[EEN452] Control and Operation of Electric Power Systems

Dynamic simulation of a five-bus system

Dr Petros Aristidou

Sustainable Power Systems Lab
Department of Electrical Engineering,
Computer Engineering & Informatics
https://sps.cut.ac.cy

Last updated: April 3, 2025

Contents

1 Introduction

This exercise is complementary to the teaching material of the course EEN452 Control and Operation of Electric Power Systems. It will help you better understand:

- The behavior of the synchronous generator during system dynamics and faults.
- The purpose of governors, their models, and the impact to the system frequency.
- The purpose of AVRs, their models, and the impact to the system voltage.
- The purpose of PSS, their models, and the impact to the system oscillatory behavior.
- How to perform dynamic simulations to analyze the security of power systems.

This exercise has been heavily based on teaching material provided by Prof. Thieery Van Cutsem[1].

1.1 Grading and deliverables

1. This assignment counts for 10% of the final grade.
2. You must use PyRAMSES [2] and the online platform of the lab[3]. You can use the example exercise[4] as the starting point.
3. The deliverables are to be submitted are:
   (a) A report addressing all the questions detailed in the assignment (**in PDF format**).
   (b) The JupyterNotebook (ipynb file) with the student implementation with all the files needed to execute the UC problem.
   * You can instead submit everything in a **single** ipynb file, making use of the Markdown cells to answer the questions instead of submitting a separate PDF.
4. Delayed submissions will be penalized by 2% reduction for every delayed day.
5. Any signs of plagiarism will be penalized with 0%.
6. If the ipynb code does not execute on the lab server, then the report will not be accepted and will be marked with 0%.

[1] `https://thierryvancutsem.github.io/`
[2] `https://pyramses.sps-lab.org/`
[3] `https://sps.cut.ac.cy/jhub`
[4] `https://sps.cut.ac.cy/jhub-5-bus`

2 System model

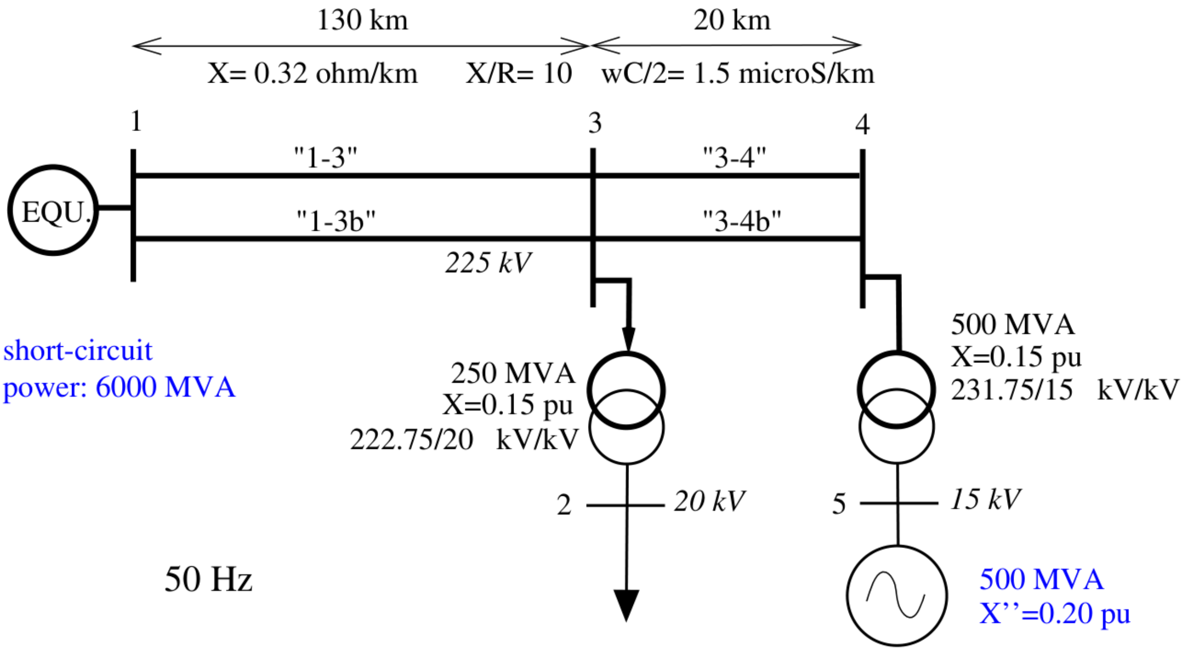

Figure 1: Five-bus system oneline diagram

2.1 Generator at bus 5: synchronous machine data

The synchronous machine is modeled as detailed in class[5].

