Control and Stability in Wind Energy Converters Using Transfer Function Analysis

Assignment 3 : Torque Generation and Turbine-Rotor Interaction Process

Renewable Energy Technology in Electric Networks WS 2020/2021

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System Implemented in Simulink at the End of this Course

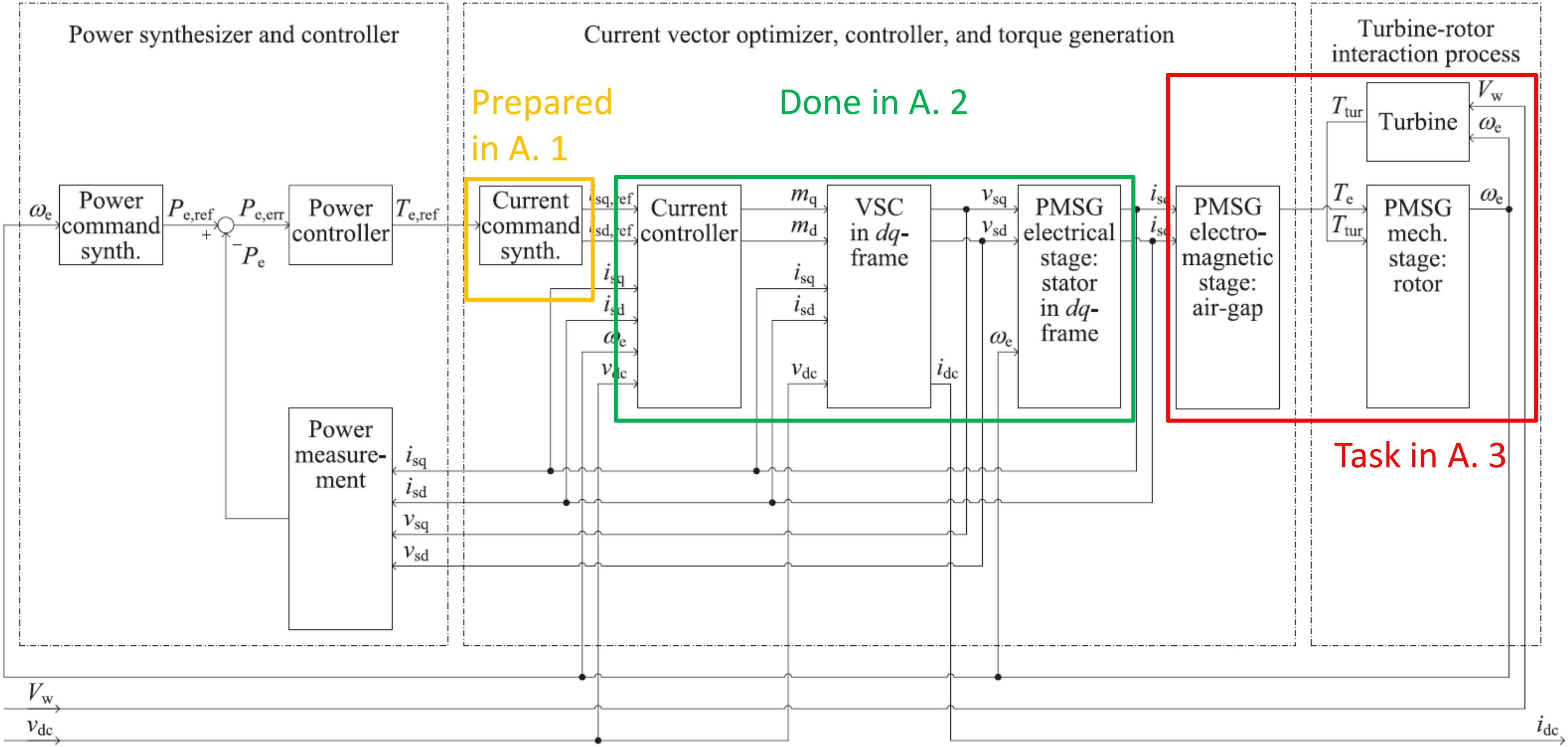
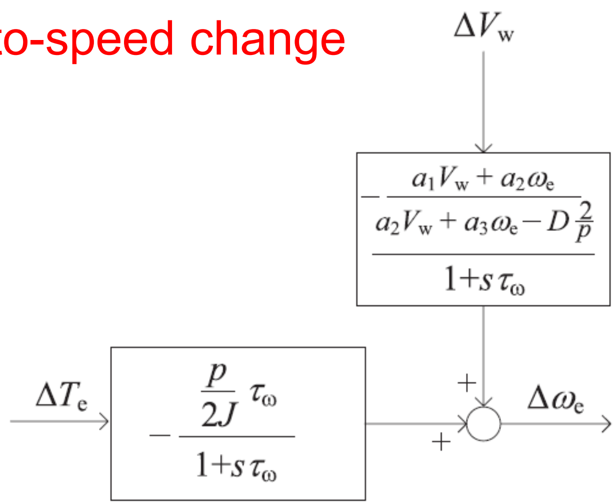


Fig. 2. Block diagram of WECS with functional stages framed by dashed lines.

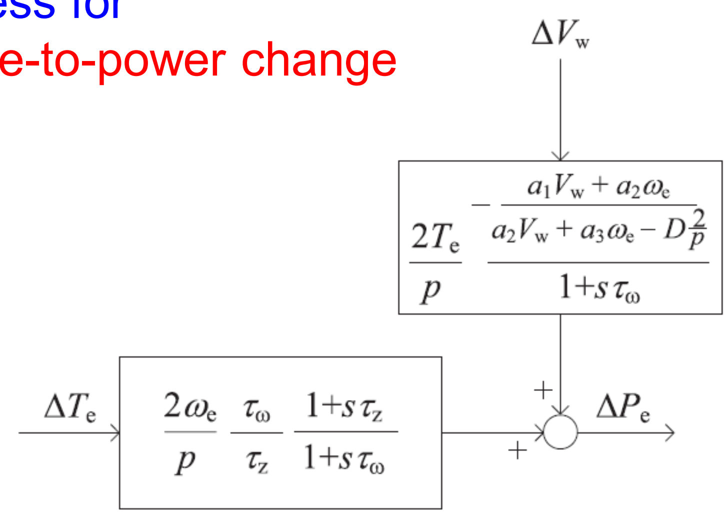
Assignment 3: Task 1
Linearized Turbine-Rotor Interaction Process for Analysis of Torque-to-Speed Change and Torque-to-Power Change

For the following analysis of the turbine-rotor interaction process, please implement both block diagrams shown below in Simulink.
Neglect mechanical friction.

Turbine-rotor interaction process for
torque-to-speed change



Turbine-rotor interaction process for
torque-to-power change



Assignment 3: Task 1
Linearized Turbine-Rotor Interaction Process for Analysis of Torque-to-Speed Change and Torque-to-Power Change

For the simulation, the following parameters need to be determined:

- Determine the overall inertia J of generator and turbine in your .m-file.:

$$H = J\frac{1}{2}\frac{\omega_{0\mathrm{m}}^2}{S_{\mathrm{base}}}$$

Assumption: $S_{base} = P_{e,base}$.

