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Title: Active disturbance rejection control of a permanent magnet synchronous generator for wind turbine applications

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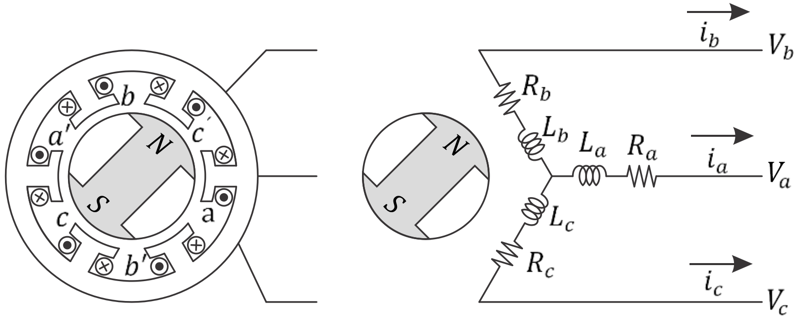
Introduction

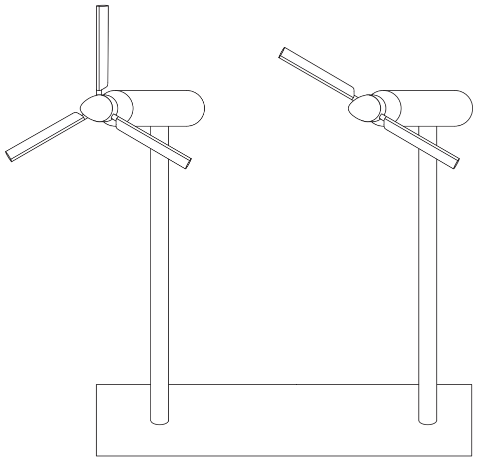


Permanent Magnet Synchronous Generator:

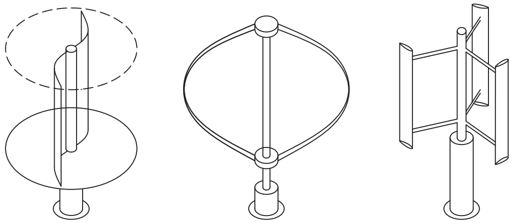
- PMSG is an electrical machine that transforms rotational mechanical energy into electrical energy.
- The frequency of the electric current generated is intimately related to the angular speed.
- Three phase star connection

Wind Turbine:

- Wind Energy Conversion system specialized in convert the kinetic energy of the wind into electrical power.
- Vertical Axis
- Horizontal Axis
- Fixed speed
- Variable speed
- Fixed Pitch
- Variable Pitch



