Wind Power Plants and future Power System Frequency Stability

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Event on Future Power System Operation
Lund University, Sweden, June 12, 2012
1. Quality of system frequency
2. Frequency stability – Basics
3. Frequency and inertia requirements – year 2011
4. Frequency response candidates (technical available)
5. Evaluation and recommendation
6. Conclusion
Associated paper reference

Inertia for Wind Power Plants – State-of-the-art review – year 2011
Peter W. Christensen, Germán Claudio Tarnowski

10. International Workshop on Integration of Wind Power in Power Systems
Århus, October 2011
Quality of system frequency
Quality of frequency stability

Gradually declining in many locations around the world – but not due to wind power

- Market imperfections around full hour shift (frequency erosion)
- Systems operated closer to their limits
- Decreased damping of oscillations
- Looking forward – e.g. UK - nuclear units increasing - 1300 to 1800 MW
Quality of frequency stability

Example - Europe (frequency erosion)
Frequency stability

Example - loss of 800 MW (Nordel)

- 3 distinct phases, (the grid is highly inductive at 50 Hz)
Frequency stability – inertial and governor response

- Inertial response – angle (1. global communication mechanism)
- Primary response – frequency (2. global communication mechanism)
Frequency/Inertia requirements year 2011
Frequency control requirements – year 2011

Primary frequency control

• App. 50 % of all grid codes have this requirement
• Only a few countries seems to use the functionality actively
• Implementation aspects can differ quite a lot around the world

The grid must beside regular transmission – also have the transmission capability to transfer inertial power as well as primary frequency response power (more flow patterns with renewables)
Inertia requirements – year 2011

Overview

<table>
<thead>
<tr>
<th>Country/state</th>
<th>Requirement</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>REE Spain</td>
<td>No formal requirement</td>
<td>REE encourage development but does not foresee a need for this for the Spanish mainland for a long time</td>
</tr>
<tr>
<td>Hydro Quebec Canada</td>
<td>Equivalent response as would have been provided by a synchronous machine with a inertia constant, $H=3.5$ s</td>
<td>Basically undefined</td>
</tr>
<tr>
<td>Ercot – Texas USA</td>
<td>No formal requirement</td>
<td>Have been under discussion for a number of years</td>
</tr>
<tr>
<td>UK</td>
<td>No formal requirement</td>
<td>NGET has been studied this for the last 2-3 years.</td>
</tr>
<tr>
<td>Ireland</td>
<td>No formal requirement</td>
<td>Have been studied and so far been concluded not critical</td>
</tr>
<tr>
<td>Denmark</td>
<td>Similar to Hydro-Quebec</td>
<td>Same as for HQ</td>
</tr>
<tr>
<td>ENTSO-E Draft EU</td>
<td>The TSO shall have the right to require an equivalent delivery related to the rate of change of frequency</td>
<td>Basically undefined</td>
</tr>
</tbody>
</table>
Inertia requirements – year 2011

Conclusion

• Currently no grid code contain real tangible requirements – only few loose indications.
• Inertia has not been implemented in any commercial project yet
• Together this seems to indicate that the need is not there currently.
## Frequency response candidates

Please consult the table in the associated paper to see the details

<table>
<thead>
<tr>
<th>Candidates for frequency response</th>
<th>Classical synchronous machine</th>
<th>Wind 1 ( \frac{df}{dt} ) controlled (hard)</th>
<th>Wind 2 ( \Delta f ) controlled (gentle 1)</th>
<th>Wind 3 ( \Delta f ) - temporary term (gentle 2)</th>
<th>Wind 4 ( \Delta f ) (bang-bang)</th>
<th>Wind 5 ( T_0 + \frac{df}{dt} + \Delta f ) (soft hard primary)</th>
<th>Wind 6 ( T_0 + \Delta f ) (soft fast primary)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Comment</strong></td>
<td>Curtailed type</td>
<td>Overload type</td>
<td>Overload type</td>
<td>Overload type</td>
<td>Overload type</td>
<td>Overload type</td>
<td>Curtailed type</td>
</tr>
<tr>
<td>Fast inertia + slow primary power response</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Seems likely to be UK preferred option</td>
</tr>
<tr>
<td><strong>Input signal</strong></td>
<td>Voltage angle ( f, \text{ speed} )</td>
<td>( \frac{df}{dt} )</td>
<td>( \Delta f )</td>
<td>( \Delta f ) + response shaping</td>
<td>( \Delta f ) + optional terms</td>
<td>( \frac{df}{dt} ) + ( \Delta f )</td>
<td>( \Delta f )</td>
</tr>
<tr>
<td><strong>Filtering, triggering</strong></td>
<td>Different types</td>
<td>Very sensitive and critical</td>
<td>Not critical for performance</td>
<td>Not critical for performance</td>
<td>Not critical</td>
<td>Critical to some degree</td>
<td>Not critical for performance</td>
</tr>
<tr>
<td><strong>Control law (inertial governor)</strong></td>
<td>( P = (U_1U_2 \sin \psi) X )</td>
<td>Gain, proportional to system ( \frac{df}{dt} )</td>
<td>Droop</td>
<td>( \Delta f ) transient time constant</td>
<td>Two position bang-bang + trigger settings</td>
<td>Gain ( x \frac{df}{dt} ) + ( \Delta f ) transient time constant</td>
<td>Droop</td>
</tr>
<tr>
<td><strong>Overload (short term)</strong></td>
<td>Not typical – water power has inherently high spring response</td>
<td>5-10 % PN</td>
<td>5-10 % PN</td>
<td>5-10 % PN</td>
<td>5-10 % PN</td>
<td>5-10 % PN</td>
<td>Not intended</td>
</tr>
<tr>
<td><strong>Fall-back (speed recovery)</strong></td>
<td>Firm response</td>
<td>Need not to stall Double dip</td>
<td>Need not to stall Double dip</td>
<td>Need not to stall Double dip</td>
<td>Need not to stall Double dip</td>
<td>Need not to stall Firm (if curtailed)</td>
<td>Firm response</td>
</tr>
<tr>
<td><strong>Tmin – retriggering</strong></td>
<td>Continuously ready</td>
<td>5-10 x ( T_{activation} )</td>
<td>2-10 x ( T_{activation} )</td>
<td>5-10 x ( T_{activation} )</td>
<td>2-5 x ( T_{activation} ) Guess</td>
<td>5-10 x ( T_{activation} ) Continuously (curr)</td>
<td>Continuously ready</td>
</tr>
<tr>
<td><strong>Curtailment</strong></td>
<td>Yes, 1-5 %</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes, can be</td>
</tr>
<tr>
<td><strong>Evaluation</strong></td>
<td>Viable option</td>
<td>No</td>
<td>Not robust</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes (if curtailed)</td>
</tr>
<tr>
<td><strong>Main reason</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>UK suggest 10 %</td>
</tr>
</tbody>
</table>

