ELEC0047 - Power system dynamics, control and stability

Turbines and speed governors

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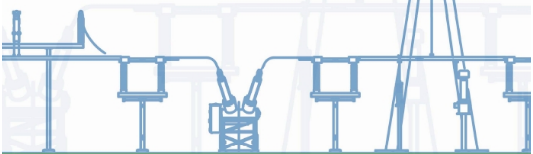
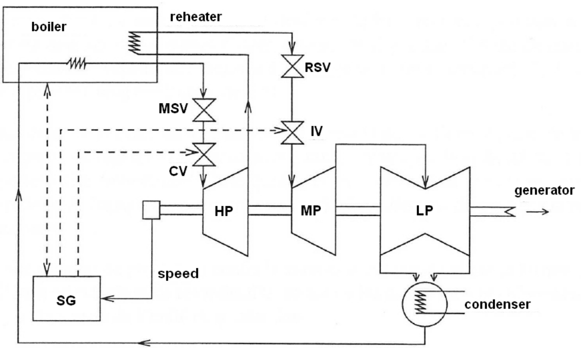
Dynamic Models for Turbine-Governors in Power System Studies

PREPARED BY THE
Power System Dynamic Performance Committee
Power System Stability Subcommittee
Task Force on Turbine-Governor Modeling



Steam turbines



SG: speed governor

measures speed and adjusts steam valves accordingly

CV: control (or high pressure) valves

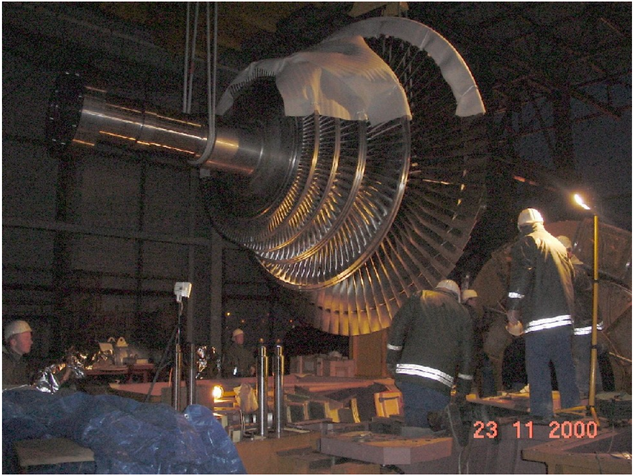
maneuvered by speed governor in normal operating conditions

IV: intercept valves

fully opened in normal operating conditions; closed in case of overspeed

MSV, RSV: main stop valve and reheater stop valve

used as back-up in case of emergency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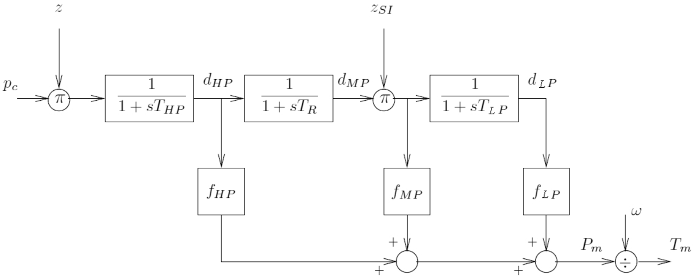
Assumptions:

- power developed in one turbine stage $\div$ steam flow at exit of that stage
- steam flow at entry of HP vessel $\div$ valve opening z $\div$ steam pressure p_c
- steam flow at exit of a vessel follows steam flow at entry with a time constant

Per unit system:

each variable is divided by the value it takes when the turbine operates at its nominal power P_N. Time constants are kept in seconds.



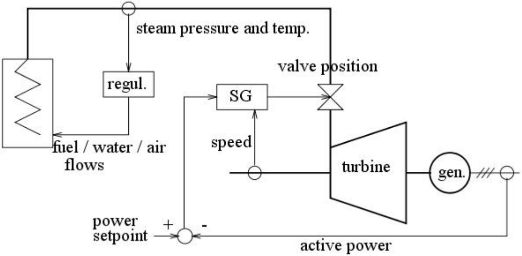
$T_{HP} \simeq 0.1 - 0.4$ s $\quad$ $T_R \simeq 4 - 11$ s $\quad$ $T_{LP} \simeq 0.3 - 0.5$ s

$f_{HP} \simeq 0.3$ $\quad$ $f_{MP} \simeq 0.4$ $\quad$ $f_{HP} + f_{MP} + f_{LP} = 1$