$$R_a = 0. \quad X_\ell = 0.15pu \quad m = 0.10 \quad n = 6.0257$$
$$X_d = 2.20 \quad X'_d = 0.30 \quad X''_d = 0.20pu$$
$$X_q = 2.00 \quad X'_q = 0.40 \quad X''_q = 0.20pu$$
$$T'_{do} = 7.00 \quad T''_{do} = 0.05 \quad T'_{q\circ} = 1.50 \quad T''_{q\circ} = 0.05 \text{ s}$$
$$H = 4 \text{ s}$$

(values in pu on the generator 500 MVA base)

[5] `https://sps.cut.ac.cy/courses/een452/sync_mac_model.pdf`

2.2 Generator at bus 5: speed governor and steam turbine

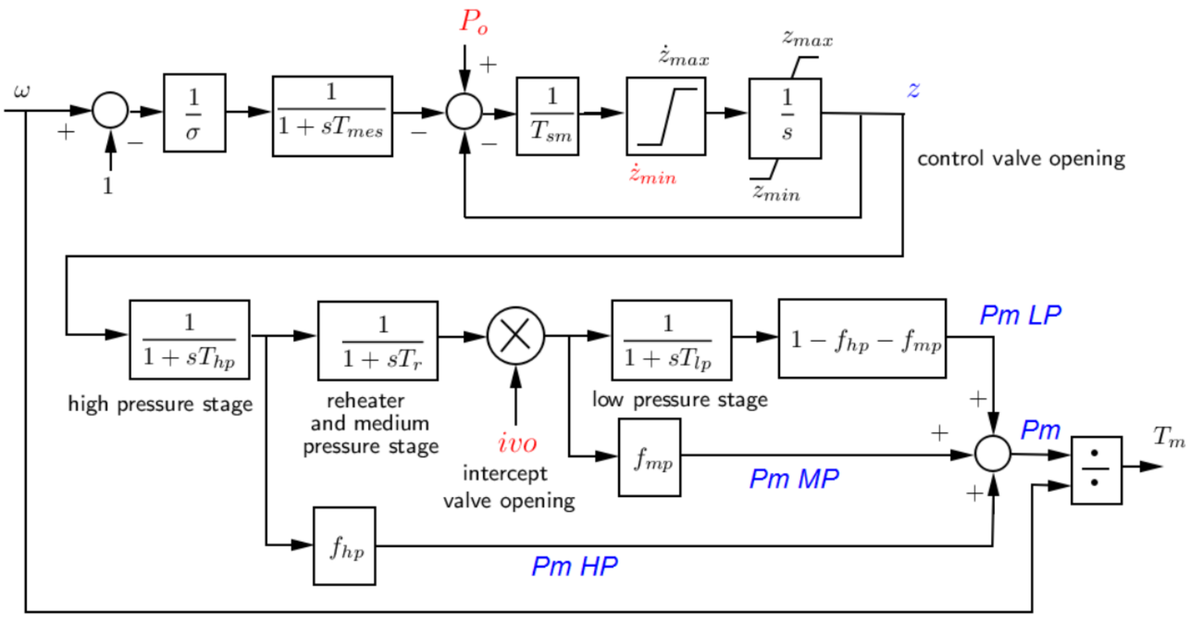

Figure 2: Speed governor

$$P_{nom} = 460\ MW \quad \sigma = 0.04 \quad T_{mes} = 0.1 \text{ s} \quad T_{sm} = 0.4 \text{ s}$$
$$\dot{z}_{\min} = -0.05\text{pu/s} \quad \dot{z}_{\max} = 0.05\text{pu/s} \quad z_{\min} = 0. \quad z_{\max} = 1.\text{pu}$$
$$T_{hp} = 0.3 \text{ s} \quad f_{hp} = 0.4 \quad T_r = 5.0 \text{ s} \quad f_{mp} = 0.3 \quad T_{lp} = 0.3 \text{ s} \quad \text{ivo} = 1$$

