Hydroelectric Power Plants; Construction, Operation & Failures
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• Brief Norconsult introduction
• Hydro Power in a global energy source perspective
• Hydro Power plant types, definitions and description of major components
• Common failures during operation
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  – Generators
  – Waterway
• Risks, and ways to mitigate them
• Questions
Countries where Norconsult has had projects
Norconsult's role within hydro power

- Norconsult is Norway's largest consulting company with 2400 employees.
- In the hydropower industry since 1917, and has planned and designed approximately 70% of the 340 Norwegian hydropower plants larger than 10 MW, plus a significant number of plants worldwide.
- We assist hydropower plant owners during all phases of new projects, upgrades and in solving operational problems. We perform vibration and pressure measurements to determine the dynamic behaviour of hydropower units and perform special investigation if needed.
- Norconsult has one of the world largest condition evaluation database based on vibration measurements where data from more than 400 generators and turbines are collected.
- Experience also include advanced field measurements such stress measurements during operation, on prototype turbine runners since 1997, of different types and from different suppliers.
- Our key activities also include trouble shooting, assistance after breakdown, root cause analyses etc., for plant owners, equipment suppliers and insurance companies (both for preventive measures and independent failure investigation).
Global Energy Source Distribution

Renewable energy, end of 2008 (GW)

- Large hydropower
- Biomass heating*
- Solar collectors for hot water/pace heating*
- Wind power
- Small hydropower
- Ethanol production**
- Biomass power
- Geothermal heating*
- Solar PV, grid-connected
- Biodiesel production**
- Geothermal power
- Concentrating solar thermal power (CPS)
- Ocean (tidal) power

* GWth
** Billion liters/year

Total vs. Renewable

860

85
121
145*
250*
50*13
67**
12**
0.5
0.3

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## Hydro Power Production Countries

Ten of the largest hydroelectric producers as at 2009.\[28][30]\n
<table>
<thead>
<tr>
<th>Country</th>
<th>Annual hydroelectric production (TWh)</th>
<th>Installed capacity (GW)</th>
<th>Capacity factor</th>
<th>% of total capacity</th>
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<tbody>
<tr>
<td>China</td>
<td>652.05</td>
<td>196.79</td>
<td>0.37</td>
<td>22.25</td>
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<tr>
<td>Canada</td>
<td>369.5</td>
<td>88.974</td>
<td>0.59</td>
<td>61.12</td>
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<tr>
<td>Brazil</td>
<td>363.8</td>
<td>69.080</td>
<td>0.56</td>
<td>85.56</td>
</tr>
<tr>
<td>United States</td>
<td>250.6</td>
<td>79.511</td>
<td>0.42</td>
<td>5.74</td>
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<tr>
<td>Russia</td>
<td>167.0</td>
<td>45.000</td>
<td>0.42</td>
<td>17.64</td>
</tr>
<tr>
<td>Norway</td>
<td>140.5</td>
<td>27.528</td>
<td>0.49</td>
<td>98.25</td>
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<tr>
<td>India</td>
<td>115.6</td>
<td>33.600</td>
<td>0.43</td>
<td>15.80</td>
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<td>Venezuela</td>
<td>85.96</td>
<td>14.622</td>
<td>0.67</td>
<td>69.20</td>
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<td>Japan</td>
<td>69.2</td>
<td>27.229</td>
<td>0.37</td>
<td>7.21</td>
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<td>Sweden</td>
<td>65.5</td>
<td>16.209</td>
<td>0.46</td>
<td>44.34</td>
</tr>
</tbody>
</table>
Hydro Power Plant, principal sketch

- Attractive: Eco-friendly - no emissions, profitable, low O&M costs, long lifetime
- But: All components can and do fail, including surrounding elements such as rock, soil and concrete
Hydro Power Plant, high head - principal sketch

- Power house components exposed to high pressure
- Relatively low flow

*Head* = hydraulic head = pressure of water column = vertical distance between upper and lower reservoir
Hydro Power Plant, low head - principal sketch