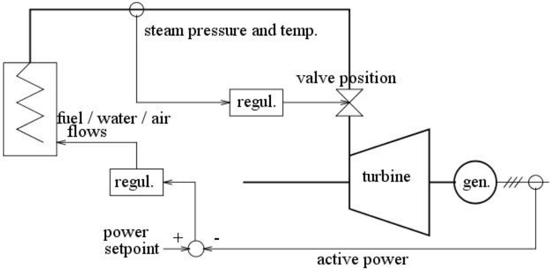
Interactions between turbine and boiler

- for large disturbances, the change in steam flow d_{HP} results in an opposite change in steam pressure p_c
- taking this into account requires to model the boiler and its controllers
- we only mention the boiler and turbine control modes

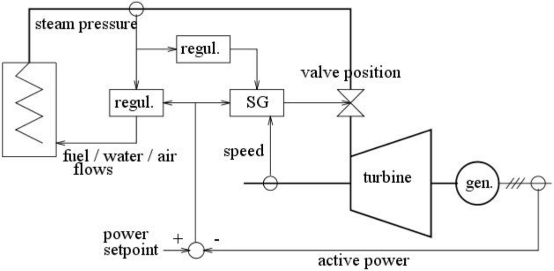
"Boiler-following" regulation



"Turbine-following" regulation

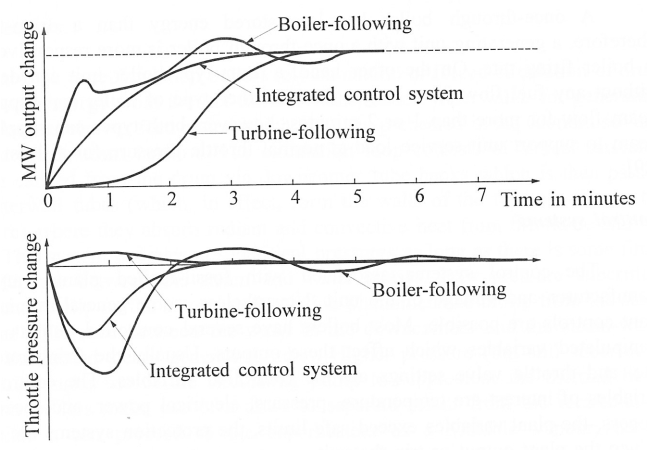


"Coordinated" or "integrated" regulation



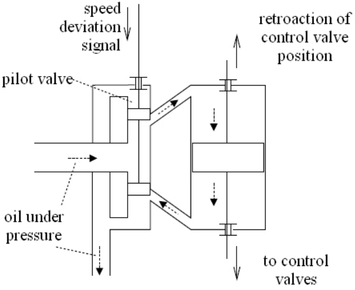
Example

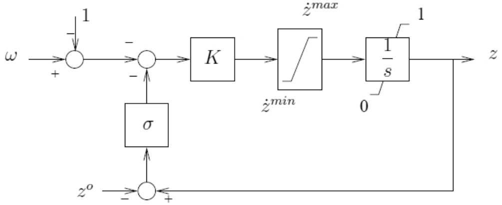
Responses to a demand of large production increase: comparison of the three regulations



Speed governors of steam turbines

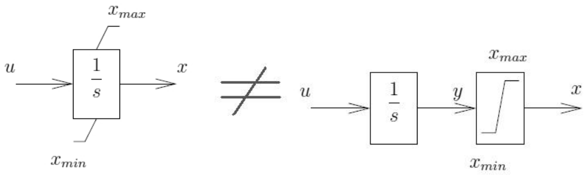
Servomotor modelling





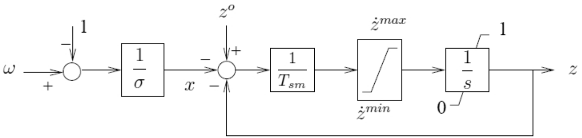
z: opening of control valves ($0 < z < 1$ in per unit)
z^o: valve opening setpoint (changed when power output of unit is changed)
σ: permanent speed droop (or statism)

