Steam Turbine Seminar -17
Lund University
Something on hydraulics…

N.B. This is an old setup with 1 of 2 – the state-of-the-art is 2 out of 3 trip redundancy (both the protection system and the hydraulics)

- The safety system works like a three-way valve
- The trip system will simply de-pressurize the hydraulics system
- Most “direct” trips such as speed and condenser pressure have been replaced by 2/3 measuring devices (and trips)
- The 2/3 philosophy makes it possible to “test” the trip all the way to the hydraulics
- ESV movability test
Trip logic – non exhaustive principle

Hard-wired

<table>
<thead>
<tr>
<th>Ch.1</th>
<th>Ch.2</th>
<th>Ch.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>P cond &lt; max</td>
<td>P cond &lt; max</td>
<td>P cond &lt; max</td>
</tr>
<tr>
<td>High brg temp</td>
<td>High exh temp</td>
<td>N.N.</td>
</tr>
<tr>
<td>≥1</td>
<td>≥1</td>
<td>≥1</td>
</tr>
</tbody>
</table>

PLC

<table>
<thead>
<tr>
<th>1oo2</th>
<th>2oo3</th>
</tr>
</thead>
<tbody>
<tr>
<td>N.N.</td>
<td>Vibrations</td>
</tr>
<tr>
<td>≥1</td>
<td>≥2</td>
</tr>
</tbody>
</table>

Lube oil pres

| Bus |
| 2oo3 |
| ≥2 |

Trip block 2oo3

≥1

Pcond < max

≥2

Speed < max

≥2

N.N.

≥1

High brg temp

≥1

High exh temp

≥1

Pcond < max

≥2

N.N.

≥2

Vibrations

≥2

Lube oil pres

≥2
Trip block – two out of three logic

Channel A  Channel B  Channel C

Hydraulic supply unit

Pressure switch

Manual trip valve

ESV
Trip block – test

Tripped channel

Hydraulic supply unit

Pressure switch

ESV

Manual trip valve

No pressure!
Trip block – trip

Hydraulic supply unit

Tripped channel

No pressure!

ESV

Manual trip valve

Pressure switch

ESV

Manual trip valve
The "Duck-Curve"…

Japan

California

Sweden

**Fig. 1**

*California’s Duck Curve*

Trends in resource development are leading toward a growing need for flexible generating capacity starting in 2015.

![Graph showing California's duck curve with peak demand at 4.3 GW/h](image-url)

- **2012 (actual)**
- **2013 (actual)**
- **2014**
- **2015**
- **2016**
- **2017**
- **2018**
- **2019**
- **2020**

- Natural load: March 31
- Over generation risk
- Ramp need: ~13,000 MW in three hours

4.3 GW/h
Flexibility

Start
Steady state
Active generation control
Spinning reserve
off-peak turndown
SS
Shutdown

Frequency response PFR + SFR
Fast ramp-up and ramp-down support
Minimum environmental load
Islanding, off-grid

Black start and support of grid restoration
Fast start-up
Primary frequency response
Secondary frequency response
Acceleration and stabilization of load ramps
Operating reserve for peak power
Minimum load
Islanding off-grid

Flex operation line (with SIESTART)
Standard operation line

Load
Start
Steady state
Active generation control
Spinning reserve
off-peak turndown
SS
Shutdown

Load

Courtesy of Siemens
Start-up transient stress

![Graph showing start-up transient stress](image)

Typical ST roll via IP steam admission and the ensuing warm-up period [6]. Representative of a single-shaft GTCC cold start (total three hours). Note how the quasi-stationary Phase II is preceded by a short non-stationary period.

Courtesy of John Gülen, “Gas Turbine Combined Cycle Fast Start: The Physics Behind the Concept"
Turbine pressures vs. flow (load)

\[ Q = U \cdot A \cdot LMTD \]
\[ Q = m_{CW} \cdot c_{p,CW} \cdot (T_{CW,in} - T_{CW,out}) \]
\[ Q = m_{Steam} \cdot (h_{Steam} - h_{Cond}) \]
Condenser pressure vs. flow (load)

Relative pressure [%] vs. Relative flow [%]

- Condenser pressure
- Linear
- Extraction #1 pressure
- Pressure ratio

Turbine load

\[ Q = U \cdot A \cdot LMTD \]
\[ Q = m_{CW} \cdot c_{p,CW} \cdot (T_{CW,in} - T_{CW,out}) \]
\[ Q = m_{Steam} \cdot (h_{Steam} - h_{Cond}) \]
The proof...
## Grid codes

