Project TET4180

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***Abstract*—This project is a part of the course TET4180 Power system dynamics and control at NTNU. The project goal is to choose a power system component to design and tune, and create a simulation model to conduct system studies. The system component chosen for this project group is the Automatic Voltage Regulator (AVR) of type SEXS.**

I. Introduction

This project focuses on the design and tuning of an Automatic Voltage Regulator (AVR) and its impact on power system dynamics. By simulating Kundur's two-area model under disturbances, both with and without the AVR and Power System Stabilizer (PSS), the project aims to analyze how these components influence system response and stability.

Potential challenges include limited coding experience and a lack of familiarity with AVR modeling.

II. Theory

A. Stability

System models can be linear or non-linear. Linear models simplify analysis, while non-linear models better represent real-world dynamic behavior. The system state, defined by a vector of state variables, evolves over time within a mathematical space called the *state space*. Analyzing this space, often using differential equations, helps predict system behavior. Equation 1 shows the state-space form of a linearized non-linear system, where x is the state vector and u is the control input vector [1].

$$\Delta \dot{x} = A \Delta x + B \Delta u \tag{1}$$

The equilibrium state of a state space model is key to understanding stability and its respos to disturbances [1]. The swing Equation 2 is essential for analysing transient stability in power systems. It is a non-linear differential equation describing how the rotor angle (δ) of a synchronous generator changes over time during disturbances, linking rotor acceleration to mechanical input and electrical output power.[2]

$$M \cdot \frac{d\Delta\omega}{dt} = P_m - P_e - D\Delta\omega, \qquad \frac{d\delta}{dt} = \Delta\omega = \omega - \omega_s \tag{2}$$

where M is the inertia coefficient of the generator's rotating mass, $\Delta\omega$ is the rotor speed deviation, P_m and P_e is the mechanic and electric power, D is the damping coefficient and δ is the rotor angle.

Depending on the size of the disturbance, stability can be categorized into *Steady State Stability* and *Transient Stability*.

1) Steady state stability: Steady-state stability is the system's ability to return to an equilibrium after small disturbances. In linear systems, stability does not depend on disturbance size; however, for nonlinear systems, stability under small disturbances does not guarantee transient stability. At equilibrium, all state derivatives are zero, and small disturbances allow for linearization of the system's differential equations for analysis [1]. Recalling the state-space model in Equation 1 and the Swing equation in Equation 2, the Swing equation for a synchronous generator can be linearized by choosing the rotor speed deviation $\Delta\dot{\omega}$ and rotor angle deviation $\Delta\dot{\delta}$ as state variables, with the mechanical power P_m as the input:

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \end{bmatrix} = \begin{bmatrix} 0 & 2\pi f_N \\ \frac{K'_E}{2H} & -\frac{D}{2H} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \Delta P_m \tag{3}$$

where H is the inertia coefficient and K_E transient synchronizing power coefficient.

2) Transient stability: Transient stability refers to a system's ability to remain stable after a large disturbance, such as a short circuit, line tripping, or a major load change. It assumes the system was steady-state stable before the disturbance and can return to or near equilibrium afterward. During such events, electrical and mechanical power can lose synchronism, disrupting the balance between generation and demand. The maximum fault clearing time before instability occurs is called the critical clearing time.[1]

B. Eigenvalues

Given the state space model $\dot{x} = Ax$, the system's modes are determined by the eigenvalues λ_i of A. Each eigenvalue can be written as $\lambda_i = \alpha_i + j\Omega_i$, where α_i (the real part) indicates growth ($\alpha_i > 0$) or decay ($\alpha_i < 0$, and Ω_i (the imaginary part) sets the oscillation frequency. If $\Omega_i = 0$, the mode is not oscillatory. Formally, a number λ is an eigenvalue of A if there exists a non-zero vector w such that $Aw = \lambda w$.[1, p.561]

C. Modelling and design of AVR

The Automatic Voltage Regulator (AVR) is responsible for maintaining a desired voltage level at the generator terminals by controlling the exciter voltage that drives the field winding to perform voltage stability. Figure 1 shows a general closed loop block diagram for the AVR. The main input signal to the AVR are the terminal voltage of the generator, V_g. Core elements include a comparator (measuring voltage error), an amplifier/gain stage, and a lead–lag block. The exact arrangement varies by AVR type and application.

