UNIVERSITÀ DI TRENTO

DEPARTMENT OF
INDUSTRIAL ENGINEERING

Renewable Energy Conversion Systems

Lecture 9

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MSc Degree in Mechatronic Engineering,
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Lecture 9: Outline

Main topic:

Wind Energy Conversion Systems:
control aspects

- General control structure of a wind turbine
- Inner (current) control of a permanent magnet synchronous generator (PMSG)
  - Description of the PMSG dynamics through transfer functions
  - Basics of design and tuning of linear current controllers in a synchronous reference frame
- Outer control loop of a PMSG: basics of design and tuning

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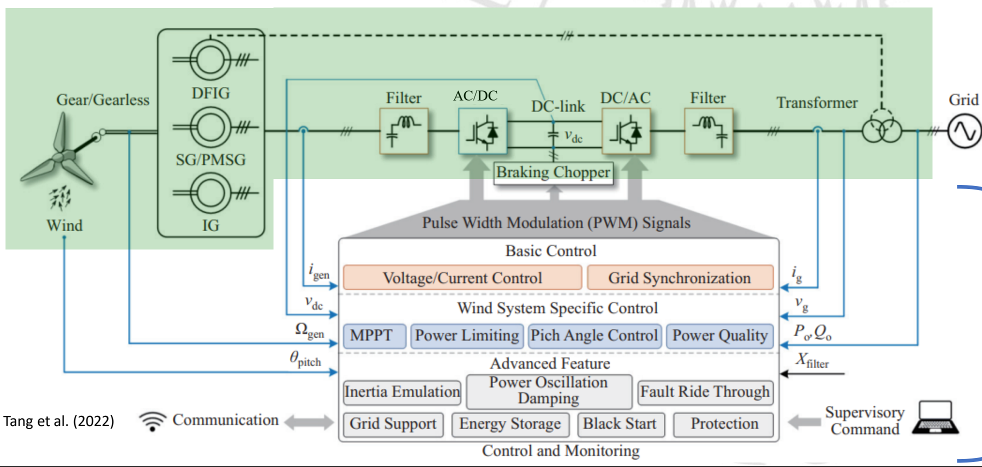
Overall scope

General control structure of a wind turbine power converter

Drive train configuration of a wind turbine



Several control layers

Source: Zhongting Tang et al. (2022)

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Overall scope

The control of wind power systems typically includes three levels. The control functions for the power converter system, i.e., the power interface between the wind turbine and the grid, which include both the machine side converter and the grid side converter, are detailed as follows:

(1) Basic control
(2) Specific control
(3) Advanced (control) features

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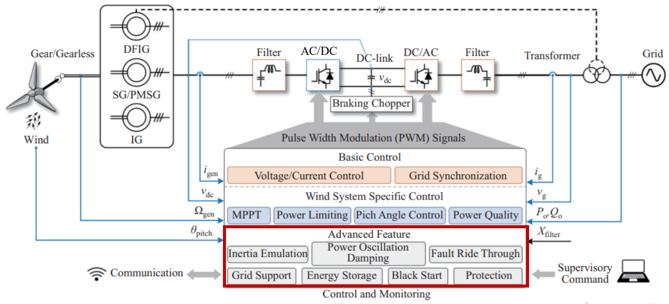
Overall scope



(3) Advanced features: many advanced control functions for wind power converters have been introduced to enable an intelligent, reliable, and grid-supportive system. Response to grid faults (e.g., voltage ride-through operation) and grid support capability (injecting or absorbing reactive power) should be provided to ensure grid-friendly wind power systems. Subsystems in the wind turbine, e.g., generator/grid side converters, pitch angle controller, etc. also need to be coordinated to ride through abnormal grid conditions

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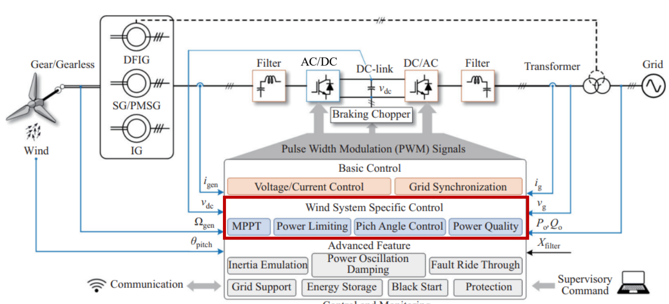
Overall scope