- Large components, high discharge, low head
The selection of turbine type is based on the combination of head and discharge.
Vertical pelton turbine - Principal sketch

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Horizontal Pelton turbine - principal sketch
Vertical Francis turbine - principal sketch

© KVÆRNER / Rainpower
Horizontal Francis - principal sketch
Kaplan turbine - principal sketch

© KVÆRNER / Rainpower
Bulb turbine (low head) - principal sketch

© KVÆRNER / Rainpower
Generator types

- Synchronous type (asynchronous for mini hydro applications)
- Vertical and horizontal orientation
- Horizontal orientation
- Vertical orientation

© KVÆRNER / Rainpower

© VG Power
Failures and breakdowns

• Example of total generator and turbine breakdown; generator fire, shaft rupture, parts thrown off
• Causing fatalities, severe plant damage, and years of outage
Pelton breakdown - buckets thrown off
Pelton breakdowns, cont'd

- Crack propagation at bucket root, causing the runner to throw the bucket off, through housing etc.
Pelton turbine breakdowns

- Bucket cracks, especially dangerous when it occurs in the root area

- Insufficient crack resistance from workshop (poor specification - wrong choice of material or production method, poor hydraulic and/or mechanical design, poor material or workmanship, poor inspection follow-up)

- Insufficient crack inspection routines during operation

- Sand / particles
Pelton turbine breakdowns

- Deflector or injector breakdown
- Injector entering the rotating runner, causing breakdown
- Non-functioning deflector, causing the generator to overspeed and fail (is however supposed to handle some minutes of runaway speed)
Cavitation

- Cavitation pitting eats up the runner (photo above <1 year of operation)
- Caused by poor turbine or plant design, allowing local water pressure to get too low
Cracks in Francis runners
Cracks in Francis runners - historical view

© KVÆRNER / Rainpower
Cracks in Francis runners - historical view

© KVÆRNER / Rainpower
Francis turbine breakdowns, cont'd
Francis Runner Breakdowns - A Hot Potato

- There has been an increasing number of failures of Francis runners in Norwegian hydro power plants due to crack propagation in the blades after only short time in operation
- High efficiency achieved, but at the cost of mechanical strength

How to mitigate this risk?

When tendering for new turbines and replacement runners:
- Strict evaluation criteria for turbine efficiency and pricing
- General criteria for mechanical robustness, these criteria may be difficult to quantify
- More use of field measurements on prototypes? Present the major dynamic forces acting on the runner blades, and evaluate the effect against field measurements on prototype runners?
Generator failures, damage and root causes

Data from a recent Cigre survey of 1200 generators from five countries:

- Insulation
- Thermal
- Mechanical
- Bearing

![Root causes chart]

Figure 2: Root causes

© Cigre (International Council of Large Electric Systems)
Generator failures

- Rotor coil cracking
- Stator sheet insulation failure
Full scale stator winding destruction

© Cigre
Generator failures, outage time

Figure 5: Distribution of the incidents by root cause of failure and by outage

© Cigré
Sediments, global distribution

Average sed. cons. 20% bedload is incl.

13250 ppm
5300 ppm
2650 ppm
1325 ppm

Desert

1325 ppm ≈ 1 m³ deposit
1000 m³ water
Sand erosion
Sand erosion
Waterway transients out of control..
Some problems caused by poorly designed turbine governor or hydraulic transients out of control:

- Breakdown of turbine or mechanical balance components due to pressure rise exceeding design limits.
- Breakdown of turbine or generator due to speed rise exceeding design limits.
- Water hammer, especially in long tailrace tunnels; torn off water column and backflow towards turbine.
- Air pocket entrance in the waterway. Air expanding up through the surge chamber creek intake or gate chamber shafts can cause severe damage, blowing steel and concrete away.
- Excessive headwater level rise at run-of-river plants during load rejection can cause damage.
- Unstable /oscillating power and grid frequency.
During operation the water column is comparable with a goods train on its way down the tunnel system.

