CONTROL ASPECTS OF WIND TURBINES

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Presentation Outline

- Power in Wind
- Maximum Power Point Tracking
- Connection Topologies
- Active Power Control – How?
- Grid Integration: Challenges
- Grid Integration: Possible Solutions
- Intelligent Control

Power in the wind

- The total power that is available to a wind in watts,

$$P_w = 0.5\ m_w\ v^2 = 0.5\ \rho\ A\ v^3,$$

where, $m_w = \rho\ A\ v$

ρ	density of the air (kg/m^3)
A	the exposed area (m^2)
v	the velocity (m/s)

- The mechanical power,

$$P_m = c_p\ P_w = 0.5\ c_p\ m_w\ v^2 = 0.5\ \rho\ c_p\ A\ v^3$$

where,

c_p	performance co efficient

Power in the wind – Bet'z Limit

- Assume, inlet wind velocity is 'v_i' and the output velocity is 'v_o' and the mass flow rate, m_w, through the system is approximately 'ρ A v_{ave}'

  where, $v_{ave} = \frac{1}{2}(v_i + v_o)$.

- Wind Power, P_w

$$P_w = \frac{1}{2} m_w \left(v_i^2 - v_o^2\right)$$

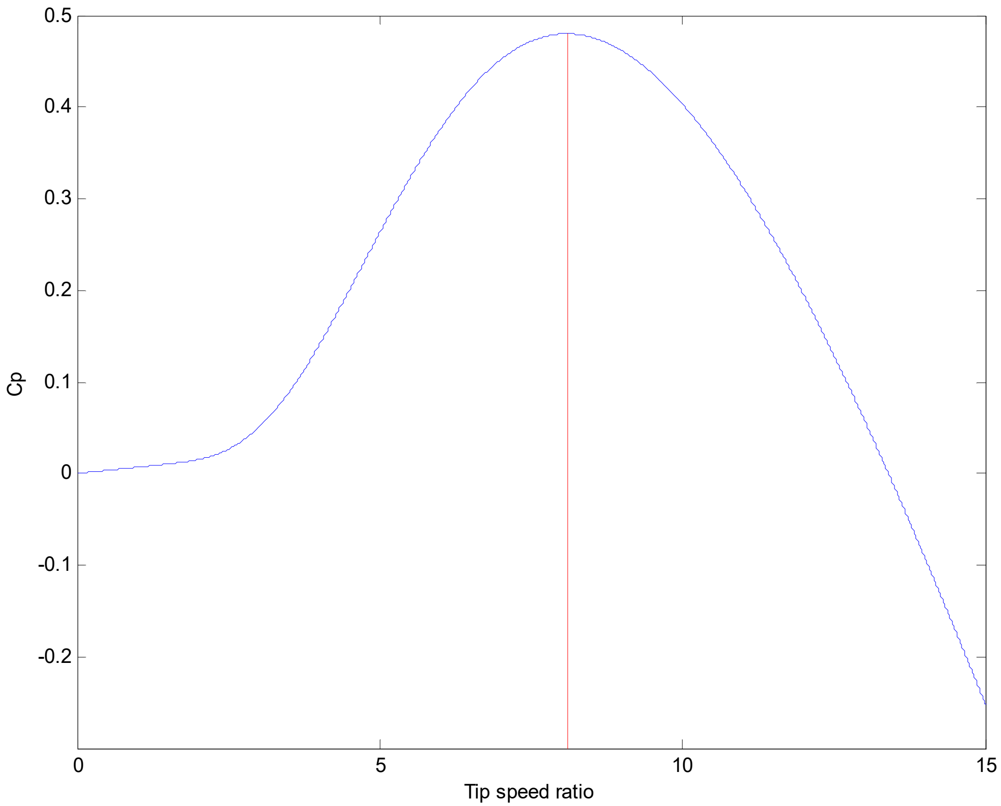
$$= \frac{1}{4}\rho A(v_i + v_o)\left(v_i^2 - v_o^2\right)$$

$$= \frac{1}{4}\rho A v_i^3 \left(1 + \frac{v_o}{v_i} - \left(\frac{v_o}{v_i}\right)^2 - \left(\frac{v_o}{v_i}\right)^3\right)$$

- Solving for maximum value,

$$P_{m_{max}} = \frac{16}{27} P = 0.593\, P_w$$

Power in the wind



- C_p is a function of both λ & θ (pitch angle),

$$C_p = f(\lambda, \theta)$$

where,

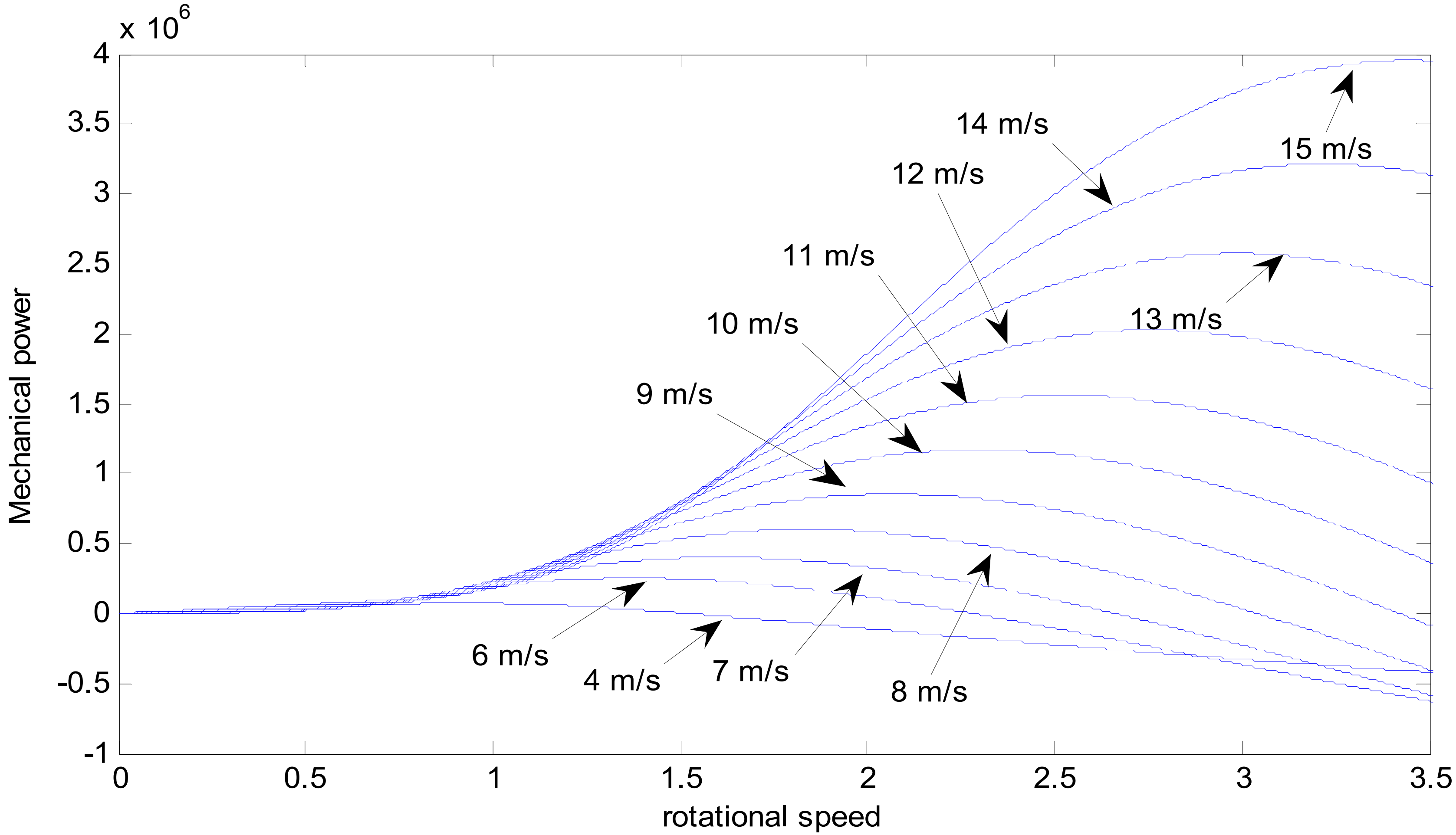
Tip speed ratio, $\lambda = \omega_t R / v_{wind}$