(2) Specific control: Since the wind speed varies, the generated power also fluctuates. The mechanical system and power converter should be controlled to maximize energy harvesting by adjusting the rotational speed of the turbine.
When the wind speed is lower than the rated value, the wind turbine can apply Maximum Power Point Tracking, if the wind speed exceeds the rated value, the pitch angle should be regulated to limit the generated power.
On the grid side, wind power systems should meet power quality requirements

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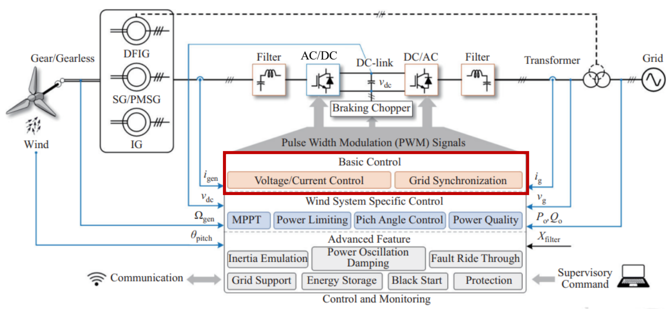
Overall scope



(1) Basic control: Like all grid-connected converters, the basic control for wind power converters mainly considers current regulation, stabilization of the DC-link voltage, and grid synchronization.

The objective of the basic control is to obtain efficient and reliable power conversion. In addition, the basic control should provide good steady-state and dynamic performance to ensure stable and safe operation

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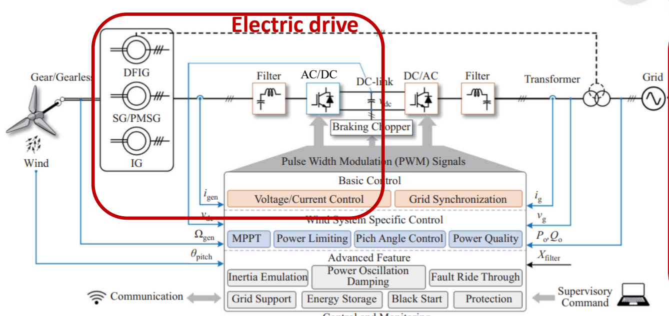
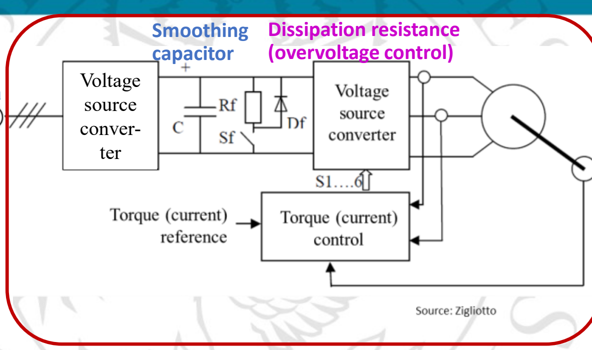
Generator side control





The goal is the torque control, which is normally implemented as a current control
The torque reference can, in turn, be generated by an outer loop (e.g. speed, power etc.)

Measurements required:
- Phase currents (normally 2 out of 3) **- Rotor position θ_m**

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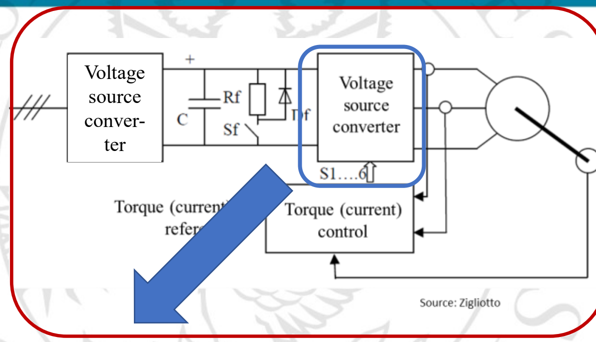
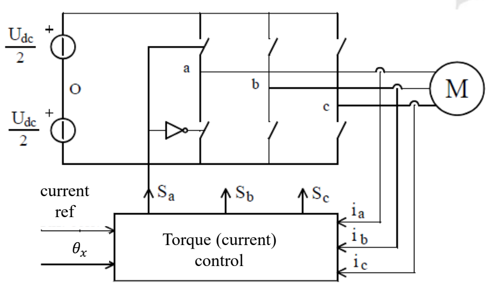
Generator side control