The non-windup integrator



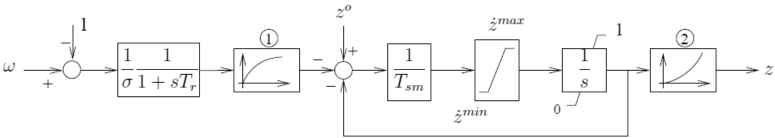
$$
\begin{aligned}
\dot{x} &= 0 \quad \text{if } x = x_{max} \text{ and } u > 0 \\
&= 0 \quad \text{if } x = x_{min} \text{ and } u < 0 \\
&= u \quad \text{otherwise}
\end{aligned}
$$

Equivalent block-diagram



$T_{sm} = 1/(K\sigma)$ servomotor time constant ($\simeq$ a few 10^{-1} s)

A little more detailed model



- T_r: time constant of "speed relay" (additional amplifier) ($\simeq$ 0.1 s)
- a transfer function $(1 + sT_1)/(1 + sT_2)$ may be used to improve dynamics
- block 2 accounts for nonlinear variation of steam flow with valve opening
- block 1 compensates block 2

Steady-state characteristics

turbine:

$$p_c = 1 \text{ pu} \qquad \Rightarrow P_m = z$$

speed governor: assuming z is not limited:

$$z = z^o - \frac{\omega - 1}{\sigma}$$

and referring to the system frequency f (in Hz) with nominal value f_N (in Hz):

$$z = z^o - \frac{f - f_N}{\sigma f_N}$$

combining both:

$$P_m = z^o - \frac{f - f_N}{\sigma f_N}$$

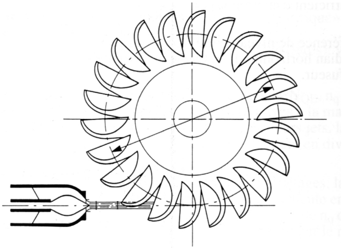
z^o seen as a power setpoint, in pu on the turbine power.

Hydraulic turbines

Action (or impulse-type) turbines

The potential energy of water is converted into pressure and then into kinetic energy by passing through nozzles. The runner is at atmospheric pressure. The high-velocity jets of water hit spoon-shaped buckets on the runner.

Pelton turbine



used for large water heights (300 m or more)

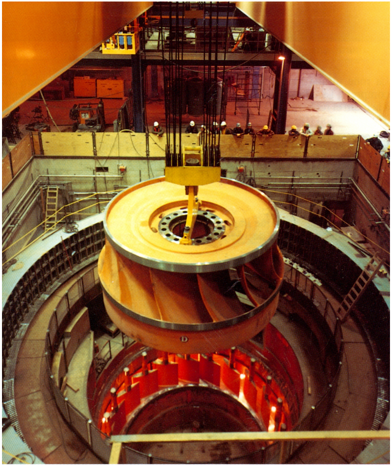
Reaction turbines

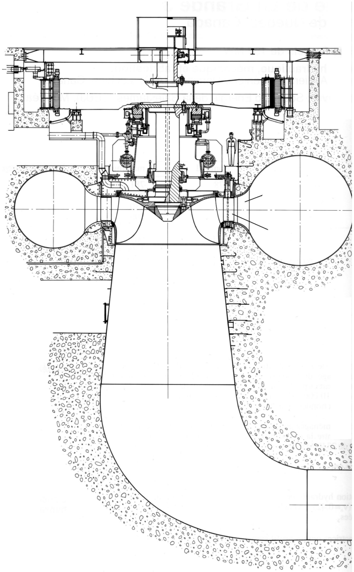
The potential energy of water is partly converted into pressure. The water supplies energy to the runner in both kinetic and pressure forms. Pressure within the turbine is above atmospheric.

Require large water flows to produce significant powers.

Rotation speeds are lower than with impulse turbines.

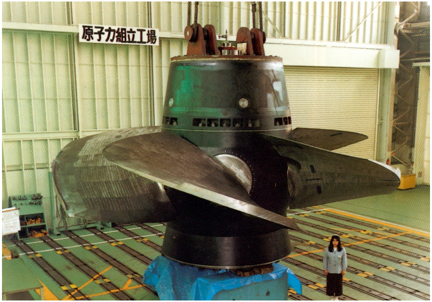
Francis turbine

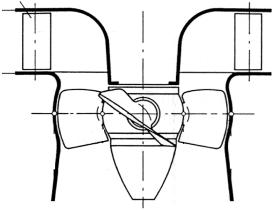




for water heights up to $\simeq 360$ m

Kaplan turbine



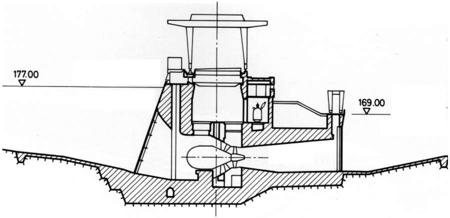


For water heights up to $\simeq$ 45 m

Variable-pitch blades can be used (angle adjusted to water flow to maximize efficiency)

