Project 3
Small Perturbation Angle Stability

Figure 1 shows the WSCC 9-bus test system employed for the proposed project. The impedances of the lines and the reactances of the generators are given in a common per-unit base. The loads are modelled as constant impedances and given in per unit. The frequency of the grid is 50 Hz. The grid is implemented in PowerWorld and MatLab; all the files can be found in the folder provided on WeBeep.

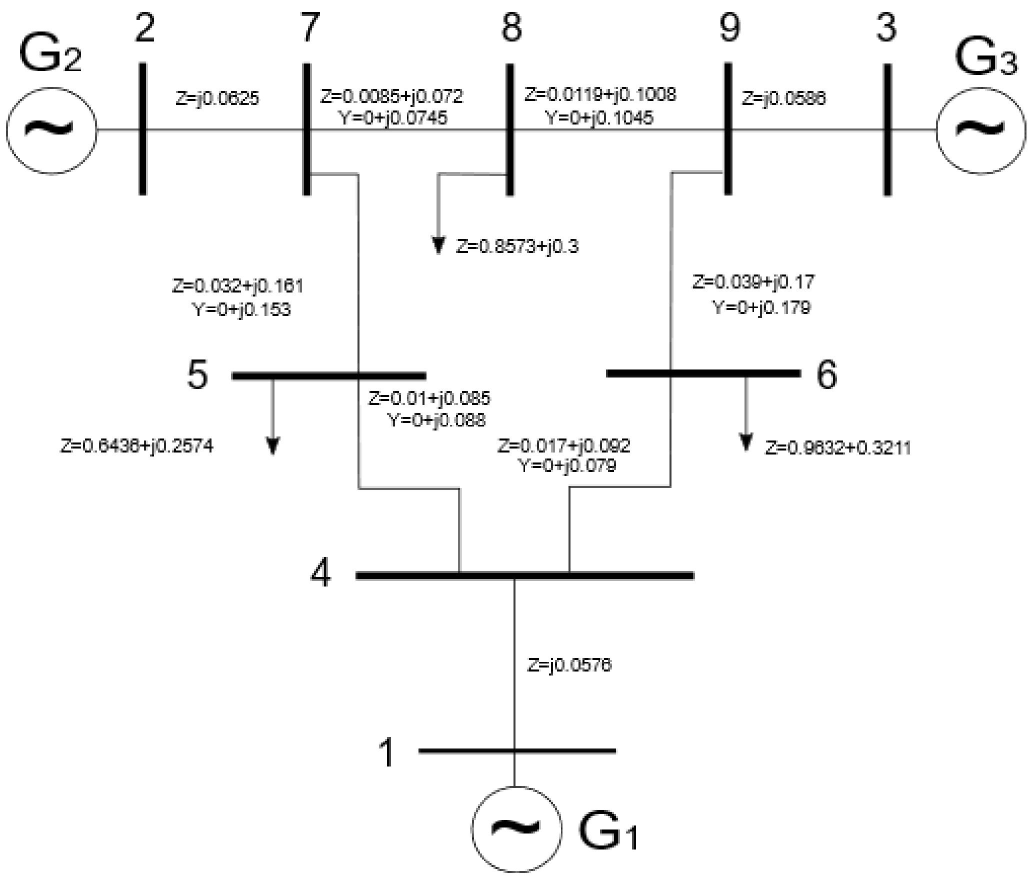

Figure 1. WSCC test system.

Consider the fourth-order model for the generators, where the electrical torque (T_{ele}) can be expressed as a function of fluxes (ψ) and currents (I) by:

$$\psi_q = \psi_q'' - I_q X_d''$$

$$\psi_d = \psi_d'' - I_d X_d''$$

$$T_{ele} = \psi_d I_q - \psi_q I_d$$

The swing equation, according to the PowerWorld notation, is (ω_0 in [rad/s]):

$$\dot{\delta} = \Delta\omega * \omega_0$$

$$\dot{\omega} = \frac{1}{2H}\left(\frac{P_{mec} - D * \Delta\omega}{1 + \Delta\omega} - T_{ele}\right)$$

The machine parameters are listed in Table 1:

Table 1. Machine data.