ω_t turbine rotational speed

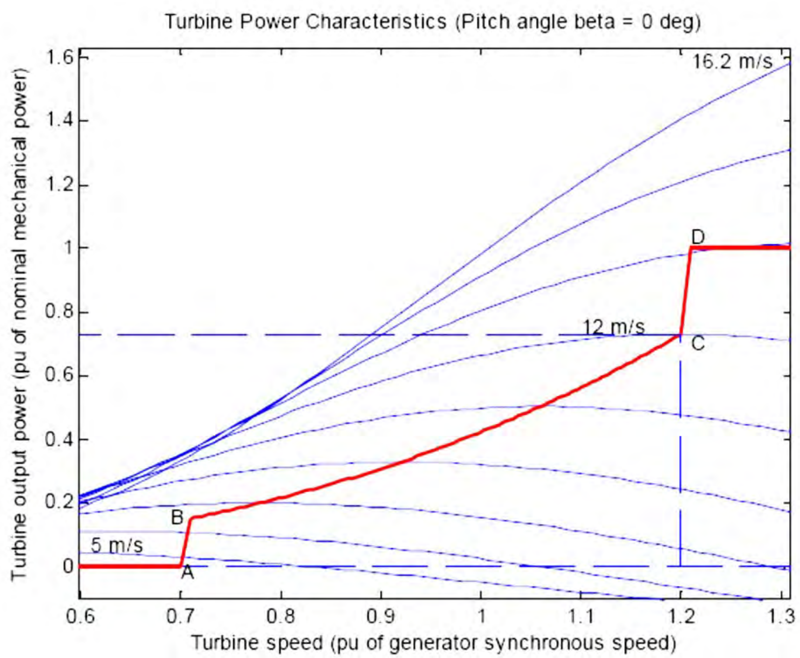
R rotor radius

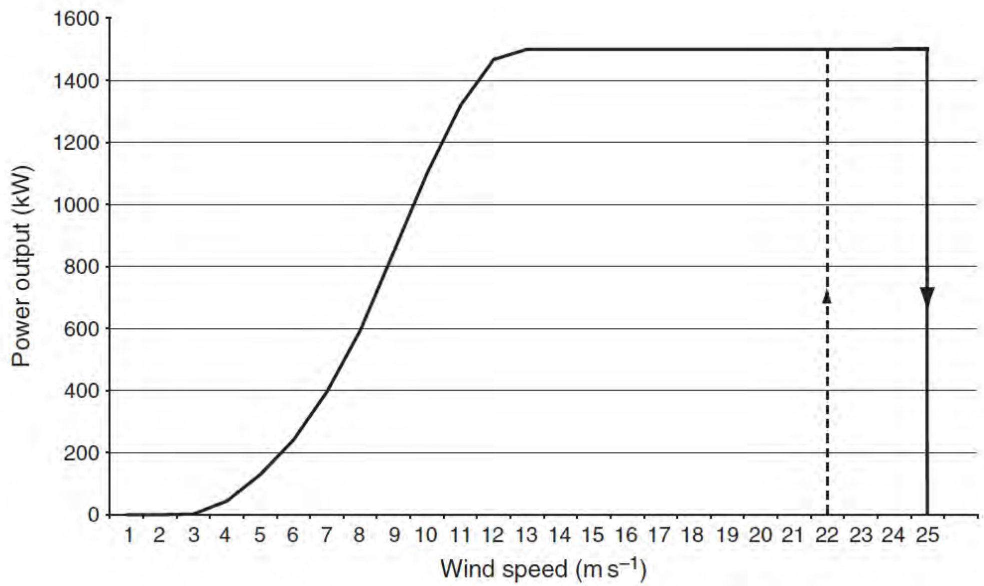
v_{wind} wind speed.