2.3 Generator at bus 5: automatic voltage regulator, excitation system, overexcitation limiter

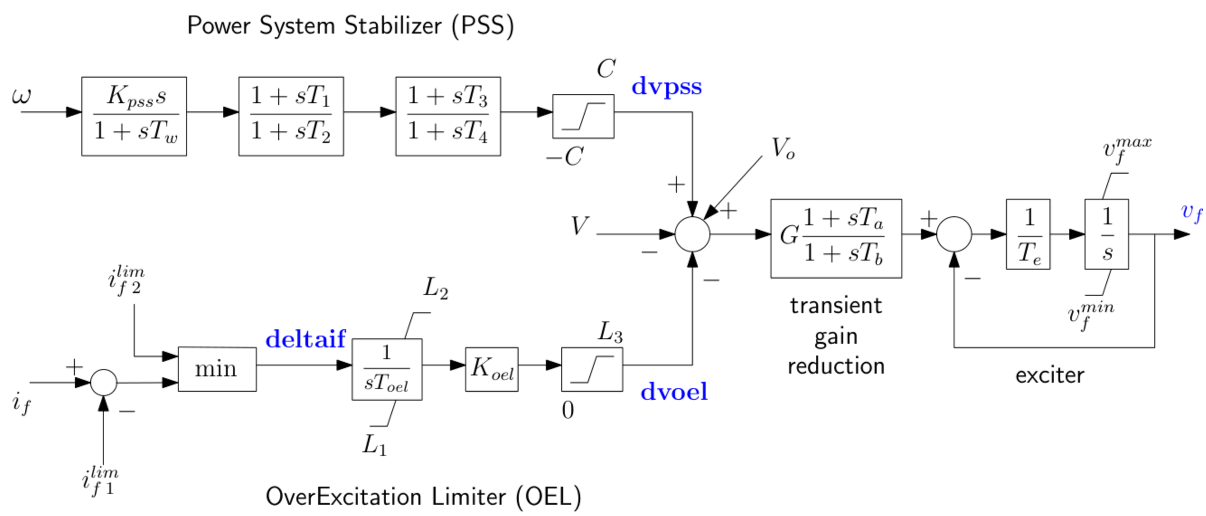

Figure 3: Automatic voltage regulator, excitation system, overexcitation limiter

$$G = 70. \quad T_a = T_b = 1 \text{ s} \quad T_e = 0.4 \text{ s} \quad v_f^{\min} = 0. \quad v_f^{\max} = 5\text{pu}$$
$$K_{pss} = 50 \quad T_w = 5 \text{ s} \quad T_1 = T_3 = 0.323 \text{ s} \quad T_2 = T_4 = 0.0138 \text{ s} \quad C = 0.06\text{pu}$$
$$i_{f1}^{\lim} = 2.90\text{pu} \quad i_{f2}^{\lim} = 1.00\text{pu} \quad T_{oel} = 8 \text{ s} \quad K_{oel} = 2.0$$
$$L_1 = -1.1 \quad L_2 = 0.1 \quad L_3 = 0.2\text{pu}$$

2.4 Load tap changer controlling voltage at bus 2

- transformer ratio: $[0.88, 1.20]$
- number of tap positions: 33
- voltage dead-band: $[V^o - 0.01 V^o + 0.01]\, pu$
- delay before first tap change: 25 s
- delay between subsequent tap changes: 10 s