- Calculate the optimal operating point ($P_{\mathrm{tur,opt}}$, $\omega_{\mathrm{e,opt}}$, $T_{\mathrm{e,opt}}$) of the wind turbine at a wind speed of 10 m/s in your .m-file for the assumption that $P_{\mathrm{e,ref}} = P_{\mathrm{tur,opt}}$.
- Calculate the corresponding time constants τ_{ω} and τ_{z} for this operating point ($c_0 = 2.25 \cdot 10^{-2}$, $c_1 = 2.18 \cdot 10^{-2}$, $c_2 = -0.23 \cdot 10^{-2}$)

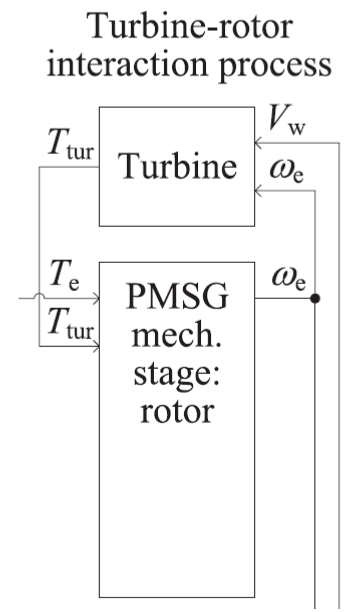
Assignment 3: Task 1
Linearized Turbine-Rotor Interaction Process for Analysis of Torque-to-Speed Change and Torque-to-Power Change

a) Simulate a torque change of ΔT_e = 1*10^5 Nm and plot the resulting speed change and power change, respectively. ΔV_w = 0 m/s.
Explain the reaction of speed and power on a torque change.

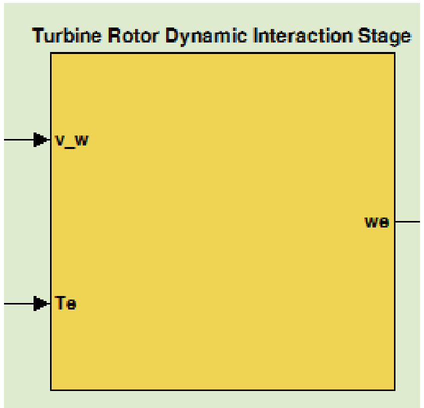
b) Simulate again with ΔT_e = 1*10^5 Nm and ΔV_w = 0.1 m/s.
Plot the results for both cases. Explain the results.

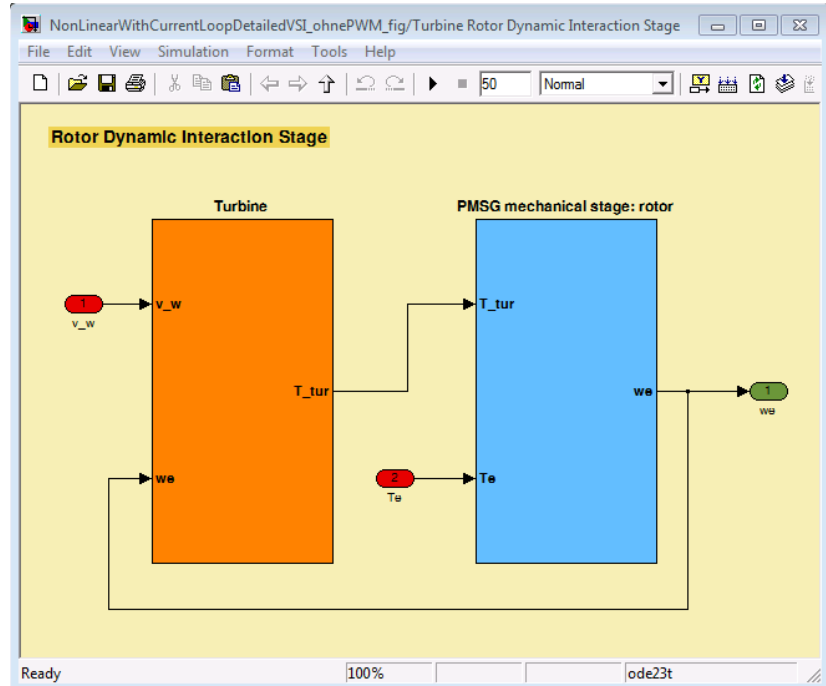
Assignment 3: Task 2
Implementation of the Non-Linear Model of the Turbine-Rotor Interaction Process in Simulink

- Implement both blocks of the turbine-rotor interaction process in Simulink.
- Run a simulation of this Simulink model.
  Assume V_w = 10 m/s. Set T_e accordingly. See task 1.
  Define the initial value of the integrator in your Simulink model as $\omega_{e,opt}$.
- Plot T_{tur}. Compare T_{tur} to T_e and explain the result.



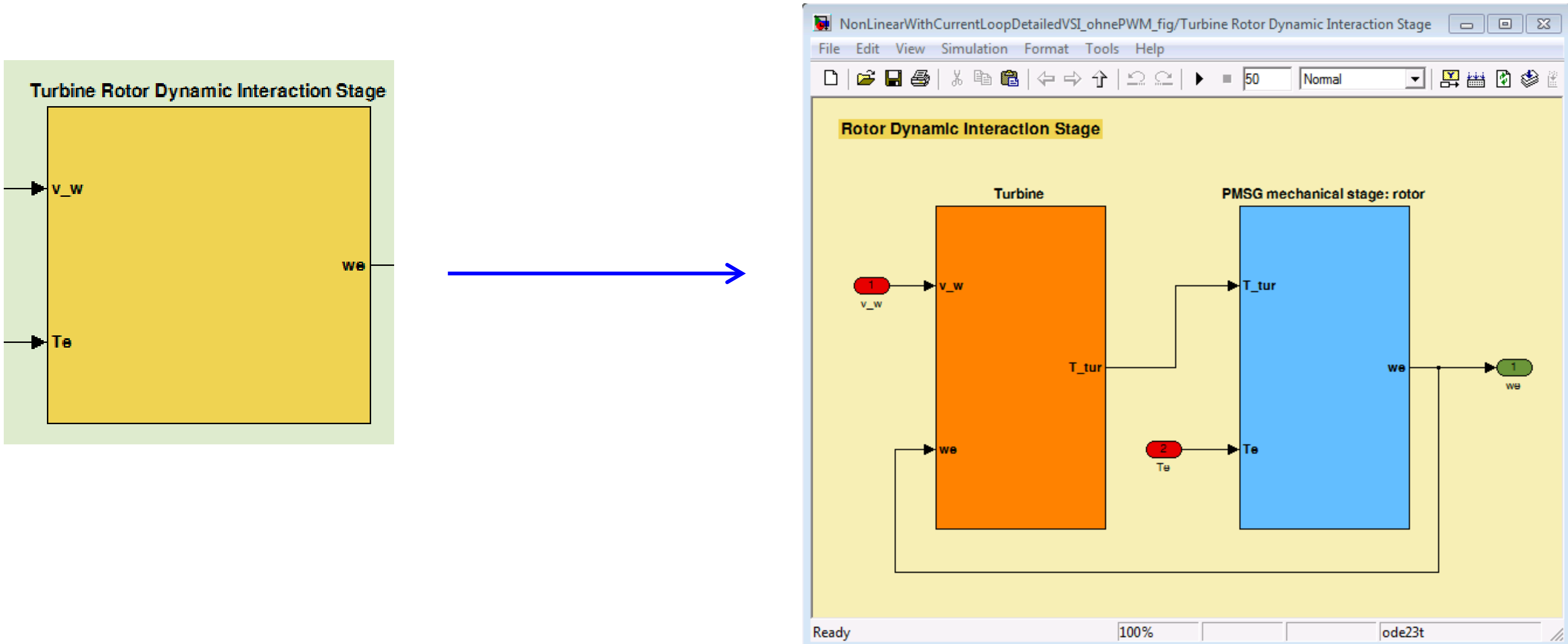
Assignment 3: Turbine Rotor Dynamic Interaction Stage





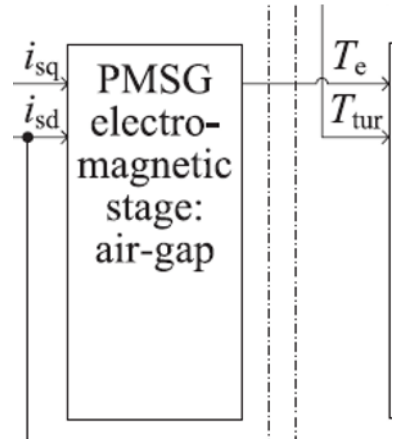
- **Turbine:** $T_{\mathrm{tur}} = \frac{1}{2}\pi\rho R^3 V_{\mathrm{W}}^2 C_{\mathrm{T}}(\lambda)$
- Use a lookup table determining $C_{\mathrm{T}}(\lambda)$.
- λ is calculated by $\lambda = \frac{\omega_{\mathrm{m}} R}{V_{\mathrm{W}}}$ with input V_{w} and input ω_{e} coming from PMSG as a measured value. Thus, λ changes and is not necessarily $\lambda_{\mathrm{opt}} = 7$ when the wind speed changes. The power controller controls the power to optimum dependent on V_{w} and ω_{e} at this moment.