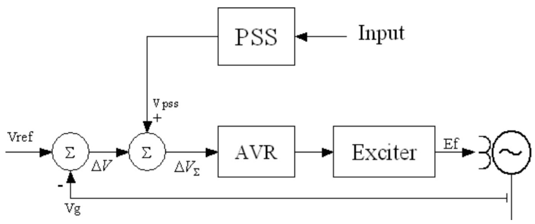


Fig. 1: Example of a block diagram for a voltage control system

1) Gain/Amplifier: The gain amplifies the voltage error ΔV. For P-regulators the gain is decided by the gain coefficient K_A as shown in Equation 4. For PI- and PID-regulators time constants are included to adjust control actions based on past error.

$$H = K_A \tag{4}$$

A well-designed AVR regulates voltage accurately while also damping rotor oscillations and power swings after a fault, but these purposes are in conflict. A fast-response exciter with high gain improves voltage control but may cause poorly damped, growing rotor angle oscillations, leading to frequency instability [1, p.409]. To avoid this, a Lead-Lag, can be added to the AVR.

2) Lead Lag: The lead-lag block enables a fast (low time constant) response while maintaining high loop gain. The time constants T_1 and T_2 shape the transient response: T_1 provides a quick, phase-advanced reaction to voltage errors, while T_2 adds damping to avoid overshoot and instability by reducing gain at power swing frequencies. The transfer function is given in Equation 5.

$$H(s) = \frac{1 + T_1 s}{1 + T_2 s}, \qquad T_1 < T_2 \tag{5}$$

3) PSS: A PSS enhances damping by injecting a control signal in phase with rotor speed deviations. Implemented as a supplementary loop to the AVR, it provides an output V_{pss} only during transients ($V_{pss} = 0$ at steady state). Common inputs include generator active power, speed deviation, or terminal voltage frequency. When speed deviation ω is used, the signal is low-pass filtered to remove noise and passes through a washout filter to isolate the oscillatory component $\Delta\omega$. A phase compensation stage (lead–lag blocks) then aligns the PSS voltage with $\Delta\omega$.[1, p.410-412]

III. Simulation model

A. AVR SEXS

The AVR model from TOPS that has been analysed and simulated for this project is the Simplified Excitation System (SEXS). This is an AVR which includes a Transient Gain Reduction (TGR) block, and the control loop is shown in Figure 2. Simulations will be carried out with and without the PSS to see the effects on the system.

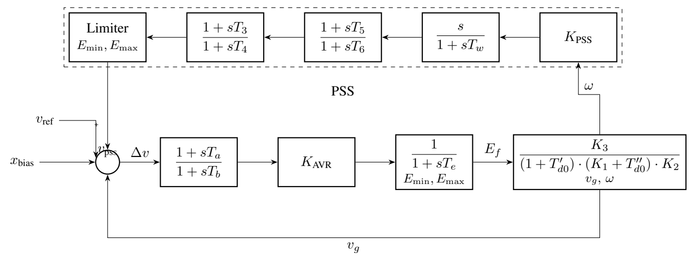


Fig. 2: Block diagram of the AVR SEXS and PSS from Tops

To analyse the stability of the voltage control loop, both Bode plots and eigenvalues can be used, as well as frequency and voltage response plots.