Power in the wind

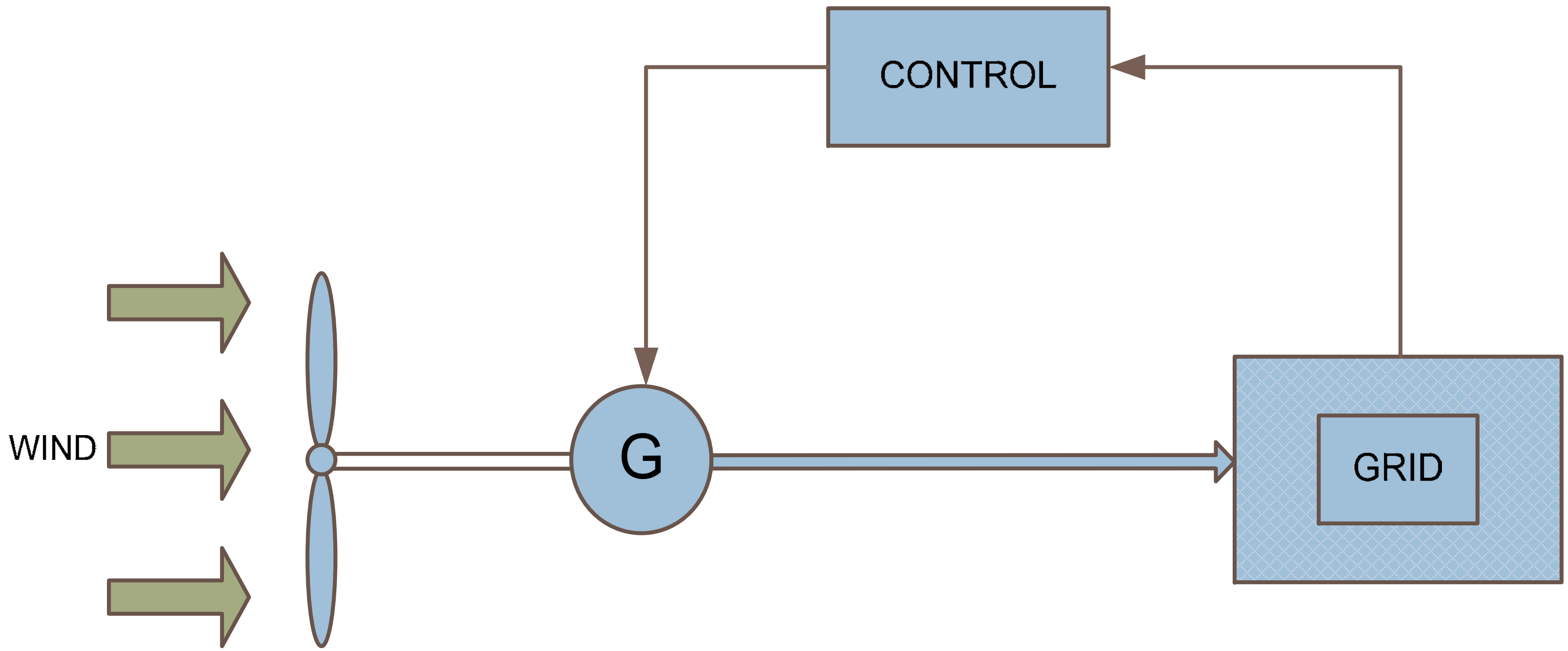


Power Curve - Hysteresis

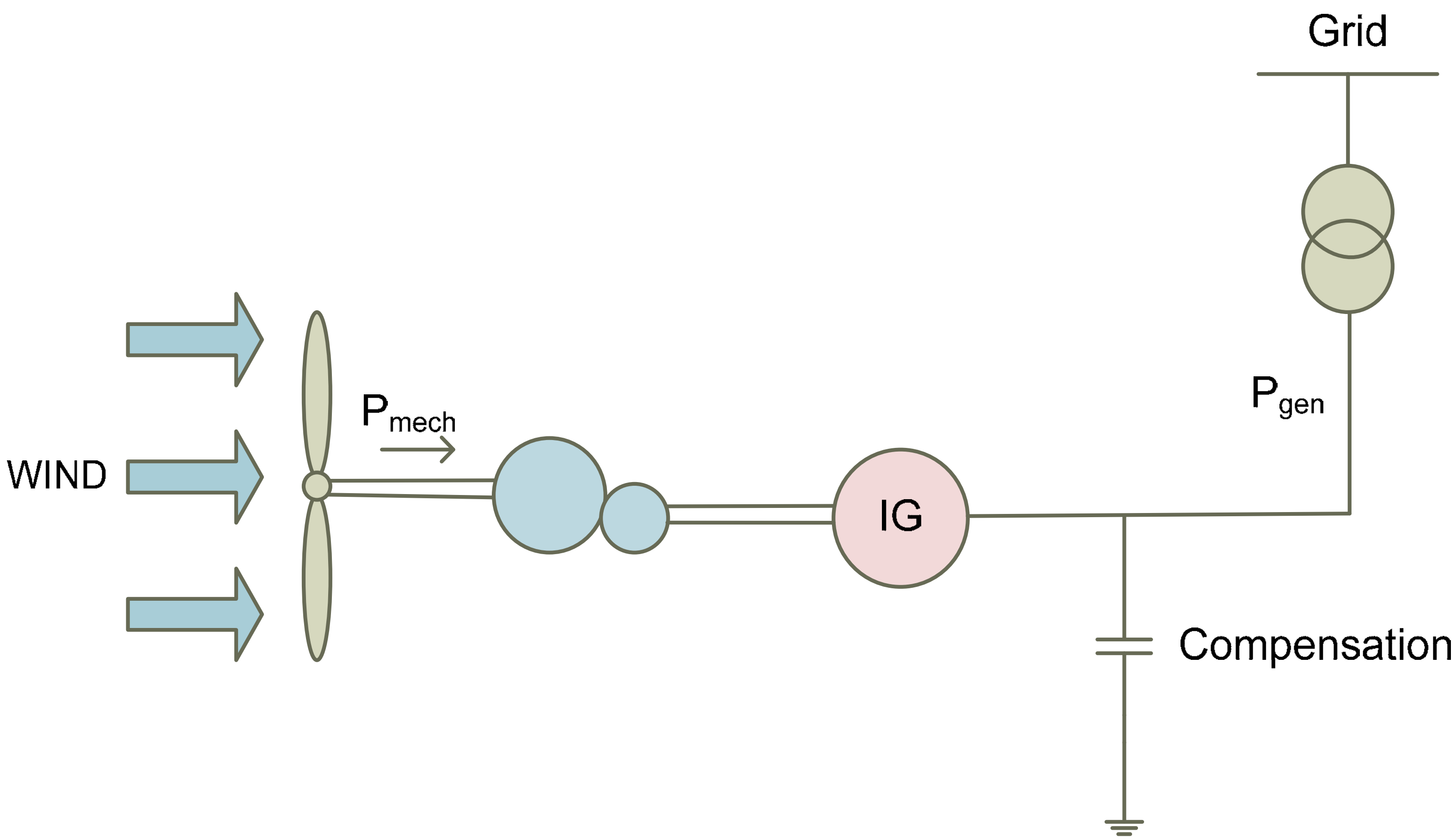




General Structure of WECS

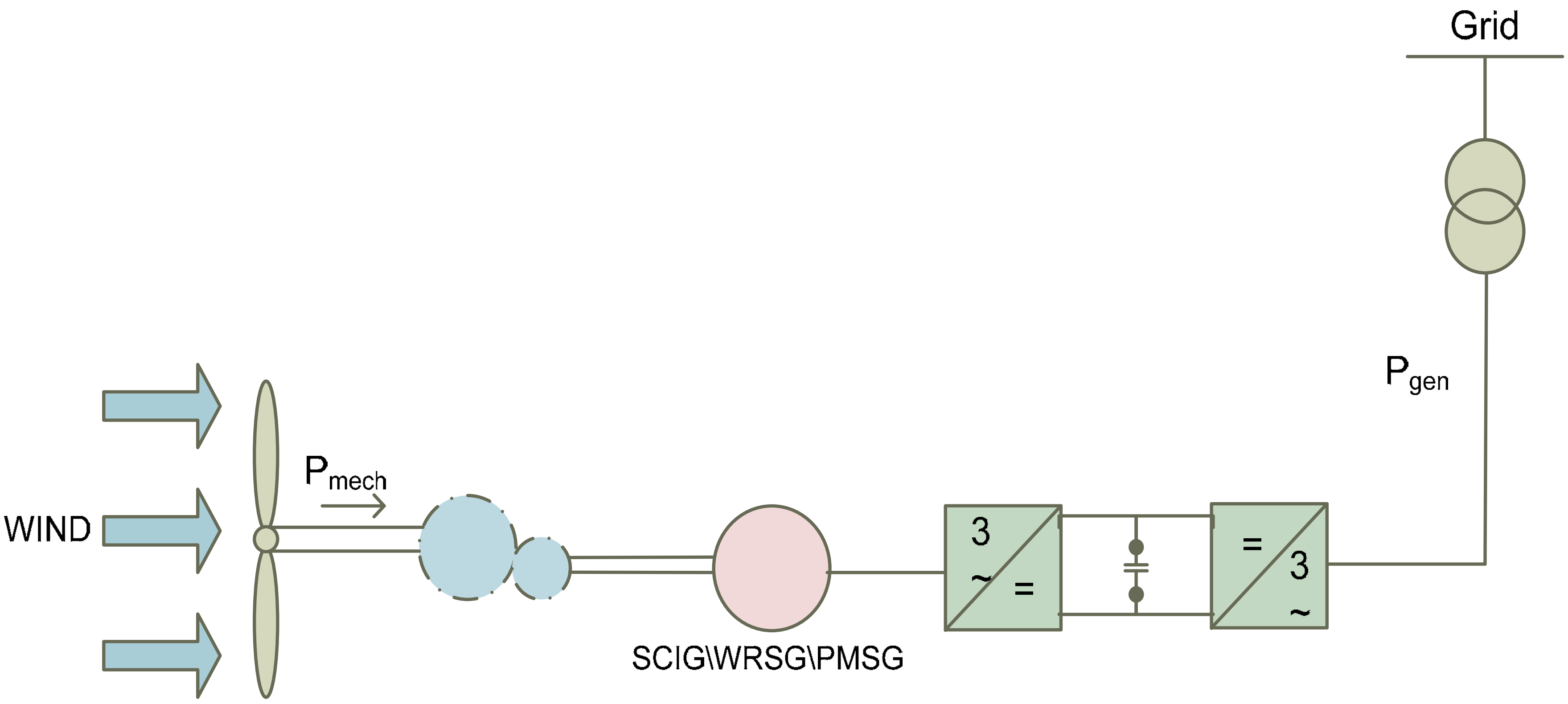


Danish Concept – Fixed Speed



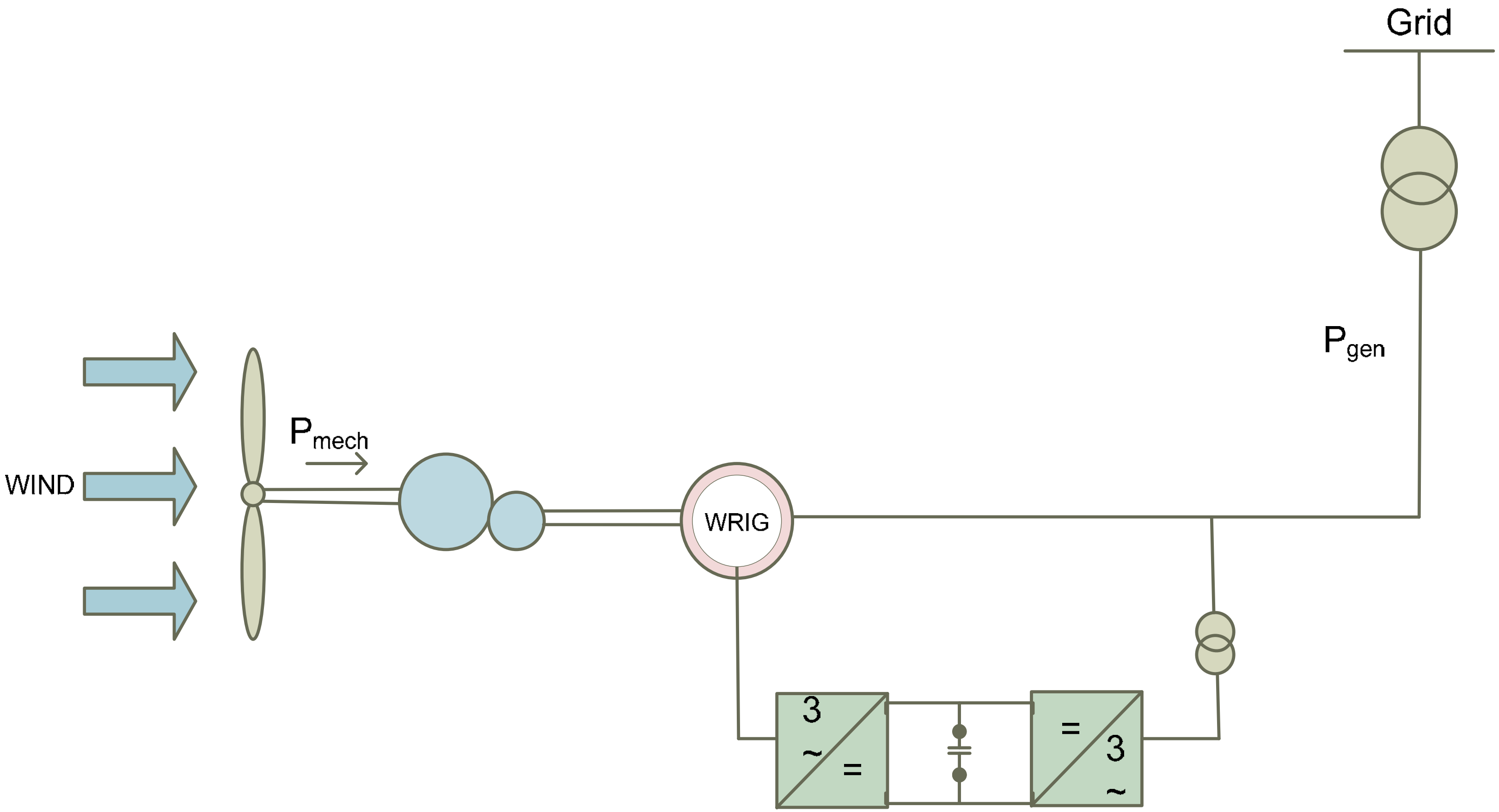
Danish Concept

Direct in line wind turbine system



Direct in line wind turbine system

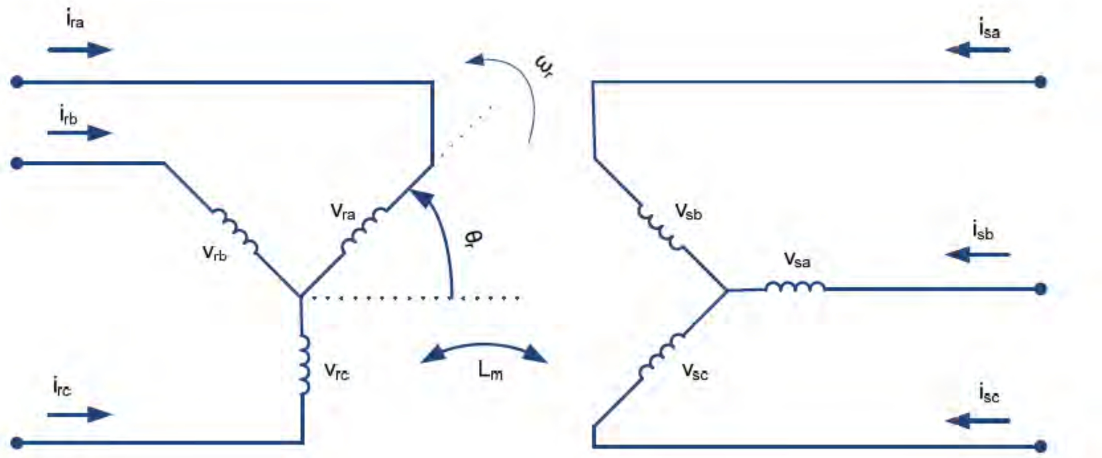
Doubly Fed Induction Generator (DFIG)



Active Power Control

How do they do it?

