Wind Power Plant Integration to Power System Using HVDC and FACTS

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Contents

• Applicable machines overview
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• Requirements of legislative
• FACTS application
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Introduction

• The rapidest growing part of power system
• Development is donated by state subsidies
• Regulation demand from the site of transmission system operator
• Big wind farm connection
• Transmission lines length increasing
Wind as energy source
Wind as energy source
Applied solution - induction or asynchronous machine

• The oldest solution
• For higher power variable number of poles
• Slewing wings system
• Voltage stability – SVC or STATCOM
Applied solution – induction machine
Applied solution – induction machine
Induction machine with variable rotor resistance
Doubly-fed induction generator
Doubly-fed induction generator

- 50% new installations in Europe
- Minimize convertors costs
- Variable speed (20 – 30%)
- Machine’s mechanical stress decrease
Doubly-fed induction generator
Solution with variable rotating speed
Solution with variable rotating speed

• Machine with or without gear
• Generator is connected to the grid through convertor
• Influence to the grid limitation
• Reactive power compensation
Wind power farms – operating in power system

• Complicated production planning
• Effect of sources penetration
• Long line connection – voltage control
• Power system operator control possibility
  – 1/3 of WPP installed power in Germany has possibility to be disconnected for system control
  – In some countries conditioned by the power system operator legislation
Wind farms – Technical impact

- Minimal allowance to system insertion
- Voltage and frequency regulation is limited
- Resistance to failures is limited
Wind farms – Technical impact

• Power quality
  – Higher harmonics
  – Flicker
  – Rezonance
    • Long lines
    • Resonance frequency is higher than 20\textsuperscript{th} harmonics
### Grid Code

<table>
<thead>
<tr>
<th>Grid Code</th>
<th>BC</th>
<th>BD</th>
<th>AF</th>
<th>FE</th>
<th>AH</th>
<th>HG</th>
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<tr>
<td>Denmark</td>
<td>25%</td>
<td>0.1 s</td>
<td>0.75 s</td>
<td>25%</td>
<td>10 s</td>
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<td>Germany (EON)(^1)</td>
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<td>Germany (EON)(^2)</td>
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<td>0.625 s</td>
<td>3 s</td>
<td>10%</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Ireland (EirGrid)</td>
<td>15%</td>
<td>0.625 s</td>
<td>3 s</td>
<td>10%</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Spain</td>
<td>20%</td>
<td>0.5 s</td>
<td>1 s</td>
<td>20%</td>
<td>15 s</td>
<td>5%</td>
</tr>
<tr>
<td>Spain (Canary islands)</td>
<td>0%</td>
<td>0.5 s</td>
<td>1 s</td>
<td>20%</td>
<td>15 s</td>
<td>5%</td>
</tr>
<tr>
<td>UK (NG)</td>
<td>0%</td>
<td>0.14 s</td>
<td>1.2 s</td>
<td>20%</td>
<td>2.5 s</td>
<td>15%</td>
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</table>
Economical aspects

• Investment and operating costs of wind farm
  – Choice of suitable area (climate conditions, connection to power grid)
  – Losses in power system
    • Application of HVDC
  – Reliability and accessibility to power grid integration
AC connection of WPP

- The most frequent connection
- Power electronics? – depends on length of connecting line and grid power stability at place of connection
- „Long lines“ – cable l>100km, overhead l>400km
- issues – reg. U, static and dynamic stability, power quality
- FACTS (Flexible AC Transmission System)
  - SVC, STATCOM, TCSC, SSSC
  - Energy accumulation
  - → higher transmission line capacity, better power dynamics, voltage control
Critical cable length

- line – $Q_C \sim U^2$, $Q_L \sim I^2$
- $Q_{Ccab} \sim 20 \div 50 Q_{Covh}$ (losses)
- Critical length: $I_{\text{charging}} = I_{n(\text{max})}$
  $I_\Sigma = \sqrt{I_P^2 + I_Q^2}$
- $I_{\text{crit}}$: $P_{\text{max}} = U_C I_n \cos 30^\circ = 87\% S_n$
- $I_{\text{crit}}/2$: $P_{\text{max}} = U_C I_n \cos 15^\circ = 97\% S_n$
- $2*I_{\text{crit}}$
  $P_{\text{max}} = 0$
Compensation

