech,p2}}{\Delta p_{p2}}.$$

$$\Delta \dot{p}_x = \frac{\beta_{fluid}}{V_{fluid}} \left(Q_{p1} + Q_{p2} - Q_m \right)$$

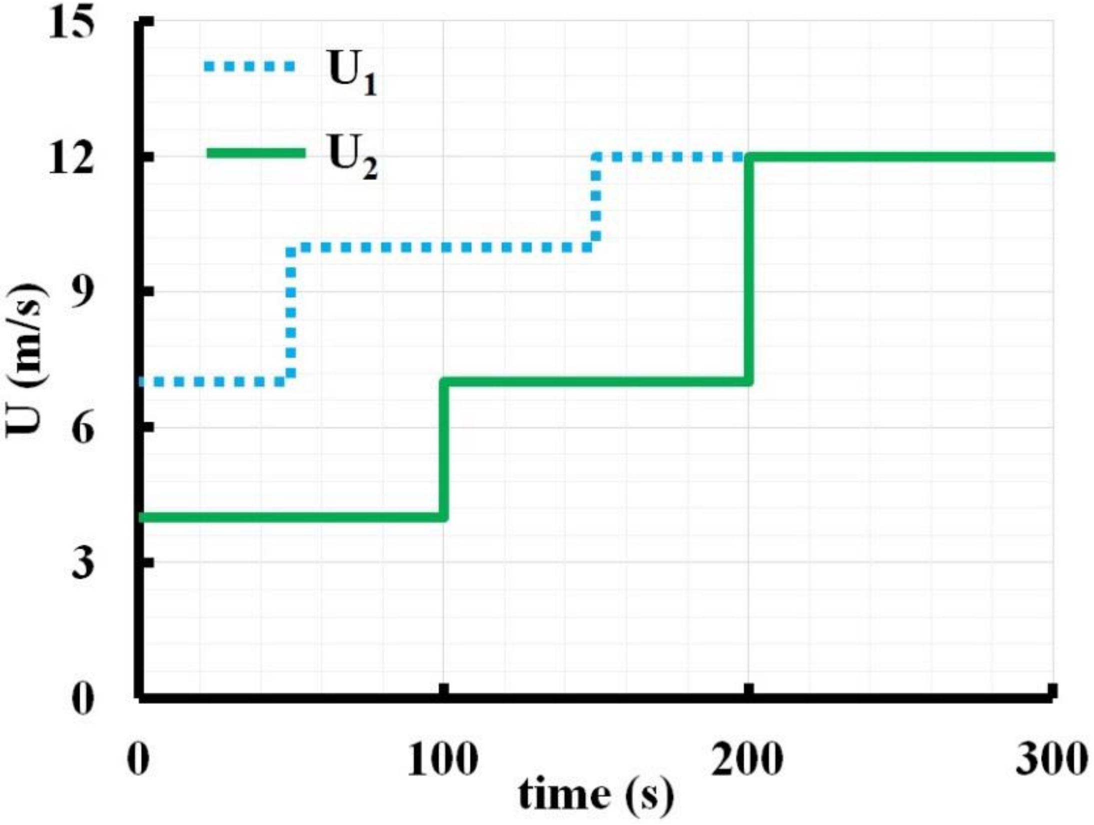
$$Loss_{total} = Loss_{mech,pump1} + Loss_{mech,pump2} + Loss_{leak,pump1} + \ldots$$
$$\ldots Loss_{leak,pump2} + Loss_{mech,motor} + Loss_{leak,motor} + Loss_{fric}.$$