Model of Wound Rotor Induction Machine



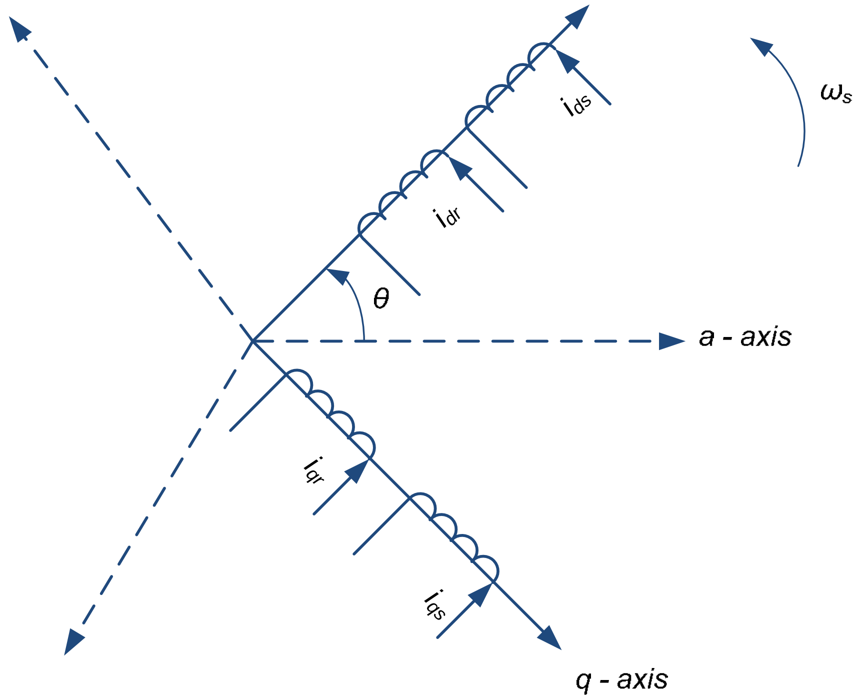
Machine model in abc frame, equations for stator winding,

$$v_{as} = R_s i_{as} + \frac{d\lambda_{as}}{dt}, \quad v_{bs} = R_s i_{bs} + \frac{d\lambda_{bs}}{dt} \quad \& \quad v_{cs} = R_s i_{cs} + \frac{d\lambda_{cs}}{dt}$$

where,

$$\lambda_{as} = \left(L_{self,s} + L_{leak,s}\right) i_{as} + L_{mut,s}\left(i_{bs} + i_{cs}\right) + L_{sr}\left\{\cos\theta_r i_{ar} + \cos\left(\theta_r + \frac{2\pi}{3}\right) i_{br} + \cos\left(\theta_r - \frac{2\pi}{3}\right) i_{cr}\right\}$$

Reference Frame Theory



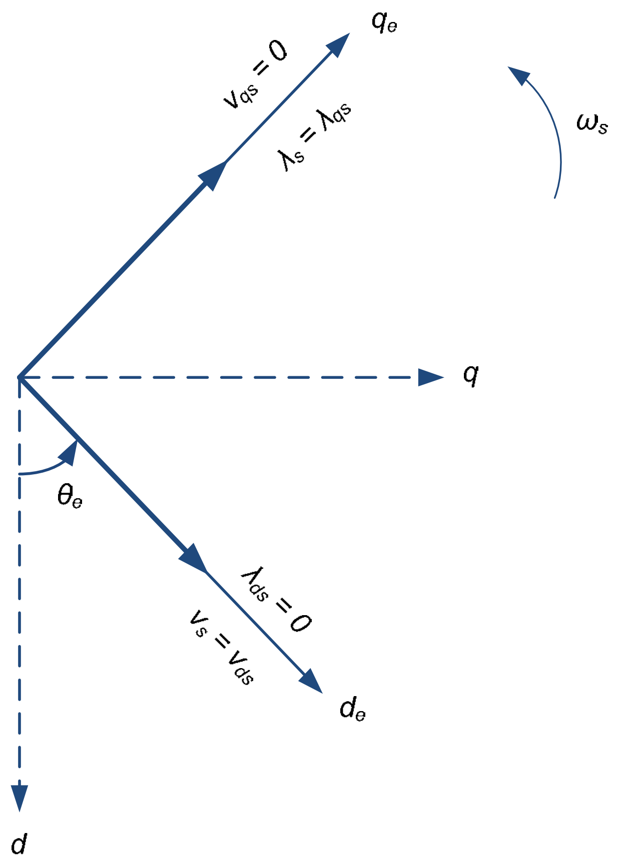
Transformation matrix to convert quantity into d - q axes from abc axes is ,

$$T_S = \frac{2}{3}\begin{bmatrix} \sin\theta & \sin(\theta - 120) & \sin(\theta + 120) \\ \cos\theta & \cos(\theta - 120) & \cos(\theta + 120) \end{bmatrix}$$

and inverse transformation is given by,

$$T_S^{-1} = \begin{bmatrix} \sin\theta & \cos\theta \\ \sin(\theta - 120) & \cos(\theta - 120) \\ \sin(\theta + 120) & \cos(\theta + 120) \end{bmatrix}$$

Control Concept –
Line Voltage Oriented Control



Electromagnetic torque in line voltage oriented frame is given by,

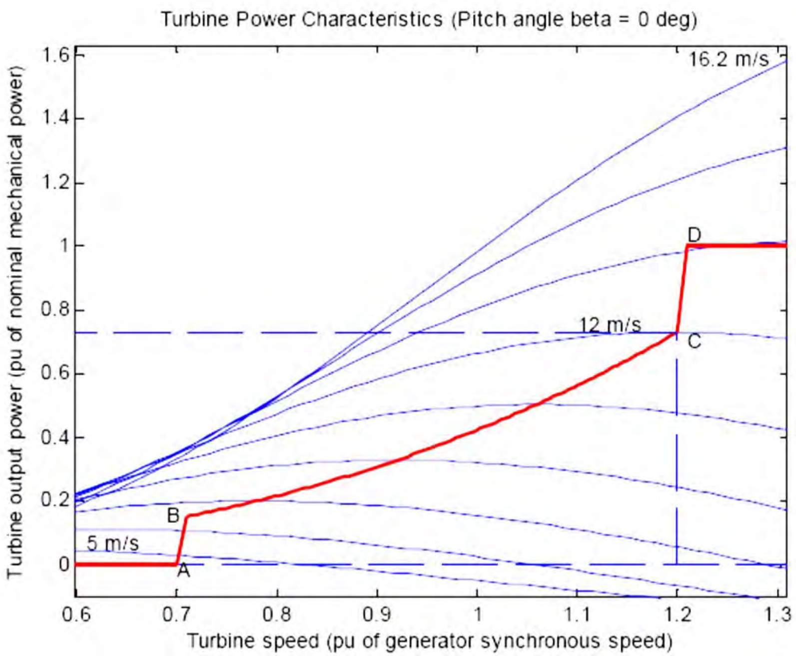
$$T_e = \lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}$$

$$= -\lambda_{qs} i_{ds} = \frac{L_m}{L_{ss}} i_{dr} \lambda_{qs}$$

and,

$$\lambda_{qs} = -(v_{ds} - r_s i_{ds})$$

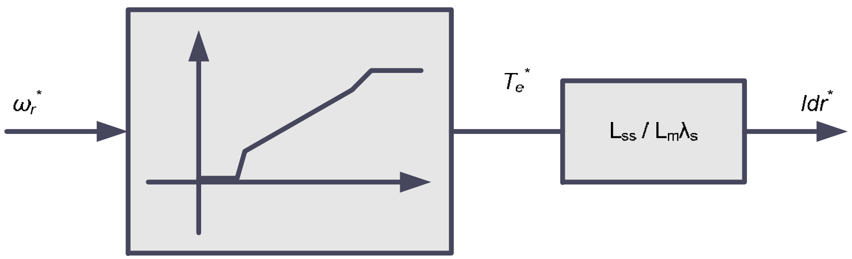
MPPT-Maximum Power Point Tracking



Turbine characteristics and tracking characteristic

$$T_e^* = \frac{L_m}{L_{ss}} \lambda_{qs} i_{dr}^*$$

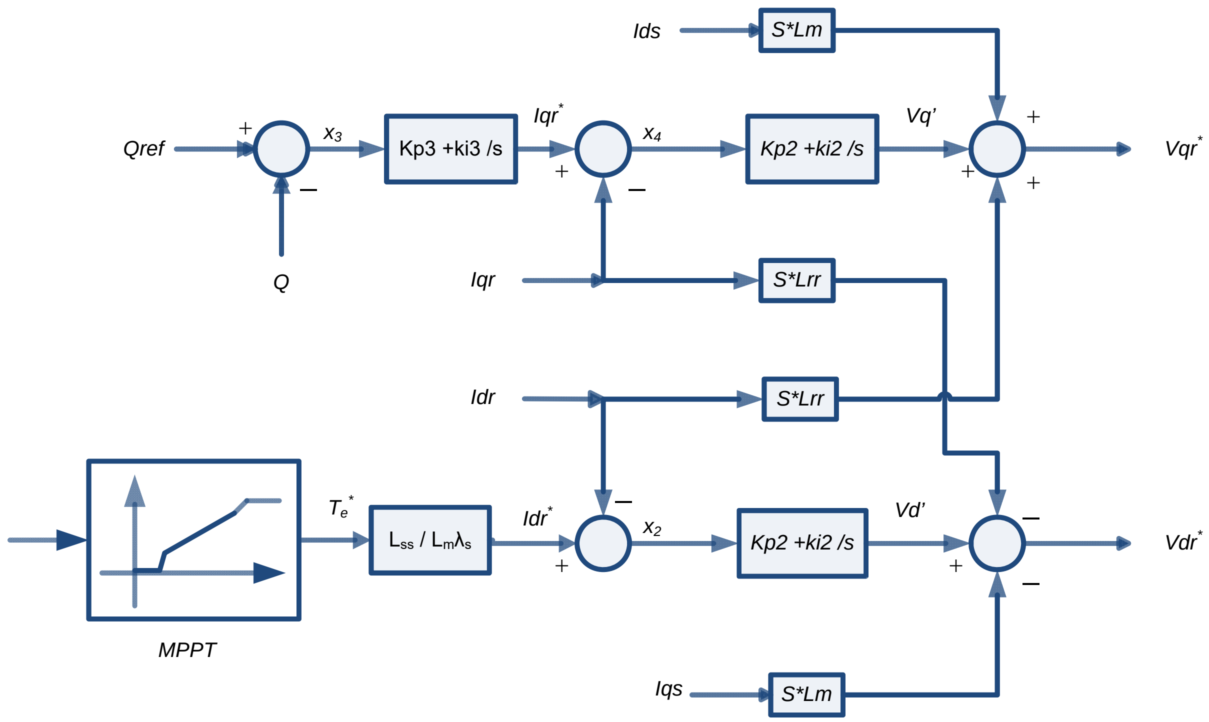
$$\Rightarrow i_{dr}^* = \frac{L_{ss}}{L_m \lambda_{qs}} T_e^*$$



Reference current calculations for tracking maximum power point.