To have a high performance PMSM drive, closed-loop current control performed through current controlled PWM inverters is needed





θ_x represents the position of the reference frame selected for the control.
The components of the space vector of desired currents are derived by torque (and speed) references

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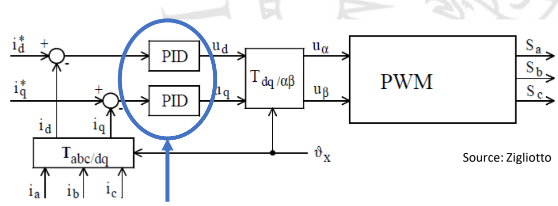
Current control of the generator

Although several alternatives are possible for the implementation of the current controller, e.g., depending on which reference frame they use for control design and tuning or if they actually use PWM modulation for the generator of the control pulses to the voltage source converter, the most used controllers for wind turbines are implemented in the synchronous reference frame (and use a PWM modulator) by use of proportional-integral-derivative (PID) regulators

- Suitable for digital implementation where coordinate transformations including sinusoidal functions are stored in look-up tables



Bi-phase(dq) synchronous current controller with PID

Linear controllers (operating with constant signals -if the reference system is properly selected- they can give zero error in steady state)

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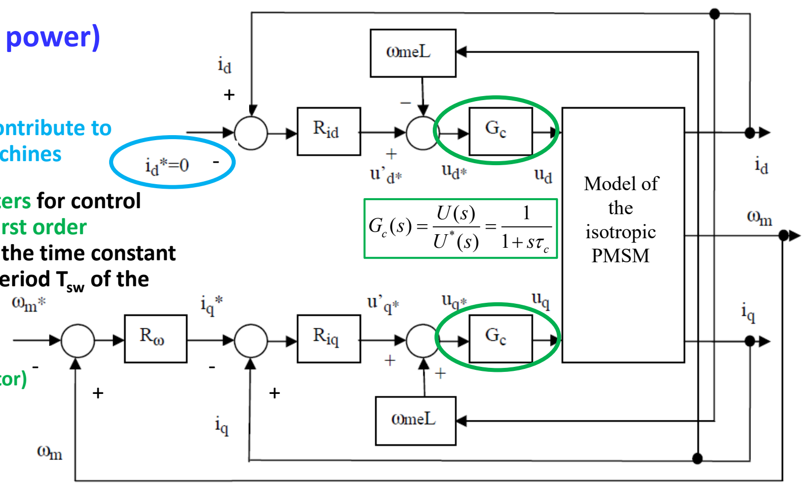
Control of a (magnetically isotropic) PMSM

Cascaded speed (or power) and torque control

I_d components does not contribute to the torque in isotropic machines

When modeling **PWM converters** for control design purposes, generally a **first order** approximation is used, where the time constant τ_c is related to the switching period T_{sw} of the converters

(e.g. $\tau_c = T_{sw}/2$ for digital PWM modulator)