Assignment 3: Turbine Rotor Dynamic Interaction Stage



- **PMSG mechanical stage rotor:** $J\frac{2}{p}\frac{\mathrm{d}\omega_\mathrm{e}}{\mathrm{d}t} = T_\mathrm{tur} - T_\mathrm{e} - \cancel{T_\mathrm{d}}$
- Reorganize this equation with respect to ω_e
- The initial condition of the integrator is to be set to ω_e at the given wind speed!!

Assignment 3: Task 3
Implementation of the Non-Linear Model of the Torque Generation in Simulink



- Implement the torque generation as a subsystem in Simulink, similar to the block shown on the right.
- Run a simulation for the optimal current values i_{sq} and i_{sd} at a wind speed of V_w = 10 m/s. Chose a suitable simulation time in order to show that your torque generation works.
- Plot i_{sq}, i_{sd} and T_e.
- Connect this subsystem to your simulink model of the turbine-rotor interaction process, see task 2. Run a simulation and plot ω_e.

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Assignment 4: Nonlinear Wind Turbine Model

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Wind Turbine and PMSG Parameters

	Symbol	Quantity	Value
Turbine	P_{tur}	Rated Power	3 MW
	V_{w}	Rated wind speed	12 m/s
	n	Rated mechanical angular velocity	18 rpm
	$C_{\mathrm{p,opt}}$	Maximum power coefficient	0.446
	r	Rotor radius	45 m
	λ_{opt}	Optimal tip speed ratio	7
	H	Inertia constant of turbine and PMSG	5 s
PMSG	p	Number of poles	160
	R_{s}	Stator resistance	50 mΩ
	L_{sd}	Stator d-axis inductance	4 mH
	L_{sq}	Stator q-axis inductance	6 mH
	Φ_{m}	Flux induced by magnets	16.2 Wb

Wind Energy Conversion System

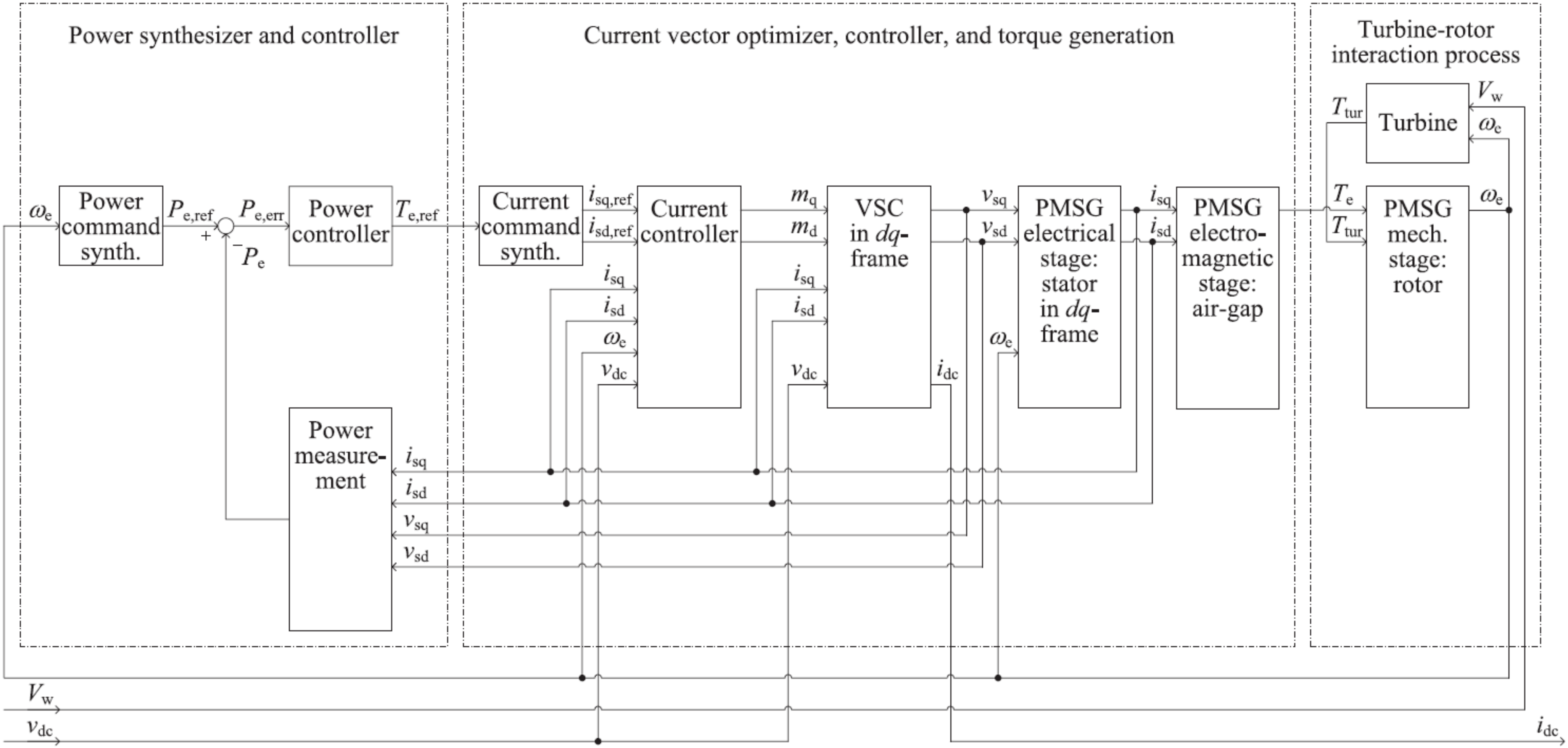


Fig. 1: Block diagram of WECS with functional stages framed by dashed lines.

Assignment 4: Implementation of the Full Model

- **Create the nonlinear model of Fig. 1 in MATLAB/Simulink** neglecting the damping. As illustrated in this block diagram, divide the system into three subsystems „Power synthesizer and controller“, „Current vector optimizer, controller and torque generation“, „Turbine-rotor interaction process“. Each of the three subsystems contain blocks which are again subsystems.
- **Wind speed V_w and DC-voltage V_{dc} are given as:**
  - **V_w = 10 m/s**
  - **V_{dc} = 6 kV**
- Subsystems „Current vector optimizer, controller and torque generation“ and „Turbine-rotor interaction process“ were done in Assignments 1 – 3.
- Subsystem „Power synthesizer and controller“ still needs to be implemented.

Assignment 4: Task 1 Design of the power controller

- Design the power controller for the operating point at a wind speed of V_w = 10 m/s. The closed-loop time constant τ_{pl} is 5 % of the mechanical lag time constant. Give the values of the controller parameters.

- The controller design is verified by simulation of a linear model of the power control loop. Apply a change of the reference power of -50 kW to the linear model.