Rotor Side Current Controller

تقنيات الطاقة المستدامة
Sustainable Energy Technologies



$$i_{dr}^{*} = \frac{L_{ss}}{L_m \lambda_{qs}} T_e^{*}$$

$$v_{ds} = r_s i_{ds} + \frac{1}{\omega_s}\frac{d\lambda_{ds}}{dt} - \lambda_{qs}$$

$$\Rightarrow \lambda_{qs} = -\left(v_{ds} - r_s i_{ds}\right)$$

$$v_{dr}^{*} = v_d' - s\omega_s L_{rr} i_{qr} - s\omega_s L_m i_{qs}$$

$$v_{qr}^{*} = v_q' + s\omega_s L_{rr} i_{dr} + s\omega_s L_m i_{ds}$$

Rotor Side Converter Control

SET
تقنيات الطاقة المستدامة
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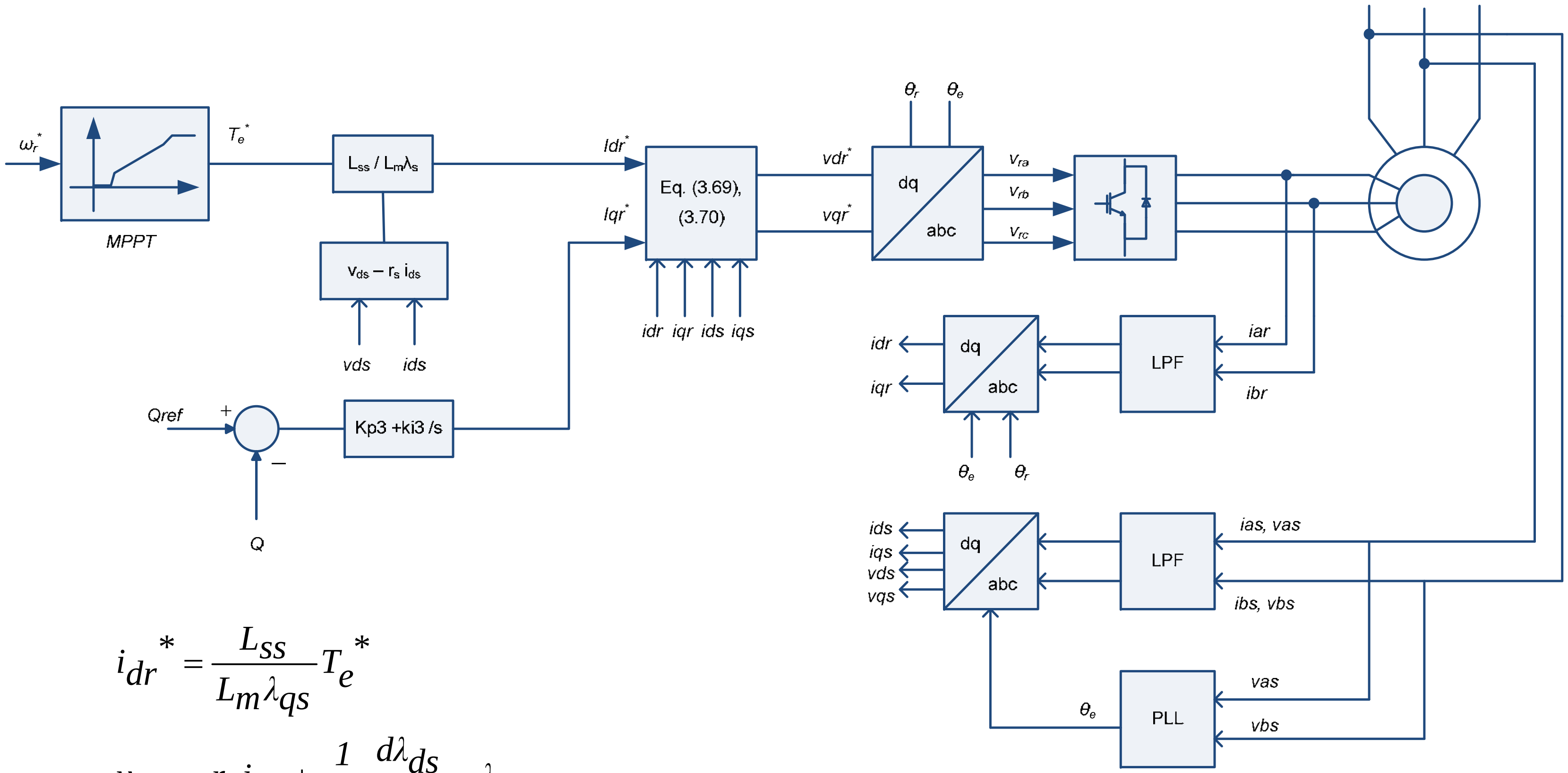


$$i_{dr}^{*} = \frac{L_{ss}}{L_m \lambda_{qs}} T_e^{*}$$

$$v_{ds} = r_s i_{ds} + \frac{1}{\omega_s}\frac{d\lambda_{ds}}{dt} - \lambda_{qs}$$

$$\Rightarrow \lambda_{qs} = -\left(v_{ds} - r_s i_{ds}\right)$$

Grid Integration

Grid Integration

- Concerns:
  - LVRT, Grid Support Services, Economic Concerns
- Possible Solutions: 
  - Ancillary grid support services
  - Wind Power Forecasts

  - Intelligent Control: *Nature Mimicking Algorithms*

Grid Inertia

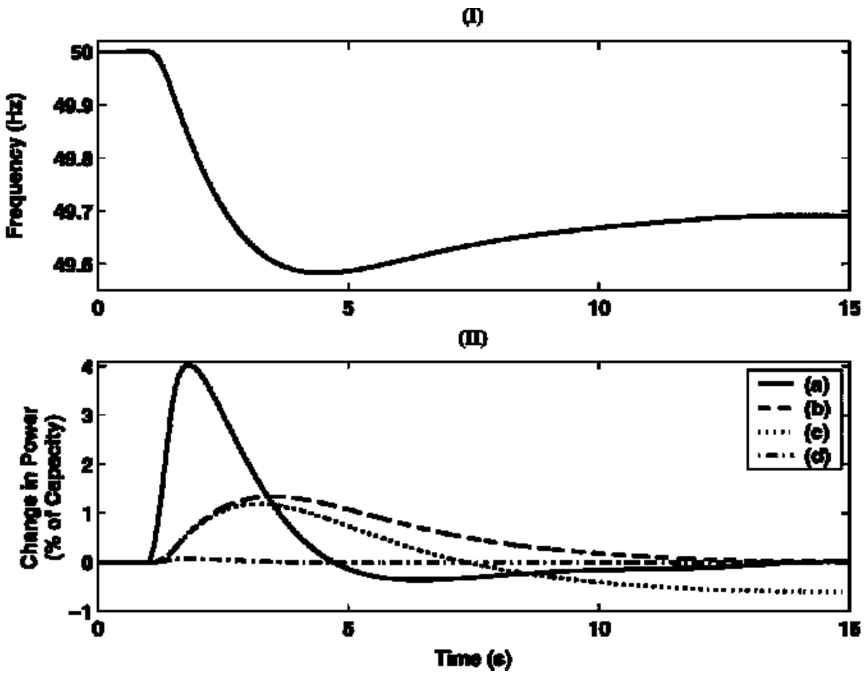
Courtesy: GE Energy

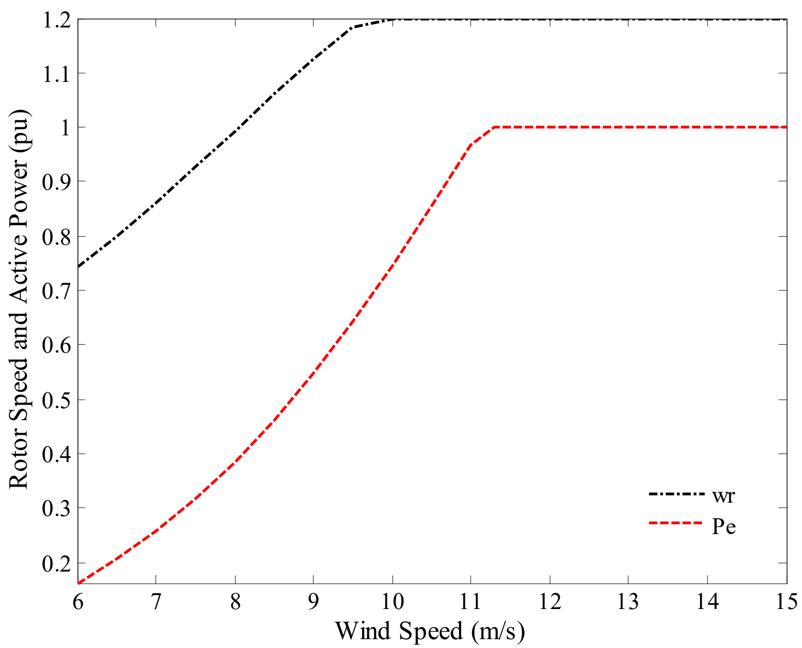
- Gird Inertia : Supply – Demand mismatch
- Synchronous Generator: Inherent Response
- Wind Turbines
  - Inertia?
  - Primary Frequency Support?

