Risks of adaptive control of NPP electrical systems and stability of the grid

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Flexible operation research has gained more traction in recent years and some countries have long experience from actual operation. Countries like France, Russia and Germany have operated NPPs to balance power system. Flexible operation of NPPs in power systems with diverse options for balancing has been seen as not profitable. Claims from literature have been presented that operation cost per MWh produced increases about 4% to some claiming that costs will be lower than regular operation for modern plants. Study on Swedish power system found that flexible operation up to 20 TWh of wind power is theoretically possible without noticeable impact to yearly capacity factor of the NPPs if all unit took part in the flexible operation.

Balancing possibilities in FCR-N market was estimated with assumption of 4.6% additional cost of flexible operations. Using market data from 2016, there were 1144 hours when flexible operation could have been profitable. In this case 4.6% increase was calculated respect to Nordpool SPOT price but in reality there is plant specific operation cost. Also a rough estimation of system where all power plants would take part in automatic frequency regulation was done. With that, the capacity factor decrease per plant was estimated to be only 0.5% with two months of measured frequency data with 1 s interval.

Interview of Fingrid was organized for the project. Fingrid sees that 2020 onwards rotating generation will be more limited in the power system and there also will be less controllable power plants. This means that price variations might be large. There has been some talks with flexible nuclear power with energy producers but all of them currently have better resources than NPP’s for balancing purposes. There has not been instances that Fingrid had to demand nuclear power plant to reduce power or demand disconnection. Market based solutions have been enough for now. For voltage control however there has been more requests to change reactive power injection / voltage setpoint. Call to change output power would go from Fingrid operations center straight operator of the nuclear power plant. When grid frequency is outside normal operation region, the grid code demands power plant to be controlled lower or higher output linearly respect to deviations in frequency.

Instead of bidirectional balancing, nuclear power plants could serve better in down regulation reserve in cases for system over-frequency and normally leave bids to down regulation balancing market. This practice would guarantee down regulation capacity even if NPPs would never win the bids to actually activate. It should be noted that FCR-D for disaster situations is only defined for situations when there is lack of power in the system (and not for over-frequency). For system stability respect, there are no large risks in NPP participating to balancing. The most obvious risk to system stability is that if large nuclear plant is taking major role in system balancing and plant disconnects from grid when there is low inertia in the grid(summer time). For risk analysis perspective, role of single plant in balancing should be limited. It is likely that pressures on all generation to participate more actively on system balancing will increase and it is very likely that new NPPs will be required to take part at some point of their long operation life cycle.
Preface

This work was carried out in the Electric Systems and Safety in Finnish NPP’s project, ESSI. The work is follow up on request of SAFIR research programme to start research of electric systems regarding nuclear power plants. SAFIR research focuses of safety of nuclear power plants. ESSI project phase one was 2017 and this the continuation in 2018, The ESSI project includes research themes open phase conditions, modelling nuclear power plant electrical system for lightning strikes and requirements for flexible operation of nuclear power plant which is the topic of the report. Focus is in external power system related to flexible operation.

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# Acronyms and abbreviations

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<th>Description</th>
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<tbody>
<tr>
<td>NPP</td>
<td>Nuclear power plant</td>
</tr>
<tr>
<td>IAEA</td>
<td>International atomic energy agency</td>
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<tr>
<td>FCR</td>
<td>Frequency containment reserve</td>
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<tr>
<td>FCR-N</td>
<td>Frequency containment reserve in normal operation</td>
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<tr>
<td>FCR-D</td>
<td>Frequency containment reserve in disaster</td>
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1. Introduction

Power systems are in continuous development towards increasing amounts of variable renewable energy such as solar and wind power. This has generated increasing need for balancing power for the power system. Nuclear power will likely be one of the last large power plants with large amounts of natural inertia as plants with CO₂ emissions are likely not able to operate in ever increasing regulatory emission limits of the future. In addition to natural inertia, new generation plants (permits since 2012) have capability to change output power in flexible manner. This work was done in ESSI project of SAFIR program to investigate possible risks and possibilities for flexible nuclear power in power grid and system balancing perspectives.

