Turbines and speed governors

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Dynamic Models for Turbine-Governors in Power System Studies

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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
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.*

\[ T_{HP} \approx 0.1 - 0.4 \text{ s} \quad f_{HP} \approx 0.3 \]
\[ T_R \approx 4 - 11 \text{ s} \quad f_{MP} \approx 0.4 \]
\[ T_{LP} \approx 0.3 - 0.5 \text{ s} \quad f_{HP} + f_{MP} + f_{LP} = 1 \]
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
**Servomotor modelling**

\[ z : \text{opening of control valves} \quad (0 < z < 1 \ \text{in per unit}) \]

\[ z^o : \text{valve opening setpoint} \quad (\text{changed when power output of unit is changed}) \]

\[ \sigma : \text{permanent speed droop (or statism)} \]
The non-windup integrator

\[ \dot{x} = 0 \quad \text{if} \ x = x_{\text{max}} \text{ and } u > 0 \]
\[ = 0 \quad \text{if} \ x = x_{\text{min}} \text{ and } u < 0 \]
\[ = u \quad \text{otherwise} \]
Equivalent block-diagram

\[ T_{sm} = \frac{1}{K\sigma} \quad \text{servomotor time constant (} \sim \text{ a few } 10^{-1} \text{ s)} \]

A little more detailed model

- \( T_r: \) time constant of “speed relay” (additional amplifier) (\( \sim 0.1 \) 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:

\[ p_c = 1 \text{ pu} \quad \Rightarrow P_m = z \]

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 $\approx 45$ 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

\[ \rho \quad \text{specific mass of water (kg/m}^3\text{)} \]
\[ g \quad \text{gravity acceleration (m/s}^2\text{)} \]
\[ Q \quad \text{water flow (m}^3\text{/s)} \]
\[ v \quad \text{water speed in conduit (m/s)} \]
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:

\[ H = \frac{E}{\rho g} \text{ (m)} \]

where \( E \) is the energy delivered by 1 m$^3$ of water.

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

\[ P = EQ = \rho g HQ \]

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.:**
   
   \[ P_m = \rho g H (Q - Q_v) < P \]

2. **water flow:**
   
   \[ Q = k_Q z \sqrt{H} \]

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

3. **acceleration of water column in conduit:**
   
   \[ \rho L A \frac{dv}{dt} = \rho g A (H_s - H) \]

   \[ Q = A v \Rightarrow \frac{dQ}{dt} = \frac{gA}{L} (H_s - H) \]
Passing to per unit values

base of a variable = value taken by variable at nominal operating point of turbine:
- mechanical power $P_m = \text{nominal power } P_N$ of turbine
- head $H = \text{height } H_s$
- gate opening $z = A$
- water flow $Q = \text{nominal value } Q_N$
- water speed $v = Q_N/A$

At nominal operating point:

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

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 $K_P = \frac{1}{1 - Q_{v \ pu}}$
Normalizing the flow equation:

\[ Q_{pu} = z_{pu} \sqrt{H_{pu}} \]

Normalizing the water acceleration equation:

\[ \frac{dQ_{pu}}{dt} = \frac{g \ A \ H_s \ H_s - H}{L \ Q_N \ H_s} = \frac{1}{T_w} (1 - H_{pu}) \]

where \( T_w = \frac{L \ Q_N}{g \ A \ H_s} = \frac{L \ v_N}{g \ H_s} \) is the water starting time at nominal operating point.

\( T_w \) = time taken by water, starting from standstill, to reach nominal speed under the effect 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 \(\Delta z\) and \(\Delta P_m\) ?

\[
\Delta Q = \sqrt{H^o} \Delta z + \frac{z^o}{2\sqrt{H^o}} \Delta H
\]

\[
sT_w \Delta Q = -\Delta H
\]

\[
\Delta P_m = K_P H^o \Delta Q + K_P (Q^o - Q_v) \Delta H
\]

Eliminating \(\Delta Q\) and \(\Delta H\) yields:

\[
\Delta P_m = K_P (H^o)^{3/2} \frac{1 - (Q^o - Q_v)}{z^o \sqrt{H^o}} T'_w s \frac{T'_w}{1 + s \frac{T'_w}{2}} \Delta z
\]

where \(T'_w = T_w \frac{z^o}{\sqrt{H^o}}\) is the water starting time at the considered operating point.

If \(Q_v\) is neglected:

\[
\Delta P_m = K_P (H^o)^{3/2} \frac{1 - s T'_w}{1 + s \frac{T'_w}{2}} \Delta z
\]
non-minimum phase system: zero in right half complex plane

- initial reaction opposite to final reaction
- Example: response $\Delta P_m$ to step change in gate opening of magnitude $\Delta Z$:

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

- 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: \( T_p \approx 0.05 \text{ s} \) \( K \approx 3 - 5 \text{ pu/pu} \)

- with \( \sigma \approx 0.04 - 0.05 \), 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 \( \sigma \)
  \( \Rightarrow \) the power plant will participate less to frequency control: not desirable
- other solution: add a compensator that temporarily increases the value of \( \sigma \)
In the very first moment after a disturbance:

\[
\lim_{s \to \infty} \sigma + \frac{s \delta T_r}{1 + s T_r} = \sigma + \delta
\]

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

In steady state:

\[
\lim_{s \to 0} \sigma + \frac{s \delta T_r}{1 + s T_r} = \sigma
\]

\(T_r:\) “reset time”: \(\simeq 2.5 - 25s\)

characterizes the time to come back to the permanent speed droop.

In some speed governors, the transfer function

\[
K \frac{1 + s T_r}{1 + s(\delta / \sigma) T_r}
\]

is used in the feed-forward branch of the speed governor
Hydro plant:
- generator: 300 MVA, 3 rotor winding model
- turbine: 285 MW, $T_w = 1.5$ s $Q_v = 0.1$
- automatic voltage regulator: static gain $G = 150$
- exciter: time constant $T_e = 0.5$ s
- speed governor: $\sigma = 0.04$
  - mechanical-hydraulic: $K = 4$ $\dot{z}^{\text{min}} = -0.02$ $\dot{z}^{\text{max}} = 0.02$ pu/s $T_p = 0$
- 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: $\delta = 0.5 \quad T_r = 5 \text{ s}$
Mechanical-hydraulic speed governor without compensation ($\delta = 0.$)
Speed governor with PI control

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Servomotor</td>
<td>$K = 4$  $\dot{z}<em>{\text{min}} = -0.02 \text{ pu/s}$  $\dot{z}</em>{\text{max}} = 0.02 \text{ pu/s}$</td>
</tr>
<tr>
<td>PI controller</td>
<td>$T_m = 1.9 \text{ s}$  $K_p = 2$  $K_i = 0.4$  $\sigma = 0.04$</td>
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</tbody>
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