1) Bode plots: At least 6 dB of gain margin and 45° of phase margin are typically required for adequate frequency stability. With the AVR SEXS parameters from Table I, the Bode plot was plotted in MatLab, and shows that the system is stable but has a phase margin below 45°, indicating weak damping. Decreasing K_A to 50 raises the phase margin above 45°, improving frequency stability and damping. This supports the discussion in Chapter II-C1 that a gain that is too high can worsen the rotor oscillation damping. However, since the system is already stable and a PSS will be introduced, the parameters from Table I are retained when looking at the design and tuning for the PSS.

2) Eigenvalues: The eigenvalues for the AVR infinite bus system is showed in Figure 7. All the eigenvalues lie on the left side of the imaginary axis, indicating that the system is stable. The farther left they are, the more quickly those modes decay over time. Any non-zero imaginary parts indicate oscillatory modes; because their real parts are negative, these oscillations are damped. Eigenvalues close to the imaginary axis suggest weak damping and may dominate the system's slower dynamics.

B. AVR with PSS

With the PSS connected as shown in Figure 2, various parameters for K, T_1 and T_2 were tested to achieve a fast and well-damped response (Table II). Eigenvalue analysis showed that scenario 2 offers the fastest response (Figure 8), with all damping factors above 5%. Compared to the system without a PSS (Figure 7), the critical modes shift further left in the complex plane, and the two highest electromechanical modes increase in damping from 15% to 17%. A small load change test (Figure 10 vs. Figure 9) confirms reduced oscillations when using the PSS. However, the two second highest electromechanical modes has decreased damping ratio. The importance of these two modes is unclear for the group as the overall oscillation of rotor speed is improved with the PSS.

IV. System study

A. TOPS AVR SEXS model

The Kundur's two area model will be used for the simulations. The system contains eleven buses and two areas, where each area has two generators each. In chapter III, the AVR SEXS and the PSS component built in tops was used to design and tune with parameters fit for the single bus infinite grid model. Hence these parameters will likely not be the best choice for the Kundur's two area model and will therefore be adjusted to ensure voltage stability for a small disturbance.

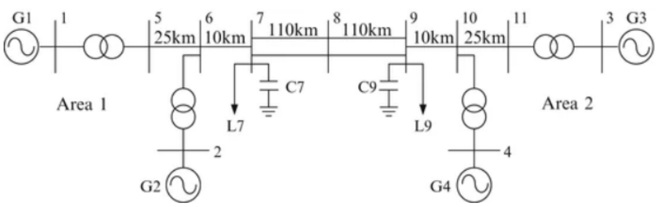
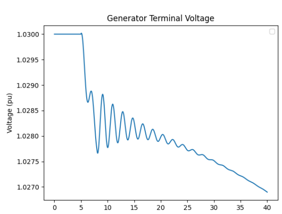


Fig. 3: Kundur's two area model

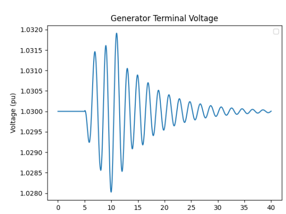
For the simulations there are three different scenarios, without regulator, with AVR and with AVR and PSS. The parameters used for the AVR model are listed in Table III.

B. Small disturbance - Load change (0 + 0.01j)

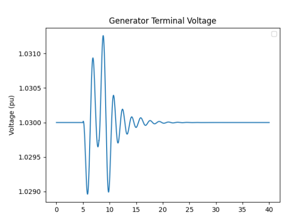
A load change of $0 + 0.01j$ p.u was applied to bus 4 between 5 to 8 seconds. As shown in Figure 4, the voltage becomes unstable without the AVR and PSS, whereas including only AVR or both AVR and PSS ensures stable voltage recovery.



(a) Voltage respons w/o control



(b) Voltage response w AVR



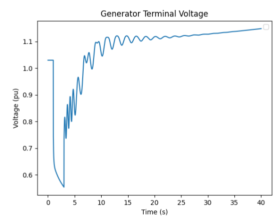
(c) Voltage response w AVR and PSS

Fig. 4: Voltage response.