Horizontal Axis



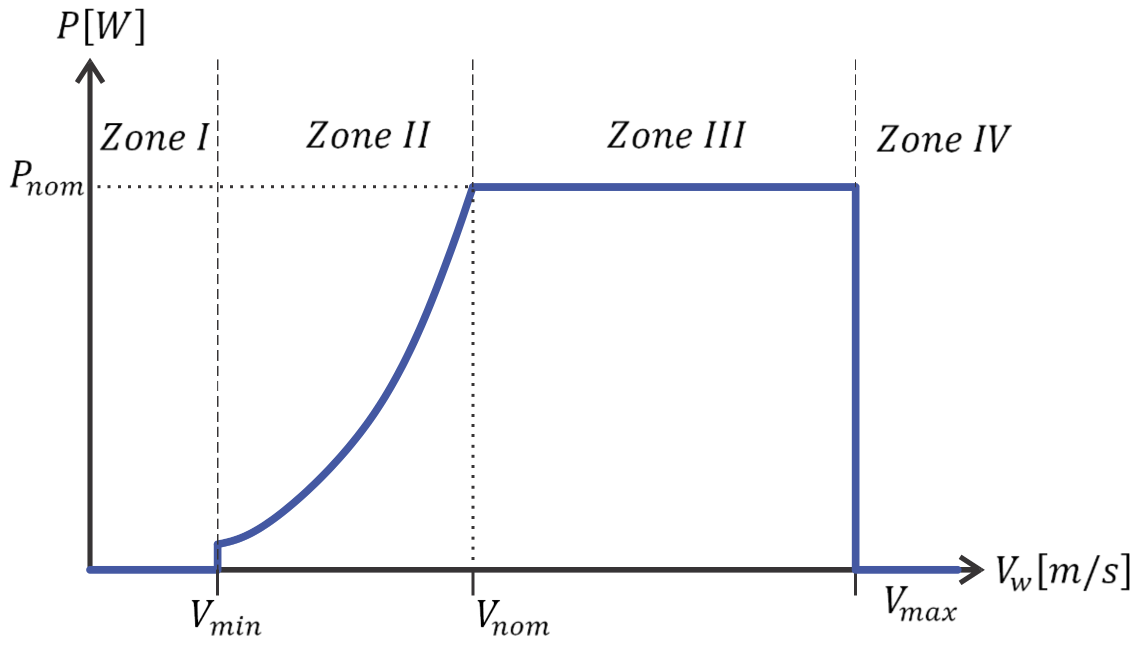
Vertical Axis

Introduction

A horizontal axis variable Pitch, variable speed wind turbine

Work zones

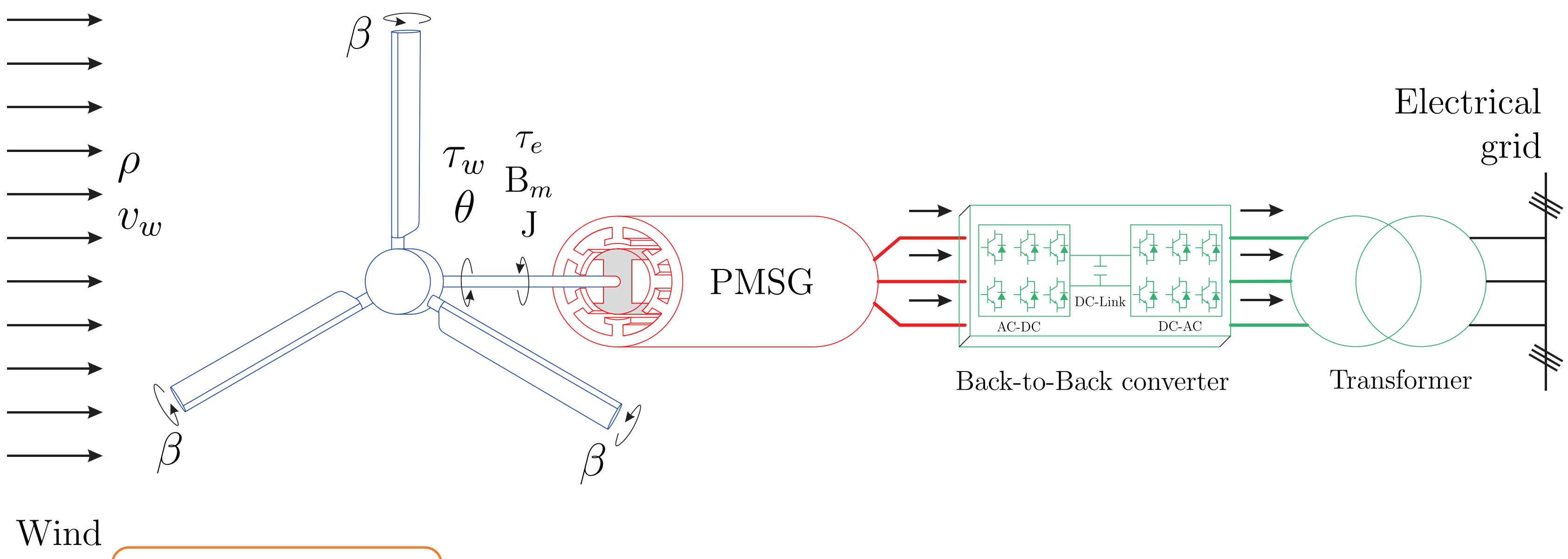
- Zone I
  - $v_w < v_{min}$
  - The wind is two low
  - No energy extraction
- Zone II
  - $v_{min} < v_w < v_{nom}$
  - Maximum Power Point Tracking
  - PMSG control
- Zone III
  - $v_{nom} < v_w < v_{max}$
  - Pitch Control
- Zone IV
  - $v_w > v_{max}$
  - Wind turbine must stop
  - No energy extraction



Power extraction curve

Methodology

Modeling



Subsystems

- Blades
  - Convert the wind's kinetic energy into kinetic rotational
- PMSG
  - Convert the kinetic rotational into electrical power
- Back-to-Back converter
  - Manage the power between the electrical grid and the Wind Turbine

Methodology

Blades

Power extracted from the wind

$$P_w = \frac{1}{2}\rho A v_w^3 C_p(\lambda_t, \beta)$$

$$A = \pi r_t^2$$

Power Coefficient

$$\begin{cases} C_p(\lambda_T, \beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\beta^{c_5} - c_6\right) exp\left(\frac{-c_7}{\lambda_i}\right) \lambda_i = \left[\left(\frac{1}{\lambda_T + c_8\beta}\right) - \left(\frac{c_9}{\beta^3 + 1}\right)\right]^{-1} \end{cases}$$

	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9
Heier (1998)	0.5	116	0.4	0	–	5	21	0.08	0.035
Fixed speed	0.44	125	0	0	0	6.94	16.5	0	−0.002
Variable Speed	0.73	151	0.58	0.002	2.14	13.2	18.4	−0.02	−0.003

Torque

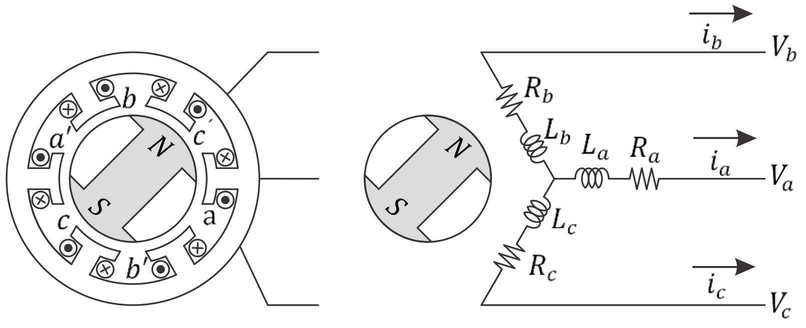
$$\tau_w = \frac{P_w}{\omega_T} = \frac{1}{2}\rho\pi r_T^3 v_w^2 \frac{C_p(\lambda_T, \beta)}{\lambda_t}$$

Mechanical Equation

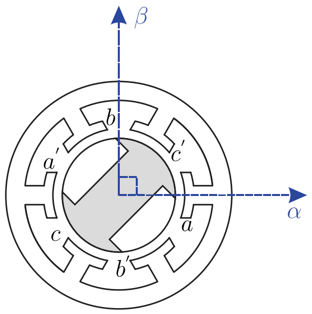
$$J\ddot{\theta} + B\dot{\theta} + \tau_e = \tau_w$$

Methodology

PMSG



Synchronous Reference frame



Park Angle

$$\theta_p = n_p\theta$$

Electromagnetic torque

$$\tau_e^{dq} = \frac{n_p\lambda_0}{\kappa} i_q = k_m i_q$$

Electrical Equations / Control inputs

$$v_d = R_s i_d - \frac{3}{2} L_s i_q n_p \frac{d}{dt}\theta + \frac{3}{2} L_s \frac{d}{dt} i_d$$

$$v_q = R_s i_q + \frac{3}{2} L_s i_d n_p \frac{d}{dt}\theta + \frac{3}{2}\kappa\lambda_0 n_p \frac{d}{dt}\theta + \frac{3}{2} L_s \frac{d}{dt} i_q$$

