EE 500E Energy & Environment Seminar

Power system operation challenges (and some possible solutions)

Prof. Kjetil Uhlen
Electric Power Engineering
NTNU / .. now visiting UW

Source: Statnett
Outline

• The Nordic power system
• Development trends
• Challenges in power system operation
• Key research topics (“some possible solutions”)
  – WAMS: New tools for operators
  – Improve control performance
  – Collaboration and coordination of reserves through HVDC
• Concluding remarks
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The Nordic Power system

Regional control centre

National control Centres
The Nordic Power system as part of the European...

- Hydro dominated in north and west
- Nuclear in Finland and south Sweden
- Less and less fossil
- Wind and solar increasing
- More HVDC links..
Power system operation

- Operation planning – Grid congestions - Reserves
- Market clearing, Generation planning (optimization), ..
- Operation and control – Balancing - Security
Nordic Grid and Electricity Market

Important power transfer corridors

Bottlenecks

12 Market zones – «Elspot areas»

Market coupling within Europe
Generation dispatch

.. Strongly weather dependent

In 1996:
Hydropower
deficit = 23 TWh

Year 2000:
Hydropower
surplus = 40 TWh

..and wind

Large variations with
renewable energy sources!

Source: NordPool
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The green shift...

Solar takeover – Vision or reality?
Electrification of transport

All that is part of the ..
... Smart Grid – the new, digital energy landscape
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Power systems

- Large interconnected system
  - pros
  - cons

- Balancing challenge!

Kilde: entso-e
Power systems

• Large interconnected system
  – pros
  – cons

• Balancing challenge!

• Society increasingly dependent on security of power supply
Major challenges in operation

- Towards **100 % renewable electricity** generation
  - Larger variability
  - More uncertainty
  - Increasing complexity
- More dynamics!
- Less time for actions!
- Resilience and predictability equally important

Source: Statnett
Variations in generation today!

Security and quality of supply requires:

- Sufficient grid capacity
- Reserves
- Controllability (speed and flexibility)

(NORWAY)
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What are the options?

- More variability
- Faster changes
- More complexity
- Less inertia

**Flexibility**

(What does it mean?)

- Better tools for operators → *Increase situational awareness*
- More automatic control
- Improve control performance → *faster response from units*
- Better collaboration and coordination of reserves (*larger pool of reserves*)
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Controlling the grid:

Increased complexity requires better control centres, more automation and improved situational awareness!

• We need:
  – «full» awareness of the process
  – "full" control of the process

  – In all states…
  – From normal operation to extreme disturbances
  – At all times….
Developement of control centres

Analog Tech.

From analog to digital

SCADA
Digital v.1.

From digital to digital "+

SCADA/EMS
Digital v.2.

Appearance of
EMS applications

SCADA/EMS + PMU

PMU data starts being used in control rooms for monitoring displays & alarming (2002 - 2014)

Today: SCADA/EMS + PMU + PMU Applications for Monitoring Specific phenomena

The Future?
What is a phasor?

The starting time defines the phase angle of the phasor.

Starting time is arbitrary.

But, the differences between phase angles are independent of starting time!
By synchronizing the sampling processes for different signals – which may be hundred of miles apart, it is possible to put their phasors on the same phasor diagram.
Why are phase angles important?

\[ P_{Flow} \approx \frac{U_A U_B}{X} \sin(\theta_A - \theta_B) \]

- Phase angle \( \approx \) Power flow
Tools available for Wide Area Monitoring

Voltage angles

50.1 Hz

49.9 Hz
Detecting power system oscillations...
Prototype application for power oscillation monitoring
From ambient data and ringdown analysis after disturbances

We have proposed 2 methods to estimate the oscillation magnitude. That is why there are figures for the captured oscillation and the magnitude.
Balancing and stability

- Not only about frequency and active power
- Voltages must be maintained at acceptable levels
- ...and be stable!

Source: Statnett
Prototype implementation at STATNETT’s regional control centres

6.7.2018
Roadmap and vision for the future control centre

• More wind, solar and HVDC links contribute to a more complex and dynamic power system.

• Increasing need to observe the dynamics in the power system.

• Increasing need for automatic control.

• PMUs are a key to manage the future power system.

• Experience and use trigger ideas for new applications.

• Important to involve operators in the whole process.
The Norwegian Smart Grid Laboratory

https://www.ntnu.edu/smartgrid
The National Smart Grid laboratory (NSGL)
PMUs / WAMS in the smart grid lab

THE NATIONAL SMART GRID LABORATORY

Applications

NTNU
Norwegian University of Science and Technology
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Power System Support from Variable Speed Operation of Hydropower Plants

Tor Inge Reigstad, Kjetil Uhlen
Benefits of Variable Speed Hydropower from a system perspective

- **Support**: Improved frequency control and grid stability, providing flexibility:
  - Faster control of active and reactive power
  - Higher reactive power capability at low power
- **Inertia**: Better utilization of the rotation mass energy in the generator and turbine during faults and transients.
- **Optimization**: Improved efficiency at part load
- Improved power control in pumping mode

- But, there are uncertainties..
Potential problems or uncertainties:

- **Contribution to short circuit capacity**: Converter short circuit current is limited, challenging protection.
- **Modelling**: Adaptations to the turbine/waterway models?
- **Utilization**: How much can the speed be varied?
- **Control**: More degrees of freedom: How to coordinate controls (governor and converter controls)?
Modeling, control optimization and power system analysis

- Hydraulic system (water ways)
- Governor
- Turbine
- Synchronous generator (?)
- Generator side converter
- Grid inverter
- Control design
- Power system analysis
Initial results (example):
Response to large disturbance (loss of generation)

System frequency

Plant response Electrical and Mechanical power

Response with Conventional plant

Response with Variable speed Hydro
Example continued:
Response in grid frequency and shaft speed

**System frequency**
- Conventional solution with grid connected synchronous generator
- Response with Variable speed Hydro

**Generator speed and synchronous speed/frequency**
- Synchronous speed / Electric frequency variation
- Varspeed: Generator speed variation in per unit
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Power should be produced where it is cheap and sustainable!