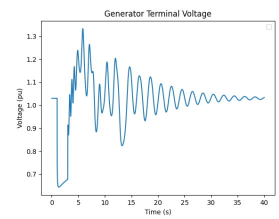
However, the simulation reveals that although the AVR alone stabilizes the voltage, it worsens rotor speed stability compared to the scenario without an AVR as shown in Appendix A. Adding a PSS to the AVR addresses this issue, leading to faster stabilization of both voltage and rotor speed oscillations and making the system more robust to small disturbances. This aligns well with the theory presented in chapter II-C1.

C. Large disturbance - Short circuit

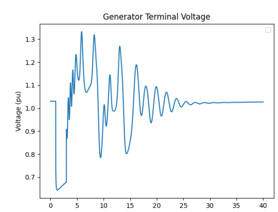
A zero-impedance short circuit of $1 \cdot 10^6$ p.u. was applied at bus 7 from 1 to 3 seconds. As shown in Figure 5, the voltage increases over time without any regulators. With AVR, oscillations occur but the system eventually stabilizes. Adding both AVR and PSS yields the fastest return to steady state, as expected. Reducing the gain or increasing the time constant could further improve damping and reduce the oscillation amplitude. In B the rotor speed, rotor angle and electric power output plots are shown. These indicate that the AVR and PSS have a negative impact on rotor speed, which could also be improved with lower gain, as argued in Appendix subsubsection II-C1.



(a) Voltage respons w/o control



(b) Voltage response w AVR



(c) Voltage response w AVR and PSS

Fig. 5: Voltage response.

V. Conclusion

From this project study, we can conclude that using an AVR an PSS for a control system gives greater and faster voltage and frequency stability when choosing parameters fit for the chosen simulation system. The results showed what the theory said, that the AVR improves voltage stability but not necessary frequency stability. This highlights the importance of the PSS component to avoid increasing rotor oscillations when AVR is reacting to voltage errors. However, the tuning of the AVR and PSS in chapter III is not ending up with a increased damping ratio for all electromechanical modes, but only some. For a bigger project, a more in-dept approach could be used to tune the AVR and PSS improving all modes.

REFERENCES

[1] Jan Machowski et al. *Power system dynamics*. English. Third Edition. Wiley, 2020.

[2] *Swing Equation: Know The Definition, Derivation, And Curve!* en. URL: https://testbook.com/electrical-engineering/swing-equation (visited on 03/28/2025).

Appendix

A. Simulation model -Initial AVR SEXS parameters

TABLE I: Parameters of the AVR SEXS control loop with the generator parameters

KA	Ta	Tb	Te	K1	K2	K3	Td0’	Td0”
100	2	10	0.5	1.15	0.65	0.375	2.49	0.06

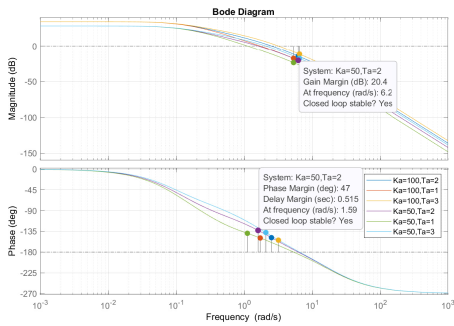


Fig. 6: Bode plot for the AVR SEXS system with different K_A and T_a

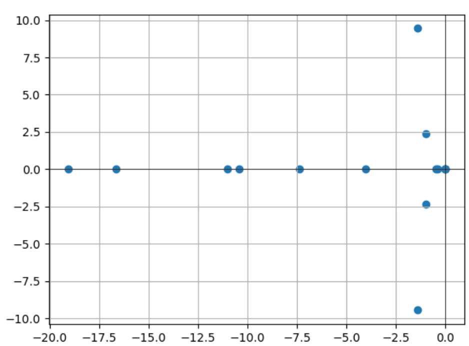


Fig. 7: Eigenvalues for the AVR system with the infinite single bus system

B. Simulation model -PSS parameters

TABLE II: PSS parameters with variation of washout gain and lead time constants.