- L compensation (passive reactor, SVC) along cable commonly up to 50-60% $Q_C$ (rest is series L)
- C compensation for inductive load, AM (AG)
SVC (Static Var Compensator)

- Power quality – harmonics, flicker, asymmetry, $\text{Cos}(\phi)$
- Application – EAF, rolling mill,… x and DS
- Components – TCR, TSC (BSC), filters
- smooth regulace $L \rightarrow Q$
SVC (Static Var Compensator)

- regulation Q and U in connection node
- (+) fast regulation (thyristors)
- (-) current $\sim U$, $Q \sim U^2$, worse in weak power grids
- Applicable for WPP with constant rotating speed (without convertors)
- Good dynamic
SVC - advantages

- SVC: voltage transient damping coming from grid → WPP stays connected
- Minimal C block switch – without voltage jump
- Voltage sag elimination caused by WPP operation
- Lower Q consumption
- Other voltage regulation is not needed
- Helps WPP to stay during fault connected
- Regulation of Q allows fast return to normal operation
- Other lines voltage stabilization
- Defends against voltage sags (start/stop, wind change)
- Opportunity of support services
STATCOM
(Static Synchronous Compensator)

- Switching components (IGBT, GTO), faster
- $U_{AC}$ determines gen./abs. Q (amplitude), P losses
- $I_{STATCOM}$ does not depend on grid $U$, only dimensioning
- $Q \sim U$, even for lower voltage levels than SVC
- Nowadays $Q > 100$ MVAr, dynamic $\sim x$ ms
STATCOM - advantages

- Same as SVC + other:
- PWM (Pulse-width modulation)
- Without harmonics filters - less surface area
- Can contribute during short-circuit (higher current for protection relays)
- More efficient (faster) for flicker mitigation
WPP and energy accumulation

- Caused by variable power output from WPP
  - High wind speed, climate conditions, high percent of WPP
- Some combinations with PV sources are exist
- Other technologies are more expensive, efficiency max. 60-70%

**LEGEND**
- m – prefix used to indicate small scale
- BESS = batteries
- CAES = compressed air energy storage
- EZ+FC = hydrogen and fuel cells
- FESS = flywheels energy storage system
- HAS = hydraulic accumulator system
- PH = pumped Hydro
- S-CP = supercapacitor
- SMES = superconducting magnetic energy
WPP and energy accumulation

- Invertors in battery based on STATCOM principle
WPP and energy accumulation - advantages

- Power quality improvement
- Smooth changes U and P during wind speed decrease
- Constant P supply in longer period
- Possible U and f control in power grids
- Helps WPP to stay voltage sag
- Securing P supply to the grid
- Possible to sell power during higher energy price
WPP and FACTS

• WPP with power electronics (DFAG, SG + convertor)
  – ability U and Q regulation at output
  – ability of smooth control during changes in P and U
  – add to the grid limited short-circuit power
  – ability to stay during fault without disconnection

• Weak grids and long lines – SVC or STATCOM

• AG – SVC (STATCOM) could be applied for fault overstay, stabilisation U, power quality.
HVDC (High Voltage Direct Current) - application reasons

- **economic**
  - DC lines and cables are cheaper than AC of the same transmission capacity
  - x DC substations are more expensive, hence, there is economic brake point (overhead line 500 – 1000 km, cable 50 – 125 km)
  - no Q flow – lower losses, transmission capacity does not decrease along the line

- **technical**
  - connection of asynchronous power systems is possible
  - no critical length of DC cable, shunt compensation is not needed

- **environmental**
  - less overhead lines, more cable usage is possible
  - Higher transmission capacity of one route corridor
HVDC (High Voltage Direct Current) - advantages

- Independent operation of connected systems
- Active power flow $P$ is fully controlled
- Faults and rapid voltage drops do not spread through the line
LCC HVDC
(Line Commutated Converters)

- thyristor bridge converter (6, 12 pulse)
- Ac voltage is needed (current stimulation, commutation)
- Current flows through thyristors just one way
- consumes Q (rectifier and convertor)
- AC filters are needed (harm., Q)
- Commutation faults at invertor caused by $U_{AC}$ drop
LCC HVDC - components

• transformer
  – withstand mix of AC and DC stress
  – operate with high harmonics stress
  – commonly tap changer is installed
• Q compensation – filters, C blocks, SVC, STATCOM,…
• AC filters
• smoothing L at DC side – damp harmonics at DC
• control and communication between DC ends
• DC cable – withstand polarity change while active power flow reversion
HVDC substation
LCC HVDC - operation