Input-Output model

$$\frac{d}{dt} i_d = \left(\frac{2}{3L_s}\right) v_d + \left(\frac{2}{3L_s}\right)\left(-R_s i_d - \frac{3}{2} L_s i_q n_p \frac{d}{dt}\theta\right)$$

$$\theta^{(3)} = -\left(\frac{n_p\lambda_0}{JL_s}\right) v_q + \left(\frac{1}{J}\right)\dot{\tau}_m \left(\frac{n_p\lambda_0}{JL_s}\right) - \left(R_s i_q + \frac{3}{2} n_p \dot{\theta}(L_s i_d + \kappa\lambda_0) + B_m \ddot{\theta}\right)$$

Differential Flatness

States of the system

$$\frac{d}{dt} i_d = \left(\frac{2}{3L_s}\right)\left(v_d - R_s i_d - \frac{3}{2} L_s i_q n_p \frac{d}{dt}\theta\right)$$

$$\frac{d}{dt} i_q = \left[\frac{2}{3L_s}\right]\left[v_q - R_s i_q - n_p \frac{d}{dt}\theta\left(\frac{3}{2} L_s i_d + \frac{3}{2}\kappa\lambda_0\right)\right]$$

$$\frac{d^2}{d^2t}\theta = \left(\frac{1}{J}\right)\left(\tau_w - B_m \frac{d}{dt}\theta - \frac{n_p\lambda_0}{\kappa} i_q\right)$$

$$i_q = \left(\frac{\kappa}{n_p\lambda_0}\right)\left(J\frac{d^2}{d^2t}\theta - \tau_w + B_m \frac{d}{dt}\theta\right)$$

Flat outputs:

$y_1 = i_d$ and $y_2 = \theta$

Methodology

Grid side converter

Synchronous Reference Frame

Park angle $\theta_p = \int \omega_p$

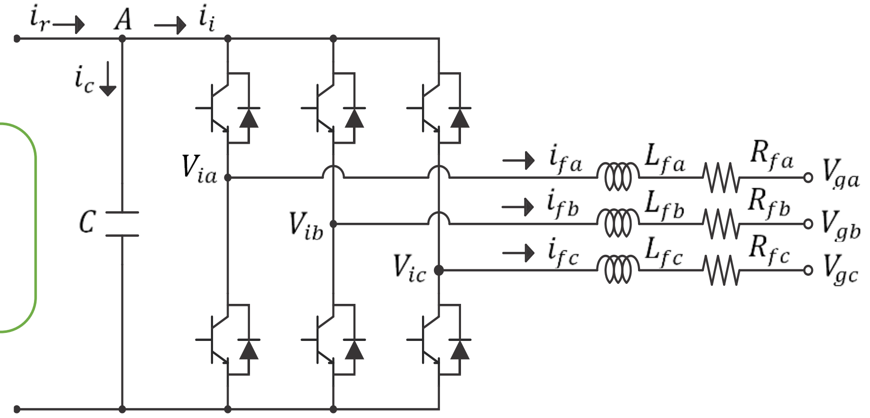
Electric equations / Control inputs

$$V_{id} = R_f i_{fd} - L_f i_{fq} + L_f \frac{d}{dt} i_{fd} + V_{gd}$$

$$V_{iq} = R_f i_{fq} + \omega_p L_f i_{fd} + L_f \frac{d}{dt} i_{fq} + V_{gq}$$

DC-link voltage

$$\frac{d}{dt} V_{dc} = \frac{1}{C} i_c = \frac{1}{C}(i_r - i_i)$$



Instantaneous Power

$$P = \frac{3}{2}(V_{gd} i_{fd} + V_{gq} i_{fq})$$

$$Q = \frac{3}{2}(V_{gq} i_{fd} - V_{gd} i_{fq})$$

$$V_{gq} = 0$$

$$P = \frac{3}{2} V_{gd} i_{fd} = V_{cd} i_i$$

$$Q = -\frac{3}{2} V_{gd} i_{fq}$$

Differential Flatness

State of the system

$$i_{fq} = -\frac{2}{3V_{gd}} Q$$

$$i_{fd} = \frac{2V_{cd}}{3V_{gd}}\left(I_r - C \frac{d}{dt} V_{cd}\right)$$

Flat outputs:
$y_3 = Q$ and $y_4 = V_{cd}$

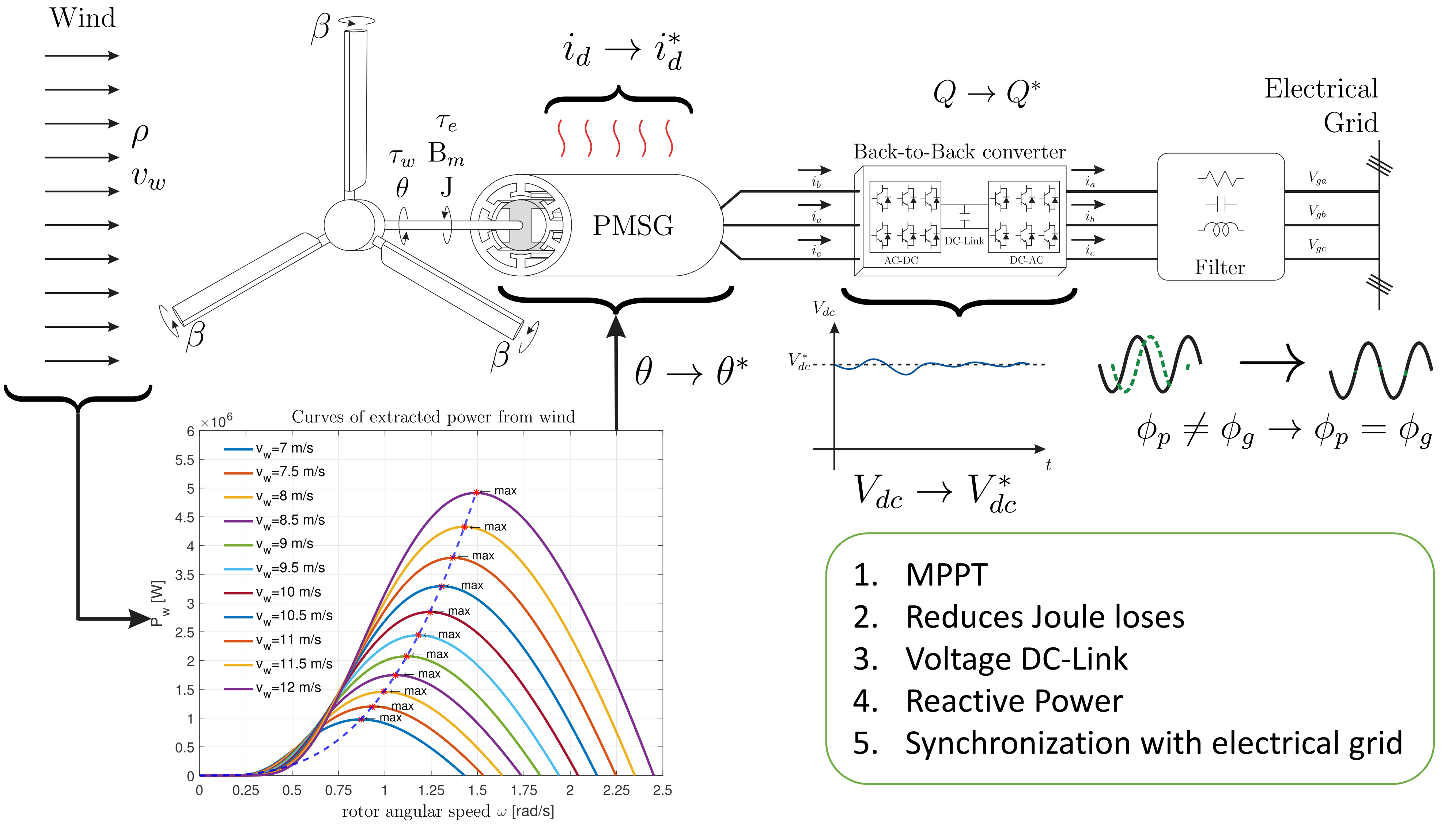
Input-Output model

$$\dot{Q} = -\frac{3V_{gd}}{2L_f} V_{iq} - \frac{3V_{gd}}{2}(-V_{gq} - R_f I_{fq} - \omega_p L_f I_{fd}) - \frac{3}{2} \dot{V}_{gd} I_{fq}$$

$$\ddot{V}_{cd} = -\frac{3V_{gd}}{2L_f V_{dc}} V_{id} - \frac{3V_{gd}}{2V_{dc}}(-V_{gd} - R_f I_{fd} + \omega_p L_f I_{fq}) + \frac{\dot{I}_r}{C} - \frac{3\dot{V}_{gd} I_{fd}}{2V_{cd}} + \frac{3V_{gd} I_{fd} \dot{V}_{cd}}{2V_{cd}^2}$$

Methodology

Control objectives



1. MPPT
2. Reduces Joule loses
3. Voltage DC-Link
4. Reactive Power
5. Synchronization with electrical grid

Methodology

Active disturbance Rejection Control

Simplified model

$$\theta^{(3)} = -\left(\frac{n_p\lambda_0}{JL_s}\right)v_q + \left(\frac{1}{J}\right)\dot{\tau}_m\left(\frac{n_p\lambda_0}{JL_s}\right) - \left(R_s i_q + \frac{3}{2}n_p\dot{\theta}(L_s i_d + \kappa\lambda_0) + B_m\ddot{\theta}\right)$$

$$\theta^{(3)} = -\left(\frac{n_p\lambda_0}{JL_s}\right)v_q + \xi_\theta = U_q + \xi_\theta$$

Output-tracking error system

$$e_\theta^{(3)} = e_{U_q} + \xi_\theta$$

$$e_\theta = \theta - \theta^*; \qquad \theta^* = \int \dot{\theta}_{opt}$$

$$e_{U_q} = U_q - U_q^*; \quad U_q^* = \frac{d^3}{dt^3}\theta^*$$

Extended State Observer

$$\dot{\hat{e}}_{y_0} = \widehat{e_{y_1}} + \lambda_3(e_{y_0} - \widehat{e_{y_0}}) = \widehat{e_{y_1}} + \lambda_3\tilde{e_0}$$

$$\dot{\hat{e}}_{y_1} = \widehat{e_{y_2}} + \lambda_2\tilde{e_0}$$

$$\dot{\hat{e}}_{y_2} = e_{U_q} + z + \lambda_1\tilde{e_0}$$

$$\dot{z} = \lambda_0\widetilde{e_o}$$

Characteristic polynomial

$$s^4 + \lambda_3 s^3 + \lambda_2 s^2 + \lambda_1 s + \lambda_0 = 0$$

Gain parameters

$$\lambda_0 = \omega_n^4$$
$$\lambda_1 = 4\zeta\omega_n^3$$
$$\lambda_2 = 4\zeta^2\omega_n^2 + 2\omega_n^2$$
$$\lambda_3 = 4\zeta\omega_n$$

Controller

$$U_q = U_q^* - k_2\hat{e}_y^{(2)} - k_1\hat{e}_y^{(1)} - k_0 e_y - z$$

Characteristic polynomial

$$s^3 + k_2 s^2 + k_1 s + k_0 = 0$$

Gain parameters

$$k_0 = p\omega_n^2$$
$$k_1 = 2\zeta\omega_n p + \omega_n^2$$
$$k_2 = 2\zeta\omega_n + p$$

Methodology

PI Controller

Current i_d

Simplified system

$$\frac{d}{dt}i_d = \left(\frac{2}{3L_s}\right)v_d + \left(\frac{2}{3L_s}\right)\left(-R_s i_d - \frac{3}{2}L_s i_q n_p \frac{d}{dt}\theta\right)$$

$$\frac{d}{dt}i_d = \left(\frac{2}{3L_s}\right)v_d + \xi_{id} = U_d + \xi_{i_d}$$