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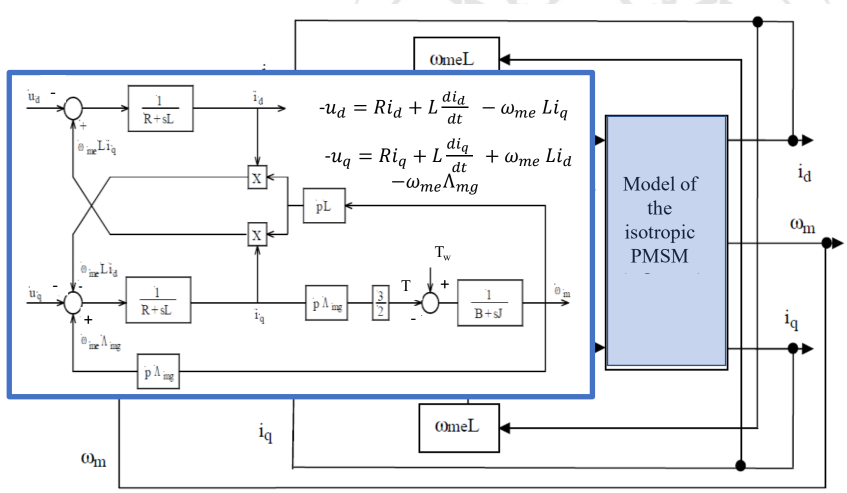
Control of a (magnetically isotropic) PMSM

Previously derived model of the PMSM in d-q ref frame



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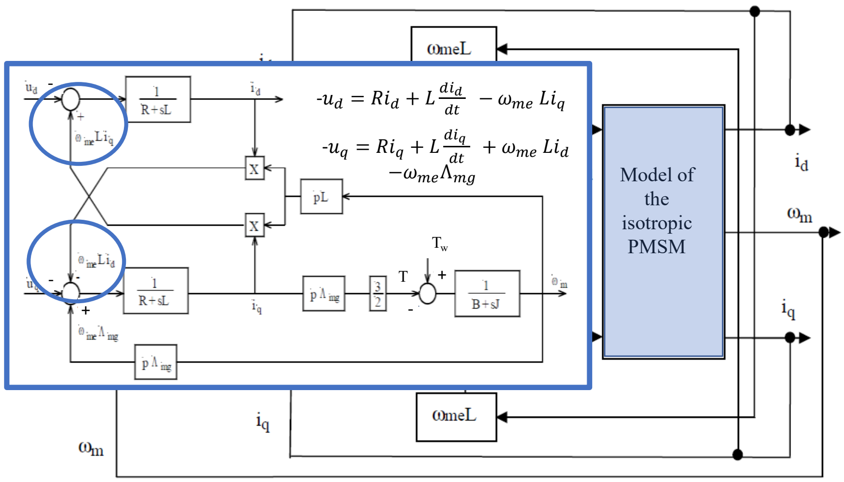
Control of a (magnetically isotropic) PMSM

Problem: The cross-coupling between the d-q axes in the generator model, implies that the control loops in the d and q axes are not independent, but they mutually influence each other, which is undesirable



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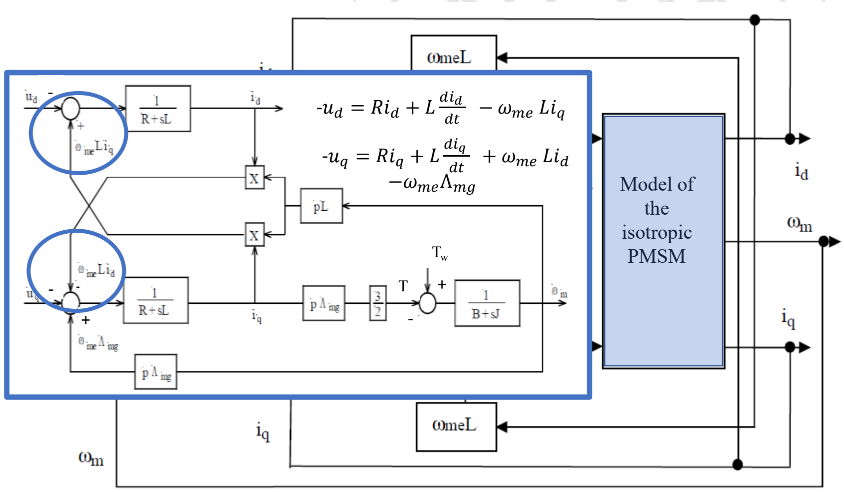
Control of a (magnetically isotropic) PMSM

Solution: As normally the converter time constant τ_c is small compared to other time constants, it is possible to compensate the generator cross-coupling adding an «equal and opposite term» at the output of the controller to get the decoupling



