Voltage Regulation of Synchronous Machines

POWER SYSTEM MODELLING AND CONTROL (EEEN40550)

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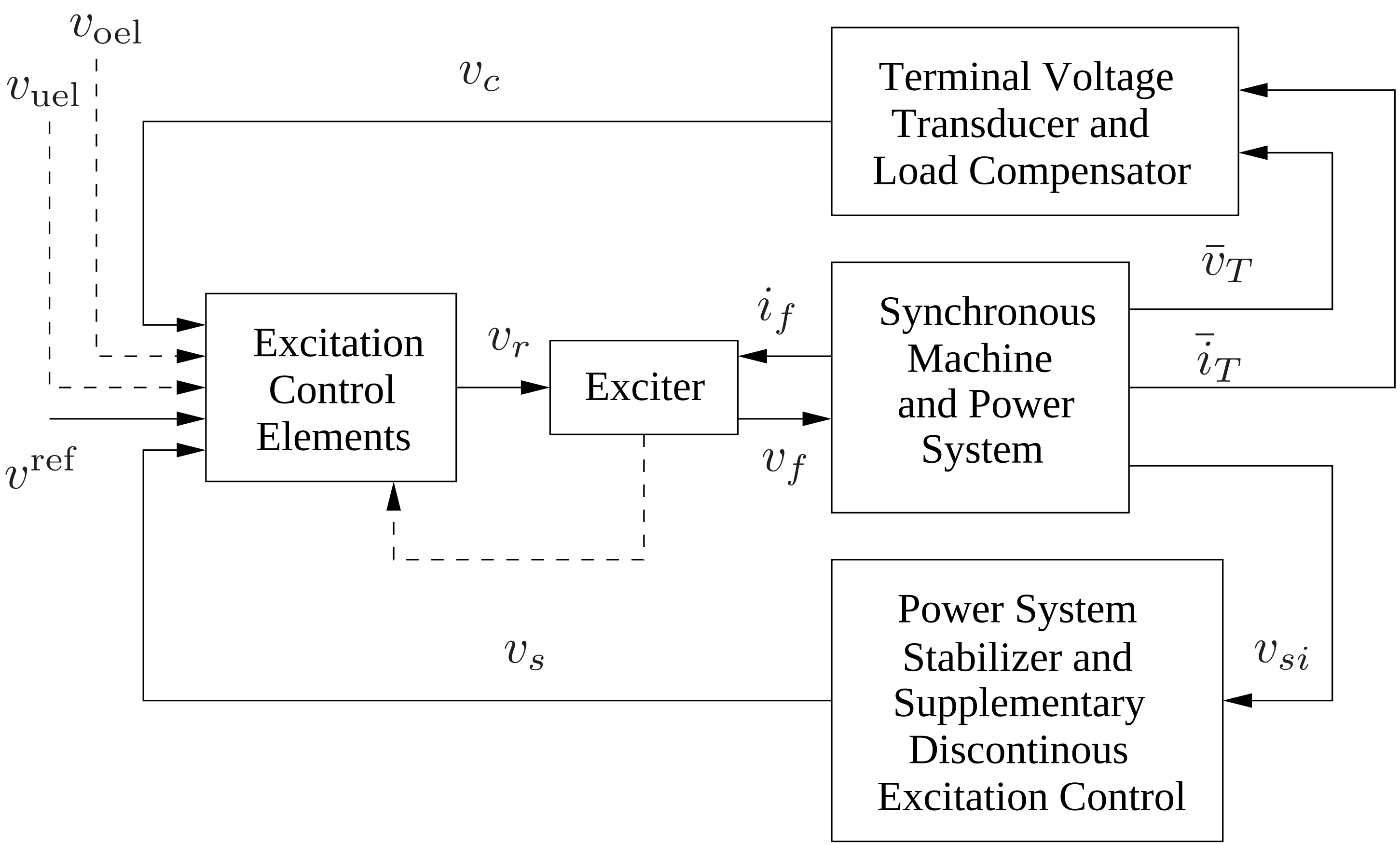
Automatic Voltage Regulation

- Automatic Voltage Regulators measure the bus terminal voltage of the machine (or any relevant bus voltage) and compare it with a reference voltage. The error signal is used to modify the field voltage of the rotor of the synchronous machine.

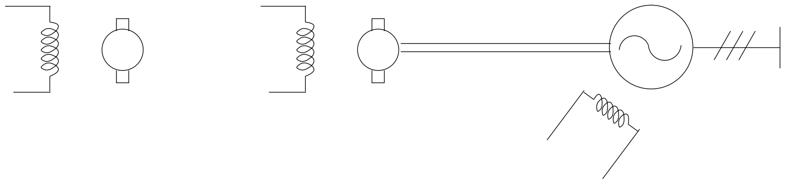
- There are several models of AVR, depending on the technology:
  - based on DC machines (slow)
  - based on power electronics (fast)
  - brushless
  - permanent magnet (no voltage control!)

Synoptic AVR Scheme

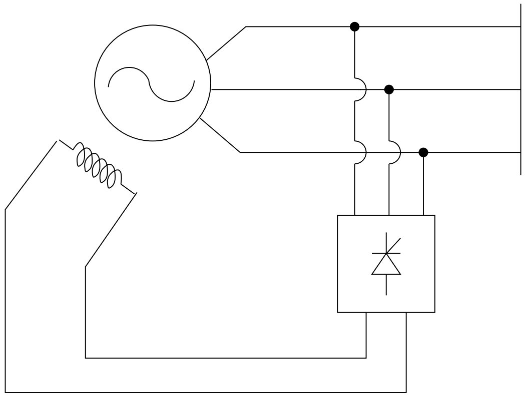


AVR Types

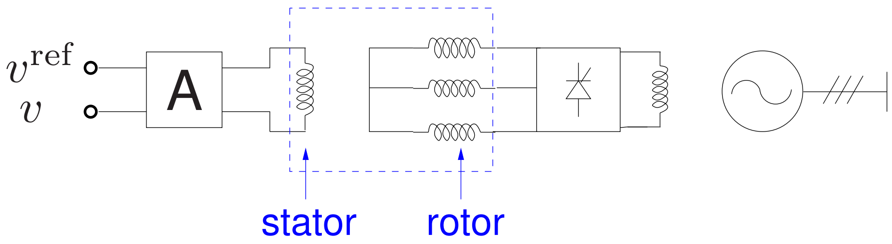
- DC machine:



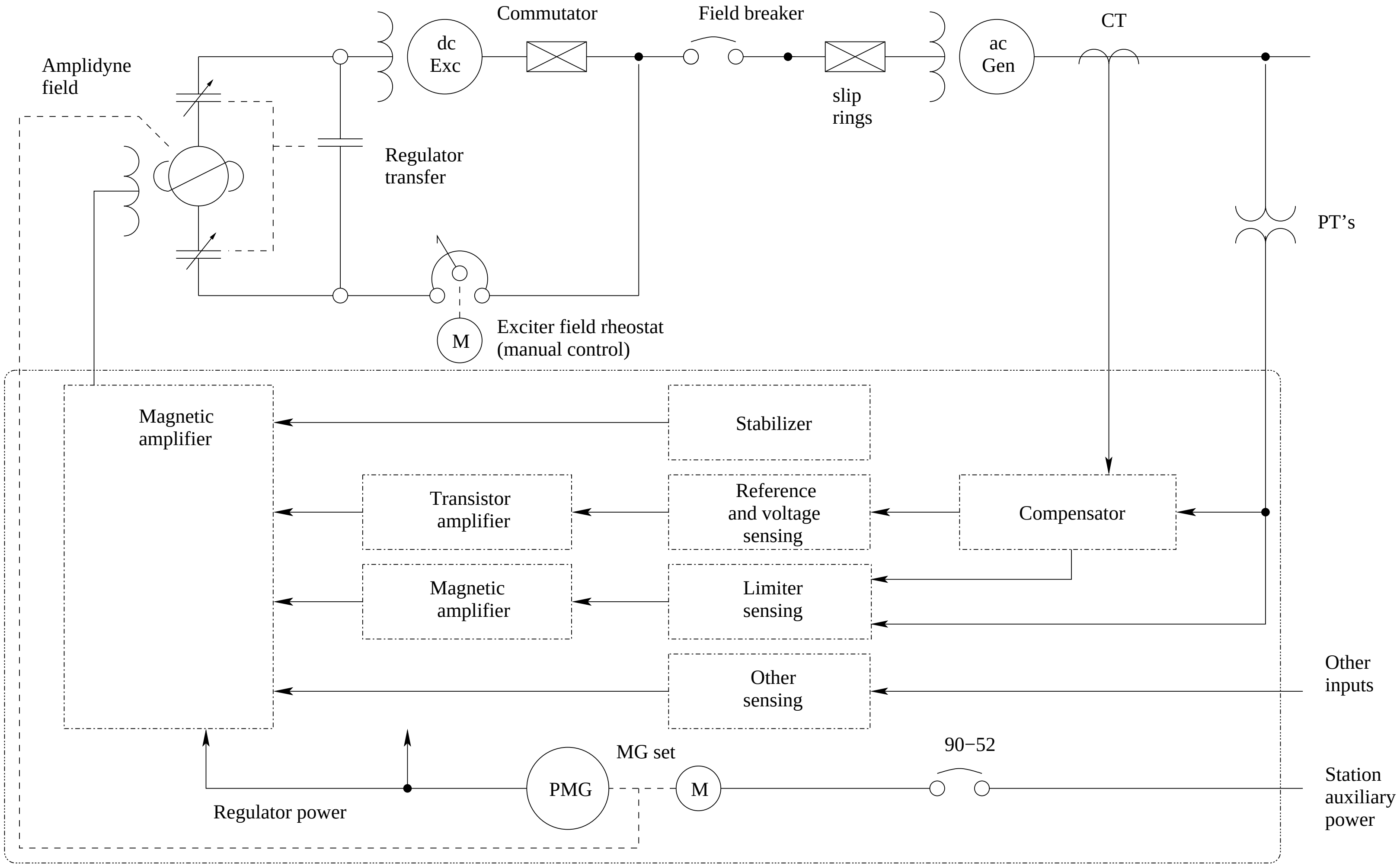
- Power Electronics Device:



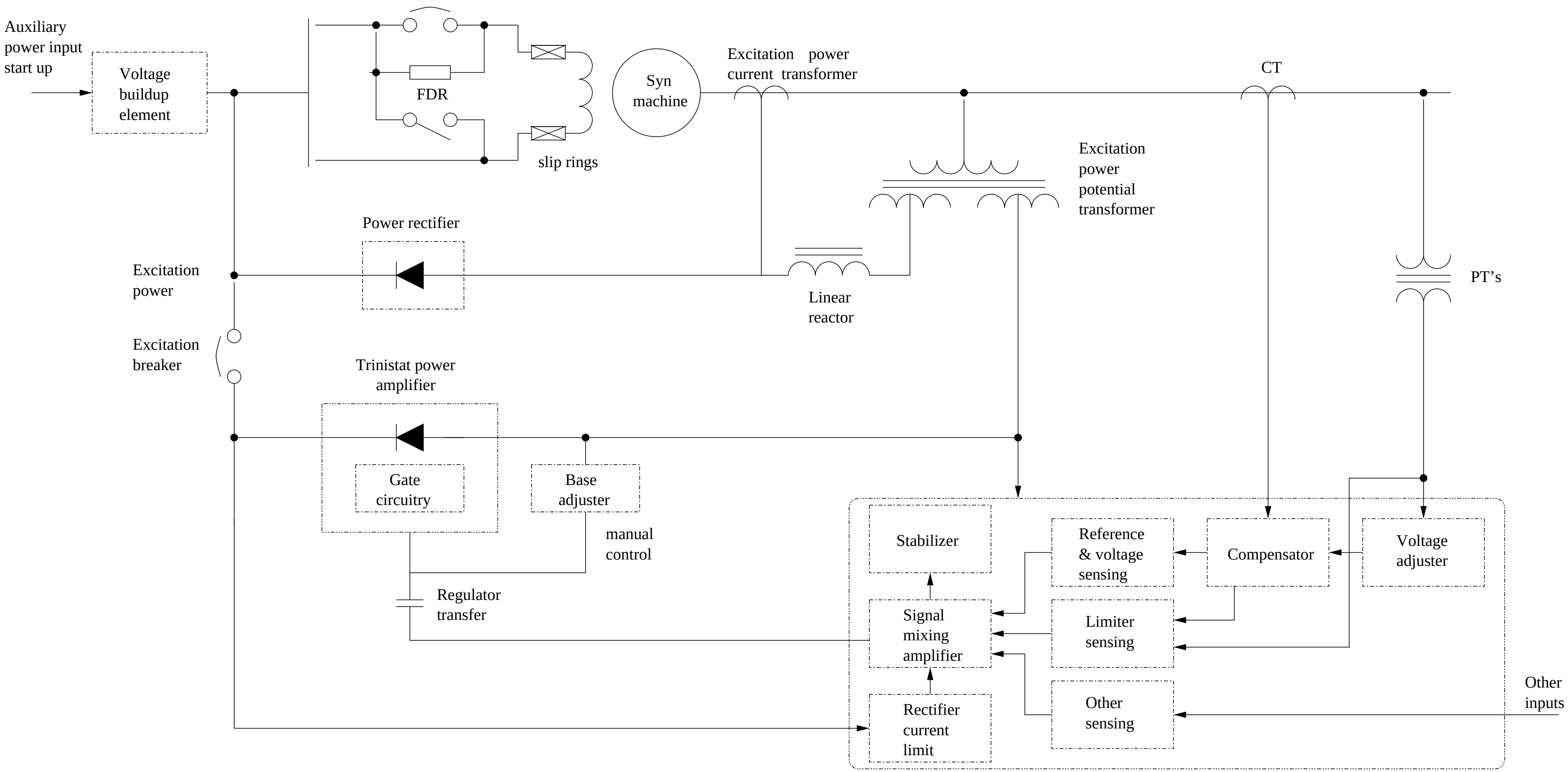
- Brushless: it includes a synchronous machine with a dual structure with respect to the main generator.



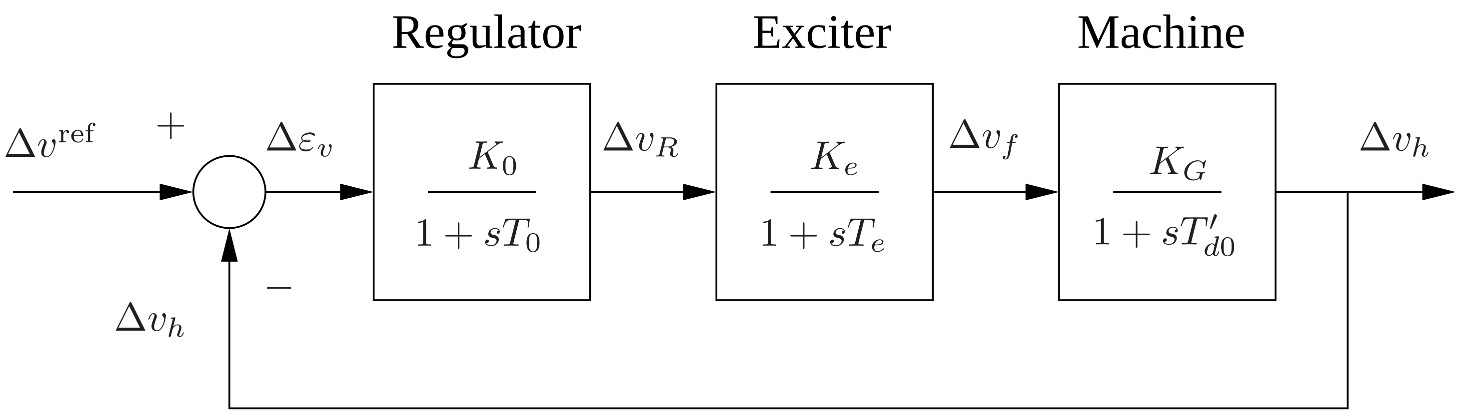
DC-Machine-Based AVR



Power-Electronics-Based AVR



Basic Scheme of an AVR



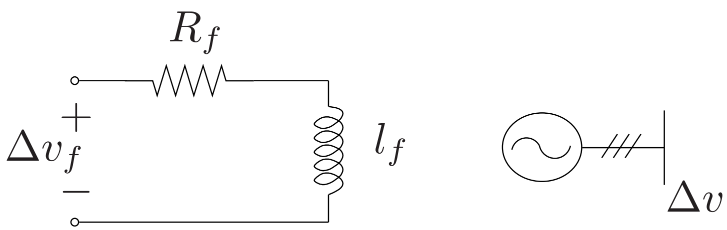
$$G_A = \frac{\Delta v_R}{\Delta \varepsilon_v} = \frac{K_0}{1+sT_0} \quad \text{with} \quad T_0 \in [0.02,\ 0.08]\ \mathrm{s}$$

$$G_G = \frac{\Delta v}{\Delta v_f} = \frac{K_G}{1+sT'_{d0}} \quad \text{with} \quad T'_{d0} \in [1,\ 5]\ \mathrm{s}$$

$$G_E = \frac{\Delta v_f}{\Delta v_R} = \frac{K_e}{1+sT_e} \quad \text{with} \quad T_e \in [0.5,\ 0.8]\ \mathrm{s}$$

Synthesis of the Transfer Function $G_G(s)$

- We have the field circuit of the machine:



$$\Delta v_f = R_f \Delta i_f + L_f \frac{\mathrm{d}\Delta i_f}{\mathrm{d}t} \quad \Rightarrow \quad \Delta v_f = (R_f + sL_f)\Delta i_f(s) = (R_f + sL_f)\frac{\Delta v}{K}$$

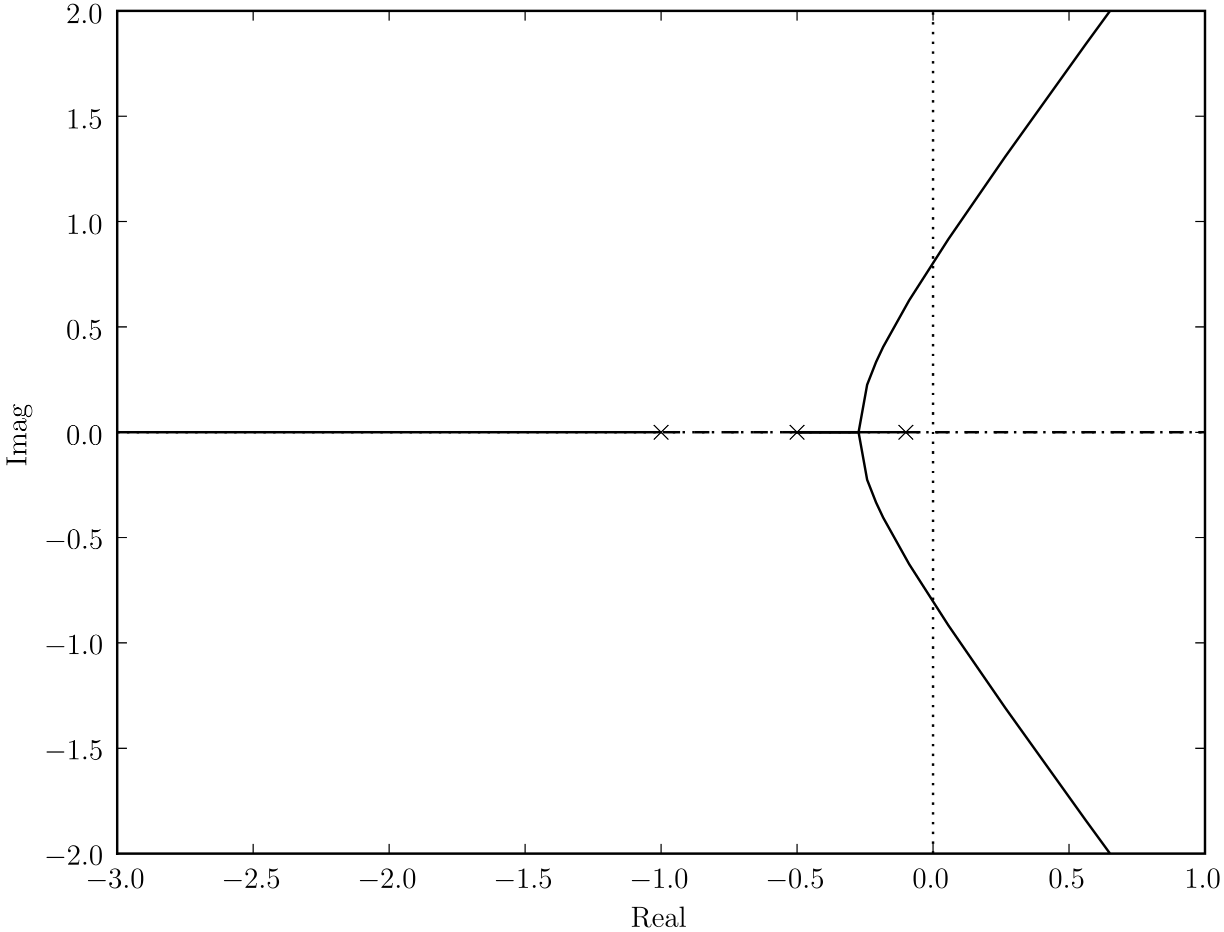
hence:

$$\frac{\Delta v}{\Delta v_f} = G_G = \frac{1}{K}\frac{1}{R_f + sL_f} = \frac{K_G}{1 + s\frac{L_f}{R_f}}$$

where

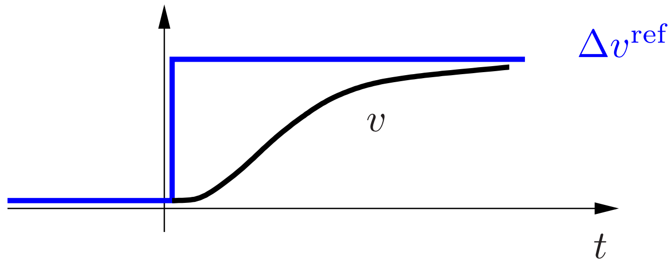
$$K_G = \frac{1}{K}\frac{1}{R_f} \qquad \text{and} \qquad T_G = \frac{L_f}{R_f} = T'_{d0} \qquad \#$$

Root Loci of a Basic AVR Scheme

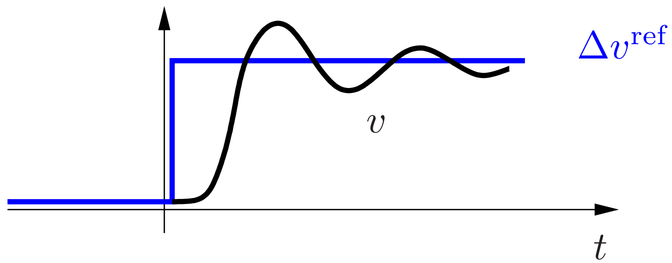


Time Response of the AVR

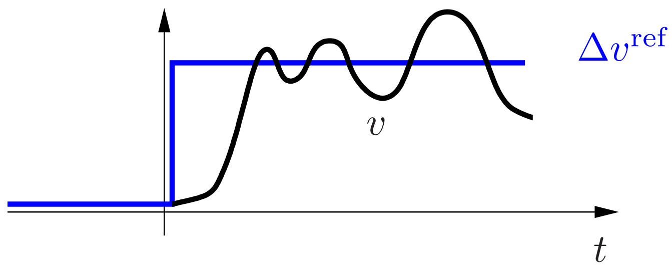
- Depending on the gain K_0, we can face three situations:



$\Rightarrow$ two real poles < 0



$\Rightarrow$ complex eigenvalues with $\mathbb{R}\{\lambda\} < 0$



$\Rightarrow$ complex eigenvalues with $\mathbb{R}\{\lambda\} > 0$

Basic AVR Scheme

- We have:

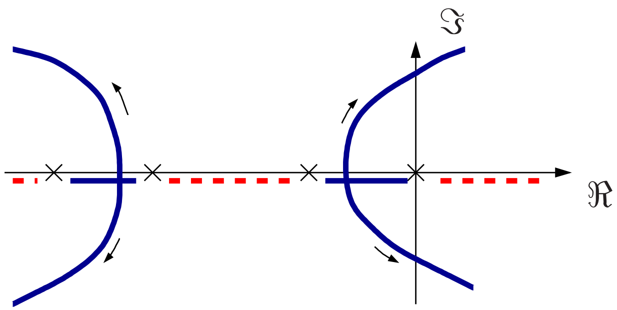
$$\frac{\varepsilon_v}{\Delta v^{\mathrm{ref}}} = \frac{1}{1 + \dfrac{K_0 K_e K_G}{(1+sT_0)(1+sT_e)(1+sT'_{d0})}}$$

→ Assume a step variation of $\Delta v^{\mathrm{ref}}(t) = \Delta(t) \quad \Rightarrow \quad \dfrac{1}{s}$

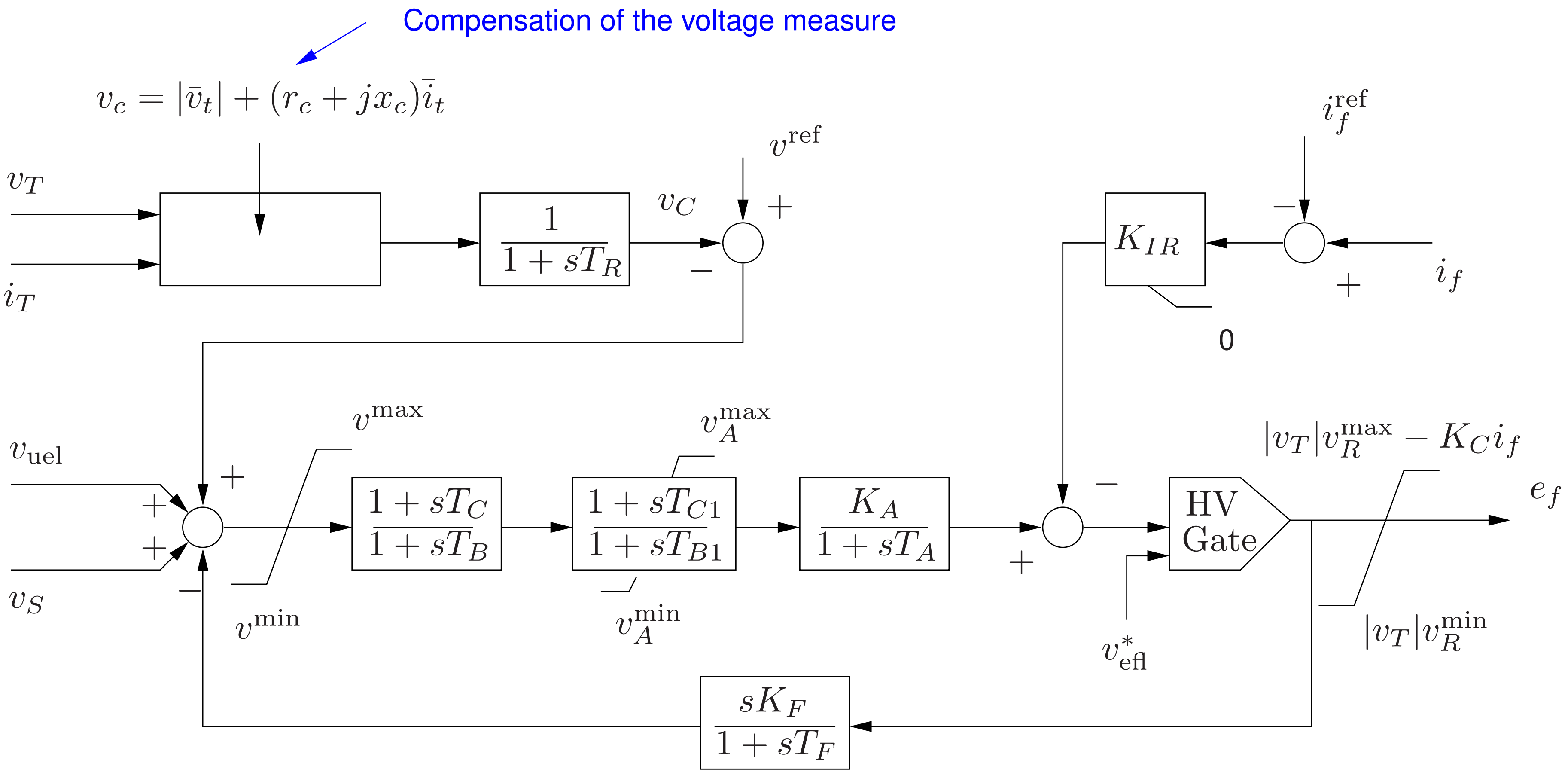
→ The static error is: $\Delta\varepsilon_v(s \to 0) = \dfrac{1}{1 + K_0 K_e K_G}$

- If we do not want the static error, we have to include an integrator:

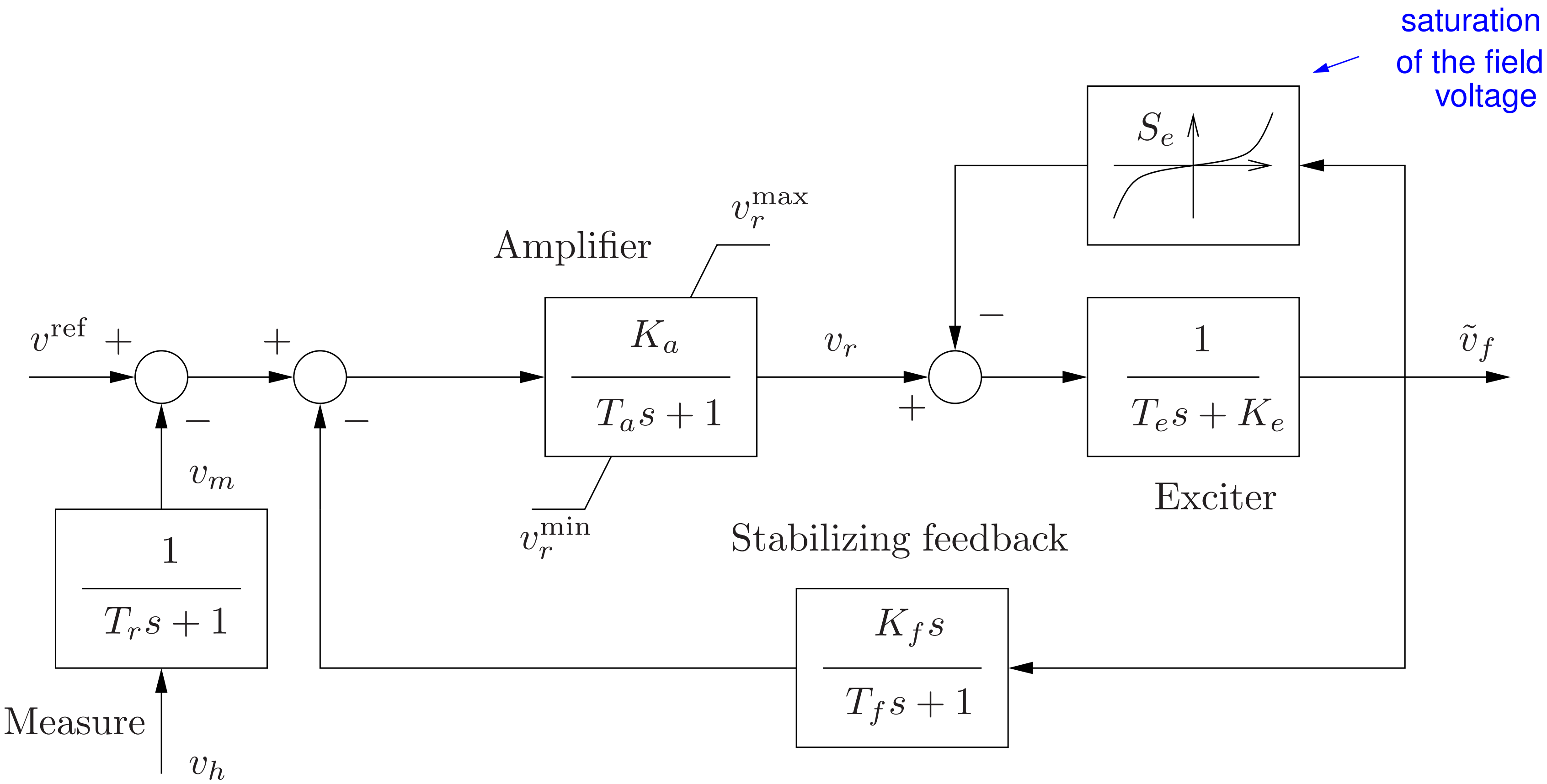
$$G_A(s) = \frac{1}{s}\frac{K_0}{(1+sT_0)}.$$



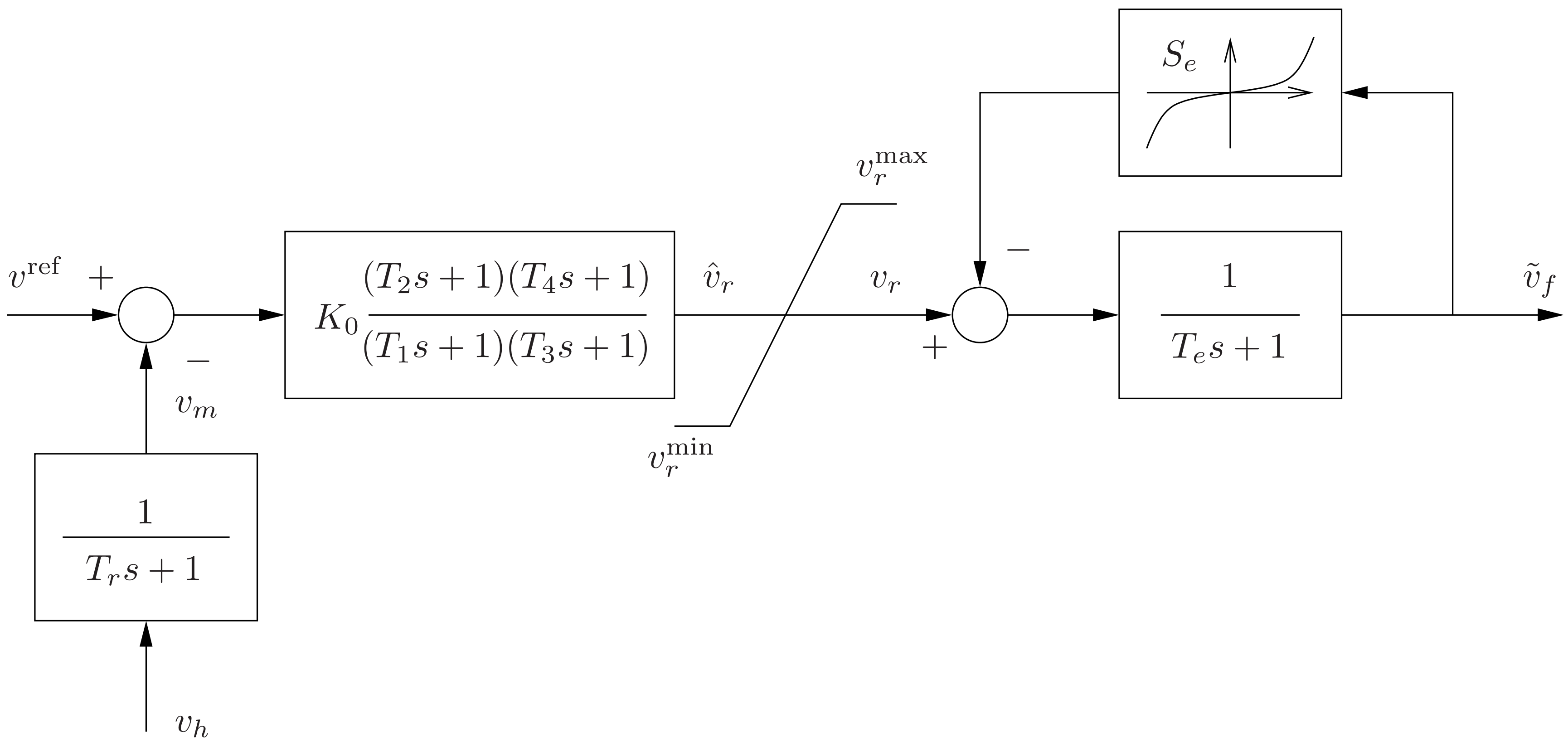
Real-World AVR Schemes



Standard IEEE Type 1 AVR Scheme



Typical AVR Scheme for Power Electronics Exciter



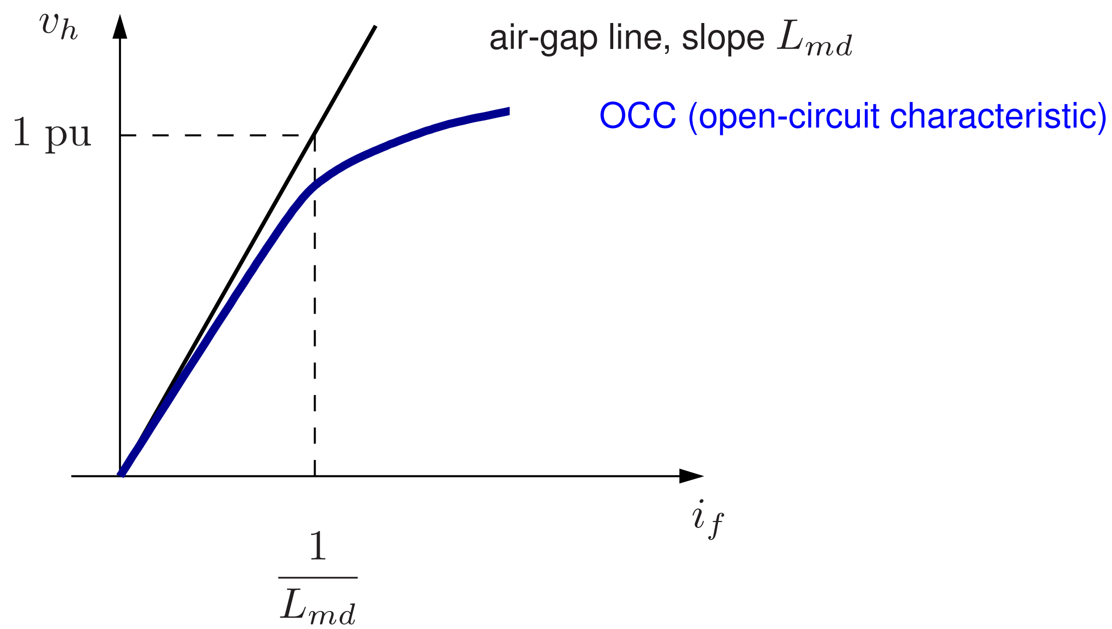
Load Compensation

- Typically the AVR controls the generator terminal voltage.
- However, there are cases in which we need to compensate the measured signal:

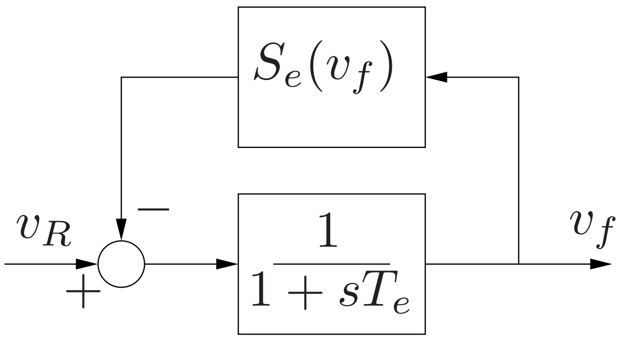
$$|\bar{v}_t| = |\bar{v}_{\rm bias} + (r_c + jx_c)\bar{i}_{\rm bias}|$$

- $r_c > 0$ and $x_c > 0 \to$ regulate a voltage *within* the generator.
  used when several generators are in parallel with a unique step-up transformer.
- $r_c < 0$ and $x_c < 0 \to$ regulate a point *beyond* the machine terminals.
  this compensates the voltage drop on the step-up transformer.