2.5 Load model at bus 2

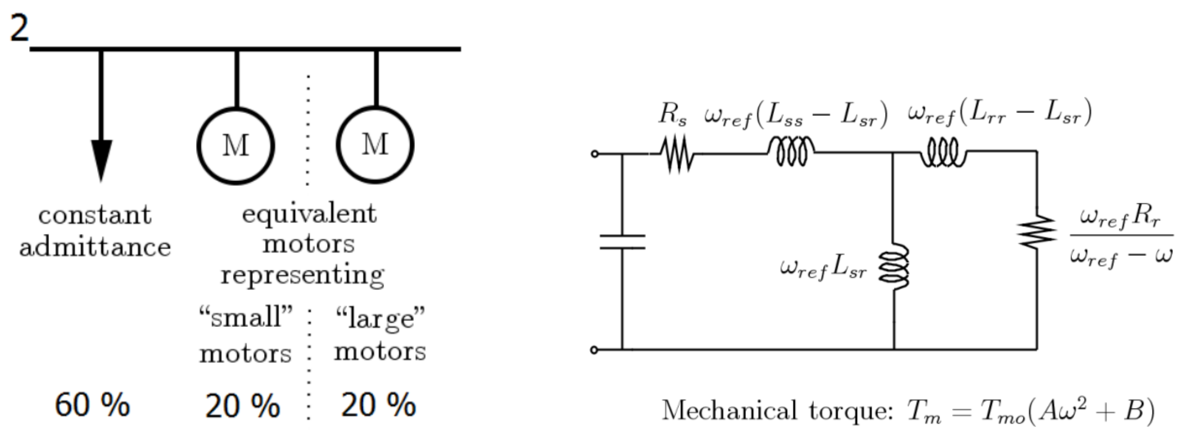

Figure 4: Load model

"small motors":

$$R_s = 0.031 \quad L_{ss} = 3.30 \quad L_{sr} = 3.20 \quad L_{rr} = 3.38 \quad R_r = 0.018\text{pu}$$
$$H = 0.7 \text{ s} \quad A = 0.5 \quad B = 0.5$$

"large motors":

$$R_s = 0.013 \quad L_{ss} = 3.867 \quad L_{sr} = 3.80 \quad L_{rr} = 3.97 \quad R_r = 0.009\text{pu}$$
$$H = 1.5 \text{ s} \quad A = 0.5 \quad B = 0.5$$

(values in pu on the motor MVA base)

3 Operating points

3.1 Operating point 1

The first operating point assumes the generator is covering the consumption of the load and exports power to the grid.