Mainly used in run-of-river hydro plants

Bulb turbine



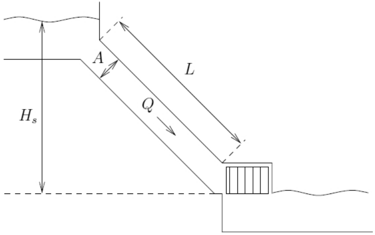
For small water heights

Mainly used in run-of-river hydro plants

Simple model of a hydro turbine

Assumptions:

- water assumed incompressible
- pressure travelling waves (hammer effect) neglected



H_s : water height

- ρ specific mass of water (kg/m^3)
- g gravity acceleration (m/s^2)
- Q water flow (m^3/s)
- v water speed in conduite (m/s)

Potential energy contained in 1 m^3 of water in upper reservoir:

$$E_{pot} = \rho g H_s$$

Total power provided by water (a part of which goes in losses):

$$P = \rho g H_s Q$$

Let's define the *head*:

$$H = \frac{E}{\rho g} \quad \text{(m)}$$

where E is the energy delivered by 1 m^3 of water.

Total power provided by water (a part of which goes in losses):

$$P = EQ = \rho g H Q$$

in steady state : $H = H_s$ during transients : $H \neq H_s$

Basic relationships:

1. mechanical power provided by turbine, taking into account losses in conduites, etc.:

$$P_m = \rho g H (Q - Q_v) \quad < P$$

2. water flow:

$$Q = k_Q z \sqrt{H}$$

z : section of gate $(0 \leq z \leq A)$

3. acceleration of water column in conduite:

$$\rho L A \, \frac{dv}{dt} = \rho g A (H_s - H)$$

$$Q = Av \quad \Rightarrow \quad \frac{dQ}{dt} = \frac{gA}{L}(H_s - H)$$

Passing to per unit values

base of a variable = value taken by variable at nominal operating point of turbine:

- mechanical power P_m = nominal power P_N of turbine
- head H = height H_s
- gate opening $z = A$
- water flow Q = nominal value Q_N
- water speed $v = Q_N/A$

At nominal operating point:

$$P_N = \rho g H_s (Q_N - Q_v) \qquad\qquad Q_N = k_Q A \sqrt{H_s}$$

Normalizing the power equation:

$$P_{m\ pu} = \frac{H}{H_s}\ \frac{Q - Q_v}{Q_N - Q_v} = \frac{H}{H_s}\ \frac{Q_N}{Q_N - Q_v}\ \frac{Q - Q_v}{Q_N} = K_P H_{pu}\,(Q_{pu} - Q_{v\ pu})$$

with $K_P = \dfrac{1}{1 - Q_{v\ pu}}$

Normalizing the flow equation:

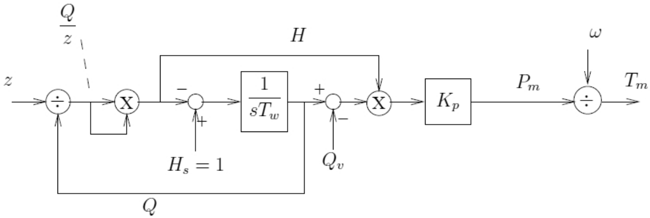
$$Q_{pu} = z_{pu}\sqrt{H_{pu}}$$

Normalizing the water acceleration equation:

$$\frac{dQ_{pu}}{dt} = \frac{g\ AH_s}{L\ Q_N}\frac{H_s - H}{H_s} = \frac{1}{T_w}(1 - H_{pu})$$

where $T_w = \dfrac{L\ Q_N}{g\ AH_s} = \dfrac{L\ v_N}{g\ H_s}$ is the *water starting time* at nominal operating point.

T_w = time taken by water, starting from standstill, to reach nominal speed under the effet of head H_s (0.5 - 4 s)



Response of a hydro turbine to small disturbances

Small disturbances around operating point $(z^o, H^o = 1, Q^o)$.