- Plot the resulting power change. Based on the simulation results, show that your controller is well designed: Are the closed-loop time constant and the steady state power change reached as expected?

- Furthermore, include the Simulink model in your report.

Assignment 4: Task 2 Power command synthesizer and power measurement

- Implement the power command synthesizer. Include the Simulink model in your report.
- Implement the power measurement block. Neglect P_L. Give the Simulink model in your report.

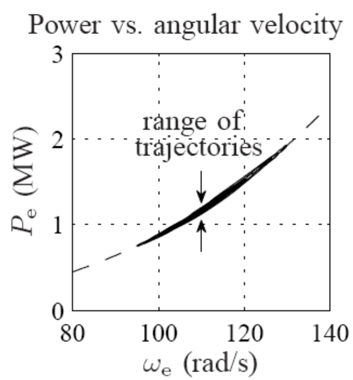
Assignment 4: Task 3 – Simulation Case 1

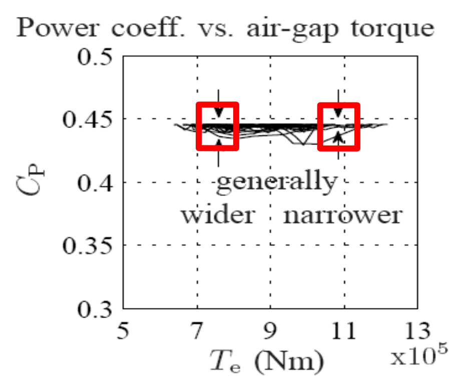
1. **Run the simulation for a constant wind speed of V_w = 10 m/s for a simulation time of 100 s**. Plot T_e, ω_e, and P_e.
   Store the final values in a vector because they are used as initial values for the second simulation with varying wind speed.
   (**Descriptions are on slide 13**)

- Remember: The initial condition of the integrator in the subsystem „PMSG mechanical stage: rotor“ is to be set to ω_e at 10 m/s!!
- Settings: Use a simulation time step size of maximum 0.1 ms. Use variable steps and the method „ode23t“.

Assignment 4: Task 3 –Simulation Case 2

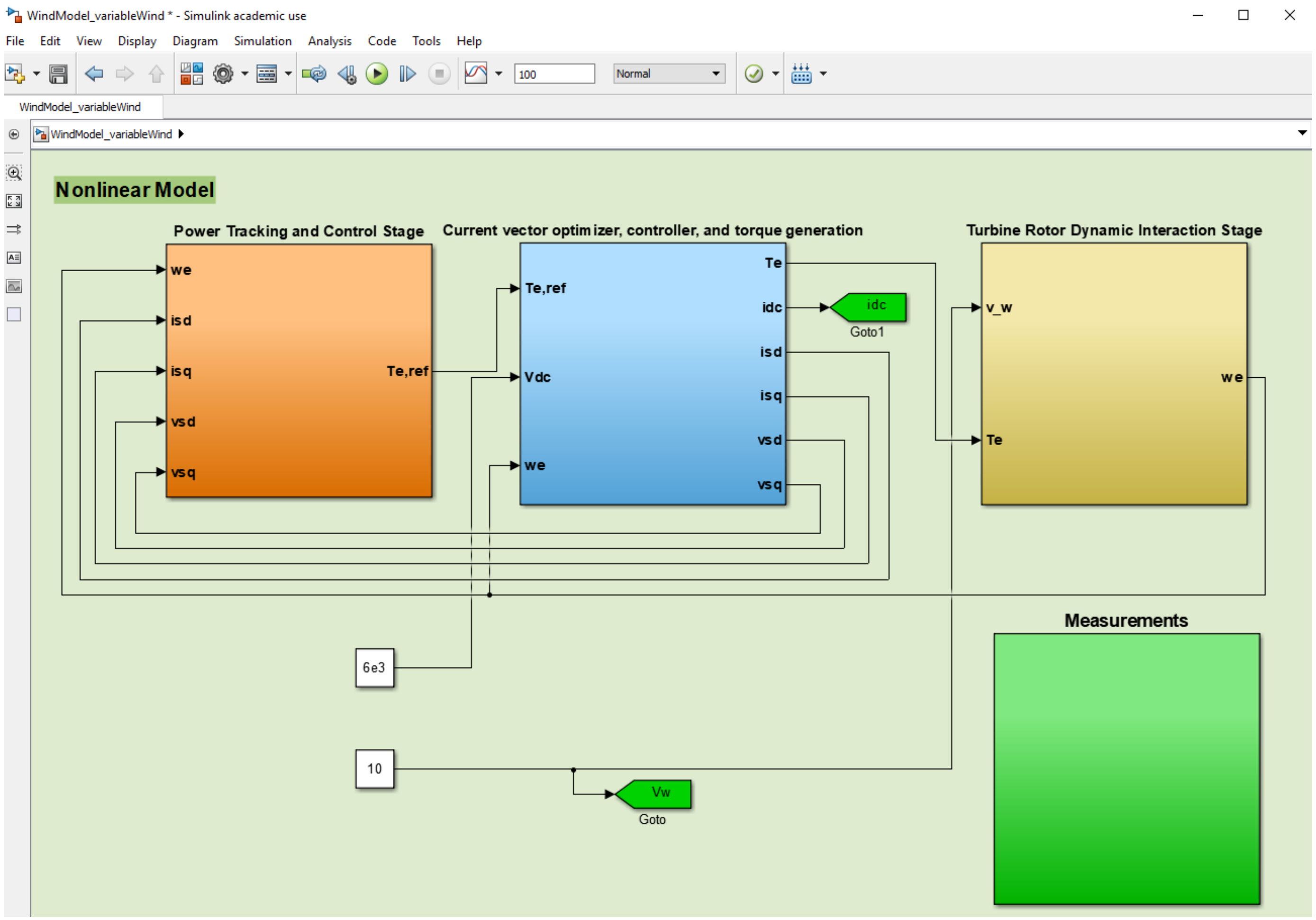
- Create a wind speed profile for 300 s with fluctuations around V_w = 10 m/s. **Show the plot in your report.** See explanations on slides 17-19.
- **Carry out a simulation for 300 s** using the created wind profile.
  - **Plot** air-gap torque $\boldsymbol{T_e}$ and stator currents $\boldsymbol{i_{sd}}$ **and** $\boldsymbol{i_{sq}}$.
  - **Plot $\boldsymbol{P_e}$ versus $\boldsymbol{\omega_e}$ and $\boldsymbol{C_p}$ versus $\boldsymbol{T_e}$,** as shown below for another example.
  - From your simulation results: Give the value of $\boldsymbol{P_e}$ **for the lowest wind speed and the highest wind** speed of your wind speed profile. For both wind speeds, compare the simulation result of P_e with the expected P_e from theory.





