Load-following capabilities of nuclear power plants

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Publication date: 2013

Load-following capabilities of Nuclear Power Plants

Erik Nonbøl
Outline

• Why load-following
• Modes of power operation
• BWR technique for load-following
• PWR technique for load-following
• Effects on components
• Effects on Economy
• Example of load-following in France and Germany
• Conclusion
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Increasing amount of intermittent energy sources

- Wind
- Solar
- Irregular variations in power supply
- Balancing of supply and demand very difficult
- Suddenly supply of large wind power has lead to negative electricity prices – lower than the variable costs even of NPP in Germany
- The share of electricity from NPP has increased in some countries thus demanded load-following also of these. This is the case in Germany and France
Power history of a French NPP

Figure E.1: Example of a typical power history during a cycle in an EDF reactor (in % of the rated power)
Load-following during 24 hours in Germany

Figure E.2: Example of the electricity generation with some German nuclear power plants.
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Modes of operation for power plants

• Base-load control mode
  – 100 % $P_r$

• Primary frequency control mode
  – $\pm 2\% P_r$ within 2-30 s

• Secondary frequency control mode
  – $\pm 5\% P_r$ within 1-30 min

• Load-following mode (part of EUR)
  – Daily–load cycling operation between 50% - 100% of reference power at a rate of 3-5 % pr/min
Frequency variation on the European grid
Minimum requirements of power regulation EUR

- Daily–load cycling operation between 50% - 100% of rated power at a rate of 3-5 % pr/min
- A lower level of minimum load can be required of the grid operator during nights and weekends
- The points above shall be fulfilled during 90 % of the fuel cycle
- Load scheduled variations from full power to minimum and back at a frequency of:
  - 2 per day
  - 5 per week
Turbine control in power regulation

\[ \dot{f} (\Delta f + \Delta P/\lambda) dt \rightarrow \text{Secondary frequency regulation} \]

\[ k\Delta f \rightarrow \text{Primary frequency regulation} \]

Load following

Turbine regulation

Steam rate adjustment

Pressure measurement

Electric power
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Power regulation of BWR

- Recirculation flow control by changing velocity of pumps
  - Increased velocity → increased moderator density → increased power - and visa versa
  - Very fast – ramps of 10%P_r /min within 40-100% P_r
  - Power distribution unchanged

- Control rod movements
  - Power distribution disturbed
  - Risk for thermal stresses
  - Pellet-cladding interactions

All the time stability of the reactor is sustained through undermoderation
Simple layout of a BWR
Power regulation of BWR

[Graph showing reactor power and coolant mass flow]
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Power regulation of PWR

• Control rod movements
  – Use of gray control rods to minimize local power peaks during power change
  – Rather fast regulation – ramps of $5\% P_r/\text{min}$ within 40-100% $P_r$
  – Power distribution deformed

• Adjusting boron concentration in coolant
  – Power distribution undisturbed
  – Slow regulation - cannot participate in frequency control
  – Mainly used for compensating burnup and xenon effects on reactivity
Power regulation of PWR - continued

• At the end of a fuel cycle (after 10 months of operation) the manoeuvrability is decreased due to reduced excess reactivity (fuel burnup)
  – Control rods in upper position
  – Boron concentration almost zero

• $^{135}$Xe poisoning is a growing problem at the end of fuel cycle – can cause prolonged shutdown times

• Therefore the load-following requirements of NPP are reduced at the end of fuel cycle

All the time stability of the reactor is sustained through undermoderation - even with boron in the coolant
Simple layout of a PWR
Modes of regulation for PWR

1) Average temperature in the primary circuit (reactor) constant, flow constant, temperature increase over core $\Delta T$ vary
   - Average = $(T_{\text{hot leg}} + T_{\text{cold leg}}) \times 0.5$
   - $\Delta T = T_{\text{hot leg}} - T_{\text{cold leg}}$
   - Pressure of secondary system (steam generator) vary

2) Pressure in secondary system constant, $(T_{\text{cold leg}}$ constant)
   flow constant, temperature increase over core $\Delta T$ vary
   - Increased power demand $\rightarrow$ increased average temp in core

3) Combination of 1) and 2)
Example of regulation of EPR
Load following where boron also participate

Figure 3.11: Example of load following in a operational mode X (N4 reactor)
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Effects on components

• Repeated local temperature variations with large gradients can lead to stress corrosion cracking of critical mechanical components – valves, bends, joints, nozzles
• Increased monitoring of fatigue strength for critical components
• Increased maintenance costs
• Increased risks of pellet cladding interaction through fast change of linear heat generation in the fuel
  – different expansion coefficients of clad and fuel can thus lead to failure of the cladding if the rate of power variations is not limited
• Grey control rods and boron regulation minimize the risk of too fast power changes
Effects on components - continued

• Effective core monitoring system of local power density is necessary to assure operation within safety limits

• Experiences from France and Germany show the effects on fuel can be minimized when operating within the defined limits set by EUR
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Effects on economy

• NPP normally operate as baseload due to high fixed costs and low variable costs

• Load-following operation leads to reduced load factor LF
  – LF = EG/REG, EG is the power delivered to the grid and REG is the reference power

• Increased maintenance costs

• Economically it is best to run NPP as baseload with high LF – however in France the load factor only is reduced with 1.2 % caused by load-following
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Variation of nuclear generation in France for 2010

The graph shows the daily variation of nuclear power generation in France for 2010, expressed as a percentage of the daily average. It also includes the average daily nuclear generation in MWh/h.