Effect of Saturation of the Field Current



Proposed saturation model



IEEE Saturation Function (Ceiling)

- A common saturation function has been proposed by the IEEE:

$$S_e(v_f) = A_e e^{B_e |v_f|}$$

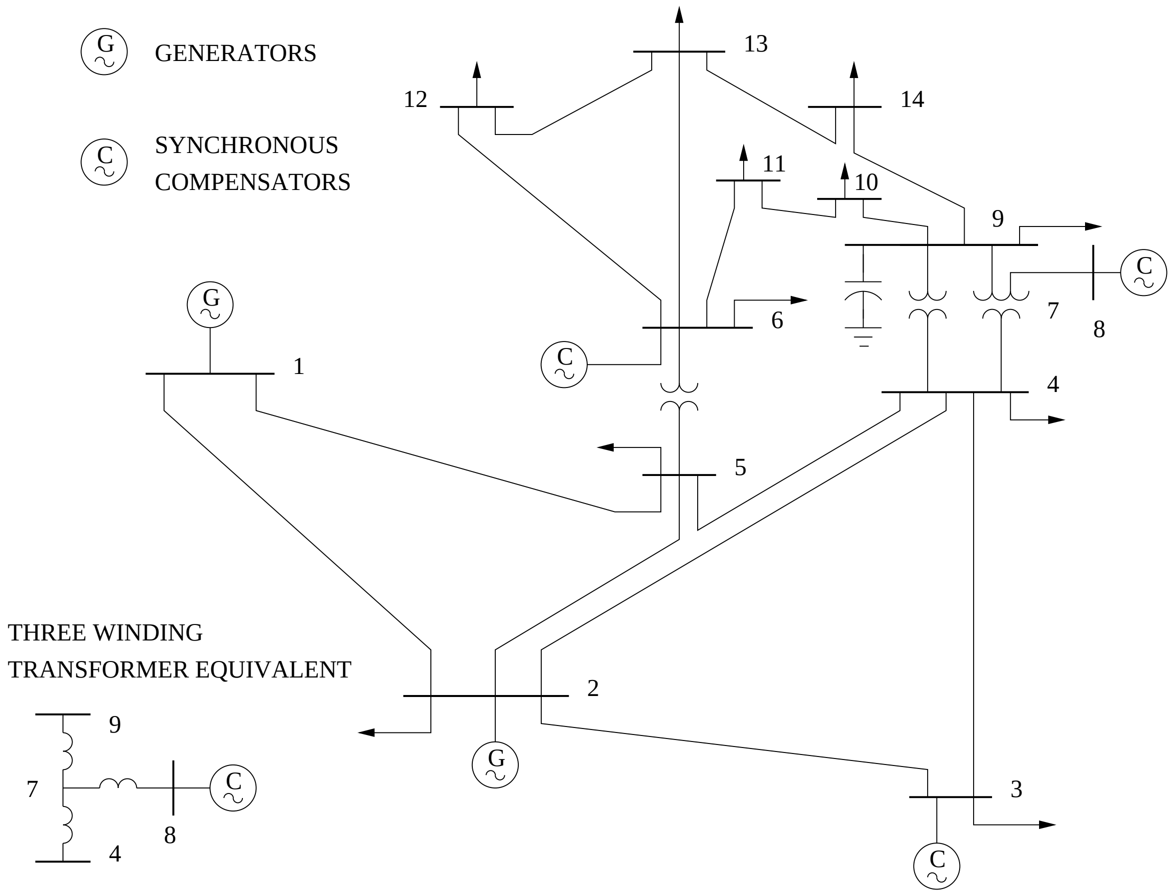
- Coefficients A_e and B_e are determined from two points of the celing function:

$$\begin{pmatrix} S_e^{\max} \\ v_f^{\max} \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} S_e^{0.75\max} \\ v_f^{0.75\max} \end{pmatrix}$$

- Typical values are:

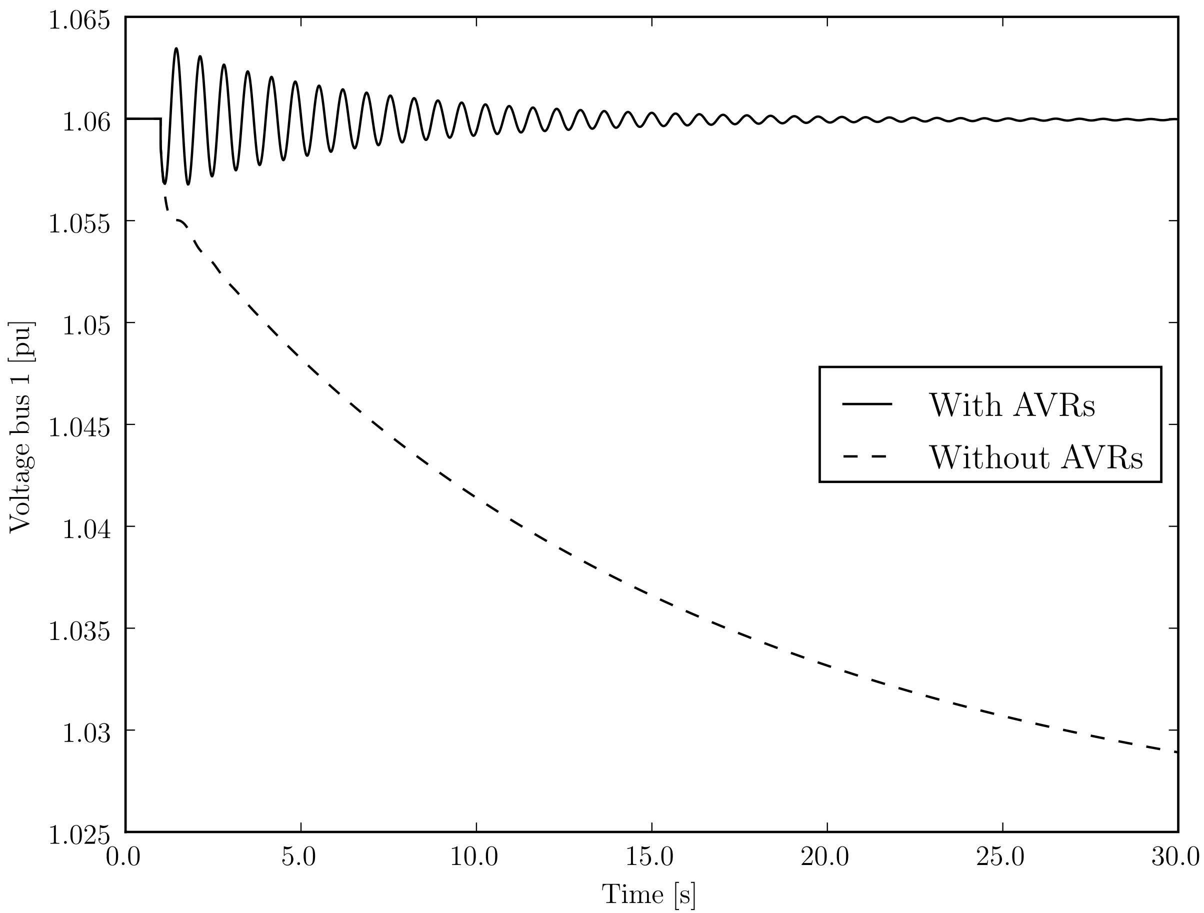
$$A_e = 0.0006 = 6 \times 10^{-4} \quad \text{and} \quad B_e = 0.9$$