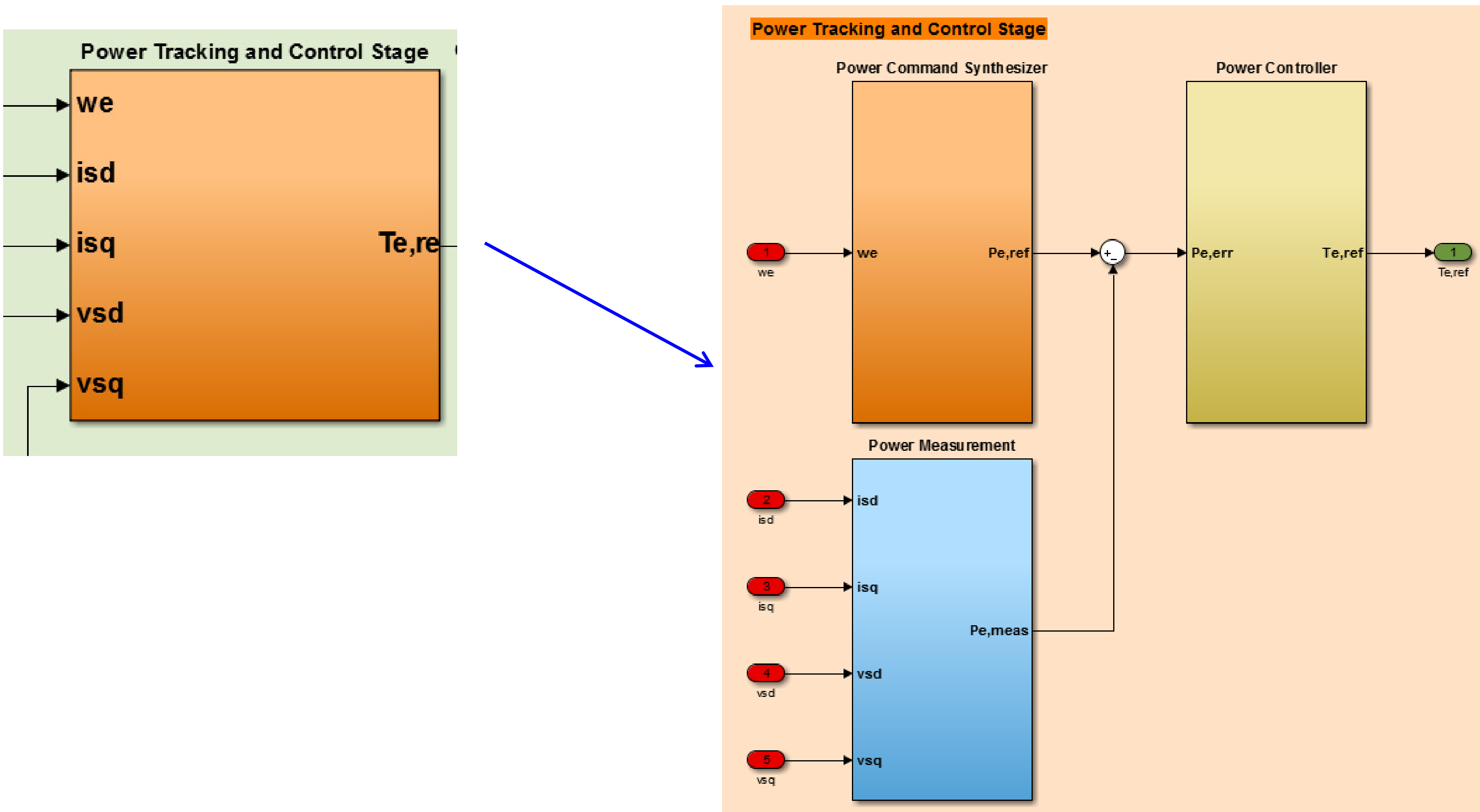
Task 1 – Nonlinear Model in Simulink

Three functional stages are implemented as three connected subsystems.

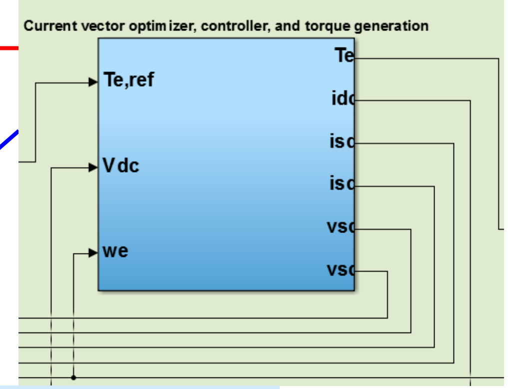


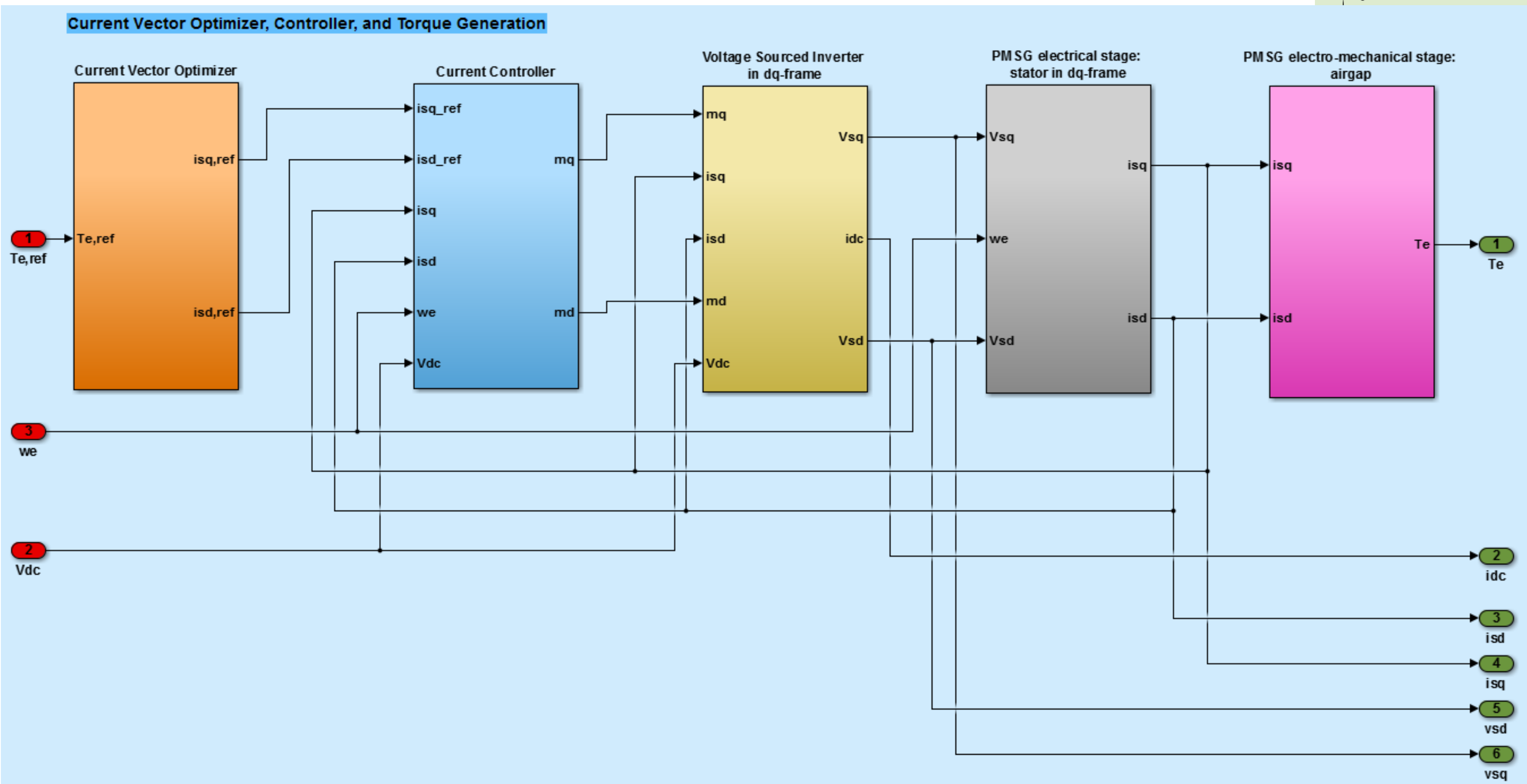
The simulation results of all parameters are included in a subsystem „Measurements". The signals are sent by „Goto" blocks and integrated in „Measurements" using „From" blocks. The „From" blocks are connected to scopes or „To File" blocks to plot the results.