PI Controller

$$U_d(s) = -\left[k_1 + \frac{k_0}{s}\right]i_d(s)$$

Gain parameters

$k_0 = {\omega_n}^2$

$k_1 = 2\zeta\omega_n$

Reactive power

Simplified system

$$\dot{Q} = -\frac{3V_{gd}}{2L_f}V_{iq} - \frac{3V_{gd}}{2}(-V_{gq} - R_f I_{fq} - \omega_p L_f I_{fd}) - \frac{3}{2}V_{gd}I_{fq}$$

$$\dot{Q} = -\frac{3V_{gd}}{2L_f}V_{iq} + \xi_Q = U_{iQ} + \xi_Q$$

Output tracking error system

$\dot{e}_Q = e_{U_{iq}} + \xi_Q$; $\quad e_Q = Q - Q^*$; $\quad e_{U_{iq}} = U_{iq} - U_{iq}^*$

$$U_{iq}^* = \frac{d^2}{dt^2}Q^*$$

Controller

$$e_{U_{iq}}(s) = -\left[k_1 + \frac{k_0}{s}\right]e_Q(s)$$

Gain parameters

$k_0 = {\omega_n}^2$

$k_1 = 2\zeta\omega_n$

Methodology

GPI control

Simplified model

$$\ddot{V}_{cd} = -\frac{3V_{gd}}{2L_f V_{dc}} V_{id} - \frac{3V_{gd}}{2V_{dc}}\left(-V_{gd} - R_f I_{fd} + \omega_p L_f I_{fq}\right) + \frac{\dot{I}_r}{C} - \frac{3\dot{V}_{gd} I_{fd}}{2V_{cd}} + \frac{3V_{gd} I_{fd} \dot{V}_{cd}}{2V_{cd}^2}$$

$$\ddot{V}_{cd} = -\frac{3V_{gd}}{2L_f V_{dc}} V_{id} + \xi_{cd} = U_{id} + \xi_{cd}$$

Output-tracking error system

$$\ddot{e}_{V_{cd}} = e_{U_{id}} + \xi_{cd}; \qquad e_{V_{cd}} = V_{cd} - V_{cd}^*; \qquad e_{U_{id}} = U_{id} - U_{id}^*; \qquad U_{id}^* = \frac{d^2}{dt^2} V_{cd}^*$$

Controller

$$U_{id}(s) = U_{id}^* - \left[\frac{k_2 s^2 + k_1 s + k_0}{s(s + k_3)}\right] e_{V_{cd}}(s)$$

Gain parameters

$$k_0 = \omega_n^4$$
$$k_1 = 4\zeta\omega_n^3$$
$$k_2 = 4\zeta^2\omega_n^2 + 2\omega_n^2$$
$$k_3 = 4\zeta\omega_n$$

Characteristic polynomial

$$s^4 + k_3 s^3 + k_2 s^2 + k_1 s + k_0 = 0$$

Methodology

SRF-PLL

Grid signals

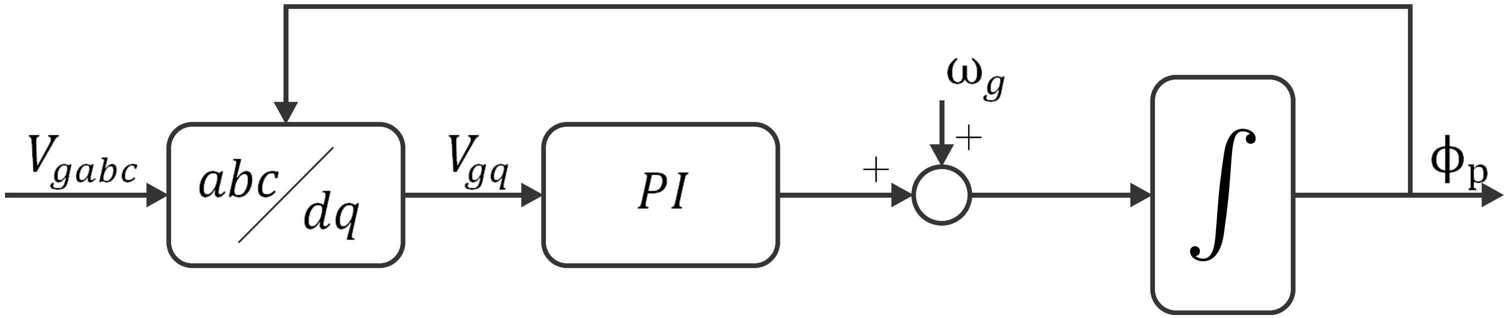
$$\begin{bmatrix} Vga \\ Vgb \\ Vgc \end{bmatrix} = \begin{bmatrix} V\cos(\theta_g) \\ V\cos\left(\theta_g - \frac{2\pi}{3}\right) \\ V\cos\left(\theta_g + \frac{2\pi}{3}\right) \end{bmatrix}$$

Synchronous reference frame

$$\begin{bmatrix} Vgd \\ Vgq \\ Vg0 \end{bmatrix} = \kappa \begin{bmatrix} \frac{3}{2} V\cos(\theta_g - \phi_p) \\ \frac{3}{2} V\sin(\theta_g - \phi_p) \\ 0 \end{bmatrix};$$