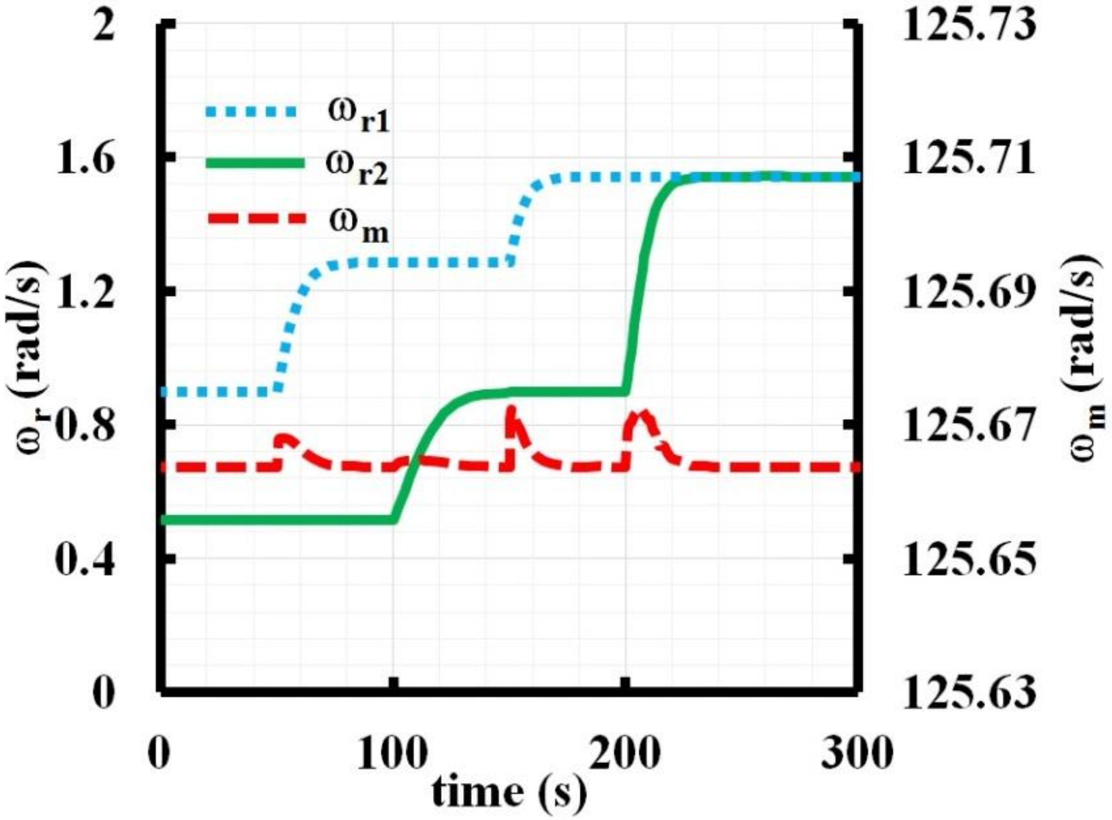
$$C_T = \frac{P_{out}}{P_{rotor1} + P_{rotor2}} = \frac{1 - Loss_{total}}{P_{rotor1} + P_{rotor2}}.$$

