Section 6c
Planning and Operations Impacts and Standards

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Outline

• Planning and Operations Challenges
  – Transmission System Impacts
• Grid Codes and Harmonization
• Examples on Wind Integration Studies and Transmission System Impacts
Outline

• Planning and Operations Challenges
  – Transmission System Impacts

• Grid Codes and Harmonization

• Examples on Wind Integration Studies and Transmission System Impacts
What are the main challenges?

Economy and Security:

• Power system security
  – Frequency Control and Regulation
  – Voltage Control and Regulation
  – Risk of blackouts and loss of load (reliability, voltage quality)
    • Operational monitoring and control
    • Technical and functional requirements for grid connection

• Power balance
  – Risk of capacity shortage (Rationing, loss of load / rolling blackouts)
    • Operation planning
    • Balance management

• Energy planning
  – Risk of energy shortage (high prices)
    • Long-term planning
    • Investments in transmission and generation
What is special about wind power?

- The wind power plant lacks a controllable “energy storage” on the input
- Generation planning becomes more challenging
Power System Security

• Challenges in operation:
  – Voltage and Frequency Control and Regulation
  – Monitoring and control (transfer limits)
  – Control Center tools (from steady state analysis → more dynamic information)

• Challenges, preventive:
  – Technical and functional requirements for installations and plants connected to the grid
  – Security standards (from pure N-1 → risk based criteria)
Power Balance

• Risk of capacity shortage (Rationing, loss of load / rolling blackouts)
  – Operation planning
  – Balance management

• Challenges:
  – Frequency control
  – Frequency response (primary reserves)
  – Balancing services (how to operate the system?)
  – Reserves (how to allocate reserves?)
  – Congestion management (good market solutions?)
  – Need for better forecasting tools

➤ Possibilities:
  – Demand side participation more important
  – Increased value of hydropower !
  – Wind Power Management (e.g., limit ramp rates, output level)
Energy Planning

- Risk of energy shortage (high prices)
  - Long-term planning and Investments in transmission and generation:
    - More difficult due to high variations in energy supply
      - Well known problem for hydro-dominated systems
      - A new challenge for systems dominated by thermal generation.

- Challenges:
  - New requirements and demand for planning tools:
    - Need for higher time resolution
    - Need for tighter integration of market models and network analysis tools.
  - Increasing need for dynamic studies (voltage stability, transient stability, etc.)
Available energy from wind and hydro power (example of annual variations)

Normalised annual production (%)

Year


Wind
Hydro
Analyzing grid capacity

P(t) = ?

Regional transmission grid

Main transmission grid

Bottleneck!

P

Time / Duration

Hydro inflow (MW)

Wind farm

Distribution grid

Hydro plant

Time (hour)

Wind speed (m/s)

Consumers load (MW)

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Summing up..

• Wind energy changes the power system:
  – Variable generation at new locations
  – Higher demand for power transmission
  – Larger variations and more frequent changes in power flows

• Energy planning:
  – Wind energy makes a positive contribution
  – Main challenge to develop good planning tools

• Power system security:
  – No big difference between wind and other conventional generation
  – Grid connection requirements (grid codes)
  – Focus on monitoring and control, competence and tools

• Power balance:
  – A main challenge for large scale integration of wind power
  – Balance management, reserves, wind forecasting tools,..
  – Market solutions
Outline

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  – Transmission System Impacts
• Grid Codes and Harmonization
• Examples on Wind Integration Studies and Transmission System Impacts
System requirements - Motivation

• That wind power plants will (and should) face similar requirements as conventional power plants regarding controllability and ability to provide relevant system services, contributing to:
  – Maximizing power transfer capacity
  – Power balance and reserves (capacity credit this is jurisdiction and not global)

• Control requirements:
  – Power Management and Frequency Regulation
  – Voltage control, and reactive power compensation
  – Both on primary and secondary control level

• Key questions:
  – What are the system performance requirements? (technical issue)
  – Which system services should be provided by wind farms? (economic issue to wind operator or to system operator)
“Grid Codes”

- The aim is to ensure system control properties that are essential for the reliability of supply, security in operation and power quality in the short end long term.
  - General laws, regulations and agreements apply

- Specific grid codes for large scale wind power are being established in most countries with significant wind power developments
Grid codes for wind power

- **Power control**
  - Ability to control power output via power limiting and/or ramp rate limiting
  - Frequency control (primary reserves)
  - Start and stop, limits on power gradients,

- **Frequency and voltage deviations**
  - Frequency and voltage limits where wind farms shall operate and when they shall stop

- **Reactive power and Voltage control**
  - Reactive compensation
  - Control Requirements (Mvar control, power factor control, Voltage control, etc.)
  - Voltage quality (Voltage variations, dips, flicker, harmonics, etc.)