<table>
<thead>
<tr>
<th></th>
<th>Germany</th>
<th>United Kingdom</th>
<th>Japan</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transmission code</strong></td>
<td>VDN</td>
<td>National grid</td>
<td>Japan Electric Association</td>
</tr>
<tr>
<td><strong>2007</strong></td>
<td>0 V—0.15 s</td>
<td>0 V—0.14 s</td>
<td>Wind power</td>
</tr>
<tr>
<td></td>
<td>85% V—15 s</td>
<td>15% V—0.14 s</td>
<td>0 V—0.15 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80% V—1.2 s</td>
<td>90% V—15 s</td>
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<tr>
<td></td>
<td></td>
<td>85% V—2.5 s</td>
<td>(2-cycle GB is permitted)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90% V—3 min</td>
<td>(2-cycle GB is permitted)</td>
</tr>
<tr>
<td><strong>FRT</strong></td>
<td>Renewable energy</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>0 V—0.15 s (brownout period undefined)</td>
<td>Max 100%</td>
<td></td>
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<tr>
<td></td>
<td>2% 1%/ΔV, Max 100%</td>
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<td>Wind power</td>
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<tr>
<td></td>
<td>20% P/min</td>
<td></td>
<td>20% V—0.3 s or less</td>
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<td></td>
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<td></td>
<td>Continuous operation</td>
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<td></td>
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<td></td>
<td>(2-cycle GB is permitted)</td>
</tr>
<tr>
<td><strong>Frequency fluctuation</strong></td>
<td>Renewable energy</td>
<td></td>
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<tr>
<td></td>
<td>&gt;±0.2 Hz droop gain 5% (MW decrease)</td>
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<td>&lt;—0.5 Hz 10%</td>
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<td></td>
<td>UP in 10 s and keep 30 min (some excluded)</td>
<td></td>
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<tr>
<td></td>
<td>Droop control</td>
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<tr>
<td></td>
<td>Control width ±2%</td>
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<tr>
<td><strong>Thermal power</strong></td>
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</table>
Grid stability

The inertia constant:

\[
\tau_I = \frac{E_r}{P_{nom}} = \frac{1/2 \cdot I_r \cdot \omega^2}{P_{nom}} = 1/2 \cdot (2 \cdot \pi \cdot f)^2 \cdot \frac{I_r}{P_{nom}} \quad \left[\frac{J}{J/s} = s\right]
\]

The inertia constant is typically within the range of 5 and 10 seconds:

**Nominal power = 500 MW**

5 s. \quad 2500 MJ

10 s. \quad 5000 MJ

Energy required during a start @ 5000 MJ, as 48 MJ/kg natural gas:

\[
\frac{5000}{48} \cdot \frac{1}{0.4} \approx 260 \text{ kg}
\]

This is equivalent of some 280000 cups of tea!
Grid stability

10 units á 500 MW running at 90 % load – 4500 MW

\[
\begin{align*}
\text{Grid demand (4500 MW)}
\end{align*}
\]

\[
\begin{align*}
\text{Speed/frequency vs. time @tau=10 s.}
\end{align*}
\]

\[
\begin{align*}
f(t) &= \sqrt{f_{\text{nom}}^2 + \frac{\Delta P}{P_{\text{nom}}} \cdot f_{\text{nom}}^2 \cdot \tau_i \cdot t} \\
\left(\frac{df}{dt}\right)_{@t=0} &= \frac{\Delta P}{2 \cdot \tau_i \cdot P_{\text{nom}}} \cdot f_{\text{nom}}
\end{align*}
\]
Grid stability

10 units á 500 MW running at 90 % load – 4500 MW

\[
\left(\frac{df}{dt}\right)_{@t=0} = \frac{\Delta P}{2 \cdot \tau_I \cdot P_{nom}} \cdot f_{nom}
\]

Self regulating

\[
\frac{df}{dt} = \frac{\Delta P - \frac{a}{100} \cdot P_{init} \cdot (f_{nom} - f) + P_{pc}}{P_{nom}} \cdot f_{nom}^2 \cdot \frac{1}{2 \cdot f \cdot \tau_I}
\]
Increased flexibility – starting

- Stress controller
  - State-of-the

- Blankets
  - Since the 80s – mature if OEM involved

- Hot air
  - High initial cost
  - Very effective

- High-speed barring
  - Risky…
Heating blankets
Hot-air ST warming

- Used by Karlshamnsverket (KKAB) since 1980s
  - Large 340MW HP-IP-LP Alstom (BBC) utility turbines
- Flanges for blower/heater
- Open vacuum breaker
  - About 15 minutes for hogging/vacuum pull
  - No corrosion risk since RH<<60 percent
Background

in emphysematous vein of the pulmonary capillaries is also shown in Fig. 5. The pressure drop is


due to the relative size of the vessel and the resistance of the surrounding tissue.