Control Strategy 2

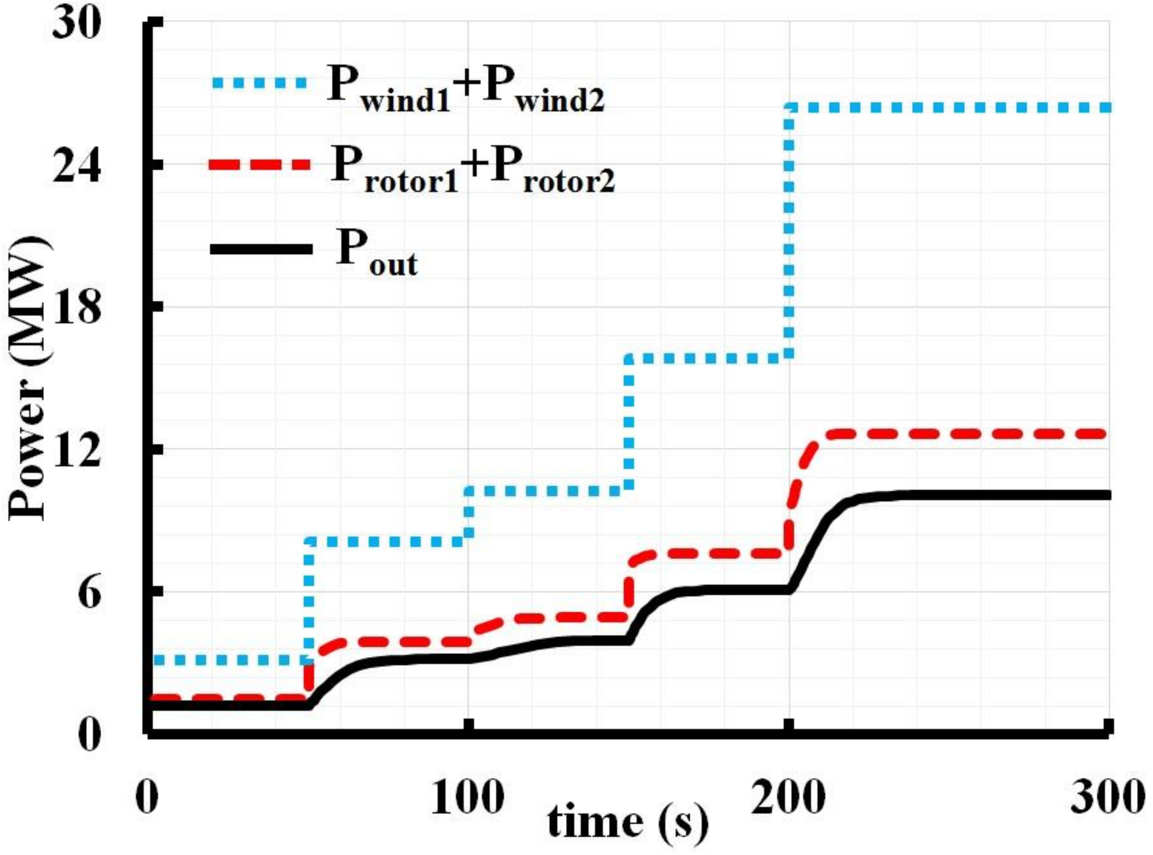
$$V_m = f(\omega_{r1}, \omega_{r2})$$

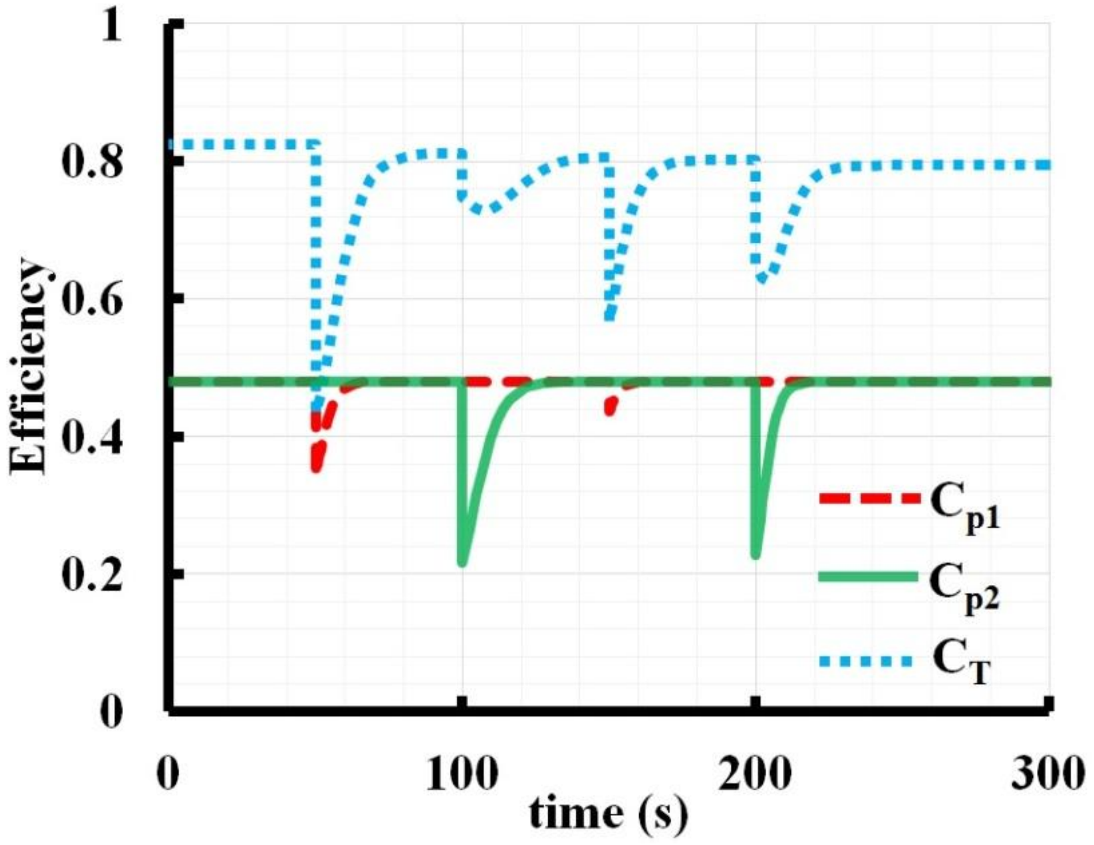
Two Turbines Configuration



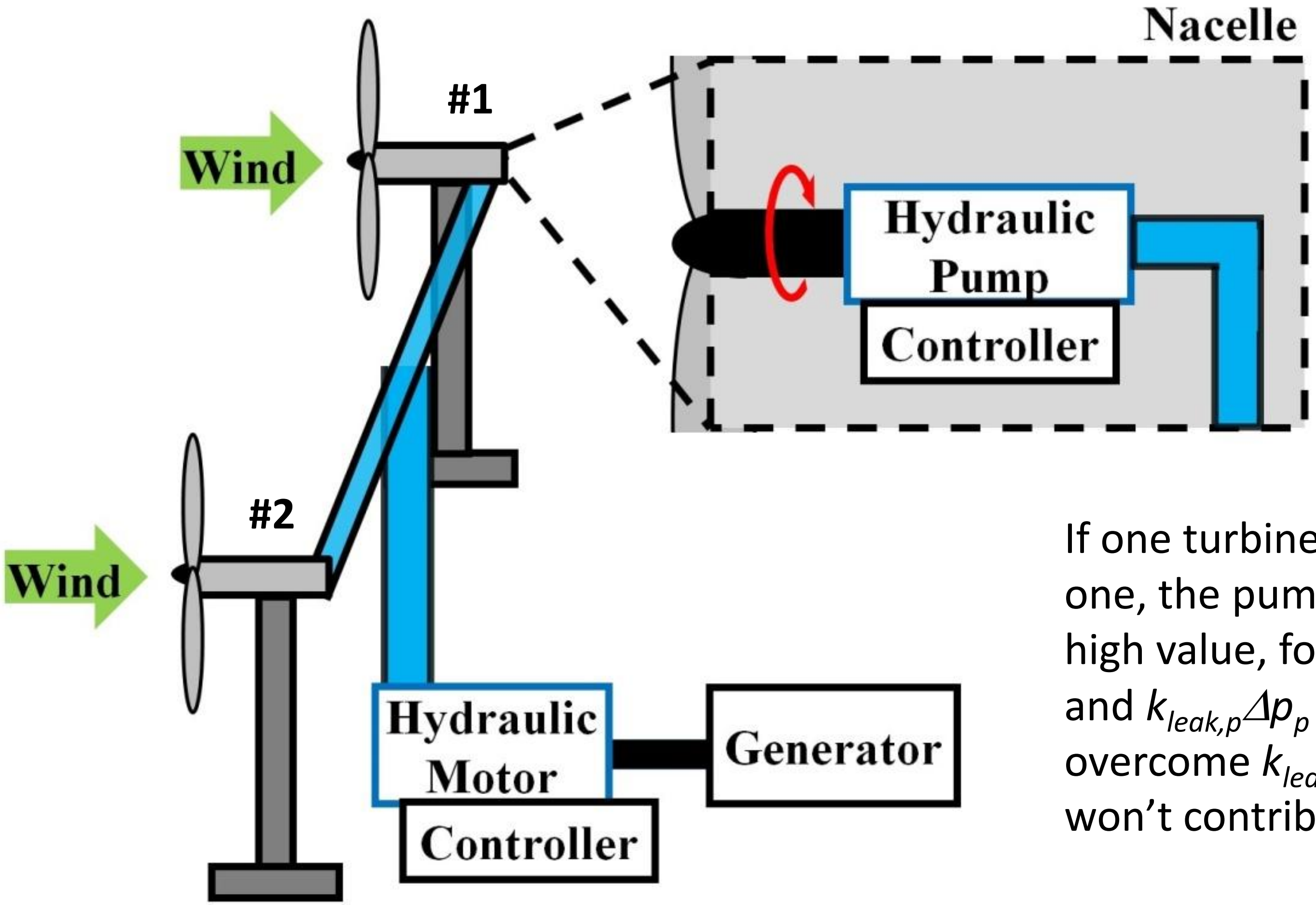


Two Turbines Configuration





Two Turbines Configuration



$$Q_p = V_p \omega_r - k_{leak,p} \Delta p_p$$

If one turbine is running at higher rotor speed than the other one, the pump differential pressure for both turbines will be at a high value, following the one that is running at the high speed and $k_{leak,p} \Delta p_p$ will be at a high value as well. If $V_p \omega_r$ cannot overcome $k_{leak,p} \Delta p_p$, the power from the low speed turbine won't contribute to the power generation.

Conclusion

In this study, control strategies are proposed for wind turbines that use a hydrostatic transmission system with the hydraulic pump in the nacelle and the hydraulic motor and the synchronous generator on the ground level to optimize wind energy capture

Single Turbine Configuration

$$\boxed{V_p = \frac{K\omega_r^2\eta_{mech,p}}{\Delta p_p}.}$$

$$\boxed{V_m = 0.0002\frac{\omega_r R}{\lambda_{opt}} - 0.0003}$$

Double Turbine Configuration

$$\boxed{\begin{aligned} V_{p1} &= \frac{K_1\omega_{r1}^2\eta_{mech,p1}}{\Delta p_{p1}}. \\ V_{p2} &= \frac{K_2\omega_{r2}^2\eta_{mech,p2}}{\Delta p_{p2}}. \end{aligned}}$$

$$\boxed{V_m = f(\omega_{r1}, \omega_{r2})}$$

Acknowledgement

I would like to thank you Dr. Ping Hsu for his kind advice and motivation for me to accomplish this study.

Any Question?