Parameter	G1	G2	G3
H [s]	23.64	6.4	3.01
Xd [p.u.]	0.146	0.8958	1.3125
X’d [p.u.]	0.0608	0.1198	0.1813
X’’d [p.u.]	0.0400	0.0900	0.1500
Xq [p.u.]	0.0969	0.8645	1.2578
X’q [p.u.]	0.0969	0.1969	0.25
Xl [p.u.]	0.0300	0.0600	0.1200
T’do [s]	8.960	6.000	5.890
T’’do [s]	0.030	0.030	0.030
T’qo [s]	0.310	0.535	0.600
T’’qo [s]	0.050	0.050	0.050

All the generators are equipped with the same exciter (IEEET1 – type 1) and Power System Stabilizer (PSS1A – The input signal is the rotor speed deviations in p.u.), whose parameters are shown in Table 2 and Table 3; the corresponding block diagrams are reported in Figure 2 and Figure 3:

Table 2. Exciter parameters.

KA	20
TA [s]	0.2
KE [p.u.]	1.0
TE [s]	0.314
KF [p.u.]	0.063
TF [s]	0.35
E1	2.8
E2	3.73
SE1	0.30338
SE2	1.28840

with: $S_{Ei}(E_{fdi}) = A * e^{B*E_{fdi}}$, where: $A = \frac{SE_1}{e^{B*E_1}} = 0.0039$ and $B = \frac{\ln\left(\frac{SE_1}{SE_2}\right)}{E_1 - E_2} = 1.555$.

Table 3. PSS parameters.

T1 [s]	0.5
T2 [s]	0.01
T3 [s]	0.5
T4 [s]	0.01
T5 [s]	10
Ks	0.1
T6 [s]	0.02
A_1=A_2	0

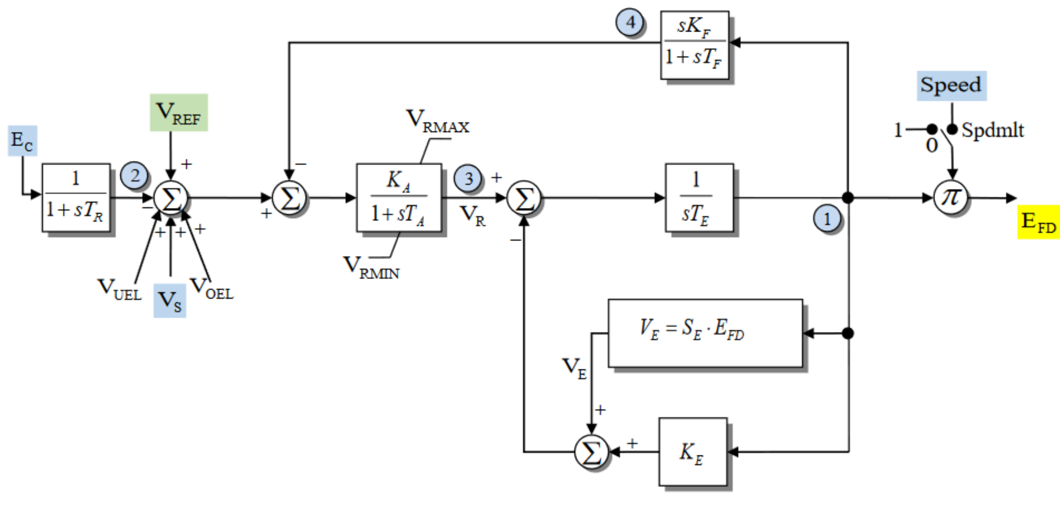

Figure 2. Exciter block diagram.

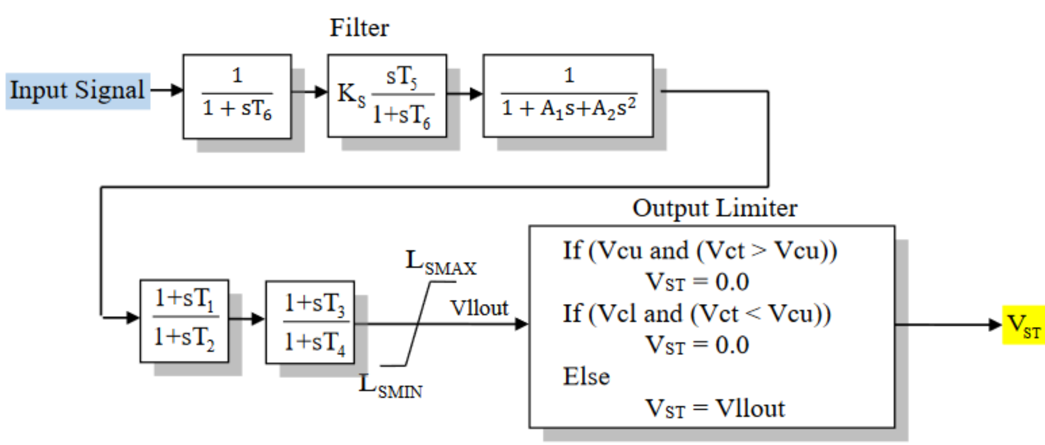

Figure 3. PSS block diagram.