Assignment 4: Power Tracking and Control Stage

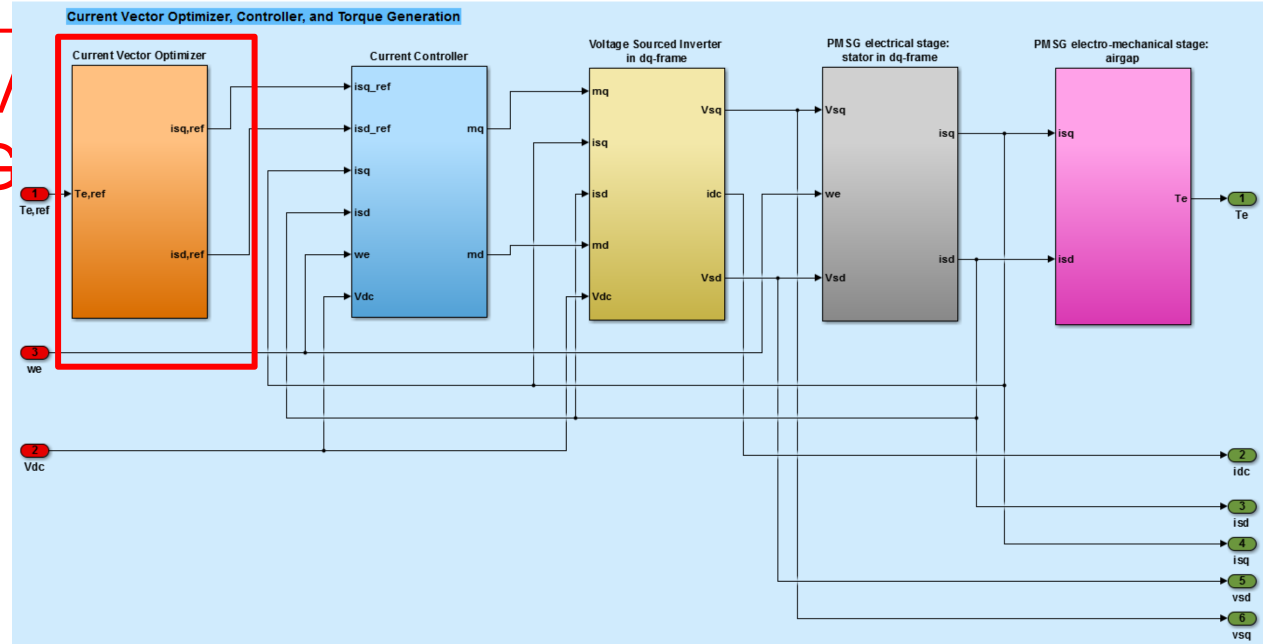


Assignment 4: Current Vector Optimizer, Controller, and Torque Generation





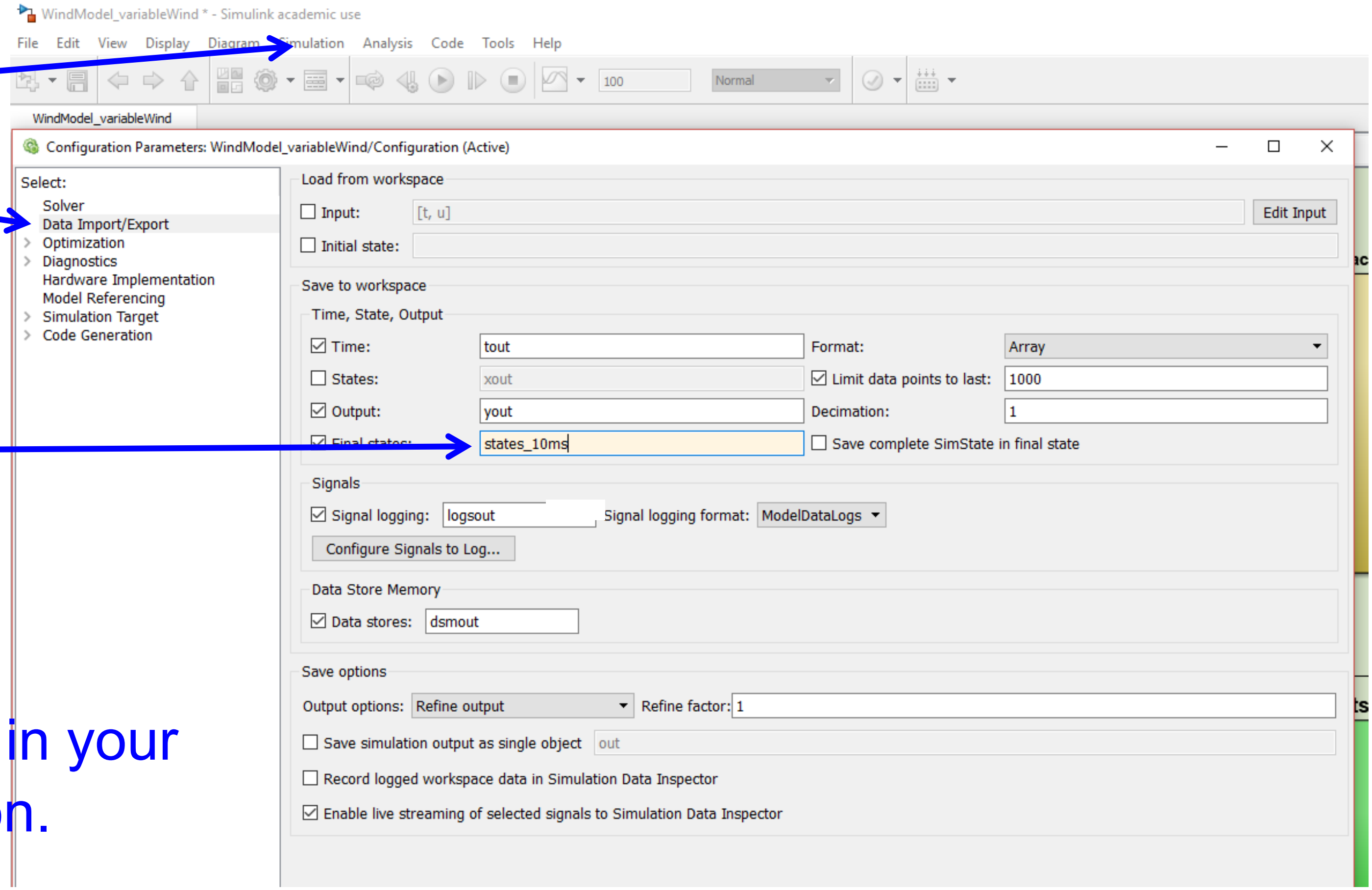
Assignment 4: Current V
Controller, and Torque G



- Implement a look-up table for $i_{sq,ref}$ (Use the block „look-up table") based on the results of assignment 1, task 2.
- Implement the equation to calculate $i_{sd,ref}$ from $i_{sq,ref}$ and Te_{ref}.