2. Methodology

Methodology of the work is an interview of Fingrid, the transmission system operator of Finland and a literature review. The literature review focuses on external power system issues as more general plant related study was done in first phase of the project. Interview of Fingrid is done related to grid stability and practical procedures how nuclear power plants could be more flexible component in Nordic power system.

3. Literature study

3.1 Flexibility requirements for generation III/III+ modern reactor from EUR

Entso-E has following requirements for grid codes related to controllability:

“With regard to Active Power controllability and control range, the Power Generating Module control system shall be capable of adjusting an Active Power Setpoint as instructed by the Relevant Network Operator or the Relevant TSO to the Power Generating Facility Owner. It shall be capable of implementing the Setpoint within a period specified in the above Instruction and within a tolerance defined by the Relevant Network Operator or the Relevant TSO (subject to the availability of the prime mover resource), subject to notification to the National Regulatory Authority. The modalities of that notification shall be determined in accordance with the applicable national regulatory framework. Manual local measures shall be possible in the case that any automatic remote control devices are out of service.” (ENTSO-E, 2013)

More specifically, controllability requirements are given in EUR requirements so that nuclear power plants must be capable of a minimum daily load cycling operation between 50% and 100% nominal power, with a rate of change of electric output of 3-5% nominal power/minute. (Lokhov, 2011)

In addition to these requirements, some plants have faster capability to change power but in narrow band. For example some plants may be able to change power several percentage per second in range of 90 to 100% of nominal power.
3.2 Role of flexible NPP’s in power system

Nuclear power market simulation with load-following possibility has been studied in “Modelling an Electricity System with Load Following Nuclear Power Plants” by Karl Gustavsson. (Gustavsson, 2014) Modelling was based on assumption of perfect forecast of variable generation such as wind power and does not assume complex market structures. Hourly time step was used. Swedish power system with 102 TWh per year demand was used as a reference. Amount of wind power in system was varied from 10, 15 and 20 TWh per year. For amount of 20 TWh per year, no nuclear reactor had to be shut down. First set of simulation only allowed PWR units to be controlled and 2nd simulation all units to be controlled.

![Figure 1](image1.png)
(a) Variable PWR.  (b) No load following.

*Figure 1. Load following simulation with PWR and no load following reference case in the study.*

To make sense of the results, capacity factor and spin factor can be used.

![Figure 2](image2.png)
(a) Total capacity factor  (b) Total spin factor

*Figure 2. Capacity factor and spin factor between cases*

Capacity factor between cases is very similar. Even with no variable control, the reactors are shut down periodically and energy results are similar (when wind power increases). The spin factor curves are more interesting. The results show that when all nuclear power plants have
controllability, more of them stay connected to grid until 20 TWh of wind power. The additional cost for load following is estimated to be about 17 - 23% from the fuel costs (Persson;Andgren;& Henriksson, 2012) but it is plant specific. Some publications also claim that there will be savings to operation costs from flexible operation (Jenkinsa;Zhoub;Poncirolic;& Vilimc, 2018). That may well be the case for some plants designed for flexible operation.

To extrapolate on the proposed cost, estimation on required balancing market return or bids can be done. 17-23% operation cost increase mentioned previously needs to be added to the costs of lost production but that depends on operation cost of the plant. It is presented that 20% of the costs of plant come from the fuel. Therefore increase related to total costs would be 3.4 - 4.6%.

If this marginal cost or flexibility is plotted against Nordpool spot and some balancing power markets, profitability against prices can be estimated.

![Figure 3. Selected markets compared against calculated premium requirement of 4.6% of over spot market (Data from https://www.nordpoolgroup.com/)](image)

For the flexible control to be profitable, the calculated price requirement should be under the flexibility market prices. This is not however the case most of the time. This is was the situation last year but situation might be different in the future like it is estimated by the Fingrid(interview on chapter 4).

With this assumption, there were 1144 hours when FCR-N price was higher than estimated marginal cost of flexibility(down regulation). In other words, flexible operation could be profitable in selected hours of the year. The calculation basically assumes that operation cost of plant is the SPOT price which is not the right but it was used because the actual cost of nuclear power is very plant specific. For conclusive evaluation, techno economic study with dynamic market analysis would be needed. (work for future projects)
3.3 Risks related to power system stability of flexible NPP operation

Power systems are designed so that there are many layers of flexibility resources. The risks are mitigated by diversity and number of options. However if small number of units contribute to large part of practical system flexibility, resources rarely used can become more unreliable. There are many reasons to assume this can be a real risk. If power plants are not regularly operated, there can be unknown problems that are not caught by the testing. Financial commitment for maintenance of plants that are rarely used can be lower also.