- **Wind. It means the world to us.**
Power response chain

Technical viable and robust solutions

Input signal → Filtering Triggering → Control Law → Actuator precondition → Actuator response → Verification

\[
df/dt \quad df/dt \text{ - very sensitive} \quad \text{Droop Bang-bang Equation} \quad \text{Overload} \quad T_0 \quad T_s \quad \text{[WTG]}
\]

\[
\Delta f \quad \text{Curtailed}
\]

T0, Tr, Ts

Plant

Wind. It means the world to us.
df/dt - sensitivity

Almost no experience by using df/dt in power systems

- Oscillations, power system noise, filtering and triggering makes in general df/dt a far too sensitive and undefined parameter to use.
Overloading / power recovery aspects

- Every overloading has to be followed by a fall-back (power recovery) to prevent stalling (loss of speed). It also becomes wind speed dependent.

Source: NGET, UK

Source: Vestas

Source: NGET, UK
Blackout – Western Power - 1994

System Frequency Response

System Frequency Leading to the 24th March 94 Blackout
Data Recorded at Muja, East Perth and Pinjar

Frequency (Hz)

Time after 7:07:00 (Sec)

- $\frac{df}{dt} = -3.5 \text{ Hz/Sec}$
- Likely Frequency Band
- $\frac{df}{dt} = -0.5 \text{ Hz/Sec}$
- $\frac{df}{dt} = -3 \text{ Hz/Sec}$

@Actual recorded frequency data
Blackout – Malaysia - 1996

System Frequency Response
Trip of Oskarshamn 3 – November 4 - 2011

System Frequency Response
Spatial wind aspects (plant level)

- Due to **wake effects** and **turbulence** inertial or power response should not be assessed just by looking at the response of a single WTG, i.e. typical aggregated models. These aspects requires further work.
Evaluation and recommendation
Power response chain

Red – solution candidates - considered not to be technical viable after evaluation

- df/dt
- df/dt - very sensitive
- Droop
- Bang-bang
- Equation
- Overload
- $T_0$
- $T_{r}$
- $T_s$
- [WTG]
- Plant
- $\Delta f$
- Curtailed
Inertial vs. primary response – 1

Classical system: extreme fast on inertia – very slow on primary
Wind power: slow on “inertia” – very fast on primary

If just the equivalent added MWs gives the same result – then what …. 

To a large degree: “wind inertia” = fast primary response (pseudo inertia)
Inertial vs. primary response –2

$+\Delta 5\%$ frequency response (wind power vs. conventional)

Red: SG inertial+governor
Black: Wind power primary

Example of primary response profiles for conventional plants

Active power output [pu]
Inertial vs. primary response –3

+Δ5%/10 % frequency response

Red: SG inertial+governor
Black: Wind power primary

Black line: identical to UK draft, September 2011
Important lessons done by others

NGET (UK) WG on inertia

• Results are in general very sensitive to adjustments in the assumptions
• For very high penetration – inertia alone can not do the work


• “the effect of increased wind generation - in lowering the inertia - is not significant compared to the effect of primary frequency control..”
Inertial vs. primary response – summery of evaluation

• It is concluded that the most suitable available option today is **Soft Fast Frequency Response, SFFR**, as it has shown to be the technically most viable and robust solution.

• Curtailment has a cost – but to force a conventional plant on the grid due to voltage stability or inertia, also has a cost.

• TSO´s are highly recommended always first to investigate the use of primary frequency control, as it is very fast, robust and has a very high performance.
Conclusion
Conclusion

1. Trend toward declining frequency quality – but not due to wind power
2. No grid code contains any tangible or exact inertia req. specification
3. Input signal, filtering, triggering, control law and actuator response are all essential for the performance which can be achieved
4. Spatial wind distribution needs to be included in the overall performance
5. Power system analysis - very sensitive to assumptions/calculation method
6. The most suitable option is Soft Fast Frequency Response, SFFR
7. Technical diversity spreading “inertia” uncontrolled - should be prevented, i.e. recommend SFFR (all stakeholders will benefit from this)
Main conclusions

1. df/dt, overload/power-recovery, or wind-speed dependent inertia, are not technically attractive or robust.

2. For very high penetration: Inertia alone will not be sufficient – also primary frequency control will be necessary to handle frequency stability.

3. TSO recommendation: TSO´s are highly recommended always first to investigate the use of primary frequency control, as it is very fast, robust and has a very high performance.
Thank you for your attention