Intelligent Inertia Emulation

- Objectives,
  - Adaptive Inertia Controller for Individual WT
  - WF level control & Co-ordination
  - Short-Term Wind Forecasting

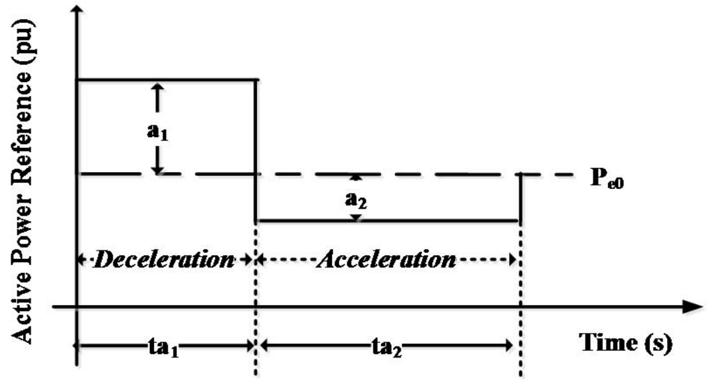
Inertial Response: Challenge

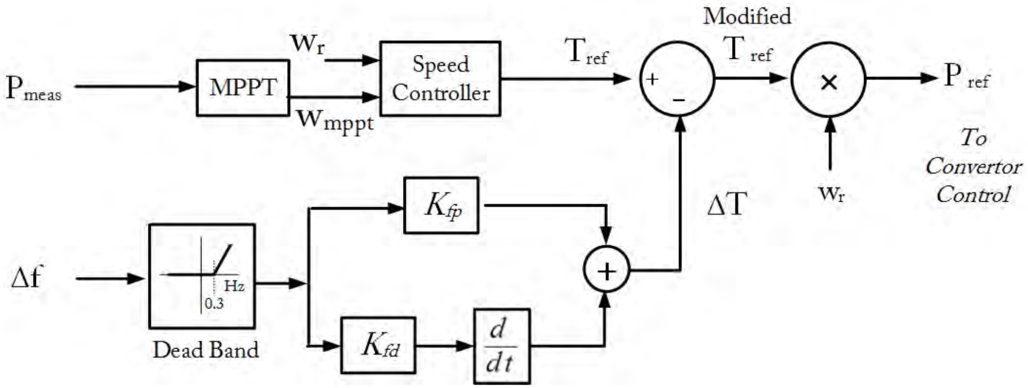




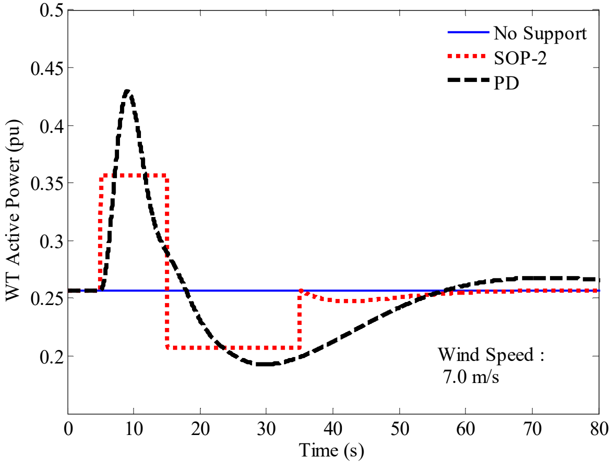
G. Lalor, A. Mullane, and M. O'Malley, "Frequency control and wind turbine technologies," Power Systems, IEEE Transactions on, vol. 20, pp. 1905-1913, 2005.