Transfer function between Δz and ΔP_m ?

$$\begin{aligned} \Delta Q &= \sqrt{H^o}\Delta z + \frac{z^o}{2\sqrt{H^o}}\Delta H \\ sT_w\, \Delta Q &= -\Delta H \\ \Delta P_m &= K_P H^o \Delta Q + K_P(Q^o - Q_v)\Delta H \end{aligned}$$

Eliminating ΔQ and ΔH yields:

$$\Delta P_m = K_P (H^o)^{3/2} \frac{1 - \frac{(Q^o - Q_v)}{z^o\,\sqrt{H^o}}\, T_w^{'} s}{1 + s\frac{T_w^{'}}{2}} \Delta z$$

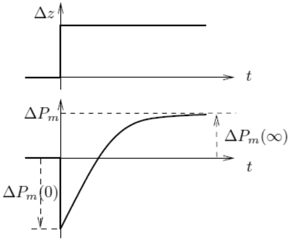
where $T_w^{'} = T_w \dfrac{z^o}{\sqrt{H^o}}$ is the water starting time at the considered operating point.

If Q_v is neglected:

$$\Delta P_m = K_P (H^o)^{3/2} \frac{1 - sT_w^{'}}{1 + s\frac{T_w^{'}}{2}} \Delta z$$

non-minimum phase system: zero in right half complex plane

- initial reaction opposite to final reaction
- Example: response ΔP_m to step change in gate opening of magnitude ΔZ:



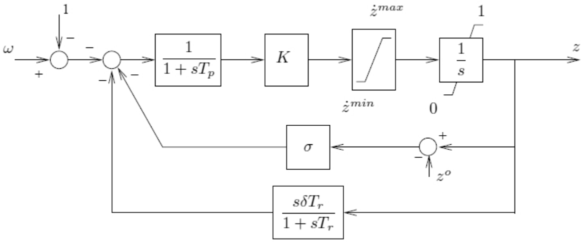
$$\lim_{t\to 0} \Delta P_m(t) = \lim_{s\to\infty} sK_P(H^o)^{3/2}\frac{1-\frac{(Q^o-Q_v)}{z^o\sqrt{H^o}}sT_w'}{1+s\frac{T_w'}{2}}\frac{\Delta Z}{s} = -2K_P H^o \frac{(Q^o-Q_v)}{z^o}\Delta Z$$

- initial behaviour: inertia of water $\Rightarrow$ speed v and flow Q do not change $\Rightarrow$ head H decreases $\Rightarrow$ mechanical power P_m decreases
- after some time: Q increases and H comes back to 1 $\Rightarrow$ P_m increases

- non-minimum phase systems may bring instability when embedded in feedback system (one branch of the root locus ends up on the zero)

Speed governors of hydro turbines

Presence of a pilot servomotor: $T_p \simeq 0.05$ s $\qquad K \simeq 3 - 5$ pu/pu



- with $\sigma \simeq 0.04 - 0.05$, the turbine and speed governor would be unstable when the hydro plant is in isolated mode or in a system with a high proportion of hydro plants
- first solution: increase σ
  $\Rightarrow$ the power plant will participate less to frequency control : not desirable
- other solution: add a compensator that temporarily increases the value of σ

In the very first moment after a disturbance:

$$\lim_{s\to\infty} \ \sigma + \frac{s\delta T_r}{1+sT_r} = \sigma + \delta$$

$\sigma = 0.04, \delta \simeq 0.2 - 1.0$, temporary droop = (6 to 26) $\times$ permanent droop

In steady state:

$$\lim_{s\to 0} \ \sigma + \frac{s\delta T_r}{1+sT_r} = \sigma$$

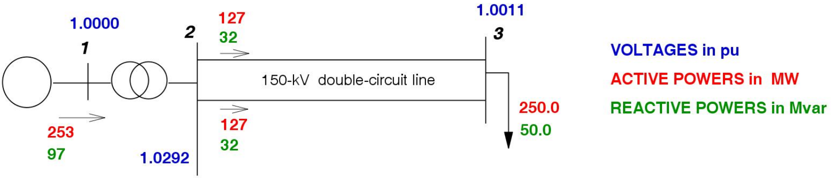
T_r: "reset time": $\simeq 2.5 - 25s$
characterizes the time to come back to the permanent speed droop.