Another risk with variable output of a large power plant is that reactive power capacity differentiates respect to output. So amount of grid support varies also as generator is limited by total VA capacity. Voltage setpoint change requests are rare but narrower limits should be assumed by the grid operator for variable output plants. Risk of generator protection trip can also increase if plant is in weaker power system and there is lack of inertia and controllable resources when control actions in plant are taken. Separate report on the risks is done in the project by Risk Pilot.

3.4 Grid outage triggered by nuclear power plant disconnecting

In 2003 there was a serious outage in transmission system in southern Sweden and Denmark. Nordic power system was operating in weaker state before the incident in with some power lines being out for maintenance. In addition three nuclear power plants were out for maintenance at same time Barsebäck (unit 2), and Oskarshamn 1 and 2.

Events leading to failure started as Oskarshamn 3 Nuclear power plant was disconnected due feed water valve issues at 12.30. 1200 MW of production was lost but other power plants in Nordic power system managed to limit frequency sag to 49.9 Hz.

The next event was at 12.35 when a mechanical isolator broke in substation which resulted of disconnection four 400 kV power lines. Ringhals nuclear power station unit 4 was disconnected and managed to transfer to house load. Again, the frequency was restored by the other power plants but voltage started to sag in south part of Sweden and in Eastern Denmark.

During next two minutes series of power lines dropped out due to various reasons but mostly due to overloading of them because transfer capacity was limited in the system. This eventually resulted in tripping of Danish power plants that were keeping the voltage from not going to zero until this point. This meant that East Denmark was automatically disconnected from Swedish power system.

The power system was next black started by disconnecting consumers and restoring voltage to power lines and selected power plants. Nuclear power plants are not designed to be black start capable units and they did not contribute to restoration of system. (Elkraft System, 2003)

3.5 Flexible operation of nuclear power plant effect on power system stability

Nuclear power plant contribute to power system stability even if they are not actively controlled to do so. This is because nuclear power plant use large synchronous generators which increase inertia of the system, the resistance to quick deviations in frequency. For some power systems, active participation primary frequency control is needed. For example France is one
of the countries where this is needed. Simulations on effect of nuclear power plant participating in system frequency balancing was done in (Wyman-Pain; Yuankai; & Li, 2016). Following table shows comparison of grid stability with and without for Initial Rate of Change of Frequency, Generation Inertia, and Minimum Frequency.

Table 1. Primary frequency response in France (Wyman-Pain; Yuankai; & Li, 2016)

<table>
<thead>
<tr>
<th></th>
<th>Initial Rate of Change of Frequency</th>
<th>Generation Inertia</th>
<th>Minimum Frequency</th>
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<tbody>
<tr>
<td>With Nuclear Response</td>
<td>0.238 Hz/second</td>
<td>5.51 pu</td>
<td>49.35 Hz</td>
</tr>
<tr>
<td>Without Nuclear Response</td>
<td>0.099 Hz/second</td>
<td>1.13 pu</td>
<td>48.91 Hz</td>
</tr>
</tbody>
</table>

As comparison some system are the opposite. Not needing to rely on NPP primary frequency control. Following table presents UK primary frequency response as comparison.

Table 2. Primary frequency response in UK (Wyman-Pain; Yuankai; & Li, 2016)

<table>
<thead>
<tr>
<th></th>
<th>Initial Rate of Change of Frequency</th>
<th>Generation Inertia</th>
<th>Minimum Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>With Nuclear Response</td>
<td>0.092 Hz/second</td>
<td>6.02 pu</td>
<td>49.37 Hz</td>
</tr>
<tr>
<td>Without Nuclear Response</td>
<td>0.101 Hz/second</td>
<td>5.30 pu</td>
<td>49.31 Hz</td>
</tr>
</tbody>
</table>

Because Finnish power system is very diverse in sources, the effect of primary frequency control of NPPs would probably be somewhere between the examples. The reason for this is that nuclear power does not have such large part in our power system and secondly Finland does not have so much gas turbines as in UK to provide so much of the primary frequency control. Therefore NPP participating primary frequency control would likely have meaningful and positive effect on system stability.