Example: IEEE 14-bus System

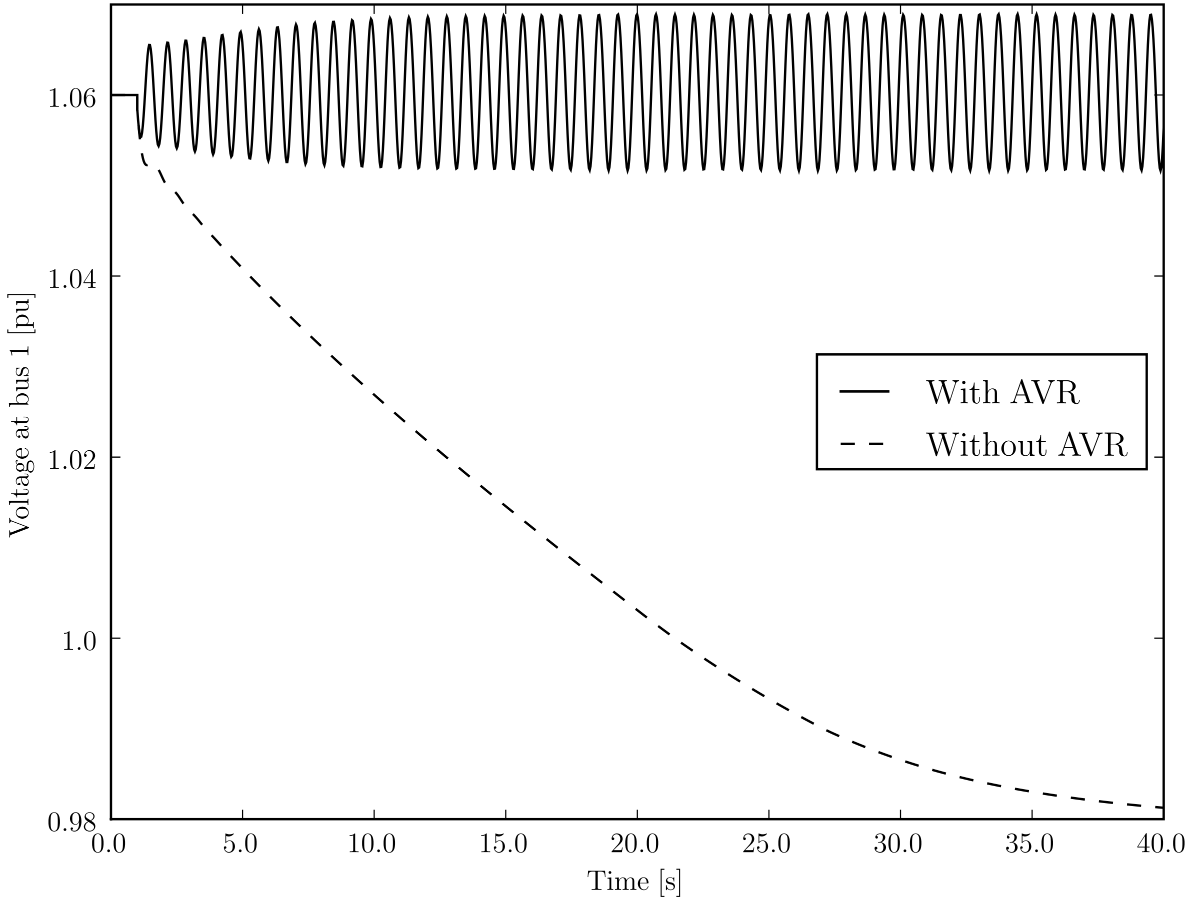


Perturbation:
line 2-4
outage
at $t = 1$

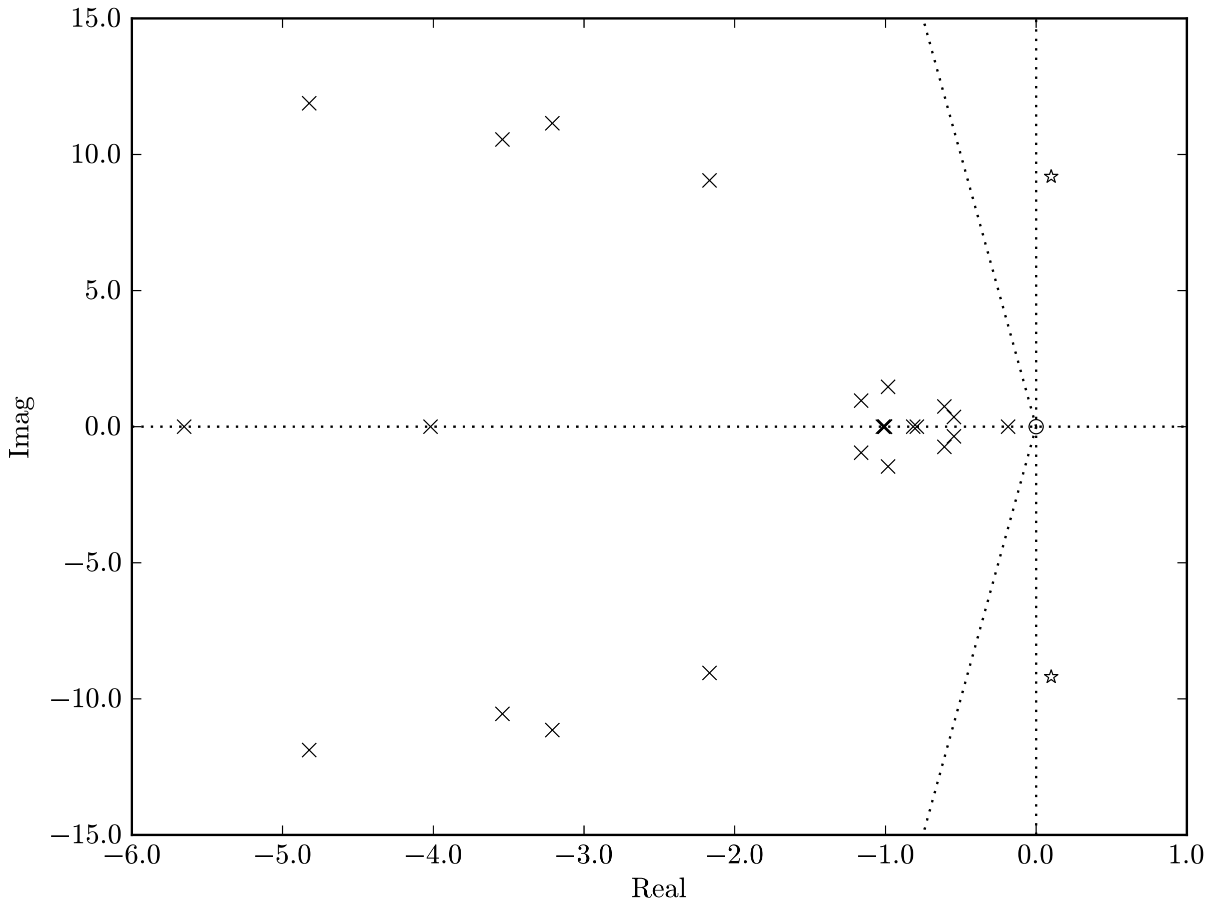
IEEE 14-bus System - Base Case Loading



IEEE 14-bus System - 120% of Base Case Loading



IEEE 14-bus System - Root Loci 120% of Base Case Loading



Power System Stabiliser (PSS)

- Let's consider the electro-mechanical model of the machine:

$$2H \frac{\mathrm{d}\omega}{\mathrm{d}t} = p_m - p_e(\delta)$$

where

$$p_e(\delta) = \frac{e'_q v_h}{x'_d} \sin(\delta - \theta_h)$$

and differentiating:

$$2Hs\Delta\omega = -\frac{\partial p_e}{\partial \delta}\Delta\delta - \frac{\partial p_e}{\partial e'_q}\Delta e'_q - \frac{\partial p_e}{\partial v_h}\Delta v_h$$

if e'_q and v_h are constant, we have:

$$2Hs\Delta\omega = -\frac{\partial p_e}{\partial \delta}\Delta\delta = -K\Delta\delta$$

Power System Stabiliser (PSS)

- where

$$K = \frac{e'_q v_h}{x'_d} \cos(\delta_0 - \theta_0)$$

- Since $\Delta\omega = s\Delta\delta$, we have:

$$2Hs^2\Delta\delta + K\Delta\delta = 0$$

- which has a pair of pure complex eigenvalues (if there is no damping):

$$\lambda_{1,2} = \pm j\sqrt{\frac{K}{2H}}$$

Power System Stabiliser (PSS)

- The PSS allows imposing:

$$\Delta e'_q = K_1 s \Delta\delta$$

- Hence, we have:

$$2Hs\Delta\omega = -K\Delta\delta - K_\omega s\Delta\delta$$

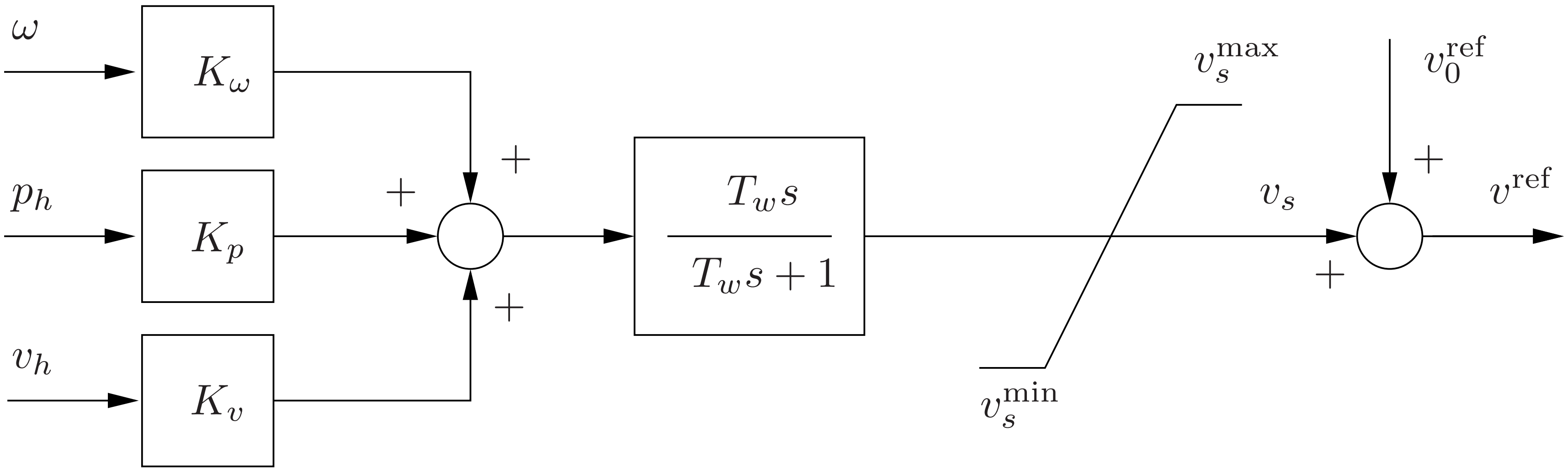
where:

$$K_\omega = K_1 \frac{\partial p_e}{\partial e'_q}$$

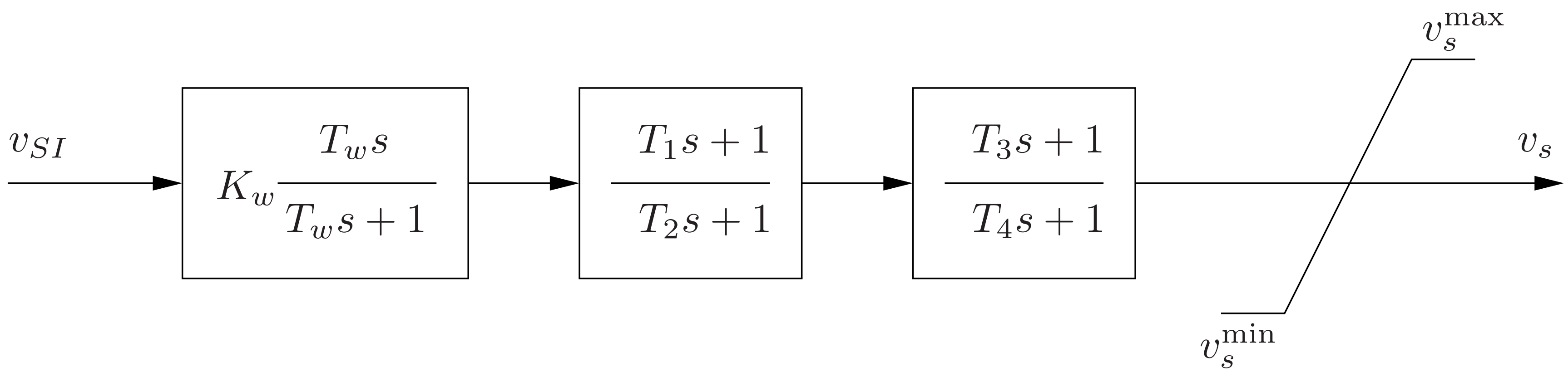
so:

$$2Hs^2\Delta\delta + K_\omega s\Delta\delta + K\Delta\delta = 0 \quad \Rightarrow \quad \lambda_{1,2} = -\frac{K_\omega}{4H} \pm j\frac{\sqrt{8KH - K_\omega^2}}{4H}$$