Scenario	K	T	T1	T2	T3	T4	Hlim
1	50	10	0.2	0.2	0.05	0.05	0.03
2	25	10	0.5	0.5	0.02	0.02	0.03
3	20	10	0.2	0.2	0.05	0.05	0.03
4	20	10	0.5	0.5	0.05	0.05	0.03

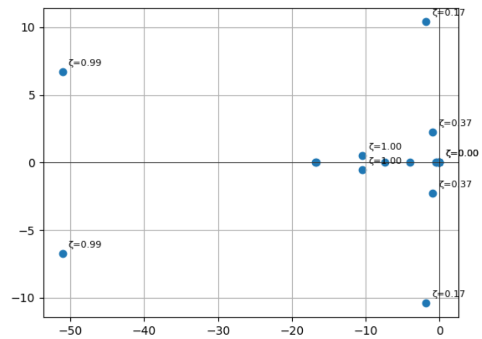


Fig. 8: Eigenvalues for the AVR with PSS system with parameters of scenario 2

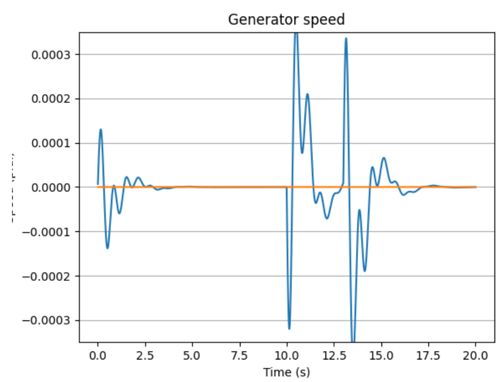


Fig. 9: System response with load change of 0.04j, w/o PSS

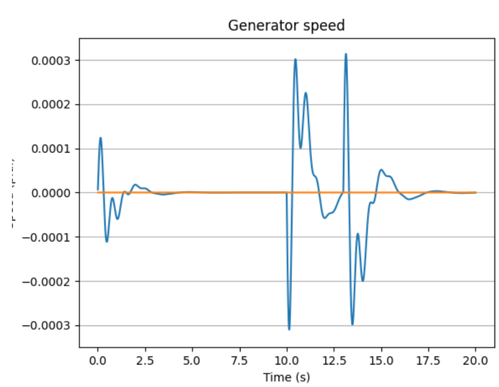


Fig. 10: System response with load change of 0.04j, w PSS

Appendix

TABLE III: Parameters of the AVR SEXS regulator

K	Ta	Tb	Te	K1	E_{min}	E_{max}