Mathematically, the daily variation of nuclear generation $G$ can be expressed as:

$$ G = \frac{\text{max} \ G - \text{min} \ G}{\text{Average} \ G} $$
Typically load-following of and EDF NPP
Figure 1.3: Example of the electricity generation in France during 2 weeks in November, 2010

- Nuclear
- Coal
- Gas
- Hydro
- Total generation
- Total consumption

MW

04:00 08:00 12:00 16:00 20:00
Monday Tuesday Wednesday Thursday Friday Saturday Sunday

VBR-seminar, DTU Nutech 18-Nov-2013
Load-following during 24 hours in Germany

Figure E.2: Example of the electricity generation with some German nuclear power plants.
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Conclusion

• It has been shown that technically NPP can participate in load-following as well as coal fired power plants with almost same response time and without jeopardizing the safety

• Economically however, base load operation is preferable due to high investment costs and minimal fuel costs

• Never the less France has proved load-following can be carried out with only 1.2 % decrease in load factor and corresponding small effect on economy

• It is foreseen that future generation of NPP will have increased load-following capabilities mainly because of faster control systems and more advanced fuel design
Comparison of power plants load-following capacities

Table 1: A comparative analysis of dispatchable power plants’ load-following capacities

<table>
<thead>
<tr>
<th>Power Plant Type</th>
<th>Start-up time</th>
<th>Maximal change in 30 sec</th>
<th>Maximum ramp rate (%/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open cycle gas turbine (OCGT)</td>
<td>10-20 min</td>
<td>20-30%</td>
<td>20%/min</td>
</tr>
<tr>
<td>Combined cycle gas turbine (CCGT)</td>
<td>30-60 min</td>
<td>10-20%</td>
<td>5-10%/min</td>
</tr>
<tr>
<td>Coal plant</td>
<td>1-10 hours</td>
<td>5-10%</td>
<td>1-5%/min</td>
</tr>
<tr>
<td>Nuclear power plant</td>
<td>2 hours - 2 days</td>
<td>up to 5%</td>
<td>1-5%/min</td>
</tr>
</tbody>
</table>

Source of information

1) Technical and Economic Aspects of Load Following with Nuclear Power Plants, OECD/NEA June 2011
2) System effects of nuclear energy and renewables in low-carbon electricity systems, OECD/NEA News No. 7164 2012/2013
3) Load-following with nuclear power plants, OECD/NEA News 2011- No. 29.2
Grid level system costs

**Table 2: Grid-level system costs in selected OECD/NEA countries (USD/MWh)**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Nuclear 10%</th>
<th>Nuclear 30%</th>
<th>Coal 10%</th>
<th>Coal 30%</th>
<th>Gas 10%</th>
<th>Gas 30%</th>
<th>Onshore wind 10%</th>
<th>Onshore wind 30%</th>
<th>Offshore wind 10%</th>
<th>Offshore wind 30%</th>
<th>Solar 10%</th>
<th>Solar 30%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penetration level</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Back-up costs (adequacy)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.06</td>
<td>0.06</td>
<td>0.00</td>
<td>0.00</td>
<td>8.05</td>
<td>9.70</td>
<td>9.68</td>
<td>10.67</td>
<td>21.40</td>
<td>22.04</td>
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<tr>
<td>Balancing costs</td>
<td>0.47</td>
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<td>0.00</td>
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<td>0.00</td>
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<td>5.30</td>
<td>2.70</td>
<td>5.30</td>
<td>2.70</td>
<td>5.30</td>
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<tr>
<td>Grid connection</td>
<td>1.90</td>
<td>1.90</td>
<td>1.04</td>
<td>1.04</td>
<td>0.56</td>
<td>0.56</td>
<td>6.84</td>
<td>6.84</td>
<td>18.86</td>
<td>18.86</td>
<td>22.02</td>
<td>22.02</td>
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<tr>
<td>Grid reinforcement and extension</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.20</td>
<td>1.72</td>
<td>0.12</td>
<td>1.04</td>
<td>0.56</td>
<td>4.87</td>
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<tr>
<td>Total grid-level system costs</td>
<td>2.37</td>
<td>2.20</td>
<td>1.10</td>
<td>1.10</td>
<td>0.56</td>
<td>0.56</td>
<td>17.79</td>
<td>23.56</td>
<td>31.36</td>
<td>35.87</td>
<td>46.67</td>
<td>54.22</td>
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