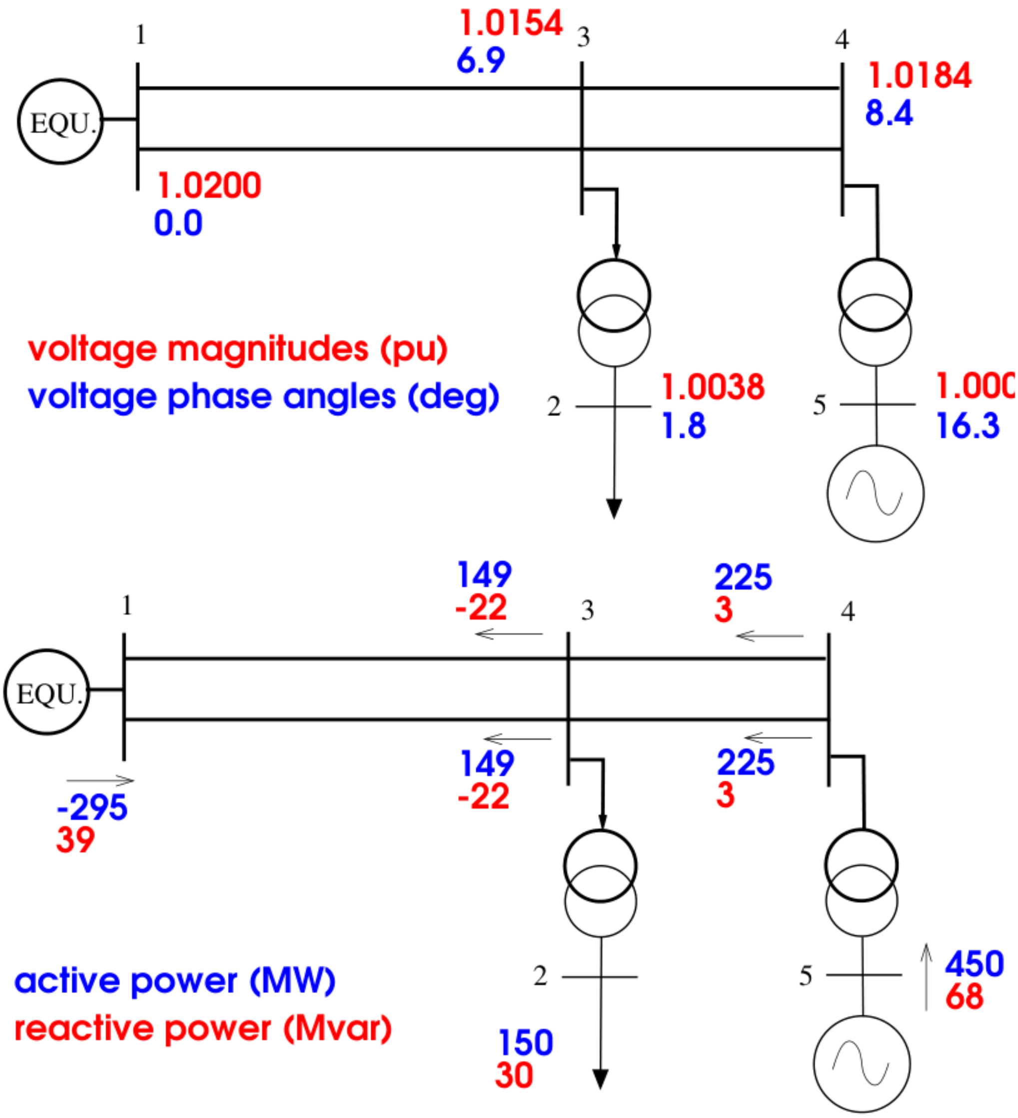

Figure 5: Operating point 1

3.2 Operating point 2

The second operating point assumes the sub-system is importing power from the grid.