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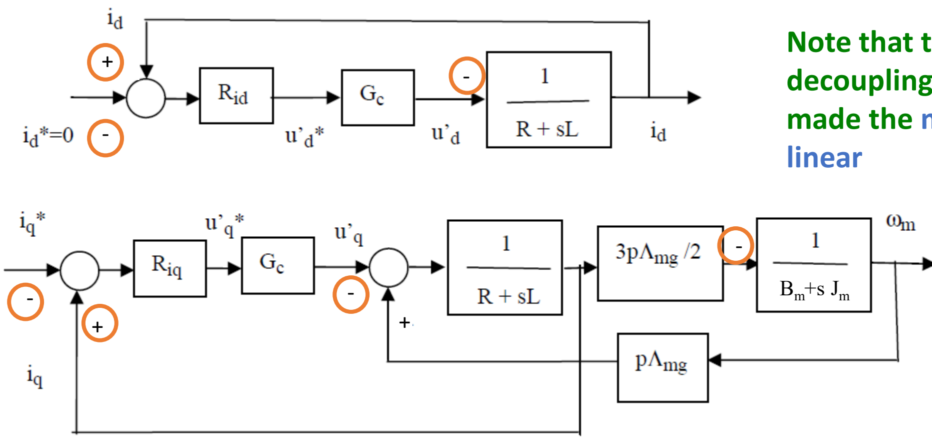
Control of a (magnetically isotropic) PMSM



Note that the decoupling terms made the model linear

Block diagram of the i_d and i_q current control after the decoupling

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Control of a (magnetically isotropic) PMSM

After decoupling equations are linear, so the model can be built in the Laplace domain:

$$-u_d = Ri_d + L\frac{di_d}{dt} - \omega_{me} Li_q$$

$$-u_q = Ri_q + L\frac{di_q}{dt} + \omega_{me} Li_d - \omega_{me}\Lambda_{mg}$$

From the second equation: $-U_q'(s) = (R + sL)I_q(s) - p\Lambda_{mg}\Omega_m(s)$

And for the torque: $\frac{3}{2}p\Lambda_{mg}I_q(s) = T_m^m(s) = T_w^m(s) - (B_m + sJ_m)\Omega_m(s)$

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Dynamic behaviour of a PMSG

Several transfer functions can be used to characterize the PM generator behavior, i.e.

$$\Gamma_{u\omega}(s) = \frac{\Omega_m(s)}{U_q'(s)} = \frac{\frac{1}{R+sL}\frac{3}{2}p\Lambda_{mg}\frac{1}{B_m+sJ_m}}{1+\frac{1}{R+sL}\frac{3}{2}(p\Lambda_{mg})^2\frac{1}{B_m+sJ_m}} = \frac{1}{p\Lambda_{mg}}\frac{1}{D(s)}$$

$$Y_q(s) = \frac{I_q(s)}{U_q'(s)} = \frac{-\frac{1}{R+sL}}{1+\frac{1}{R+sL}\frac{3}{2}(p\Lambda_{mg})^2\frac{1}{B_m+sJ_m}} = -\frac{1}{\frac{3}{2}(p\Lambda_{mg})^2}\frac{B_m+sJ_m}{D(s)}$$

Posing: $$D(s) = \frac{J_m L}{\frac{3}{2}(p\Lambda_{mg})^2}s^2 + \frac{R\,J_m + L\,B_m}{\frac{3}{2}(p\Lambda_{mg})^2}s + \frac{R\,B_m}{\frac{3}{2}(p\Lambda_{mg})^2} + 1$$

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Dynamic behaviour of a PMSG

Several transfer functions can be used to characterize the PM generator behavior, i.e.