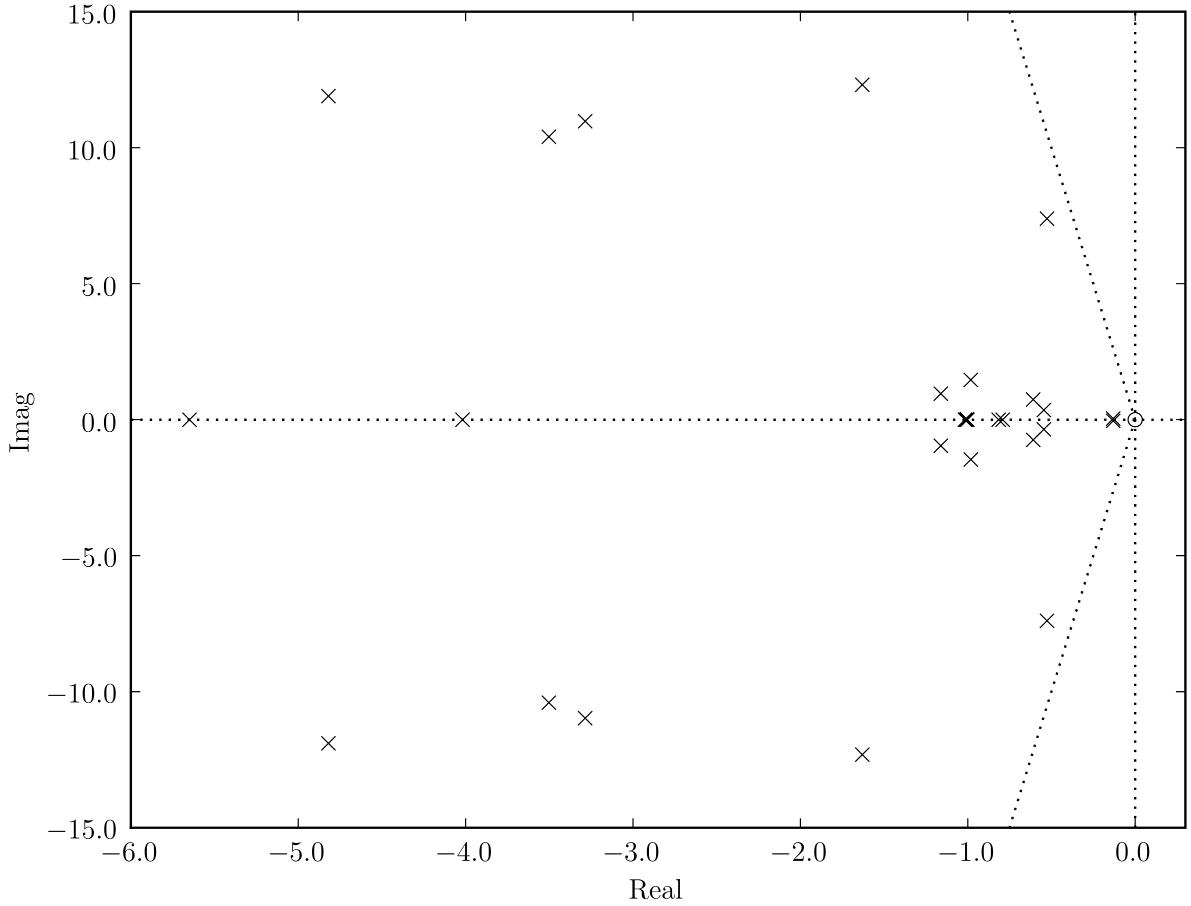
Typical PSS Scheme (I)



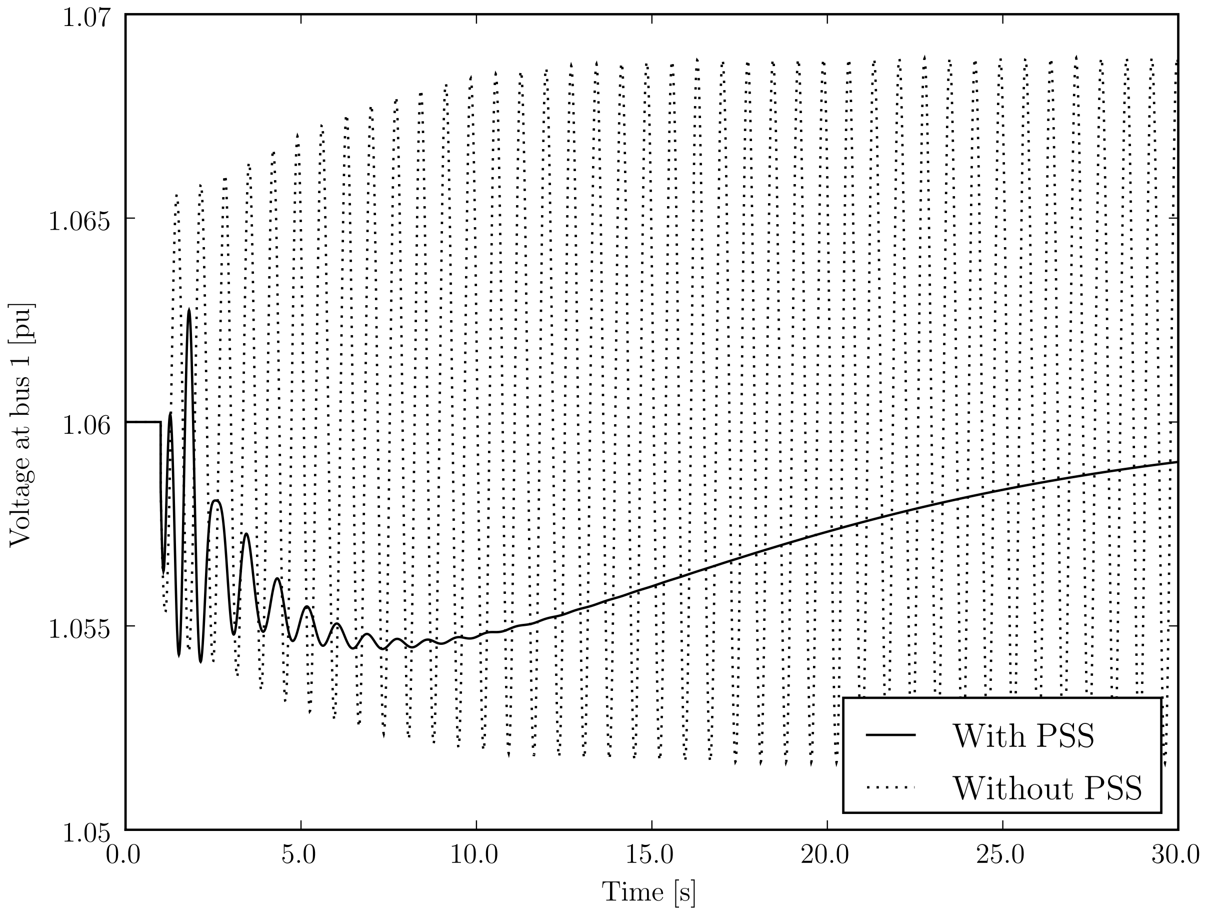
Typical PSS Scheme (II)



IEEE 14-bus System - Root Loci 120% Loading + PSS

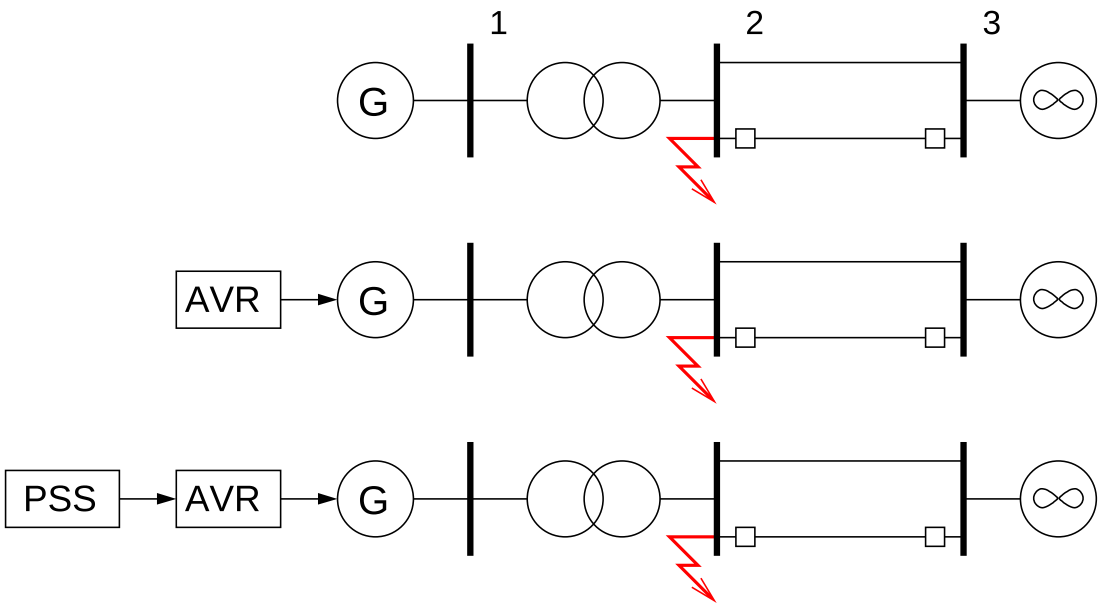


IEEE 14-bus System - Line 2-4 Outage + PSS



Example: OMIB with Different Control Schemes (I)

- Let consider the following one-machine infinite-bus system with different control schemes.