• short-circuit power Sks min. 2,5*Sn, otherwise voltage instability, commutation fault
  – Sks increased by synchr. compensator, U by SVC (STATCOM)
• low short-circuit contribution
  – (+) strong grid, (-) weak grid (current for protection relays)
• one way DC current flow because of thyristors
  – reversion of P by $U_{DC}$ polarity change (2 quadrant)
• can not operate with P < 5-10% Pn
  – DC harmonics would switch off thyristors
• both sides consume $Q \sim 0,5P$
• losses in invertor are about 0,8% P
LCC HVDC - systems

- back-to-back
- monopolar
  - simple, losses in the ground < in cables (x corrosion)
- bipolar
  - 2 independent poles, without 1 pole transmits 50% P
- dimensioning (on land – area for filters and L)
  - 150-3000 MW, 180-500 kV (R&D 800 kV, 6000 MW)
VSC HVDC
(Voltage Sourced Converters)

• Bridge convertor with switching components
  – mostly IGBT (PWM 1kHz)
  – 3f $U_{AC}$ voltage allows independent reg. P, Q
  – C compensation is not needed

• filters
  – PWM (1-2 kHz) at higher f – lower
  – not for Q compensation (not switching)
  – multilevel – less filters, better sin curve

• AC reactor
  – damps transients, stabilize VSC
  – DC capacitor
VSC HVDC

• control system
  – convertor voltage affects: 1 – U, 2 – P, both – Q

• DC cable
  – constant polarity $U_{\text{DC}}$
  – polymer. cables (cheaper)

• operation
  – 4 quadrants (P,Q independent)
  – short-circuit contribution up to $I_n$
  – $U_{\text{AC}}$ is not needed – even for passive grid

• losses
  – higher than LCC (IGBT > thyristors, PWM, more components)
  – convertor around 2% P x minimum Q
HVDC (VSC x LCC)

- 2 cables
  - LCC up to 1400 MW at ±500 kV
  - VSC up to 500 MW at ±150 kV (future. 1000 MW at ±300 kV)
Multi-terminal HVDC

- 2 classic convertors with one DC connection
- more conv. can be used – one reg. U, other P flow
- possible LCC and VSC
- advantages VSC
  - no commutation faults and full system restart needed
  - operation does not depend on Sks
  - reversion without $U_{DC}$ polarity change (LCC can have special design)
  - without telecommunication
Parallel HVDC and AC

- power flow division by HVDC control
- with VSC additional reg. U
- for example, with WPP increase
  - HVDC fully control active power flow – no circle flow
- DC strengthen offshore grid
  - and for LCC
Advantages of HVDC for WPP

• asynchronous operation is available (AG)
• fault in the grid does not transit to WPP
  – better stands during fault without disconnection
  – during fault f increase at WPP, AC grid does not accept P
  – special control measures at convertors or additional resistor
• damp power oscillations – regular WPP operation
• Advantages VSC
  – does not require commutation voltage
  – operate smoothly at any active power flow
  – without commutation faults
  – smaller (compact) station than LCC
  – for AC grid operate as gen. without Q
  – low short-circuit contribution
Future and trends

• application of FACTS and HVDC
  (+) according to locality, grid, legislation
  (-) development of turbines and generators with power electronics

• environmental aspects
  – protest against overhead lines – cables (FACTS, next HVDC)

• inaccurate production prediction
  – development of accurate methods
  – applications of storage technologies
  – areas interconnection – lower effects of changes (wind fronts)

• grid requirements
  – approximate WPP characteristics to classical sources (dynamic regulation of U and f, oscillation damping)
Future and trends

• offshore
  – less envirom. aspects, noise, easier transmission
• often distant areas, for weak grid – power electronics.
• energy storage
  – quality – UPS, C, flywheel, SMES (ms-s)
  – energy manegament – PVE, hydrogen, batteries (hours, days)
Future and trends

- DC systems
DC supergrid

- connection – elimination of inaccurate prediction in big systems, mutual systems help
- more connections to AC grid
- multiterminal system – VSC
- requirement of investments and international (political) support
- connection of places at weaker grids (shore)
  - energy to consumption centers – further strengthen – HVDC?
DC supergrid