$$\Gamma_{t\omega}(s) = \frac{\Omega_m(s)}{T_w(s)} = \frac{\frac{1}{B_m+sJ_m}}{1+\frac{1}{R+sL}\frac{3}{2}(p\Lambda_{mg})^2\frac{1}{B_m+sJ_m}} = \frac{1}{\frac{3}{2}(p\Lambda_{mg})^2}\frac{R+sL}{D(s)}$$

$$\Gamma_{ti}(s) = \frac{I_q(s)}{T_w(s)} = \frac{\frac{1}{R+sL}p\Lambda_{mg}\frac{1}{B_m+sJ_m}}{1+\frac{1}{R+sL}\frac{3}{2}(p\Lambda_{mg})^2\frac{1}{B_m+sJ_m}} = \frac{2}{3p\Lambda_{mg}}\frac{1}{D(s)} = \frac{2}{3}\Gamma_{u\omega}(s)$$

Posing: $$D(s) = \frac{J_m L}{\frac{3}{2}(p\Lambda_{mg})^2}s^2 + \frac{R\,J_m + L\,B_m}{\frac{3}{2}(p\Lambda_{mg})^2}s + \frac{R\,B_m}{\frac{3}{2}(p\Lambda_{mg})^2} + 1$$

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Design of linear controllers in the synchronous reference frame

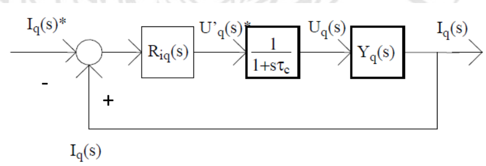
The most used controllers for wind turbine applications are linear proportional-integral-derivative (PID) controllers designed in the synchronous (i.e., d-q) reference frame

For controller design, the system is assumed linear (no saturation, limiters are neglected)

Hence its elements can be represented in the Laplace domain

The first step is selection and tuning of the regulator for the inner (current) loop. Its design can be based on any tuning methods

If designing the controller on the q-axis, it can be seen that the procedure for the d-axis would be similar, but simplified



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Design of linear controllers in the synchronous reference frame

Once the inner (current) controller has been tuned, the closed loop transfer function corresponding to the inner control loop is calculated

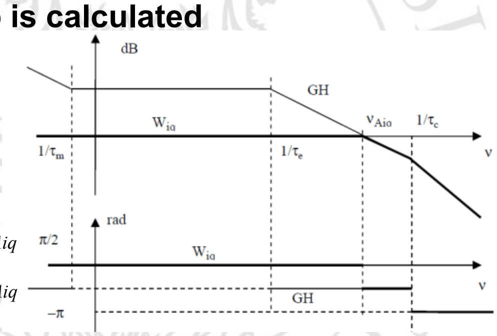
$$W_{iq}(s) = \frac{G(s)}{1+G(s)H}$$

Hp. H is a static gain

A reasonable approximation of W_{iq} can be:

$$W_{iq}(s) = \frac{G(s)}{1+G(s)H} \approx \begin{cases} 1/H & if\ |G(j\nu)H| > 1\ \ i.e.\ \ \nu < \nu_{Aiq} \\ G(j\nu) & if\ |G(j\nu)H| < 1\ \ i.e.\ \ \nu > \nu_{Aiq} \end{cases}$$

$$W_{iq}(s) = \frac{1}{(1+s/\nu_{Aiq})(1+s\tau_c)}$$



Example of simplified Bode diagram considering the use of a PI controller for the inner loop

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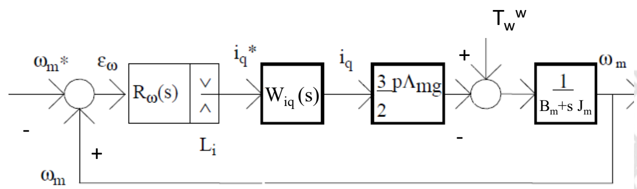
Design of linear controllers in the synchronous reference frame

The selection and tuning of the outer controller can then be performed based on:



A proportional-integral (PI) regulator is typically selected

The outer control loop in wind turbine applications is not necessarily a speed loop, but the approach to the regulator tuning would be similar, once the proper control loop and transfer functions are identified

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Lecture 9: Reference material

Lecture slides

Z. Tang, Y. Yang and F. Blaabjerg, "Power electronics: The enabling technology for renewable energy integration," in CSEE Journal of Power and Energy Systems, vol. 8, no. 1, pp. 39-52, Jan. 2022, doi: 10.17775/CSEEJPES.2021.02850.

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