Man is also more likely to experience similar symptoms when:

- HP and IP valves
- HP and IP inlet lines.

It is thus dependent on the time that has passed since shutdown, assuming natural cooling (Fig. 65).

This necessitates the steam temperature, a very significant factor in the design and operation of HP and IP turbine sections,

Owing to the different thermal characteristics of the individual components (Section 6.3.1) and the high heat capacity of the HP turbine section, the steam should be chosen within a certain time period after the last stop of the engine (as short as possible and to protect the turbine from cold shut downs) and kept at least 30 min, taken from the characteristic temperature zones (Fig. 65) and the corresponding cooling time (Fig. 65).

steam, take into account the temperature drop caused by the steam turbine's condensation and the heat of steam expansion. They also take into account the shortest possible heat-up time under load which is achieved by combining an initial temperature step with a specific subsequent temperature transient, while at the same
time an undesired cooling of the HP outlet zone is avoided.

If the plant is started cold it is essential that, apart from the aspects mentioned so far, special attention is paid to the risk of brittle fracture.

An economic and safe method of preheating components which are subjected to centrifugal forces and compression stress to a temperature which ensures adequate resistance to fracture, is to warm all turbine sections for two to three hours using auxiliary steam (p = approx. 10 to 10 bar; 

0 = approx. 250 to 350 °C) or gland steam at an elevated condenser pressure. This method permits particularly the IP exhaust area and the low-pressure rotor to be sufficiently warmed up without major start-up losses resulting from a

too long-bypass operation. Moreover, load can be applied relatively quickly even during cold starting.

No-load operation and load application:

During no-load operation, particularly the exhaust steam temperature of the HP turbine section rises, especially when the pressure in the cold reheat line is relatively high.

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High-speed barring

• Both ventilation and disk friction feed energy into the trapped steam.
  – Scales with speed cubed and density
  – Normal barring speed is approx. 200 rpm

• Potential risk of uneven temperature
  – More work with longer blades and stage diameter
  – LSB spray cooling
  – Pipe and valve from HP-extraction to condenser
Shaft glands
Gland system – Increased pressure
No or low load

- The mass flow of seal steam into the turbine(s) follow a Fanno line
- Steaming seals should be avoided
- Steam into the HPT through seal off-load pipe(s)
- Steam supply must be available
- No hard-ware modifications
Increased flexibility – in operation

• Capacity bypass
  – Loss one in use

• Extra arc
  – Small loss when not used

• Top-heater shut-down
  – Thrust force

• Condensate pump shut-down – sliding pressure mode
  – Caveat! Drum- and hot well levels
Enhanced flexibility

- HP-FWH bypass
- Capacity bypass
- Top-heater for constant FW-temp

\[ \frac{m_{\text{bypass}}}{m_{FW}} \leq 0.7 \]
Rotor stress – temperature gradients

Temperature induced stresses (radial and hoop):

\[ \sigma_r(r) = \frac{\alpha E}{1 - \mu} \left( \frac{r^2 - r_i^2}{r_y^2 - r_i^2} \right) \left[ T_r dr - \int_{r_i}^{r} T_r dr \right] \]

\[ \sigma_\theta(r) = \frac{\alpha E}{1 - \mu} \left( \frac{r^2 - r_i^2}{r_y^2 - r_i^2} \right) \left[ T_r dr - \int_{r_i}^{r} T_r dr - Tr^2 \right] \]

Simplified equations for a case without a bore:

\[ \sigma_r(r) = \alpha E \left( \frac{1}{r_{rim}} \int_{r_i}^{r_{rim}} T(r) dr - \frac{1}{r_i^2} \int_{r_i}^{r} T(r) dr \right) \approx \frac{\alpha E \Delta T}{3} \left( 1 - \frac{r}{r_{rim}} \right) \]

\[ \sigma_\theta(r) = \alpha E \left( \frac{1}{r_{rim}} \int_{r_i}^{r_{rim}} T(r) dr - \frac{1}{r_i^2} \int_{r_i}^{r} T(r) dr - Tr \right) \approx \frac{\alpha E \Delta T}{3} \left( 1 - 2 \frac{r}{r_{rim}} \right) \]