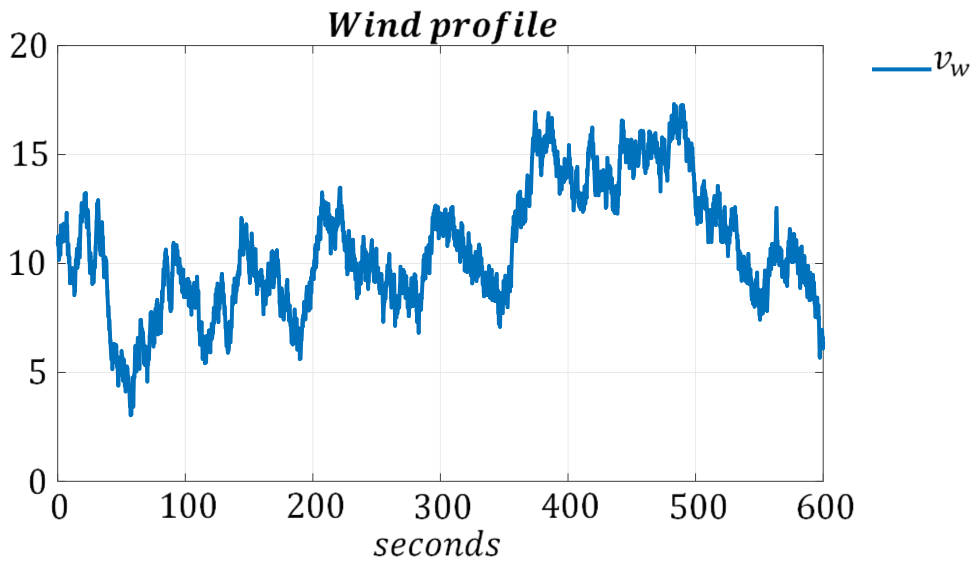
Park angle: ϕ_p

$$Vgq = \frac{3\kappa}{2} V\sin(\theta_g - \phi_p); \quad Vgq = 0 \Leftrightarrow \theta_g = \phi_p$$



Synchronous Reference Frame Phase Lock Loop

Results 5MW Wind Turbine Simulation



Filter parameters

Parameter	Symbol	Value	Unit
DC-Link capacitor	C	40	μF
Filter resistance	R_f	0.01	$m\Omega$
Filter inductance	L_f	0.5	mH

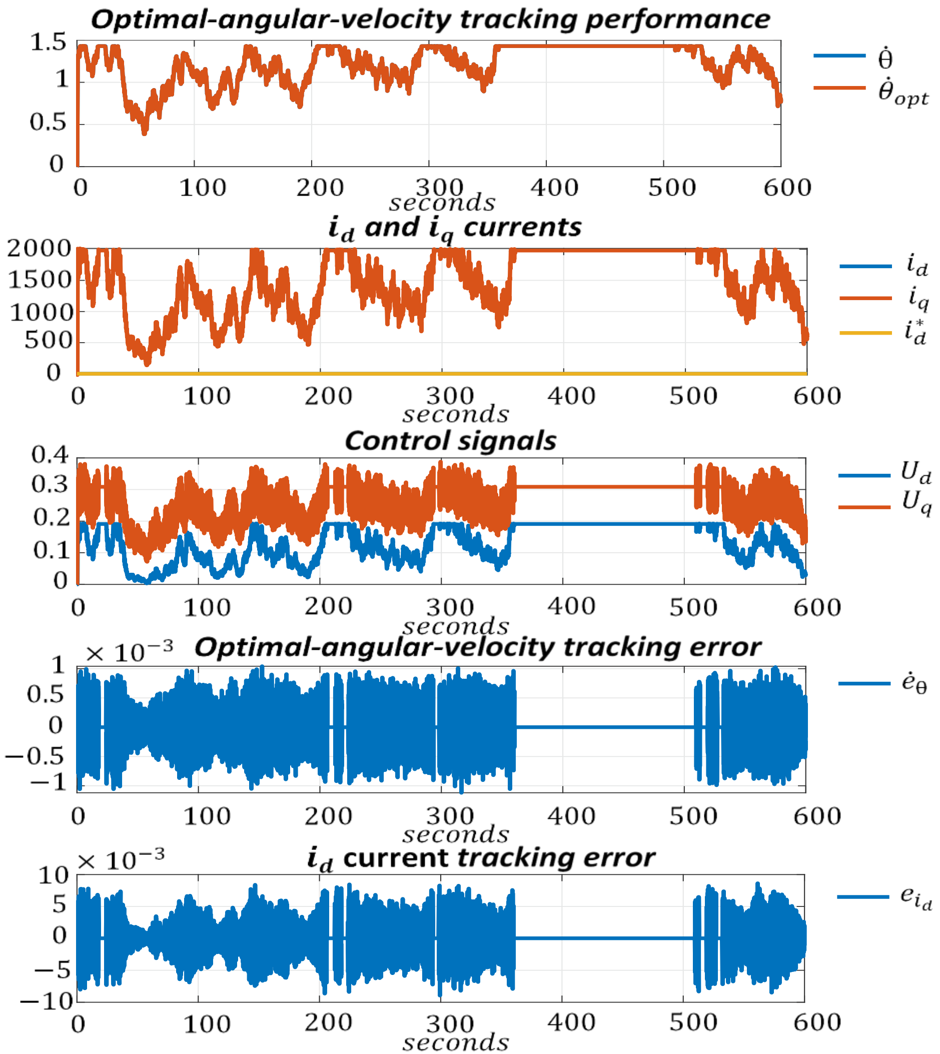
Source: (Aimene, Payman, & Dakyo, 2014)