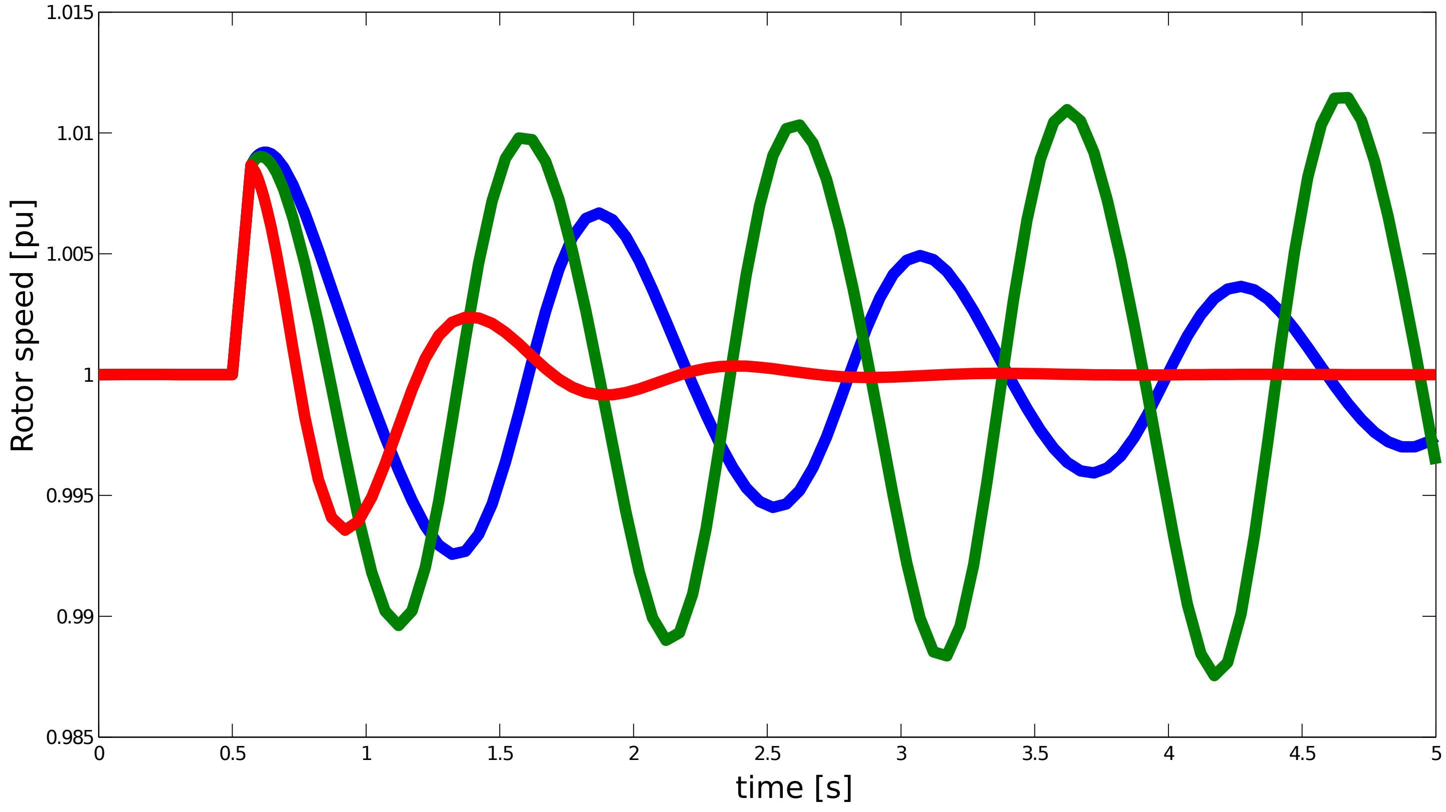


P. Kundur, “Power System Stability and Control,” Example 13.2, pp. 864-869.

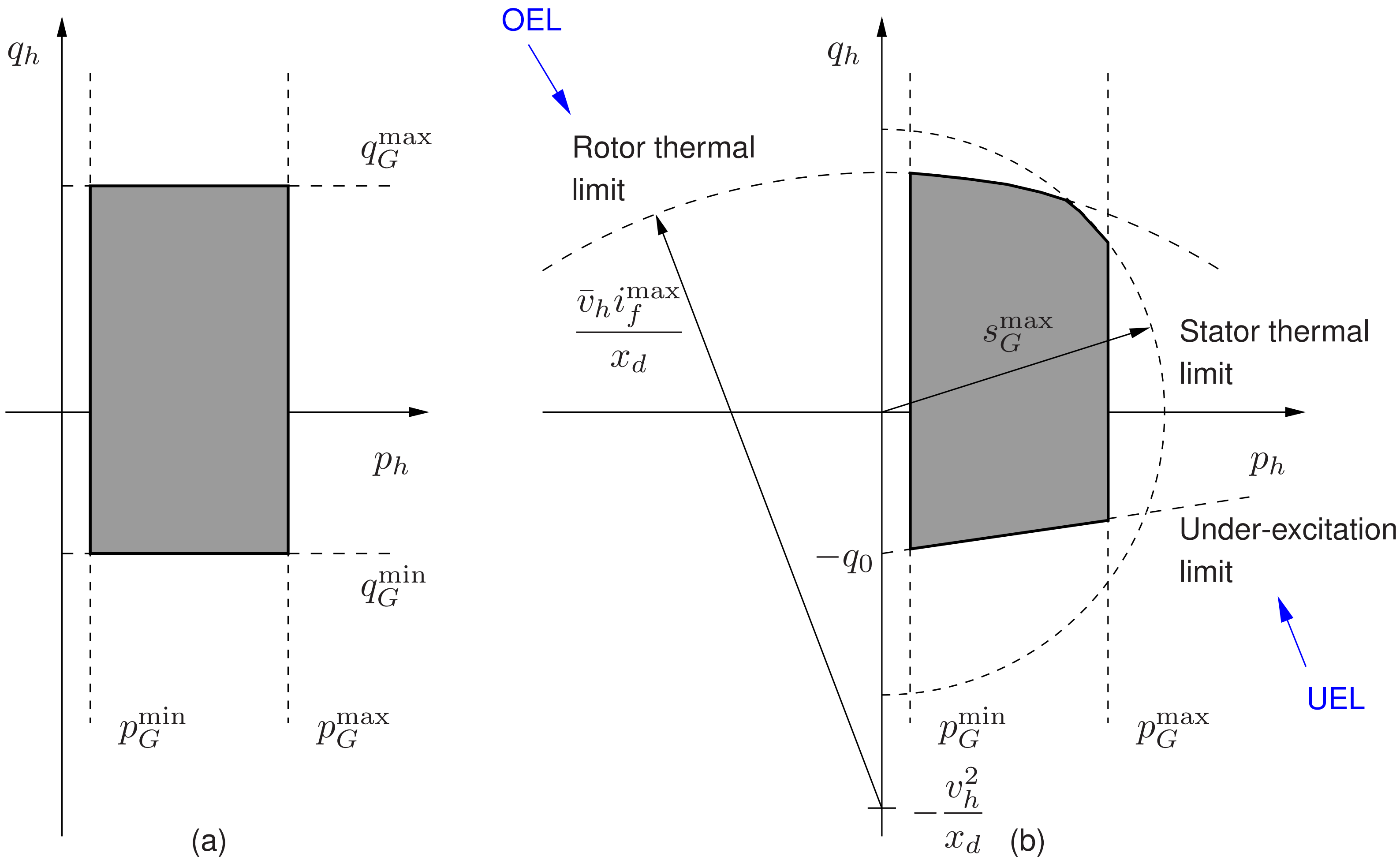
- A three-phase fault occurs close to bus 2 at $t = 0.5$ s and is cleared at $t = 0.57$ s.
- The fault is cleared by tripping one of the two lines that connect buses 2 and 3.

Example: OMIB with Different Control Schemes (II)

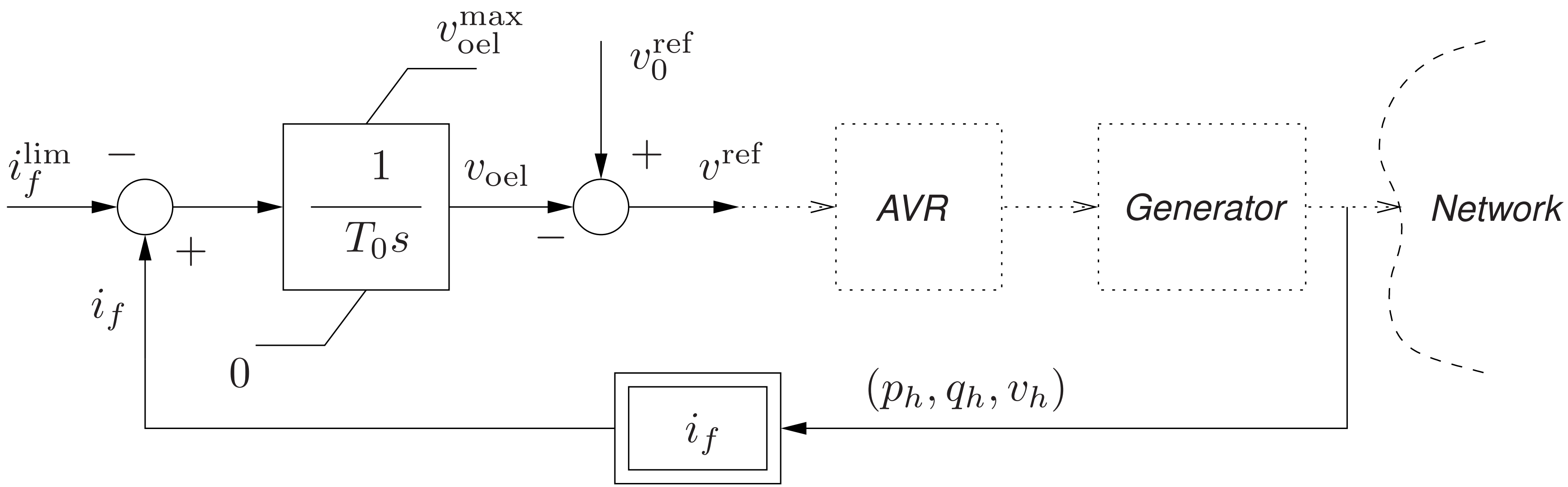
- Identify to which control scheme each rotor speed trajectory corresponds.



Generator Capability Curve



Over-Excitation Limiter (OEL)



General Expression for the Field Current

- In principle the expression of the field current depends on the machine model.
- However, if one utilizes an implicit formulation, it is possible to derive a model-independent expression, as follows:

$$\boxed{T'_{d0}\dot{e}'_q = v_f - \hat{x}_d i_f}$$

  where $\hat{x}_d = x_d - x_\ell$, and x_ℓ is the leakage reactance.
- The expression above is *implicit* as the filed current i_f depends on the firsst time derivative of e'_q.
- Note that the expression above is *always* valid, thus even in case of saturation of the machine fluxes.

Estimation of the Field Current

- For DC-machine exciters the i_f can be measured using an ammeter.
- However, other exciter technologies prevent measuring i_f (e.g. brushless).
- An approximated formula to estimate i_f is:

$$i_f = \sqrt{(v_h + \gamma_q)^2 + p_h^2} + \left(\frac{x_d}{x_q} + 1\right) \frac{\gamma_q(v_h + \gamma_q) + \gamma_p^2}{\sqrt{(v_h + \gamma_q)^2 + p_h^2}}$$

where:

$$\gamma_p = \frac{x_q p_h}{v_h} \quad \text{and} \quad \gamma_q = \frac{x_q q_h}{v_h}$$

Under-Excitation Limiter (UEL)