Assignment 4: Simulation Case 1 – Settings (Saving final values)

1. Simulation
2. Configuration…
3. Data Import/Export



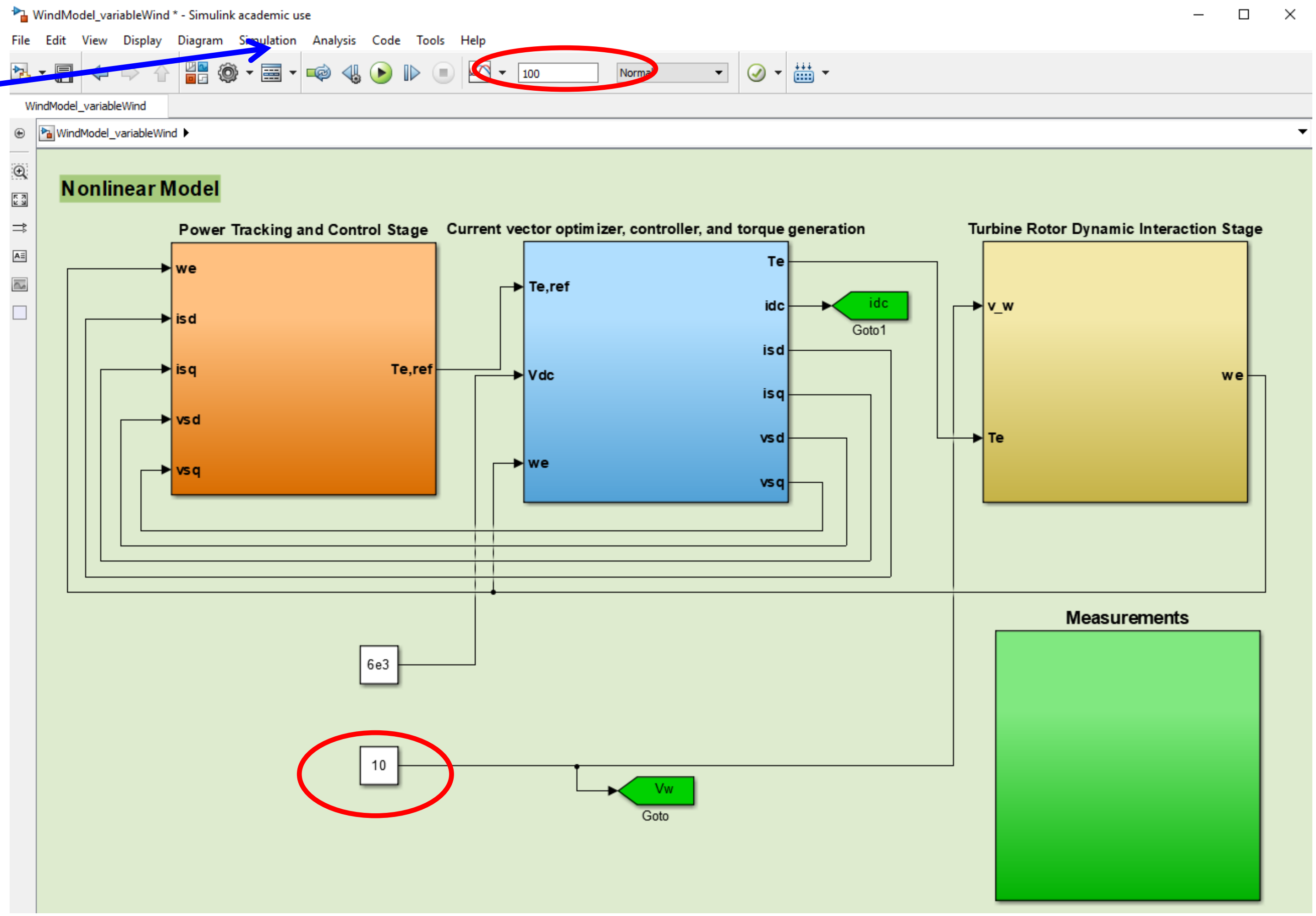
4. Choose a name for the vector with final states and enter here

5. This vector will appear in your workspace after simulation.

6. Save as a file: right mouse click and save as *states_10ms.mat*

Assignment 4: Simulation Case 1 – Settings

1. Simulation
2. Configuration…
3. Solver



Use a simulation time step size of maximum 0.1 ms.
Use variable steps and the method „ode23t“.

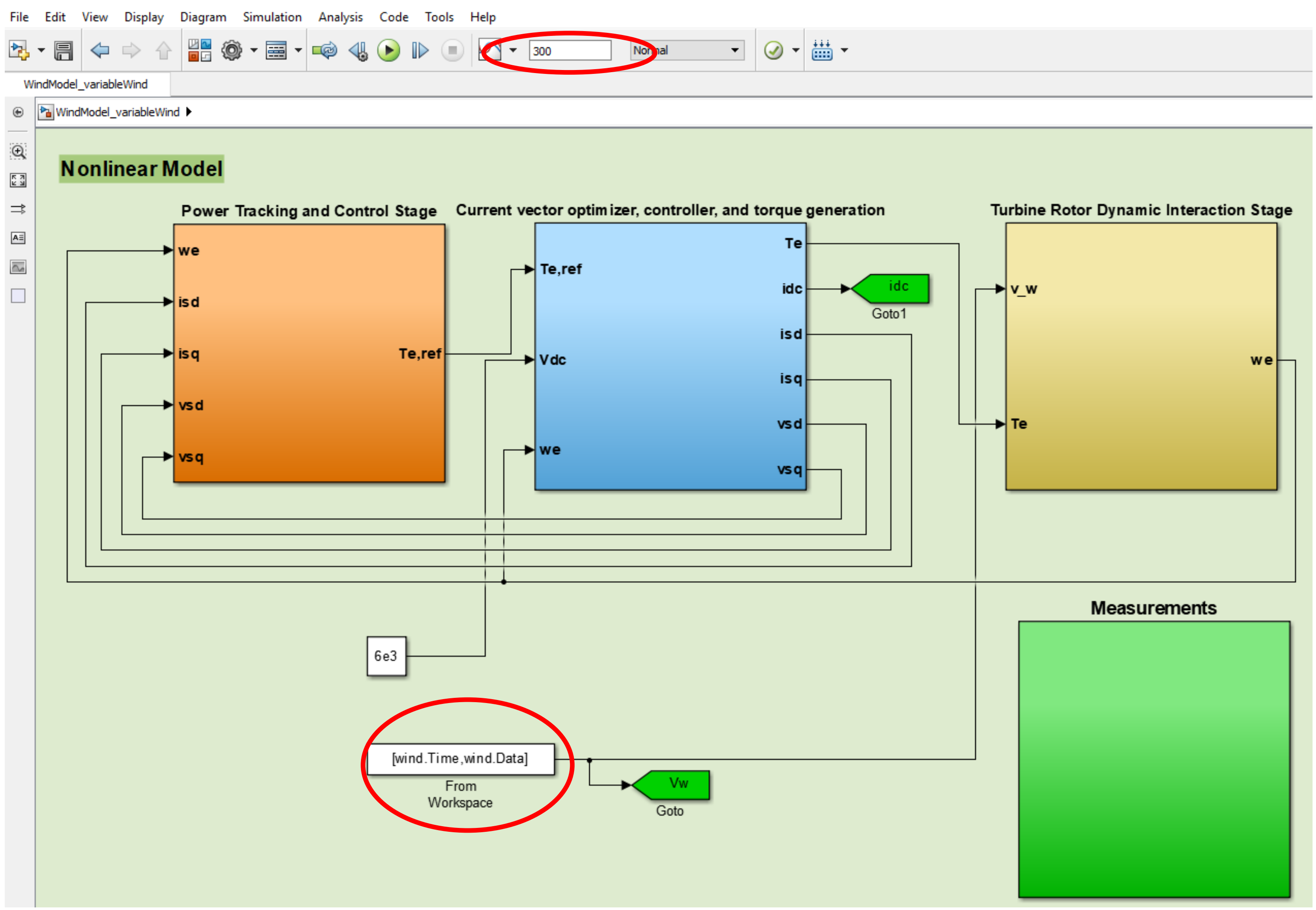
Assignment 4: Simulation Case 2 – Settings

Change the simulation time to 300 s.