In some speed governors, the transfer function

$$K\frac{1+sT_r}{1+s(\delta/\sigma)T_r}$$

is used in the feed-forward branch of the speed governor

Case study. Frequency regulation in an isolated system



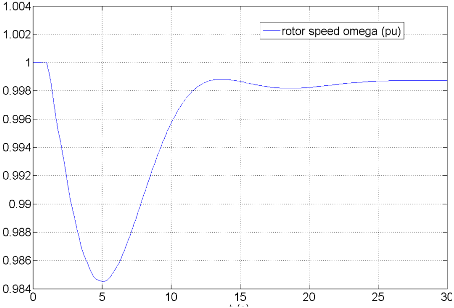
Hydro plant:

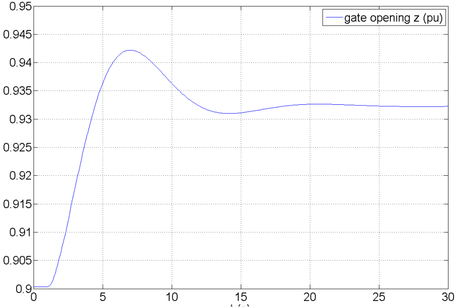
- generator: 300 MVA, 3 rotor winding model
- turbine: 285 MW, $T_w = 1.5$ s $\quad Q_v = 0.1$
- automatic voltage regulator: static gain $G = 150$
- exciter: time constant $T_e = 0.5$ s
- speed governor: $\sigma = 0.04$
  - mechanical-hydraulic : $K = 4 \quad \dot{z}^{min} = -0.02 \quad \dot{z}^{max} = 0.02$ pu/s $\quad T_p = 0$
  - PI controller: see slide No. 30

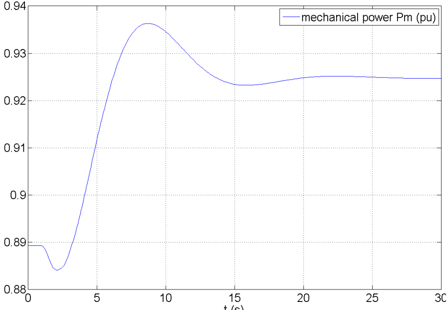
Load:

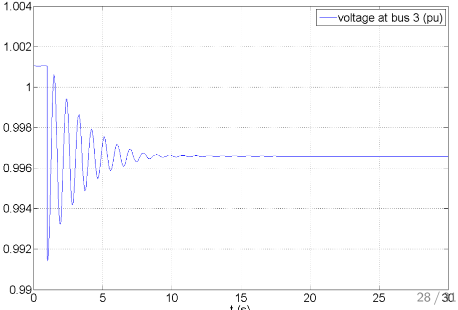
- behaves as constant impedance, insensitive to frequency
- 5 % step increase of admittance at $t = 1$ s

Mechanical-hydraulic speed governor with compensation: $\delta = 0.5 \qquad T_r = 5$ s