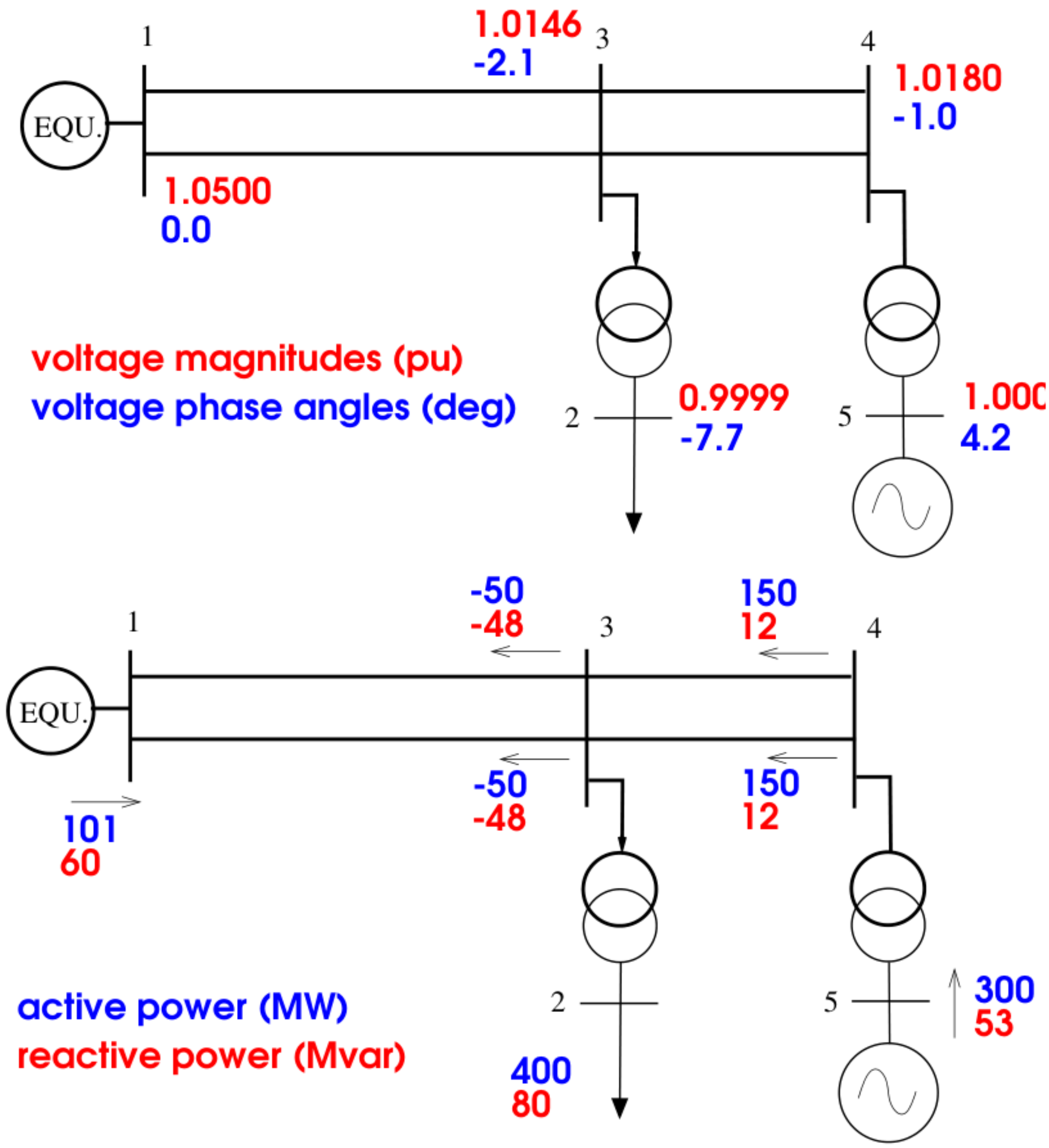

Figure 6: Operating point 2

4 Syntax of disturbances

To modify the disturbance and implement the different case studies listed below, the command *addDisturb* is used:

- To increase the power setpoint of generator G by D MW in T seconds:

  ```
  ram.addDisturb($time, 'CHGPRM TOR G P0 $D MW $T')
  ```

- To increase the voltage setpoint of generator G by D pu in T seconds:

  ```
  ram.addDisturb($time, 'CHGPRM EXC G Vo $D $T')
  ```

- To increase the value of the Thévenin voltage by D pu in T seconds:

  ```
  ram.addDisturb($time, 'CHGPRM INJ EQUIV1 ETH $D $T')
  ```

- To apply a fault at bus B with resistance R and reactance X (in Ω, can be zero):

  ```
  ram.addDisturb($time, 'FAULT BUS B $R $X')
  ```

- To clear a fault at bus B:
  `ram.addDisturb($time, 'CLEAR BUS B')`
- To trip line XYZ:
  `ram.addDisturb($time, 'BREAKER BRANCH XYZ 0')`

You need to change the variables with $ to the values required by the case studies.

5 Syntax of observables

To view the output after the simulation:

- Generator G active power: `ext.getSync('G').P.plot()`
- Generator G reactive power: `ext.getSync('G').Q.plot()`
- Generator G frequency (in pu): `ext.getSync('G').S.plot()`
- Generator G rotor angle: `ext.getSync('G').A.plot()`
- Generator G field current: `ext.getSync('G').FC.plot()`
- Generator G valve opening: `ext.getTor('G').z.plot()`
- Generator G mechanical power: `ext.getTor('G').Pm.plot()`
- Generator G excitation control: `ext.getExc('G').dvpss.plot()`
- Generator G field voltage: `ext.getExc('G').vf.plot()`
- Bus 3 voltage magnitude: `ext.getBus('3').mag.plot()`
- Bus 3 voltage magnitude: `ext.getBus('3').mag.plot()`
- Load Impedance_Load active power: `ext.getInj('Impedance_Load').P.plot()`
- Load Impedance_Load reactive power: `ext.getInj('Impedance_Load').Q.plot()`
- Motor Large_Motor active power: `ext.getInj('Large_Motor').P.plot()`
- Motor Large_Motor reactive power: `ext.getInj('Large_Motor').Qmot.plot()`
- Motor Large_Motor speed: `ext.getInj('Large_Motor').omega.plot()`
- Active power entering line 1-3: `ext.getBranch('1-3').PF.plot()`
- Rective power entering line 1-3: `ext.getBranch('1-3').QF.plot()`

You need to change the variables with $ to the values required by the case studies.