Grid connection rules in Finland demand that power plants can be controlled by the transmission system operator in emergency situations. Also power plants must be able to increase their power output linearly in under-frequency situations respect to frequency sag. However because nuclear power plants usually operate in maximum power, there is no room to increase power in this situation. No operational reserve is required as plants are free to offer capacity to different balancing markets or not.

More general risk is that rotating generation is decommissioned in Nordic power system, and among it some nuclear power plants. This could result to more forced control action by TSOs on load following capable plants. And if power system stability does not keep up with change
of production mix, security of system can be compromised and outage risk increase. And there is also risk for nuclear power plant owners as no grid means no production, and costly restarts.

The inertia relation to frequency deviation in simulation has been investigated by ENTSO-E working group formed from Nordic TSO members (Ørum; Kuivaniemi; & Laaksonen, 2013). Following figure displays simulated frequency sag in Nordic power system with different amount of inertia missing from the power system.

Figure 4. Frequency sag in simulation of 1170 MW production disconnecting with different inertia amounts. (Ørum; Kuivaniemi; & Laaksonen, 2013)

The simulated event in the figure is a plant disconnecting with size of 1170 MW.

TSO control actions to mitigate inertia problems include reduction of nuclear power which are the largest connected units currently. (Ørum; Haarla; Kuivaniemi; & Laaksonen, 2015) The mentioned regulation capacity for 0.1 Hz effect was 120 MW. Synthetic inertia is seen as one viable method to limit the depth of frequency sags. Synthetic inertia is generated power fast active power control of connected load or generator device which in practice means power electronic converters. Figure 5 displays virtual inertia simulation done in ENTSO-e Inertia 2 study (Ørum; Haarla; Kuivaniemi; & Laaksonen, 2015).
3.5.1 Estimating FCR-N participation performance of NPP

Because nuclear power plants have very large power capacity, small percentage variation in output power could easily serve power system for most flexibility needs. Table 3 displays auctioned capacity of FCR-N market (yearly auction). The FCR-N comes from frequency containment reserve for normal frequency range.

Table 3. FCR-N capacity over the recent years (yearly auction) (Fingrid, 2018)

<table>
<thead>
<tr>
<th>Year</th>
<th>FCR-N hinta (€/MWh)</th>
<th>FCR-N määrä (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>9.97</td>
<td>71</td>
</tr>
<tr>
<td>2012</td>
<td>11.97</td>
<td>72.7</td>
</tr>
<tr>
<td>2013</td>
<td>14.36</td>
<td>73.5</td>
</tr>
<tr>
<td>2014</td>
<td>15.8</td>
<td>75.4</td>
</tr>
<tr>
<td>2015</td>
<td>16.21</td>
<td>73.6</td>
</tr>
<tr>
<td>2016</td>
<td>17.42</td>
<td>89</td>
</tr>
<tr>
<td>2017</td>
<td>13.00</td>
<td>55.0</td>
</tr>
<tr>
<td>2018</td>
<td>14.00</td>
<td>72.6</td>
</tr>
</tbody>
</table>

Yearly FCR-N auctioned capacity in 2016 was 89 MW. However, the actual activated capacity is higher as there is also hourly market in addition.
To estimate the possibility of nuclear power plant to provide this control, some performance estimations of NPP needs to be done. European utility requirements limit change of power output to 3 %/min when unit is started from cold state. During normal operation (not cold start), power output should be limited to 5 %/minute (EUR, 2012). Another performance value is the power response setting, or slope of the droop.

\[
Frequency\ droop = \frac{\Delta f}{\frac{50 \text{ Hz}}{\Delta P}}\frac{\text{Hz}}{\text{MW}}
\]

For the estimation on performance, plant size of 1300 MW is selected. Frequency data from simulation is measured in period from 2016. Period is limited about 2.3 months to reduce data points for faster calculation. The plot of data is presented in Figure 7.
If we assume 10000 MW minimum production capacity in Nordic power system, the participation of the simulated plant of 1300 MW would need to cover only under 10% of the total capacity. Following estimation can be drawn with frequency droop value of 50%.