The plant on the sketch below has typical size (140 MW output, gross head 400 m, and max turbine discharge 40 m³/s, which gives 2 m/s water velocity in the headrace tunnel and 2.6 m/s in the penstock).

Total water mass in headrace tunnel and penstock adds up to 115,000 tons.
Waterway Transients - The Train Analogy

- The weight of the headrace tunnel and penstock water corresponds to the weight of a 2300 wagon train, 20 km long!
- Such a train needs a long distance to stop. Hence, if units falls out and the guide vane apparatus closes, this needs to take place in a controlled environment with sufficient closing time, keeping the pressure and speed rise within the guaranteed design limits.
- There are in fact two "trains" needed to be stopped in the headrace; one in the headrace from the intake to the surge chamber, and one in the steep part. The surge chamber upsurge will, if designed properly, occur slowly, and have little impact on the pressure rise at the turbine. The steep tunnel shaft will however be critical for the pressure rise, as the water column retardation in this part of the waterway occurs at the same time as the wicket gate (or needle) closing
- If the tailrace tunnel is long, the water column can be torn off and return to give the turbine an "uppercut" from beneath (Kaplan turbine applications are most exposed to this)
Pipe ruptures
Penstocks, ice problems
Leakage in mechanical coupling
Example of risk development in a newly commissioned high head hydro plant

- **Risks, and some impacting factors**

**Increasing trend**: Fatigue of rotating components (i.e., runner) due to increasing number of load cycles. Flattens out if well designed and manufactured. Monitored through regular crack inspections by NDT.

**Installation of a vibration monitoring system**

**Vibration alarm** - increasing vibration trend found, i.e., at generator bearing. Diagnostics & service performed.

**Teething problems**, often including component breakdown.
The basis and key element in all risk and asset management is accurate assessment of equipment condition. In order to obtain this knowledge, the following sources of information are utilized.

- **Available information**
  - Drawings
  - Reports
  - Test results
  - Photos
  - Data monitoring, trend curves

- **Interviews of plant operators and engineers**
  - Maintenance routines
  - Operational problems

- **Visual inspection of main components**
  - Description of condition state
  - The components should be evaluated against established evaluation classification rules. This will serve as input to the maintenance planning system.
  - Inspection report

- **New measurements, to obtain information not available**
Norwegian condition evaluation criteria - for others to implemented as well

- In Norway, hydropower condition evaluation handbooks are used (EBL handbooks)
- These handbooks provide evaluation guidelines dividing components into 4 different classes based on the component condition
- This provides input to the maintenance planning
- Notice that the time for refurbishment of a similar component can vary largely between different units as shown in the figure
Condition evaluation - why - how?

- Condition monitoring and proper maintenance is vital to maintain a high level of availability for a hydro plant.
- All relevant system parameters are needed to evaluate if and when an upgrade or refurbishment will be the optimum solution for the project.
- Minimization of overhaul outage time, and maximum utilization of time to other maintenance tasks, such as surface treatment and inspection of submerged structures.
- A proper plant condition evaluation before a refurbishment will uncover faults, and remedial action can be planned for in advance and included in the rehabilitation. It also gives an objective reference for evaluation of the quality delivered by the supplier.
Norconsult vibration measurements and analysis

- Norconsult performs extensive measurements, with a wide range of sensors connected for simultaneous data acquisition using our own IMPULS data acquisition & analysis system
  - Bearing housing vibration (accelerometers)
  - Shaft vibration (proximity probes)
  - Pressure pulsations
  - Mechanical stresses (strain gages)
  - Natural frequencies
  - Electric- current and voltage
  - Noise
- >400 hydropower units since 1982, pumps, gears, engines, gas turbines, compressors, ship drive lines etc. (incl Royal Navy vessels)
Questions?
Thank you for your attention!

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