Example

\[ \alpha = 1.8 \cdot 10^5 \, ^\circ \text{C}^{-1} \]
\[ E = 6.9 \cdot 10^4 \, \text{MPa} \]
\[ \Delta T = 55 \, ^\circ \text{C} \]
\[ \sigma_{r=0} = 46 \, \text{MPa} \]
### Rotor stress – temperature gradients

- The HPT-example shows a load change from full to 1/3 load
- IPT swallowing capacity and re-heater temperature controls the HPT back-pressure

<table>
<thead>
<tr>
<th>Control mode</th>
<th>ΔT first stage</th>
<th>ΔT exhaust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial arc</td>
<td>94°C</td>
<td>61°C</td>
</tr>
<tr>
<td>Throttle</td>
<td>46°C</td>
<td>28°C</td>
</tr>
<tr>
<td>Sliding</td>
<td>3°C</td>
<td>18°C</td>
</tr>
</tbody>
</table>

![Diagram]
Fatigue – low or high?

Based on Tanuma & Tadashi, "Advances in Steam Turbines for Modern Power Plants"
Casing wall temperature probe
Avancerad turbinregulator
## Aged deterioration – failures

<table>
<thead>
<tr>
<th>Type of deterioration</th>
<th>Mode of deterioration</th>
<th>Damage or incidence</th>
<th>Typical damaged portion</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Creep</strong></td>
<td></td>
<td>Crack</td>
<td>HP/IP shroud, blade groove, HP/IP casing, main pipes, main valves</td>
</tr>
<tr>
<td><strong>Embrittlement</strong></td>
<td></td>
<td>Brittle fracture</td>
<td>HP/IP rotor</td>
</tr>
<tr>
<td><strong>Fatigue</strong></td>
<td></td>
<td>Crack</td>
<td>HP/IP heat groove, bottom of blade root groove</td>
</tr>
<tr>
<td><strong>Thermal fatigue</strong></td>
<td></td>
<td>Crack</td>
<td>LP last blades groove of LP rotor, HP/IP casings</td>
</tr>
<tr>
<td><strong>Low-cycle fatigue</strong></td>
<td></td>
<td>Crack</td>
<td>HP/IP blade groove of rotor</td>
</tr>
<tr>
<td><strong>Fretting</strong></td>
<td></td>
<td>Crack</td>
<td>Blade groove of LP rotor</td>
</tr>
<tr>
<td><strong>Dynamic SCC</strong>*</td>
<td></td>
<td>Crack</td>
<td>Blade groove of LP rotor</td>
</tr>
<tr>
<td><strong>Static SCC</strong>*</td>
<td></td>
<td>Crack</td>
<td>Blade root and groove, shroud and profile</td>
</tr>
<tr>
<td><strong>Environment assisted crack</strong></td>
<td></td>
<td>Crack</td>
<td>Casing bolts (high temperature)</td>
</tr>
<tr>
<td><strong>Softening</strong></td>
<td></td>
<td>Loosening</td>
<td>HP/IP diaphragm nozzle plate (impulse), HP/IP rotor and inner casings (leak)</td>
</tr>
<tr>
<td><strong>Creep</strong></td>
<td></td>
<td>Deformation</td>
<td>Seals, bearings, valve shafts</td>
</tr>
<tr>
<td><strong>Wear/rubbing</strong></td>
<td></td>
<td>Efficiency decrease</td>
<td>Control stage nozzle and LP last stages</td>
</tr>
<tr>
<td><strong>Erosion/FAC</strong></td>
<td></td>
<td>Efficiency decrease</td>
<td>HP/IP nozzles and blades, main valves</td>
</tr>
<tr>
<td><strong>Scale deposition</strong></td>
<td></td>
<td>Efficiency decrease, stick, rubbing</td>
<td></td>
</tr>
</tbody>
</table>

*Stress corrosion cracking

Based on Tanuma & Tadashi, “Advances in Steam Turbines for Modern Power Plants”
Environment assisted crack

- Static stress
- Repetitive stress
- Vibration stress

- SCC
- Dynamic SCC
- Corrosion fatigue

- Strength – high is more suspicious for SCC
- Impurities etc.

- Temperature
- Wetness*
- Dissolved oxygen
- Impurities in steam
- Start-up and shutdown

*Wilson zone

Corrosive environment

Based on Tanuma & Tadashi, "Advances in Steam Turbines for Modern Power Plants"
Turbine damage – erosion
Solid particle erosion (SPE)

N.B. This is a very design specific problem!!!
Turbine damage – rubbing