- **Response to grid faults**
  - Stability requirements (transient) (Various types of faults)

- **Protection of the wind farm against grid faults**
  - Responsibility
  - Tolerance.

- **Communication (between wind farm and grid operator, ..)**
  - Responsibility for providing information, operational data, etc.

- **Requirements regarding documentation, analysis, testing, etc.**
Different Requirements for Different Countries

• Germany
  – Part of a strong interconnected system (UCTE)
  – Thermal dominated system

• Denmark
  – WTs spread at distribution level
  – Portfolio still dominated by wind turbines with induction machines with limited controllability

• England & Wales and Scotland
  – Large isolated system

• Ireland
  – Small isolated system
  – Big potential for wind power

• Norway
  – Part of a larger interconnected system (Nordel)
  – Highly distributed and less interconnected system
  – Hydro power dominated system
Different Requirements for Different Countries

• United States
  – Large, transmission-connected wind power plants
  – Big potential for wind power in some regions
  – Transmission capacity constraints to major wind resource areas
  – Standards still evolving
    • Some jurisdiction issues (FERC, NERC)

• Canada
  – Some regions hydro-dominated, some not
  – Alberta example
    • Thermal power dominated system
    • Low interconnection capability to the Western US systems
    • Big potential for wind power
Comparison of the Different Country Requirements

General Considerations:

- Deal with same topics, but with different descriptions
- Lack of harmonization on wind facility requirements
- Difficult to make comparisons
- Example:
  - Reactive Contribution
  - Fault Ride Through (FRT)
  - Frequency Regulation
Reactive Contribution

• To maintain voltage within specific limits

• Reactive power generated locally where it is needed
Reactive Contribution: Germany < 100 MW

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Reactive Contribution: Germany >100 MW

The diagram illustrates the dynamic performance of wind power generation, focusing on reactive power contribution. The x-axis represents reactive power (% Pn), while the y-axis shows active power (% Pn). Two variants are highlighted:

- **Variant 1**: Indicates a specific region on the graph where the reactive power contribution is maximized within the range of -50 to 50 on the x-axis.
- **Variant 2**: Marks another region where the reactive power contribution is lower, possibly for different operational conditions.

Key performance parameters include:
- **Inductive and Capacitive regions**: These denote the power factor ranges where the system exhibits inductive or capacitive behavior, influencing reactive power contributions.
- **Cos φ values**: The graph features lines marked with cos φ values, such as 0.5, 0.67, 0.9, etc., indicating different levels of power factor efficiency.
Reactive Contribution: Denmark

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Reactive Contribution: Ireland

Reactive Contribution: England, Wales and Scotland
Reactive Contribution: Comments

- Germany (<100 MW), England, Norway and Ireland (relaxation at 50 %P) have the same requirements 0.95 (ind./cap.)
- Germany (>100 MW) most strict in over excitation (0.90) less in under excitation (0.975).
- Denmark has the most relaxed requirements
not big deal since with only 20 % active power output all the WTs would be connected and hence the total reactive power capability would remain intact.

giuseppd, 3/27/2006
Reactive Power/Voltage Control in the US

- Existing NERC voltage control standards are for synchronous generators, not wind
- FERC 661-A Power Factor Design Criterion for Wind
  - Somewhat vague; transmission provider’s interpretation vary
  - Reactive support at partial output not defined
  - Dynamic vs Static support not well defined
- Canada jurisdictions have their own standard.
  - Alberta requires 0.9 PF over excitation and 0.95 PF under excitation at the low voltage side of the facility step up transformers
US FERC Reactive Support Standard