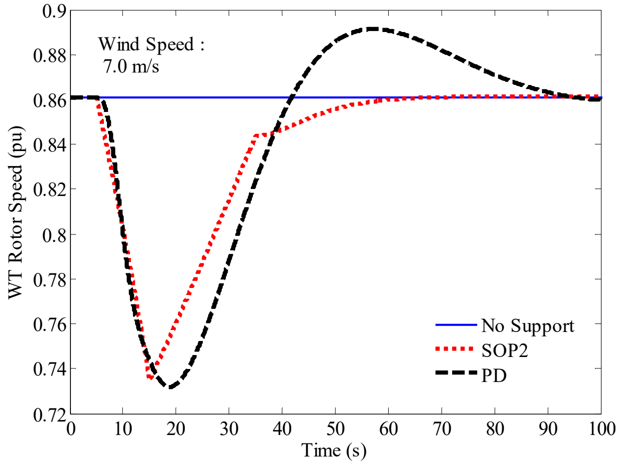
Inertial Response: Possible Solution

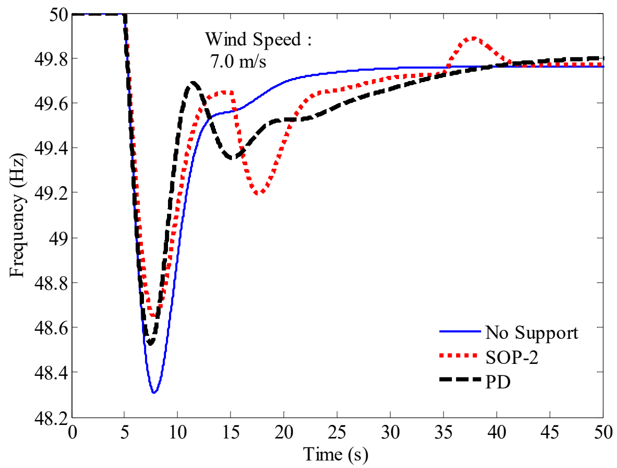




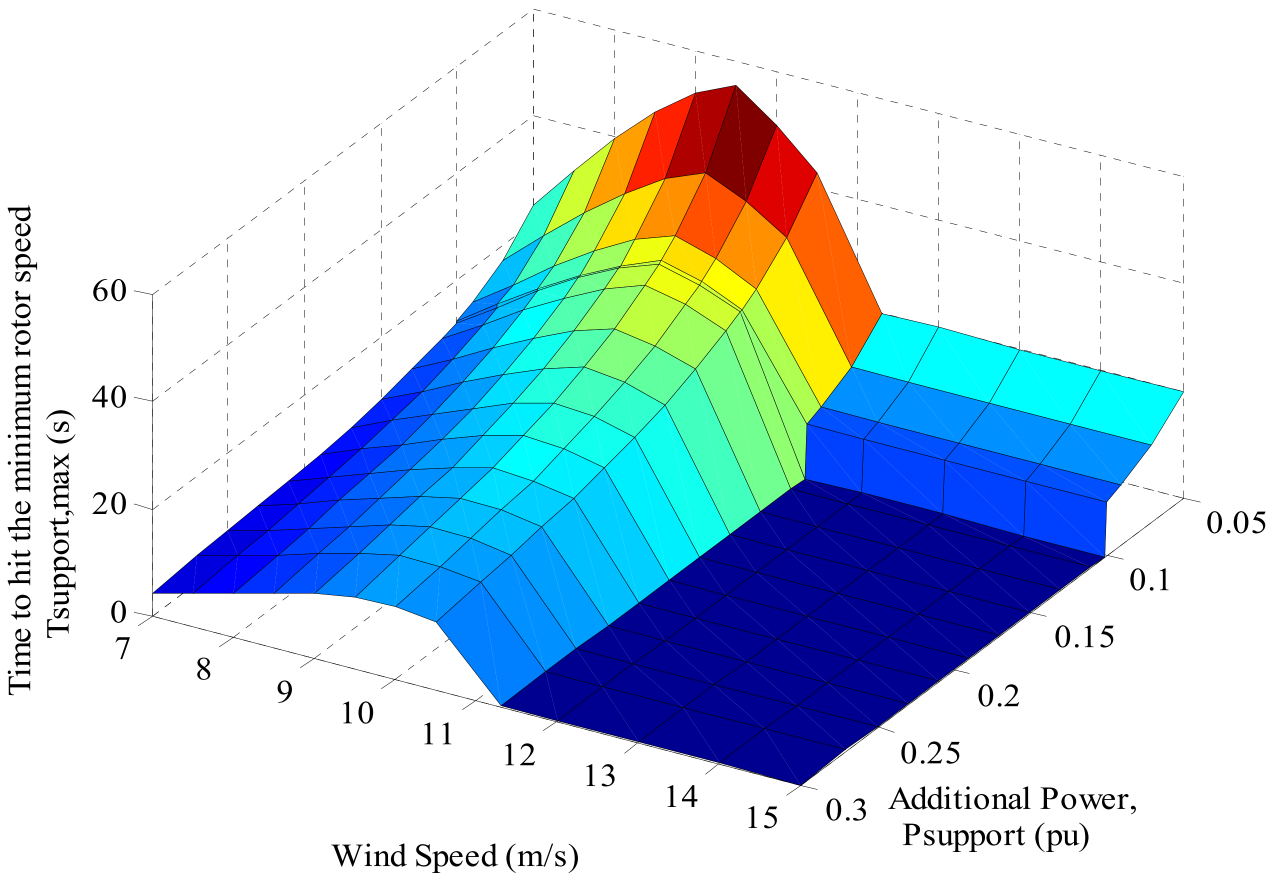
Inertial Response: Possible Solution



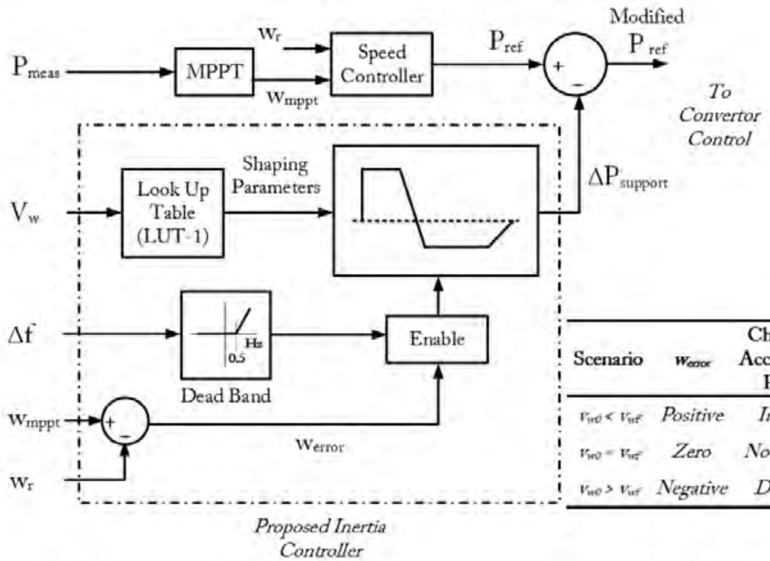




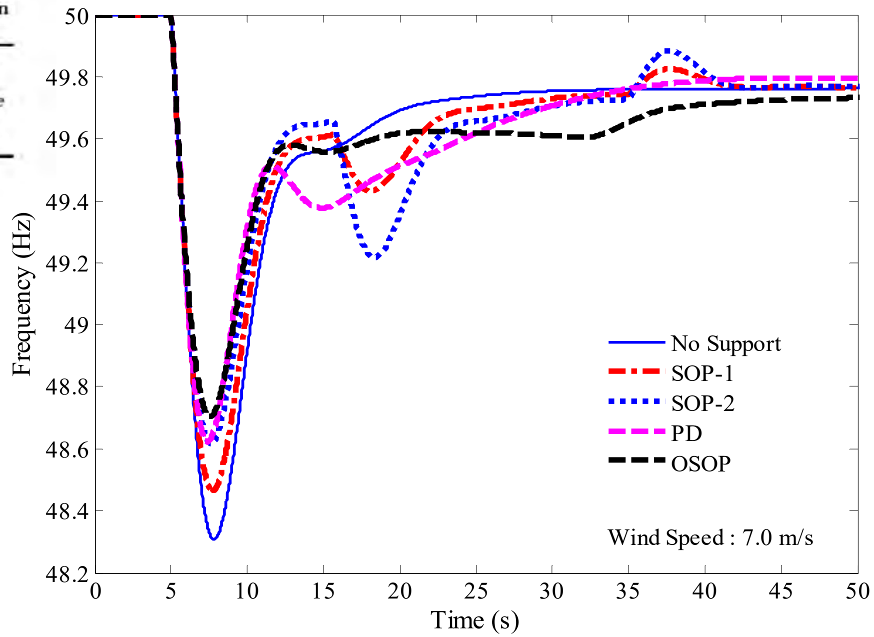
Inertial Response: Opportunities



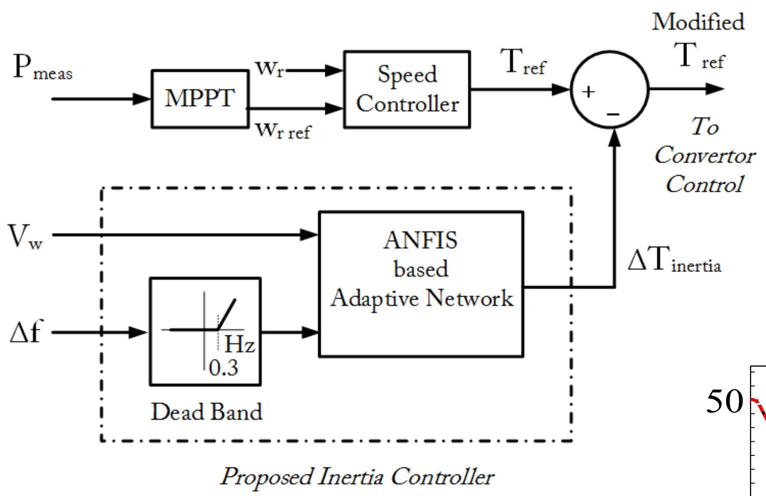
Inertia Emulation: Proposed Approach - 1

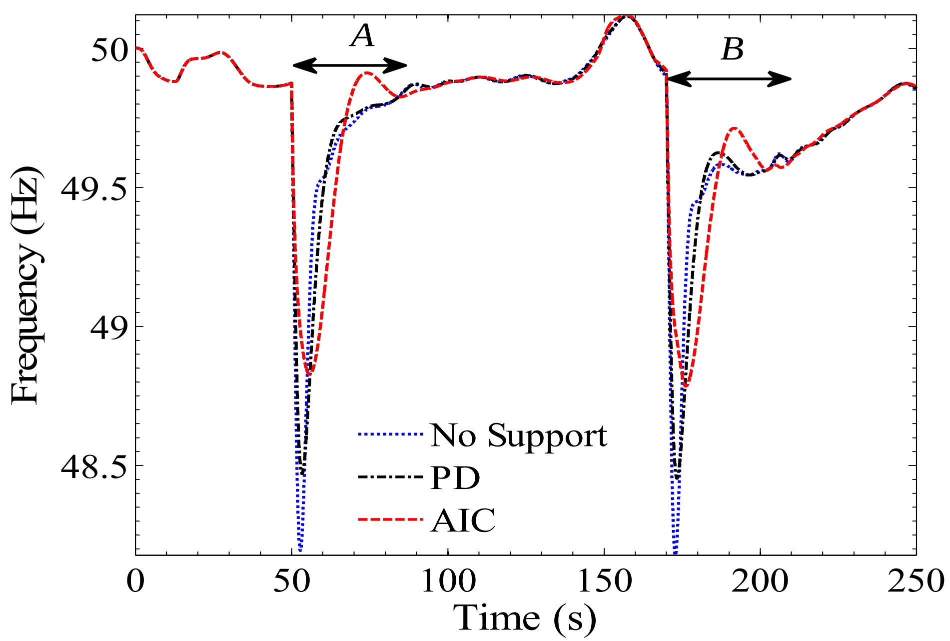


Scenario	w_{error}	Change in Acceleration Period
$v_{w0} < v_{ref}$	*Positive*	*Increase*
$v_{w0} = v_{ref}$	*Zero*	*No Change*
$v_{w0} > v_{ref}$	*Negative*	*Decrease*



Inertia Emulation: Proposed Approach - 2





MPPT, Desirable?

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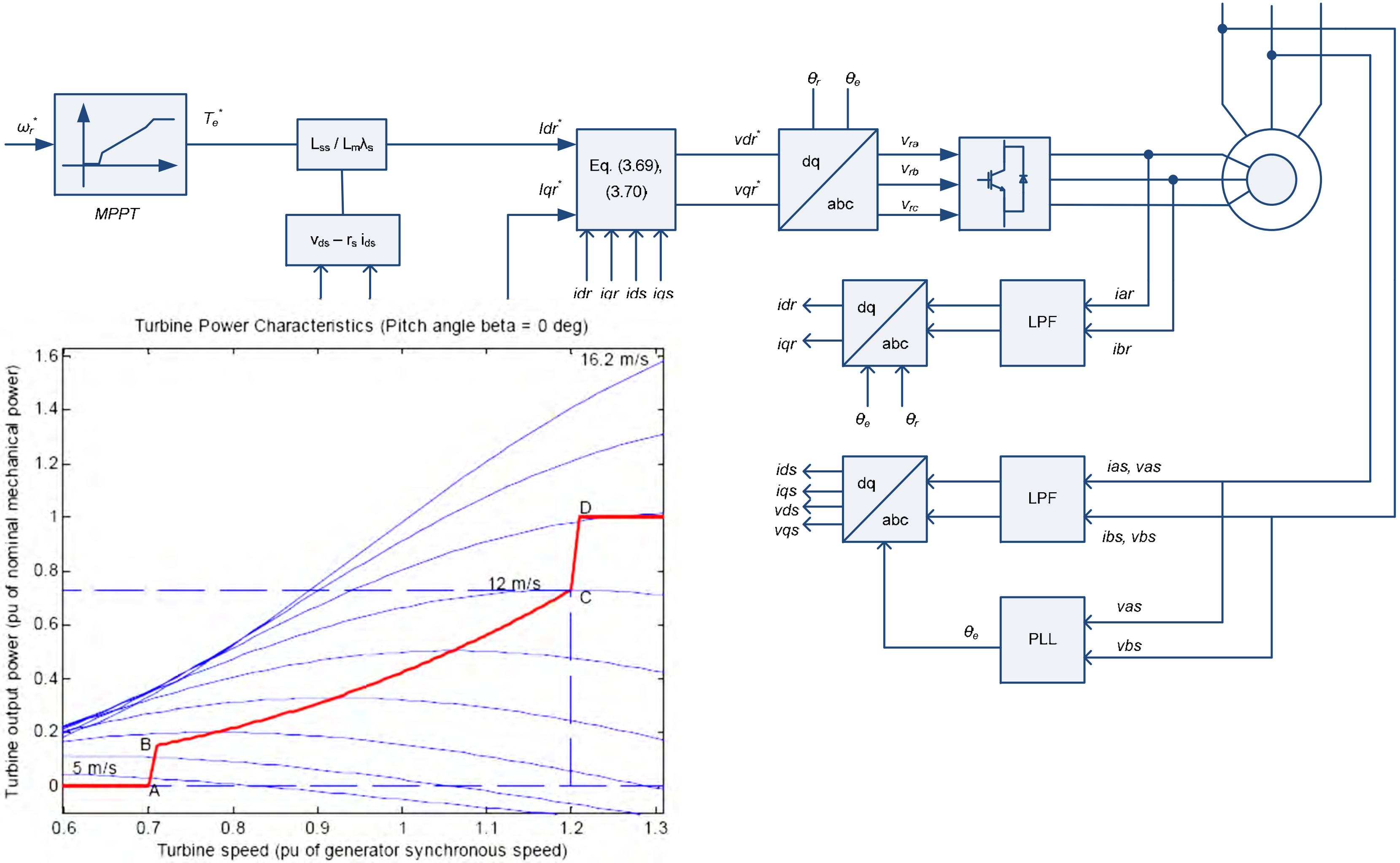
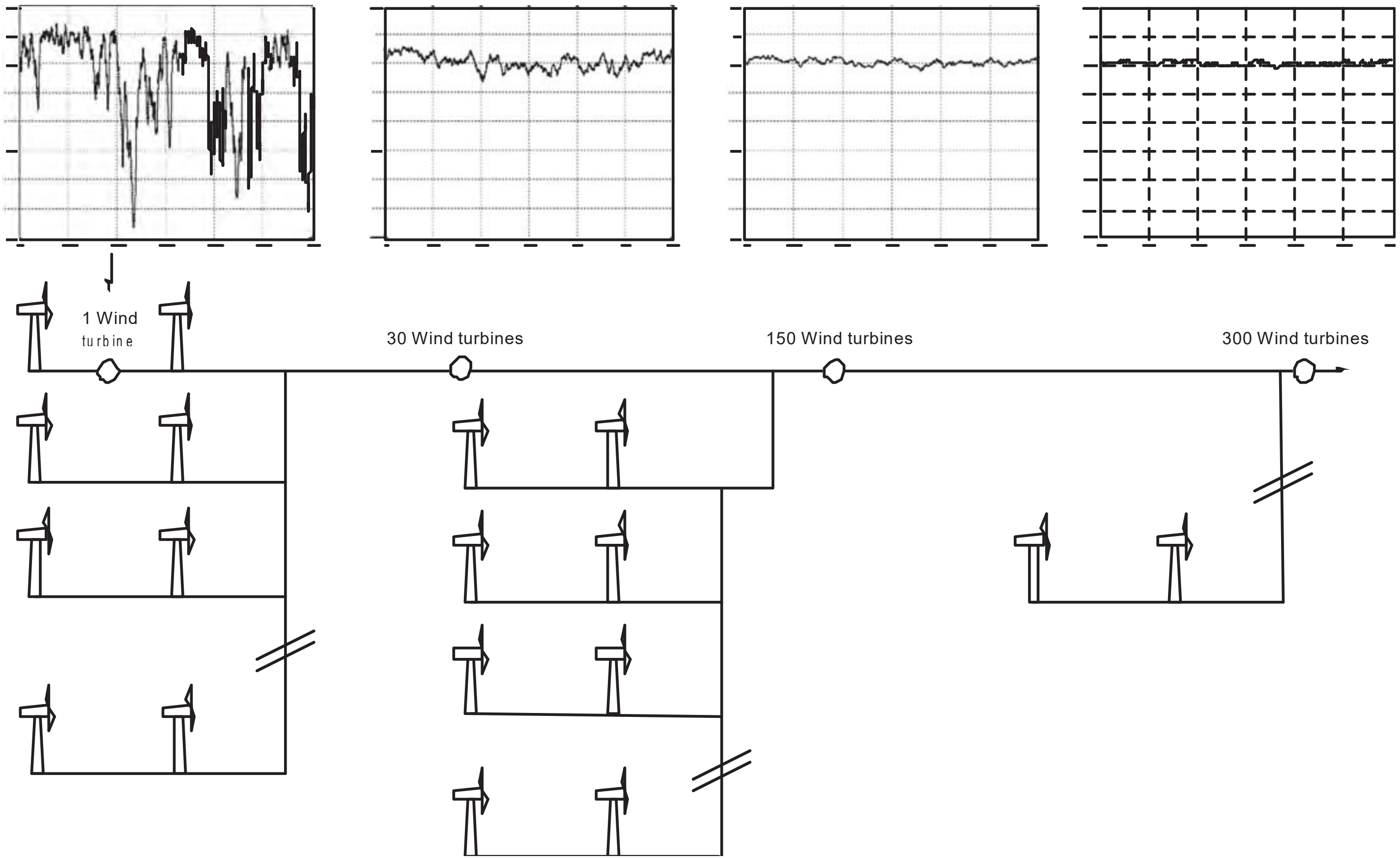