Using the Matlab script for the modal analysis and PowerWorld for the transient analysis, answer the following points:

- With all the exciters and all the PSS switched off:
    a. Plot the eigenvalues in the complex space.
    How many electromechanical modes have you obtained? Provide the damping ratio and the frequency of the electromechanical modes identified.
    Which generator oscillates against which? Can you classify the modes? Analyze the results by plotting the mode shapes.
    Can you classify the remaining non-electromechanical, oscillatory modes?
    b. After a transient (line opening), the speeds of the generators are altered. Plot the time domain behavior in PowerWorld: is it coherent with your modal analysis?
- Switch on all the exciters and redo the analysis of point 1:
    a. Do you get any improvement in the damping ratios of the electromechanical modes? Comment the results.
- Switch on also all the PSS and redo the analysis of point 1:
    a. Do you get an improvement in the damping ratios of the electromechanical modes?
    b. Change the gain of the PSS (K_S) and try to improve the damping of the electromechanical mode. Comment the results.

The **deadlines** are the follows:

- Exam in **January/February 2026**: the report of the project must be uploaded in **PDF** before **December, 29th 2025** at 23:59 on WeBeep.
- Exam in **June/July 2026**: the report of the project must be delivered in **PDF** before **May 31st, 2026** sending an email to andrea.pomarico@polimi.it
- Exam in **September 2026**: the report of the project must be delivered in **PDF** before **July 26th, 2026** sending an email to andrea.pomarico@polimi.it

The report must not exceed 20 pages

Tips:

- To switch on the exciter and the PSS in PowerWorld, double click on the generator on the oneline diagram, go to the stability page → exciters/stabilizer and tick "Active";
- In the given folder, there are four Matlab codes along with the PowerWorld file:
    a. "*Grid_WSCC_Sauer.m*": it contains the static data of the grid;
    b. "*gendat_WSCC_9_bus.m*": it contains the dynamic data of the generators and the controller's parameters;
    c. "*WSCC_analysis.m*": it is the main file;
    d. "*small_sgn_linp.m*": it creates the dynamic matrices using the static and dynamic data.
- By default, the Matlab code "*WSCC_analysis.m*" run a modal analysis without any machine controllers:

```
%                                                                              AVR    PSS
[A, B, pos_var, ~] = small_sgn_linp('Grid_WSCC_Sauer','gendat_WSCC_9_bus',  0,     0);
```

- Run the modal analysis considering the exciters by adding 1 under the "AVR" field on the code "*WSCC_analysis.m*":

```
%                                                                              AVR    PSS
[A, B, pos_var, ~] = small_sgn_linp('Grid_WSCC_Sauer','gendat_WSCC_9_bus',  1,     0);
```

- Run the modal analysis also considering the PSS by adding 1 under the "PSS" field on the code "*WSCC_analysis.m*" (<u>AVR field must be "1"</u>):

```
%                                                                              AVR    PSS
[A, B, pos_var, ~] = small_sgn_linp('Grid_WSCC_Sauer','gendat_WSCC_9_bus',  1,     1);
```

- The script "*WSCC_analysis.m*" gives:
    a. The dynamic matrix "A";
    b. The input matrix "B";
    c. The "*pos_var*" cell array gives you the ordering of the state variables.
- Change the PSS gain:
    a. In PowerWorld, change *Ks (Stabilizer gain);*
    b. In Matlab: go to the "*gendat_WSCC_9_bus.m*", in the last matrix ("*PSS*") change the values of the fifth column ("*Ks*"). By default, you find 0.1 for all the machines.
- In Matlab, use the "Compass" command to plot the mode shapes;
- Participation factors should be normalized;
- The folder "*Load_flow*" contains the Matlab files for the LF computation: it MUST NOT be erased!

Frequently asked questions:

- Which event should we select to trigger the electromechanical oscillation (line opening, load increase)?
  There is no mathematical way to identify which element has more influence on a specific mode. However, you can play with the software and identify the most suitable events (remember, we are dealing with small perturbations!)
- Participation factors and mode shape are not coherent in terms of magnitude? Not necessarily!
  Mode shape (right eigenvectors) gives you the mode phase displacement: the relative amplitude of state variables when a particular mode is excited
  Participation factors give the state variables, and hence the generators, that may have more influence on a specific mode (thus, they can control it)
- Non-electromechanical, oscillatory modes should be justified?
  You can identify which state variables are more involved
- A nearly zero frequency in one mode is obtained?
  It can be considered equal to zero due to MatLab approximation