• FERC Power Factor Design Criteria:
  – Maintain a power PF within a range of +/- 0.95 at the POI… *if the System Impact Study demonstrates that such requirement is needed for safety or reliability*
  – Provide dynamic voltage support… *if the System Impact Study demonstrates that this is required for safety or reliability*
  – SVC or STATCOM can be used to meet standard

• Possible interpretations of the FERC rule
  – Always require +/-0.95 pf range at the POI; prescribe what portion must be dynamic (e.g., 50%)
  – Case-by-case basis
    • There is no consistent, widely-applied approach to “demonstrate” need.
Reactive Support Standards in Canada

- Manitoba-Hydro

Two examples

- AESO
Fault Ride Through (FRT)

Wind Turbine should stay connected during a fault in the system to avoid large and sudden losses of generations which could lead to cascade events ending up in black outs.
FRT: Germany

Extra high (220 kV) and high voltage (60 to 110 kV)
Rate of raise of active power: 20% of rated power per second (i.e. within 5 sec)
• *Three-phase* on random line or transformer with permanent disconnection without any attempt of re-closing (FCT 0.10 seconds).
• *Two phase* fault on random line with unsuccessful re-closing (FCT will be typically 0.1 seconds, the period of deionization 0.3 seconds and the FCT at the unsuccessful re-closing 0.1-0.5 seconds).
Within 1 sec of the voltage recovery, WF shall provide 90% of its available active power.

During the voltage dip active power in proportion to the retained voltage and maximize the reactive Current.

High voltage systems (60 to 110 kV)
Requirements for super grids: 275 kV and 400 kV
Rate of rise for Active power: immediate power recovery for faults up to 140 ms;
In proportion to the retained voltage for faults greater than 140 ms
FRT: Norway

< 200 kV

> 200 kV
**FRT: Comments**

- **Voltage dip:** most strict in England (NB applies at highest voltage levels 275 kV, 400kV) and Germany (low short circuit current)
- **Duration of the voltage dip:** 625ms in Ireland and Germany
- **Rate of rise of electrical power:**
  - England: immediate (<140 ms), in proportion to the retained voltage (>140 ms)
  - Ireland: in proportion to the retained voltage
  - Germany: 5 sec or 20 sec (UCTE 550GW)
  - Norway up/down regulation 10-100 % P within 1 min
Low Voltage Ride-Through (LVRT) Standards in North America

• Standards that apply
  – WECC LVRT standard (applies to all generators in the Western Interconnection). Adopted in 2005
  – FERC Order 661-A (applies to wind generators only) Based largely on the 2005 WECC standard
  – FERC LVRT standard also applies in the Western US, so there are some conflicts. WECC trying to harmonize, conform
  – NERC does not have a North-America-wide LVRT standard. They are working on it.
  – Some utilities have their own variation (e.g., PNM)

• Jurisdictions in Canada (Provinces) have their own LVRT standards

• Standard still evolving. Need to harmonize.
FERC (US-wide) LVRT Standard

- Applies to wind generators only
- Standard
  - Tolerate 3-ph faults cleared in *normal time*, and single-line-to-ground faults with *delayed clearing*, unless
    - Wind generator is radially connected to the fault
  - Maximum clearing time not to exceed 9 cycles
  - Voltage during fault can be 0 at high side of station transformer
    - During transition period (through Dec. 2007), exception granted if voltage dipped 0.15 pu
  - Existing generators are exempt unless the generators are replaced
WECC (Western Reliability Entity) LVRT Standard

- Applies to all generators 10 MVA or above
- Standard
  - Tolerate 3-ph faults cleared in *normal time*, and single-line-to-ground faults with *delayed clearing*, unless
    - Voltage at high side of station transformer dips below 0.15 pu
    - Fault is internal to the power plant (e.g., collector system)
    - Generator is radially connected to the fault
    - Tripping is intentional as part of a special protection scheme
  - After fault, don’t trip if recovery is acceptable for a load (e.g., 20% voltage dip for 40 cycles)
  - Existing generators are exempt until replaced
- Some changes being considered to harmonize with FERC (e.g., zero voltage ride-through)
LVRT and Fault Location

- POI or connection to the grid
- Collector System Station
- Interconnection Transmission Line
- Individual WTGs
- Feeders and Laterals (overhead and/or underground)