100	2	10	0.5	1.15	-3	3

A. System study -Small disturbance

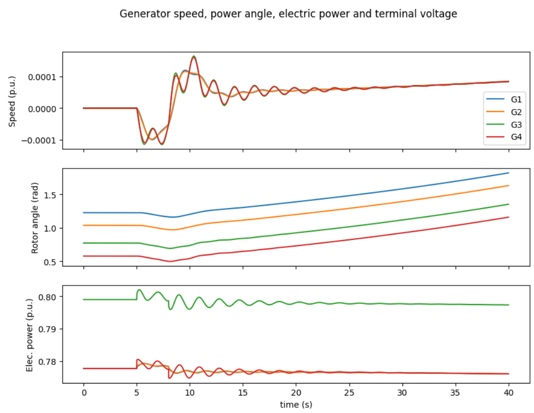


Fig. 11: Load change w/o AVR & PSS

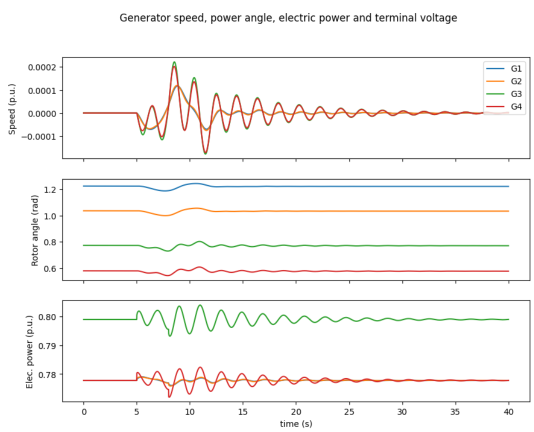


Fig. 12: Load change with AVR

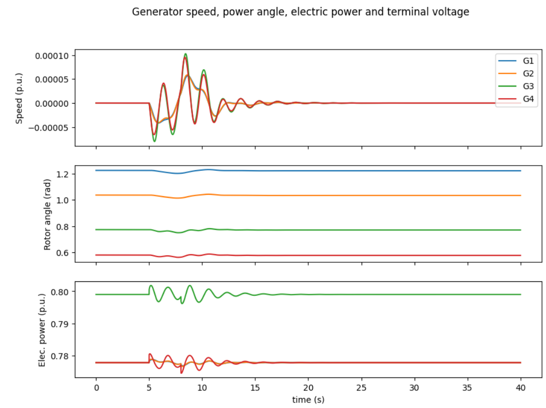


Fig. 13: Load change w/ AVR & PSS

B. System study - Large disturbance

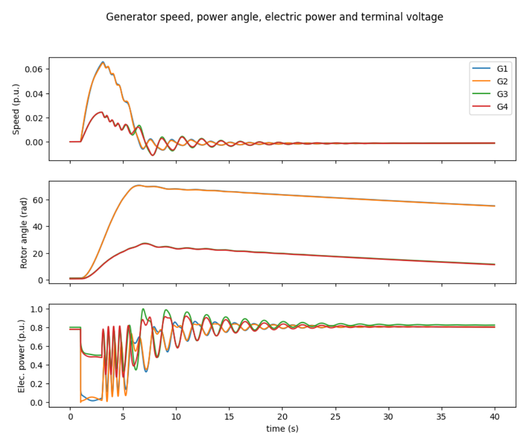


Fig. 14: Short circuit w/o AVR & PSS

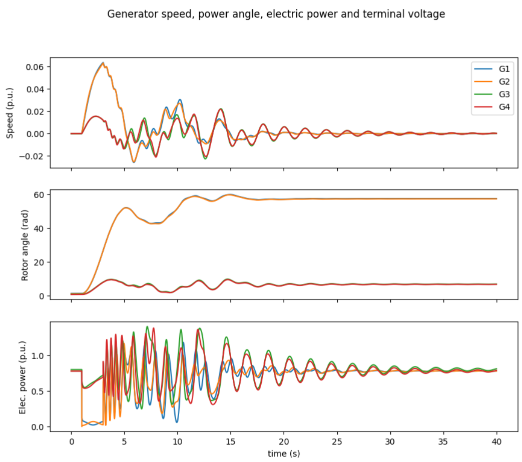


Fig. 15: Short circuit w/ AVR

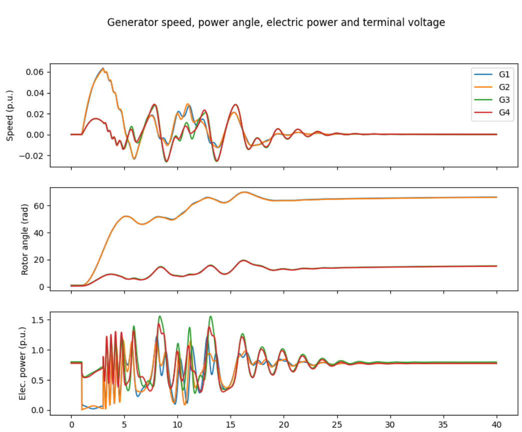


Fig. 16: Short circuit w/AVR & PSS