This automatic participation of all production to FCR-N would really eliminate the need for down regulation market altogether. The lost production as estimates would be added to bids on SPOT market. Capacity factor in Figure 8 simulation was 0.9948. Actual participation might be lower if there is some additional control delays. The only limitation in estimation was maximum change of power 3 %/min from nominal. Understandably, a dynamic power system frequency model would be needed for more conclusive estimate.
4. Summary of interview of Fingrid

An interview with transmission system operator of Finland, Fingrid was done in the project to get TSO perspective to the topics of work packages. Here is a summary of flexible operation related discussion.

Generally Fingrid welcomes nuclear power plants to provide flexibility services for the system. Finnish plants have not been used for this but it has been done in neighbor countries. New power plants will have the flexibility technology installed as it is required after 2013. In 2020 onwards rotating generation will be more limited and also less controllable power plants. This means that price variations might be large. There has been some talks with flexible nuclear power with Energy producers but all of them currently have better resources than NPP’s for balancing purposes.

There has not been instances that Fingrid had to demand nuclear power plant to reduce power or demand disconnection. Market based solutions have been enough. For voltage control however there has been more requests to change reactive power injection / voltage setpoint. There was also a question on how line of communication and action goes when Fingrid needs to command control actions of specific power plant. Communication will go straight from Fingrid operations room to the control center of the plant. Co-operation is practiced together in exercises to prepare personnel for rare events like these. It was mentioned related to Nordic power system that foreign TSO cannot call straight to Finnish power plant and demand control actions.

When grid is outside normal operation region for frequency, the grid code demands power plant to be controlled lower or higher output linearly respect to deviations in frequency. Of course usually this only means that power is decreased in over frequency as normally output is at maximum. This controllability is tested in practice by giving automation system arbitrary frequency signal. Fingrid estimates that value of power plants that can adjust output power fast will increase in the future especially if balance time step in the market is decreased to 15min. Although nuclear power plants are rather slow to change output, their large capacity makes it meaningful speed in kW/s.
5. Summary and Conclusions

Power systems are in continuous development towards increasing amounts variable renewable energy such as solar and wind power. This has generate increasing need for balancing power for the power system. Nuclear power will likely be one of the last large power plants with large amounts of natural inertia as plants with emitting CO₂ are likely not be able to operate in ever increasing emission limits of the future. In addition to natural inertia, new generation plants (permits since 2012) have capability to change output power in flexible manner. This work was done in ESSI project of SAFIR program to investigate possible risks and possibilities for flexible nuclear power. The work was dividend into three methods, literature study, flexible operation performance estimation for frequency control and Fingrid interview.

Flexible operation research has gained more traction in recent years and some countries have long experience from actual operation. Countries like France, Russia and Germany have operated NPPs to balance power system. Flexible operation of NPPs in power systems with diverse options for balancing has been seen as not profitable. Claims from literature have presented that operation cost per MWh produced increases about 4% to some claiming that costs will be lower than regular operation for modern plants. Study for Swedish power system (Gustavsson, 2014) found that flexible operation up to 20 TWh of wind power was theoretically possible without noticeable impact to yearly capacity factor of the NPPs if all unit took part in the flexible operation.

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Instead of bidirectional balancing, nuclear power plants could serve better in down regulation reserve in cases for system over-frequency and normally leave bids to down-regulation balancing market. This practice would guarantee down-regulation capacity even if NPPs would never win the bids to actually activate. It should be noted that FCR-D for disaster situations is only defined for situations when there is lack of power in the system (and not for over-frequency). For system stability respect, there are no large risks in NPP participating to balancing. The most obvious risk to system stability is that if large nuclear plant is taking major role in system balancing and plant disconnects from grid when there is low inertia in the grid (summer time). For risk analysis perspective, role of a single plant in balancing should be limited. It is likely that pressures on all generation to participate more actively on system balancing will increase and it is very likely that new NPPs will be required to take part at some point of their long operation life cycle.
6. References