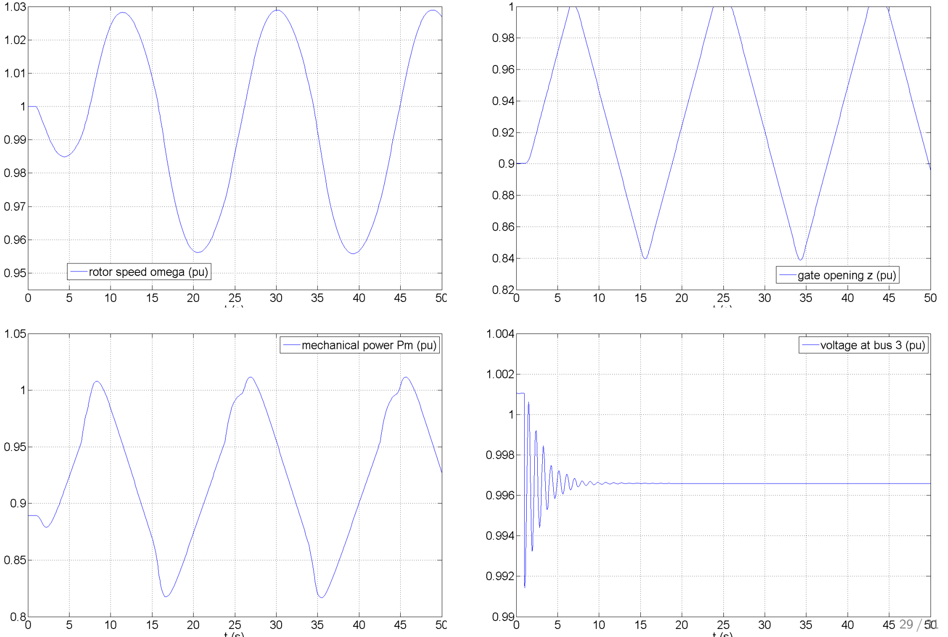




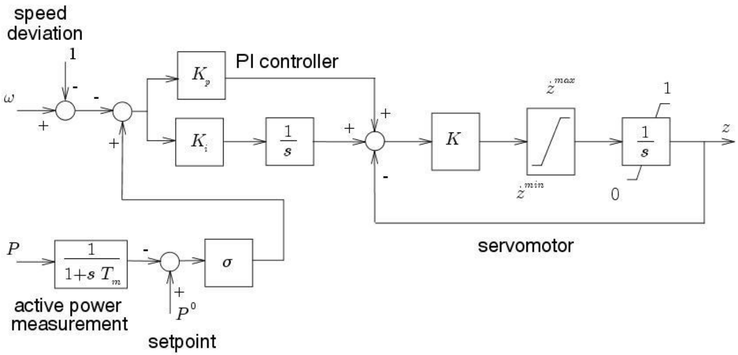




Mechanical-hydraulic speed governor without compensation ($\delta = 0.$)

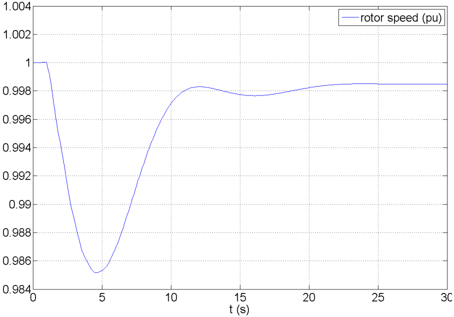


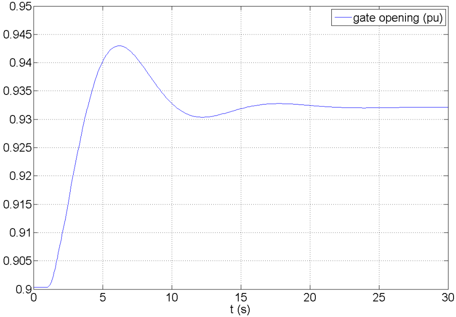
Speed governor with PI control

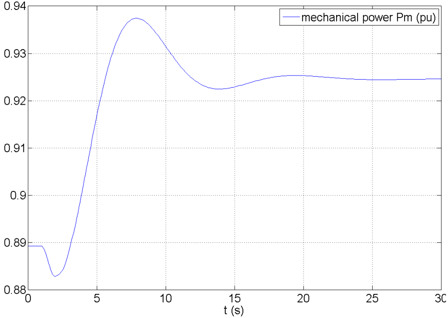


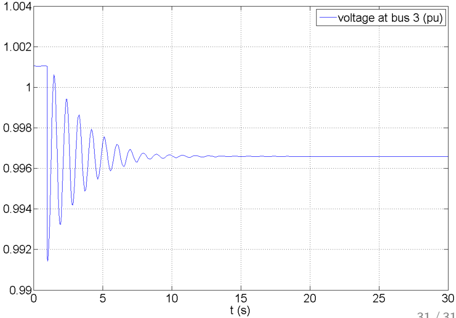
servomotor: $K = 4 \quad \dot{z}^{min} = -0.02$ pu/s $\quad \dot{z}^{max} = 0.02$ pu/s

PI controller: $T_m = 1.9$ s $\qquad K_p = 2 \qquad K_i = 0.4 \qquad \sigma = 0.04$


rotor speed (pu)
1.004
1.002
1
0.998
0.996
0.994
0.992
0.99
0.988
0.986
0.984
0
5
10
15
20
25
30
t (s)


gate opening (pu)
0.95
0.945
0.94
0.935
0.93
0.925
0.92
0.915
0.91
0.905
0.9
0
5
10
15
20
25
30
t (s)


mechanical power Pm (pu)
0.94
0.93
0.92
0.91
0.9
0.89
0.88
0
5
10
15
20
25
30
t (s)


voltage at bus 3 (pu)
1.004
1.002
1
0.998
0.996
0.994
0.992
0.99
0
5
10
15
20
25
30
t (s)