Effects of Aggregation



Reproduced from "Wind Power in Power Systems", Wiley, Ed. Thomas Ackermann, pp. 37

Further Possibilities

- Future Research
  - Effect of wakes on inertial support
  - Active Power Control for Primary Frequency Support (PFS)
  - Co-ordination of WTs for PFS
  - Wind Farm level Control
  - Short-Term Wind Forecasting

Nature Inspired Algorithms

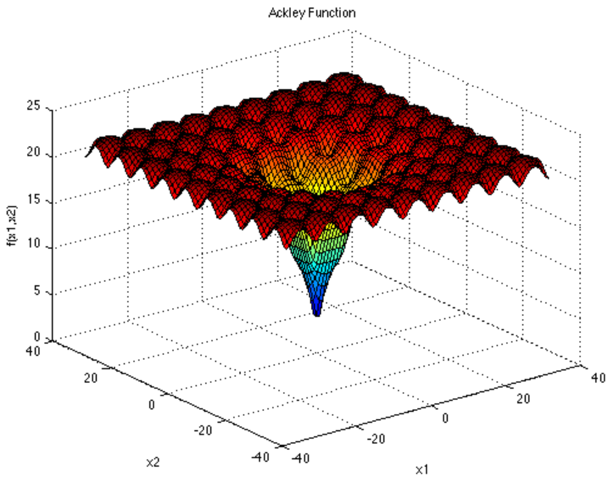
Nature Inspired Algorithms

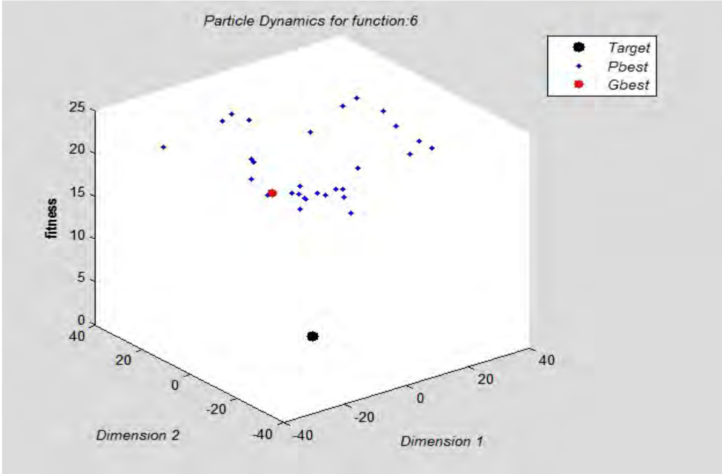
- Neural Computation – *the brain*
- Evolutionary Computation – *evolution*
- Swarm Intelligence – *group behavior*

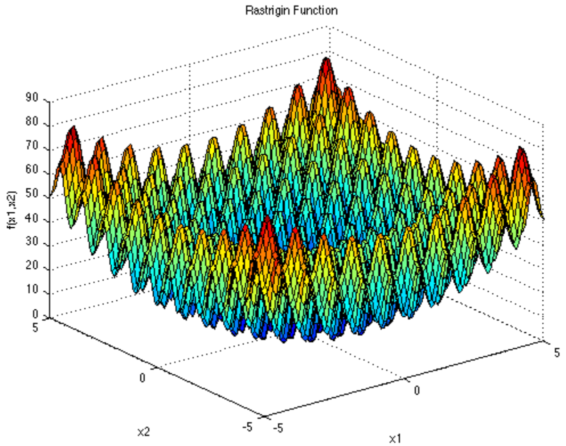
Swarm Intelligence

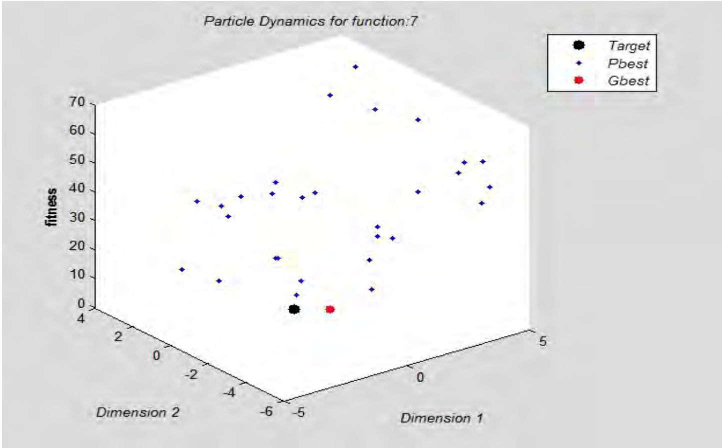
- Collective behaviors of (unsophisticated) agents
- No centralized control
- Collective (or distributed) problem solving
- Leverage the power of complex adaptive systems to solve difficult non-linear stochastic problems

Swarm in Action









Research

- Journal Publications:
  1. F. Hafiz and A. Abdennour, "A team-oriented approach to particle swarms," Applied Soft Computing (IF: 2.86), Elsevier, vol. 13, pp. 3776-3791, 2013.
  2. F. Hafiz and A. Abdennour, “Optimal use of kinetic energy for the inertial support from variable speed wind turbines”, Renewable Energy (IF: 3.36), Volume 80, Pages 629-643, August 2015.
  3. F. Hafiz and A. Abdennour, "A Neuro-Fuzzy Adaptive Inertia Controller for Variable Speed Wind Turbines," Renewable Energy, Elsevier (IF: 3.36), *Under Review*
  4. F. Hafiz and A. Abdennour, "Particle Swarm Algorithm variants for the Quadratic Assignment Problems - A probabilistic learning approach", Expert Systems with Applications, Elsevier, (IF: 2.24), pp. 413-431, 2016
  5. F. Hafiz and A. Abdennour, "Discrete team oriented particle swarms to solve the quadratic assignment problems", IEEE Transactions on System, Man and Cybernetics: Systems (IF: 2.17), *Under Review*

- Conference Proceedings:
  - F. Hafiz and A. Abdennour," Optimal Inertial Support from the Variable Speed Wind Turbines using Particle Swarm Optimization", 9th *IFAC Symposium on Control of Power and Energy Systems (CPES), 2015*
  - F. M. F. Hafiz, R. Roy, R. Maurya, and S. Ghoshal; "PSO Optimized Small Signal Stability Analysis of DFIG for WECS"; Current Trends in Technology, Nirma University, Ahmadabad; 286-292; Excel India Publishers; 2008.

Thank You