6 Experimental cases

6.1 Case 1

Implement the following case study:

- Operating point: # 2
- disturbance: at $t = 1$ s, increase of power set-point P_o by 115 MW in 10 s
- simulated time: 60 s

Comment as far as possible the evolution of:

1. the generator active power
2. the generator reactive power
3. the generator rotor angle
4. the generator field current
5. the control valve z of the turbine
6. the voltage magnitude at bus 3

6.2 Case 2

Implement the following case study:

- Operating point: # 1
- disturbance: at $t = 1$ s, increase of voltage set-point V_o by 0.05 pu in 2 s
- simulated time: 60 s

Comment as far as possible the evolution of:

1. the voltage magnitude at bus 3. In particular, explain the three "spikes" with the help of the proper curves
2. the generator active power
3. the generator reactive power
4. the generator field current.

6.3 Case 3

Implement the following case study:

- Operating point: #1
- disturbance: at $t = 1$ s, "voltage dip" in the external system simulated by a decrease of the Thévenin voltage by 0.20 pu during 0.04 s (can be considered as an impulse response)
- simulated time: 20 s

Comment as far as possible the evolution of:

1. Observe the evolution of the rotor speed of the generator

2. Observe the evolution of the PSS output (select: generator G - observable of excitation control - dvpss)
3. take the Power System Stabilizer (PSS) out of service, simulate the same disturbance and compare the evolution of the rotor speed with the previous one
4. observe the evolution of the voltage magnitude at bus 3 and comment on the similarity
5. what is the period of the dominant oscillation?

Put the PSS back in service before proceeding!

6.4 Case 4

Implement the following case study:

- Operating point: #1
- disturbance: at $t = 1$ s, a solid fault on line 1-3, cleared after 4 cycles (0.08 s) by opening the faulted circuit. The fault takes place very near bus 3, so that it can be applied at bus 3
- simulated time: 20 s

Comment as far as possible the evolution of:

1. the terminal voltage of the generator
2. the active and reactive powers of the generator
3. the rotor speed of the generator
4. the field voltage of the generator (select: generator G - observable of excitation control - vf)
5. the active power consumed by the impedance load at bus 2
6. the active power consumed by one of the motors at bus 2
7. the speed of one the motors at bus 2
8. From RAMSES outputs, determine the current in line 3-4 during the short-circuit. Consider the value just after fault occurrence, for security. Check this value with a simple circuit calculation involving the generator equivalent circuit.

6.5 Case 5

Implement the following case study:

- Operating point: #2
- disturbance: at $t = 1$ s, tripping of both circuits of line 1-3 (without fault)
- simulated time: 25 s

Comment as far as possible the evolution of:

1. rotor speed of G
2. active power produced by G

3. control valve opening (select: generator G - observable of torque controller - z)
4. turbine mechanical power (select: generator G - observable of torque controller - Pm ; in pu on the turbine nominal power).
5. Compute the final rotor speed using a formula from primary frequency control. Comment on the accuracy and try improving it.

6.6 Case 6

Implement the following case study:

- Operating point: #2
- disturbance: at $t = 1$ s, a solid fault on line 1-3, cleared after 10 cycles (0.20 s) by opening the faulted circuit. The fault takes place very near bus 3, so that it can be applied at bus 3
- simulated time: 20 s

Comment as far as possible the evolution of:

1. Observe that the voltage at bus 3 does not recover near 1 pu, but stays "locked" near 0.84pu. Find which system component is responsible for this, with the help of the proper curves
2. show that for some shorter fault duration (i.e. smaller than 0.20 s), the voltage does not stay "locked" at such a small value. Explain the underlying instability mechanism.

6.7 Case 7

Implement the following case study:

- Operating point: #1
- disturbance: at $t = 1$ s, severe disturbance in the external system simulated by a decrease of the Thévenin voltage by 0.2 pu in 1 s (the voltage remains at its low value)
- simulated time: 120 s

Comment as far as possible the evolution of:

1. Explain why the voltage at bus 3 drops so much after some time.