Varying wind speed:

- load *wind.mat*
- Then, variable *wind* appears in the workspace
- Use block „From Workspace“ to include the wind speed in Simulink

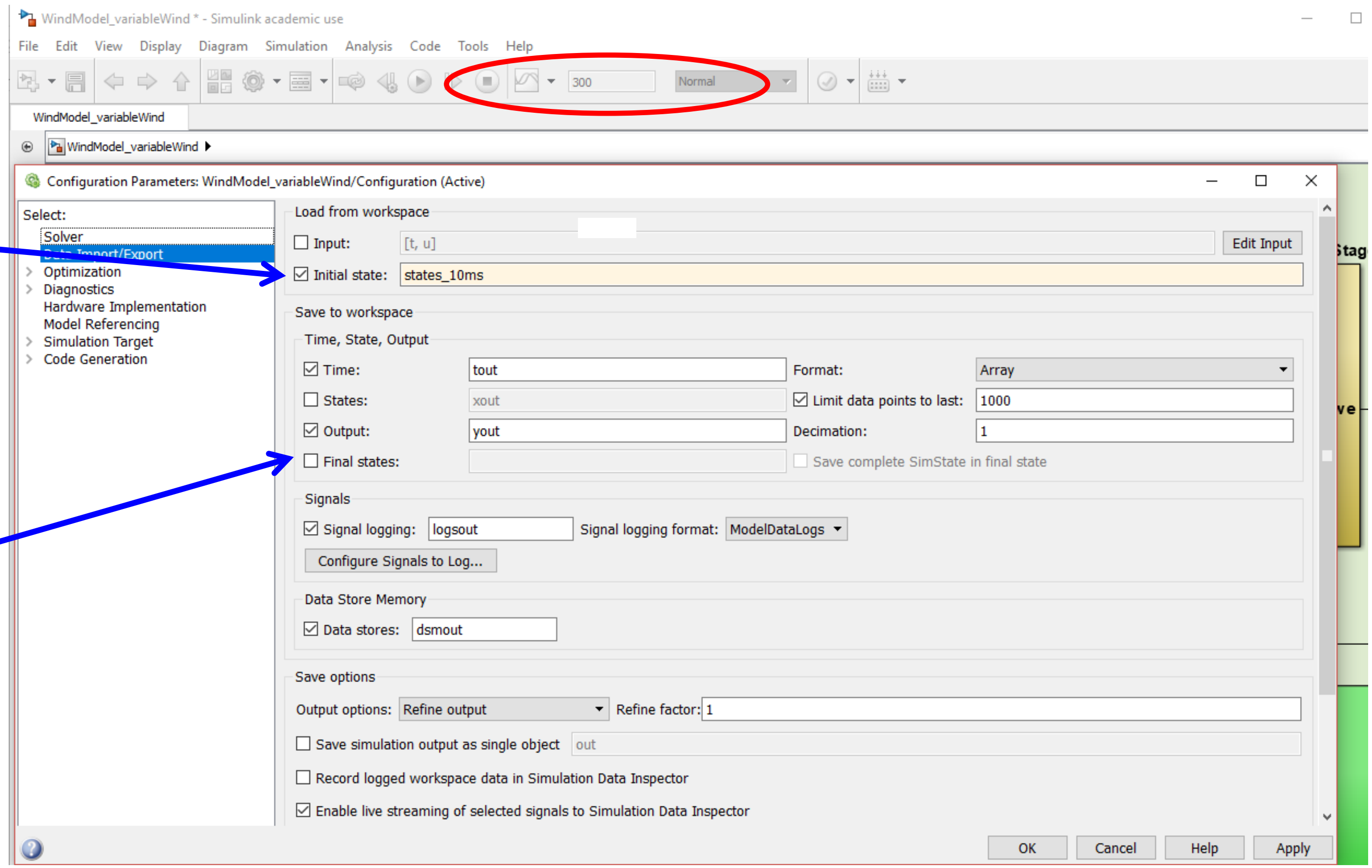
The model and other settings are as in simulation case 1.



Assignment 4: Simulation Case 2 – Settings

Enter the final states vector name of simulation case 1
(load *states_10ms.mat* if it is not in your workspace anymore from simulation case 1)

No final states



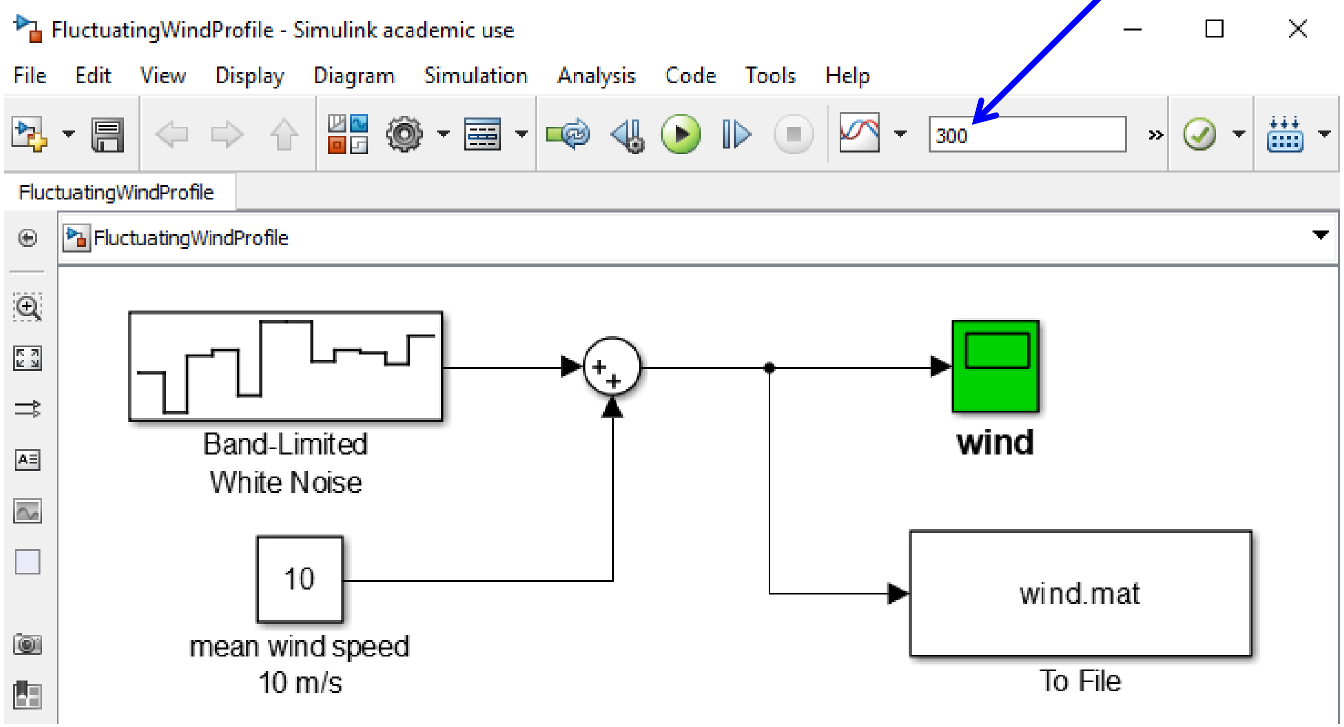
Assignment 4: Simulation 2 – Generating the Wind Profile

- Implement the blocks as shown on slides 18 and 19.
- Using „To File“ block, the varying wind speed is saved as „wind.mat“.
- Write in your MATLAB file (where all parameters are calculated):
  load *wind.mat*
- If you then run your MATLAB file, you will find the variable „wind“ in your workspace.
- **Plot the wind speed profile.**

Assignment 4: Simulation Case 2 – Generating the Wind Profile

Open a new Simulink file. This is used only once for generating the wind speed.

Simulation time MUST be 300s.



The setting of the blocks is shown on next slide.

Assignment 4: Simulation Case 2 – Generating the Wind Profile