LVRT standard applies
LVRT standard Does not apply
LVRT Standards In Canada

Two examples

AESO LVRT Standard

Manitoba Hydro LVRT standard
Frequency Regulation

• Due to unbalance between load and generation
• All generator plants shall be able to operate within a certain frequency range above and below 50/60 Hz
• Regulation performance and frequency deviations
• Requirements for frequency control
Frequency Regulation: Germany

Additional Requirements: deviating power output according to the control condition (primary control if applicable)

Basic Requirement
Frequency Regulation: Denmark

Set point value at downward regulation

Only down regulation without reduced production

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Reduced Active power in the normal range, allowing for an increase in active output if the frequency falls.

Each WF has two power-frequency control curves. The setting points will vary for each WF and shall be set by the TSO.
Frequency Regulation: England, Wales and Scotland

DC Converter Stations

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Frequency Regulation: Comments

- Germany, Norway and England require the same capability of delivering full power in the range 49.5 - 50.5 Hz.
- England and Norway have more strict requirements below 49.5 Hz (95% P) than Germany (80%)
- Capability requirement for operating WF at reduced power in Ireland, Norway and Denmark
Summing Up

- Little harmonization:
  - Different network conditions lead to different requirements
- Denmark: First grid code with rather relaxed requirements
  - WFs are spread out in the distribution network. Has not observed severe system problems due to disconnection of WFs
  - Portfolio is still dominated by wind turbines with induction machines
- Germany and England: Focus on FRT
  - Risk of disconnection and cascading outages were the main drivers for the development of the grid code
- Ireland: More focus on frequency control
  - Power/frequency control is important in a small isolated system
- Norway: focus on reactive power requirements
  - Reactive power is important being generated locally and not transmitted over long distances
- US: Focus is still on developing appropriate standards
  - Existing standards lead to different interpretations
  - NERC beginning to take lead role
- Canada: Approach similar to Europe
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Examples

Illustrating relevant problems related to system requirements (grid codes):

1) Example to illustrate the need for (and the meaning of) "fault ride through capability".

2) Example to show the need for voltage control and reactive compensation capability

3) Example to illustrate problems related to congestion management and balancing control (frequency control)

4) Power control and frequency response
1. Transient stabilitet (Fault ride-through capability)
Test System and Parameters

SVC 130 MVA

22/0.69kV

BUS1

~

22/0.69kV

BUS2

Wind Turbines
2 X 100 MVA

22/132 kV

BUS3

25 km

BUS5

~

22/132 kV

BUS6

22/0.69kV

BUS4

Synch. Gen.
200 MVA

Compensation

~

Grid

110 km

BUS7

Load
P 600 MW
Q 100 MVA

Cap. bank
20 MVA

22/132 kV

BUS8

22/132 kV

20 MVA

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Dynamic Analysis: Transient Stability (1)
Fault and tripping of a transmission line

3 Phase Fault cleared in 0.150 s

Voltage at different terminals

SVC Reactive Power

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**Dynamic Analysis: Transient Stability (2)**

Fault ride through with SVC rated 150 MVA

3 Phase Fault cleared in 0.150 s
“Traditional” modelling of wind farm; fixed mechanical power as input to the generator model

Modelling of the wind farm with a dynamical wind turbine model with fixed mechanical torque as input to the turbine
Traditional vs. non-traditional modelling

Voltage response after a temporary three-phase short-circuit at first PCC

Voltage at local bus (0.69 kV) at the wind farm

Voltage at first point of common connection (PCC, 132 kV)

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**Traditional vs. non-traditional modelling**

Effect of shaft stiffness on the response characteristics

![Graph showing the effect of shaft stiffness on response characteristics](image)

- Fixed torque ($K = \infty$)
- Base case, $K = 0.61$
- $K = 0.41$
- $K = 2.0$

Increasing stiffness

Voltage bus 71352 [pu]

Time [s]
**Fault and line outage (Effect of power level)**

**Induction generator type of wind farm with external compensation**  
(STATCOM 75 Mvar)

**Variable speed Wind farm with DFIGs (internal compensation)**
2. Voltage control and reactive power compensation

- The possibilities depend on system configuration (generator solution and network integration)
- Previously, not all wind farms have had the possibility to supply reactive power.
- The system requirements will obviously influence the choice of technology in the future.