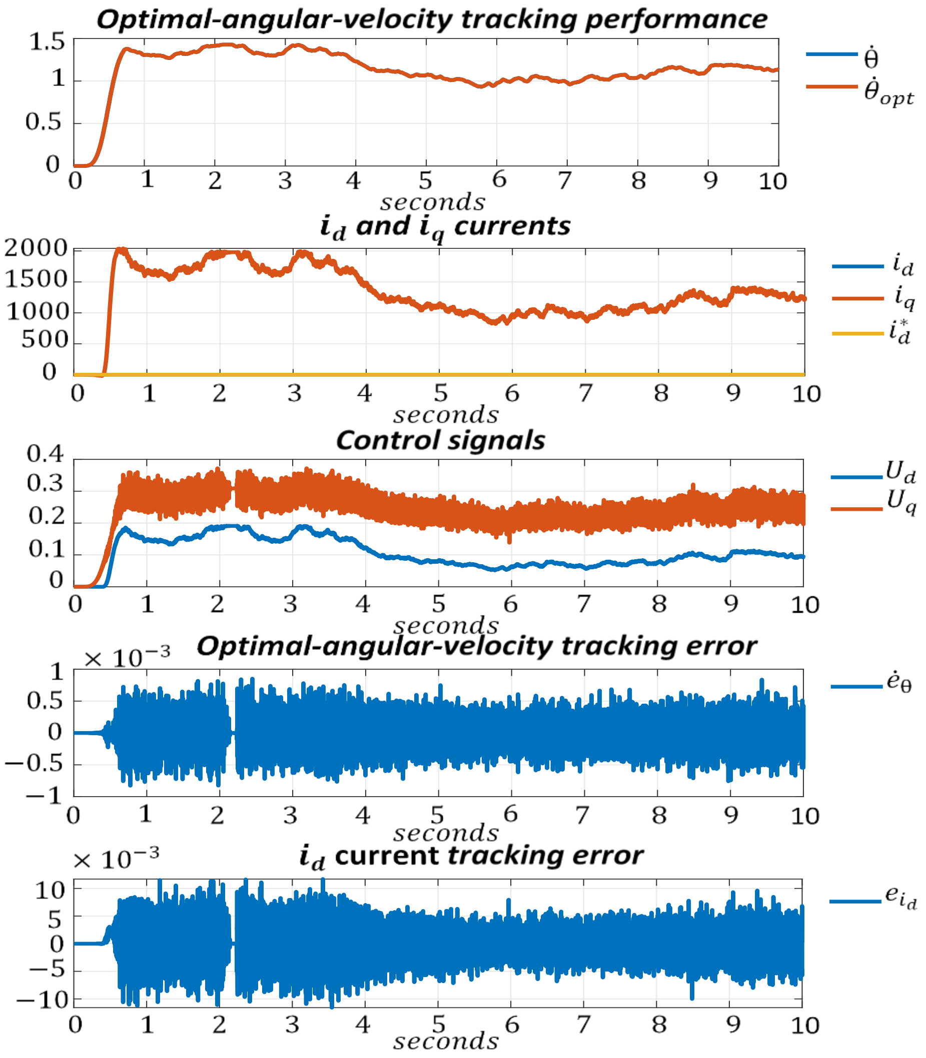
Wind Turbine parameters

Parameter	Symbol	Value	Unit
Nominal Power	$P_{w,nom}$	5	MW
Total inertia	J	1×10^4	$Kg \cdot m^2$
Blade length	r_t	56	m
Wind density	ρ	1.225	$Kg \cdot m^3$
Stator resistance	R_s	6.25	mΩ
Stator inductance	L_s	4.229	mH
Permanent magnet flux density	λ_0	11.1464	Wb
Pole pairs number	n_p	75	$-$
Nominal voltage	V_{nom}	0.9	kV
Nominal angular speed	ω_{nom}	1.447	rad/s

Source: (Aimene, Payman, & Dakyo, 2014)