The market mechanism is working:

- Norway exports power during daytime
- .. and imports during night!
  - ..driven by the price differences

www.statnett.no/Kraftsystemet/
Power system integration
Sharing and collaboration on primary and secondary reserves

Two examples:
• **Balancing control through HVDC** (now!)
• **Primary control and exchange of reserves through MTDC grids** (future?)
Power system integration
Sharing and collaboration on primary and secondary reserves

Two examples:
• Balancing control through HVDC (now!)
• Primary control and exchange of reserves through MTDC grids (future?)
Eksample: Collaboration on balance management

- January 8, 2005 a strong storm crossed over Denmark
- The wind farms of western Denmark at first produced close to rated power, but then started to cut out due to the excessive wind speed (+ 25 m/s) – the wind production was reduced from about 2200 MW to 200 MW in a matter of few hours

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<table>
<thead>
<tr>
<th>Data for DK1, west Denmark 2003</th>
<th>MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central power plants</td>
<td>3,516</td>
</tr>
<tr>
<td>Decentralised CHP units</td>
<td>1,567</td>
</tr>
<tr>
<td>Decentralised wind turbines</td>
<td>2,374</td>
</tr>
<tr>
<td>Offshore wind farm Horns Rev A</td>
<td>160</td>
</tr>
<tr>
<td>Maximum load</td>
<td>3,780</td>
</tr>
<tr>
<td>Minimum load</td>
<td>1,246</td>
</tr>
</tbody>
</table>
The joint Nordic balancing market is able to manage large variations in (wind power) generation and loads.

Source: NORDPOOL
Norwegian hydropower as Europe’s green battery → possibilities and challenges
Power flow control in DC grid: achieved by DC voltage droop

- No need for communication between terminals
- Many or all converter terminals contribute to DC voltage regulation
- DC analogy to distributed *frequency droop control* in AC systems
HVDC converter control implementation

HVDC terminals can participate in frequency control.

Enables exchange of primary reserves between asynchronous AC grids.

DC voltage droop control

Frequency droop control
EXAMPLE:
Primary frequency control response provided through the MTDC grid

- **Primary frequency control response** provided through the MTDC grid
- $P_{\text{rated}} = 800\text{ MW}$, DC droop mode
- $P_{\text{rated}} = 450\text{ MW}$, DC droop mode
- $l_{12} = 300\text{ km}$
- $l_{13} = 700\text{ km}$
- $l_{23} = 600\text{ km}$
- $l_{24} = 120\text{ km}$
- $P_{\text{rated}} = 1000\text{ MW}$, DC droop mode
- $P_{\text{rated}} = 750\text{ MW}$, DC droop mode
- $P_{\text{rated}} = 600\text{ MW}$, Variable (wind) power

All cable resistances: $r = 0.01\ \Omega$/km
All cable capacitances: $c = 5\ \mu\text{F}$/km
Bipolar DC transmission for all cases
Rated DC voltage $= +/- 200\text{ kV}$

**Offshore load** (Oil/gas platform)
- $P_{\text{rated}} = 250\text{ MW}$, Constant Power terminal
- Scotland
- $P_{\text{rated}} = 450\text{ MW}$, DC droop mode
- England
- $P_{\text{rated}} = 800\text{ MW}$, DC droop mode
- Offshore windfarm
- Offshore load (Oil/gas platform)

**Offshore load** (Oil/gas platform)
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- Offshore windfarm

**UK National Grid**
- $l_{12} = 300\text{ km}$
- $l_{13} = 500\text{ km}$
- $l_{23} = 600\text{ km}$

**NORDEL Grid**
- $l_{24} = 120\text{ km}$

**UCTE Grid**
- $P_{\text{rated}} = 750\text{ MW}$, DC droop mode
- $P_{\text{rated}} = 600\text{ MW}$, Variable (wind) power
Consider $\Delta P_{L4} = 200 \text{ MW}$ at ac grid 4.
Response to $\Delta P_{L4} = 200$ MW at ac grid 4

Frequency drop due to load increment

$U_{dc}$

$P_c$

$P_c$ 3,5
Response to $\Delta P_{L4} = 200$ MW at ac grid 4

Primary control response of converter 5 due to frequency droop
Response to $\Delta P_{L4} = 200$ MW at ac grid 4

DC voltage drop due to change in power at converter 5
Response to $\Delta P_{L4} = 200$ MW at ac grid 4

Primary control responses of converters 1,2 and 4 due to DC voltage droop.
Response to $\Delta P_L^4 = 200$ MW at ac grid 4

Frequencies in other AC grids decrease
Grid frequency responses in the presence and absence of frequency support by the HVDC link

Grid-4 frequency

With frequency support by MTDC

Without frequency support by MTDC
Findings

• Regarding primary control and balancing: It is possible to design control schemes for HVDC converters that make interconnected ac-dc grids behave “almost” like one ac grid!

• However, there are stronger interaction with voltage droop control and with inertia support and exchange of primary reserves

• With well tuned controllers, we have found no evidence of serious adverse interactions!
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- Det grønne skiftet er umulig uten NTNU Electric power…

Norge skal bli et lavutslipssamfunn, men ikke et lavinnektssamfunn. Derfor vil miljøministeren tjene penger på grønn teknologi.
«The future is digital, renewable and runs on electricity!»

- Thank you😊