**Example:**
- Relevant for larger wind farms in Norway (50 – 100 MW)
  - Realistic network model for (windy) sites in Mid-Norway
  - Regional 66 kV grid (long distances to main transmission grid)

- Choice of technical solution is the main factor determining the maximum size of the wind farm.
The importance of reactive compensation

![Diagram with reactive compensation values](image)

- V(P) at Q = -0.35P
  - "Induction generator"
- V(P) at Q = 0.0
  - "Power factor control"
- V(P) at Q = 0.2P
  - "Voltage control"
3. Example related to congestion management and balancing control in Nordel (frequency control)

- Frequency control reserves
- Congestion management
- Balancing services
- Reserves

- Illustrating Nordic collaboration and sharing of reserves across synchronous interconnections (UCTE↔Nordel)

- Example is from 8. January 2005
  - nearly 2000 MW wind power disconnected due to severe storm in Southern Scandinavia
## Western Denmark (Energinet.dk)

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<thead>
<tr>
<th>Power Source</th>
<th>MW</th>
<th>GWh</th>
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<tbody>
<tr>
<td>Central power plants</td>
<td>3,516</td>
<td>16,161</td>
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<tr>
<td>Decentralised CHP units</td>
<td>1,567</td>
<td>6,839</td>
</tr>
<tr>
<td>Decentralised wind turbines</td>
<td>2,374</td>
<td>4,363</td>
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<tr>
<td>Offshore wind farm Horns Rev A</td>
<td>160</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
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<tr>
<td>Consumption</td>
<td>21,043</td>
</tr>
<tr>
<td>Maximum load</td>
<td>3,780</td>
</tr>
<tr>
<td>Minimum load</td>
<td>1,246</td>
</tr>
<tr>
<td>Capacity export to UCTE</td>
<td>1,200</td>
</tr>
<tr>
<td>Capacity import from UCTE</td>
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<tr>
<td>Capacity export to Nordel</td>
<td>1,560</td>
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<tr>
<td>Capacity import from Nordel</td>
<td>1,610</td>
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</tbody>
</table>

Key counts of the power system of Western Denmark for the year 2003
(Source: Energinet.dk)
Elspot areas and transmission capacities

NO2
NO1
FI
SE
DK1
DK2

1000 MW
950 MW
1200 MW
800 MW

To Germany

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Real life case – balance management

- At 8 January 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 were reduced from about 2200 MW to 200 MW in a matter of 10 hours

<table>
<thead>
<tr>
<th>Data for DK1, west Denmark 2003</th>
<th>MW</th>
</tr>
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<tr>
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The case demonstrates that the existing market-based mechanisms can handle large variations in (wind) generation and demand.
Balance management and balance settlements

• NORDEL has a common real-time balancing market
  – Regulating power market (RK)
  – Generators and large consumers can participate

• Settlement of deviations from plans:
  – General principle: Deviations are paid/charged according to the regulating power price (RK price)
  – Stronger incentive to follow plans with the future “two-price” settlement (ELSPOT or RK-price)
  – Nordic harmonisation
Settlements of deviations from plans

One-price (presently in Norway)
Settlements of deviations from plans
Two-price (Future in Nordel)

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4. Power control and frequency response

- **Power control**
  - Wind farm control
  - Ability to operate at reduced power output
  - Relevant as a system control / system protection functionality

- **Automatic frequency control**
  - Frequency response relevant in certain conditions
    - At very large scale wind integration
    - Grid areas exposed to risk of islanding operation
Power control
Wind Farm Controller

Source: Energinet.dk
Primary reserves (Frequency response)

Available power

Set-point power

Available power

Reserve power

Power

Time

Power

Frequency

droop

Power

Time

Reactive power

Voltage

droop
**Power/frequency control**

**Frequency response**

\[
R = \frac{2P_n}{\delta}
\]

\[
\delta = 6\% \\
P_n = 300\, \text{MW}
\]

- Frequency response: \(R = 100\, \text{MW/Hz}\)
- Dynamic range (DR): min 15 MW
- Frequency range (FR): 10 MW
Power/frequency control

Frequency response

- Low wind
  - Variable speed

- High wind
  - Fixed speed

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