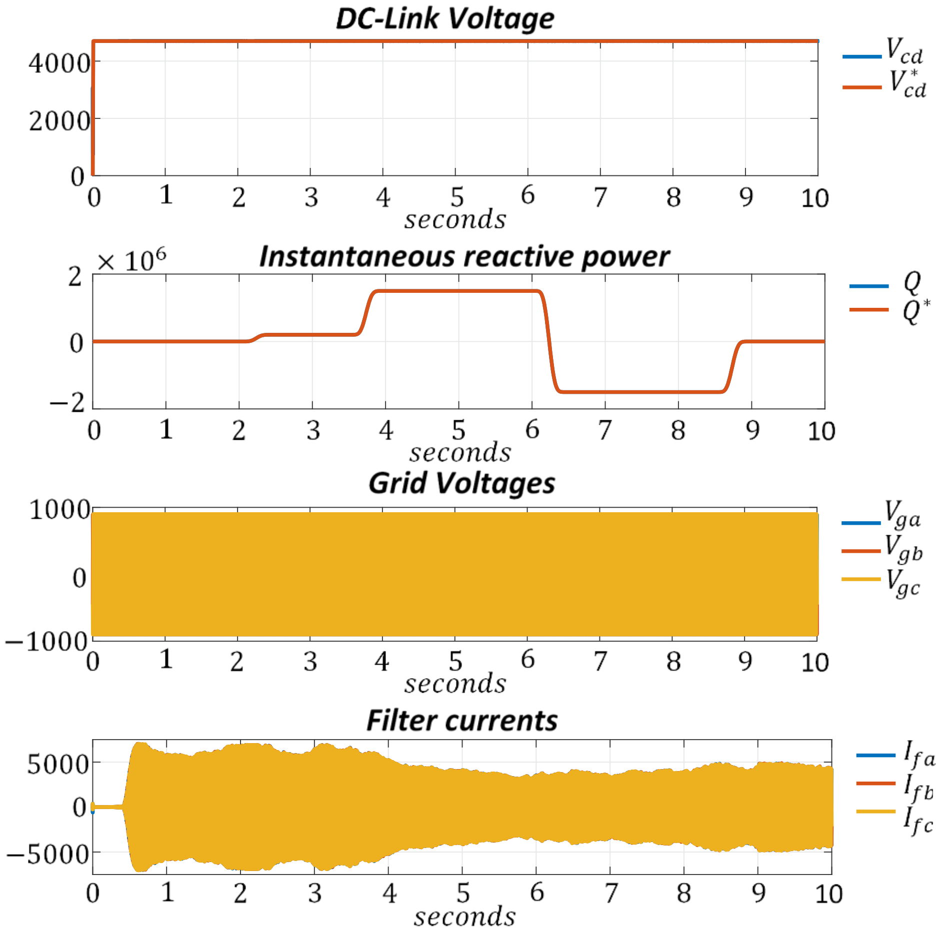
Results 5MW Wind Turbine Simulation

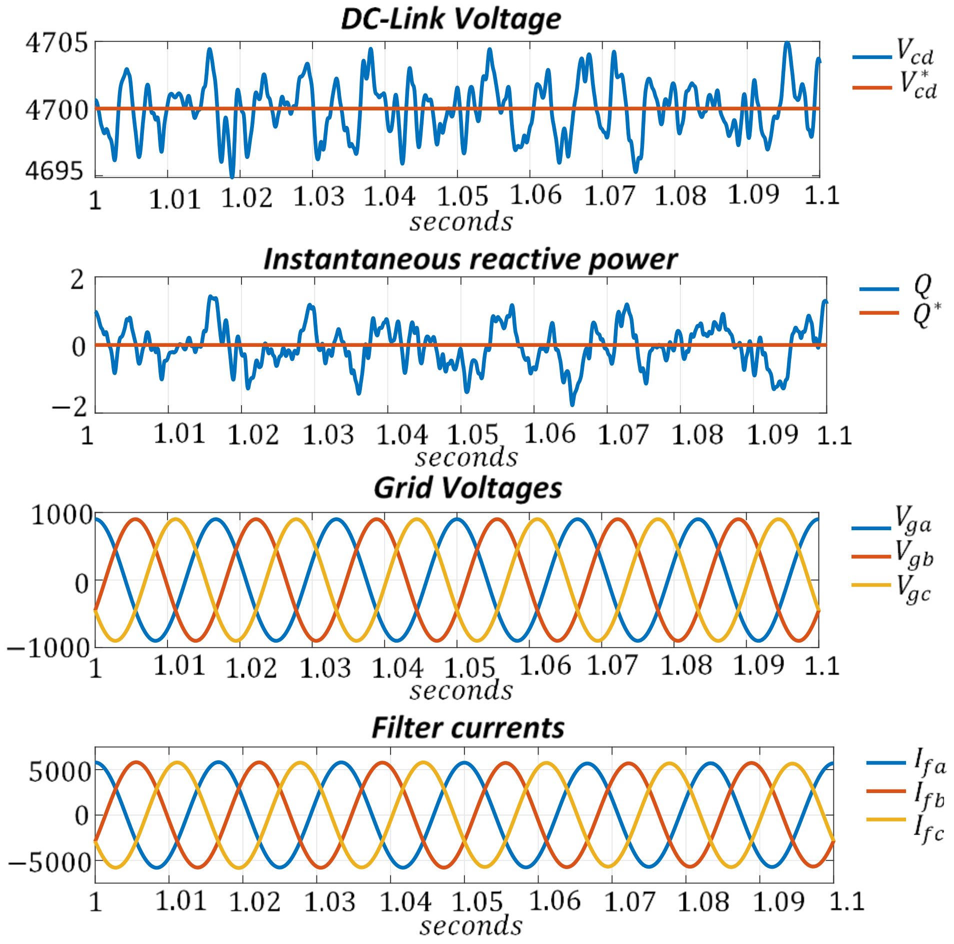




Results

5MW Wind Turbine Simulation





Conclusions

- Differential flatness property.
  - The PMSG is flat.
  - The GSC is flat using a RL Filter.
- Control of the Wind Turbine
  - An ADRC is proposed to track the maximum power point.
  - A GPI is proposed to regulate the DC-Link voltage.
  - The current i_d and the reactive power Q are controlled with two PI.
  - Synchronization with the electrical grid via a SRF-PLL.
- Numerical simulations
  - Shows a good performance using the proposed controllers.
- Further Work
  - Sensorless control.
  - Avoid measuring the wind speed.

References

- Ackermann, T. (2005). Wind power in power systems. Chichester, UK: John Wiley.
- Ackermann, T., & Söder, L. (2002). An overview of wind energy-status 2002. Renewable and Sustainable Energy Reviews, 67-127.
- Aimene, M., Payman, A., & Dakyo, B. (2014). Flatness-based control of a variable-speed wind-energy system connected to the grid. Ninth International Conference on Ecological Vehicles and Renewable Energies, (pp. 1-7). Monte-Carlo, Monaco.
- Akagi, H., Watanabe, E. H., & Aredes, M. (2017). Instantaneous power theory and applications to power conditioning. Hoboken, New Jersey: John Wiley & Sons.
- Bianchi, F. D., de Battista, H., & Mantz, R. J. (2007). Wind Turbine Control Systems. London: Springer-Verlag.
- Fliess, M., Lévine, J., Martin, P., & Rouchon, P. (1992). Sur les systèmes non linéaires différentiellement plats. CR Acad. Sci., (pp. 619-624). Paris.
- Hwas, A., & Katebi, R. (2012). Wind Turbine Control Using PI Pitch Angle Controller. IFAC Proceedings Volumes, 241-246.
- Karimi-Ghartemani, M. (2014). Enhanced phase-locked loop structures for power and energy applications. John Wiley & Sons.
- Njiri, J., & Söffker, D. (2016). State-of-the-art in wind turbine control: Trends and challenges. Renewable and Sustainable Energy Reviews, 377-393.
- Polinder, H., Ferreira, J. A., Jensen, B. B., Abrahamsen, A. B., Atallah, K., & McMahon, R. A. (2013). Trends in wind turbine generator systems. IEEE Journal of emerging and selected topics in power electronics, 174-185.
- Sira-Ramírez, H. (2018). From flatness, GPI observers, GPI control and flat filters to observer-based ADRC. Control Theory and Technology, 249–260.
- Sira-Ramírez, H., & Agrawal, S. (2004). Differentially flat systems. Crc Press.
- Sira-Ramírez, H., & Zurita-Bustamante, E. W. (2021). On the equivalence between ADRC and Flat Filter based controllers: A frequency domain approach. Control Engineering Practice.
- Sira-Ramírez, H., Luviano-Juárez, A., Ramírez-Neria, M., & Zurita-Bustamante, E. W. (2017). Active disturbance rejection control of dynamic systems: a flatness based approach. Elsevier.
- Sira-Ramirez, H., Zurita-Bustamante, E. W., & Huang, C. (2019). Equivalence among flat filters, dirty derivative-based PID controllers, ADRC, and integral reconstructor-based sliding mode control. IEEE Transactions on Control Systems Technology, 1696-1710.
- Wu, B., Lang, Y., Zargari, N., & Kouro, S. (2011). Power Conversion and Control of Wind Energy Systems. John Wiley & Sons.

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