Wind generation in weak systems

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Future Electric Power Systems and the Energy Transition
Champéry, Switzerland
5-9 February 2017
Motivation

• Motivation

• Weak systems

• Phenomena in wide-area systems

• Test cases

• Simulation models

• Analysis techniques

• Results
Motivation

• Control systems of wind (DFIG) generators are usually designed neglecting the effect of the external grid (the impedance of the grid is much smaller than the impedance of the step-up transformers).

• Wind generator manufacturers are facing considerable challenges when connecting their machines to weak systems.

• A number of issues may arise.

• This talk classifies them and proposes a common approach to address (some of) them.

• This talk summarizes a work done for Ingeteam (a Spanish manufacturer of power electronic converters for wind generators).

• We are working now in this field with Gamesa and Iberdrola.
Motivation

- Wind DFIG
Motivation

- Rotor side controls
Motivation

- Grid side controls
Motivation

• Controls design approach

Parameters of the filter

Inner loops of the grid side converter

Damping and natural frequency are typically around 70% and 25-50 rad/s
Motivation

- Controls design approach

The natural frequency of the outer loop is typically 2.5-5 rad/s
Weak systems

- According to the “IEEE Guide for Planning DC Links Terminating at AC Locations Having Low Short-Circuit Capacities”, IEEE Std. 1204-1997, an AC system is weak at the point of connection, when any of the following conditions are met
  - The short circuit ratio is low

Wide-area systems

- The mechanical inertia is low

Isolated systems
Weak systems

- The short circuit ratio (SCR) is
  - the short circuit capacity in per unit and also
  - the inverse of the short circuit impedance

\[
SCR = \frac{S_{sc} \left( MVA \right)}{S_B \left( MVA \right)} = \frac{1}{X_{sc} \left( pu \right)}
\]

\[
E = \frac{U_n}{\sqrt{3}}
\]

\[
I_{sc} = \frac{E}{X_{sc}}
\]

\[
S_{sc} = \sqrt{3} U_n I_{sc} = \frac{U_n^2}{X_{sc}}
\]

\[
X_{sc} = \frac{U_n^2}{S_{sc}}
\]
Weak systems

- Short circuit impedance is related with the length (proportional) and the voltage (proportional to the inverse of the square) of the connection line

\[
X(\text{pu}) = \frac{X(\Omega)}{Z_B(\Omega)} = \frac{\omega L\ell}{U_n^2} = \frac{2\pi f_0 \cdot 0.001 \cdot \ell}{U_n^2} S_B
\]

Length

Nominal voltage
Weak systems

- Frequency deviation is governed by the inertia of the rotating mass of generators and the response of the primary frequency regulation.

Assuming enough reserve and no activation of load-shedding

\[ \Delta \omega(\infty) = -R \Delta P \]

\[ \frac{d \Delta \omega}{dt} \bigg|_{t=0^+} = \frac{-\Delta P}{2H} \]

- Frequency: \( pu \)
- Load: \( pu \)
- Generation: \( pu \)
- Generation tripped: \( pu \)
Weak systems

- Comparison of the frequency variations in a large interconnected system and in an isolated system

![Graph showing frequency variations in different system sizes](image)

- 3000 MW loss in a 300,000 MW system
- 100 MW loss in a 1,000 MW system
- 100 MW loss in a 1,000 MW system
- 200 MW loss in a 500 MW system
Phenomena in wide-area systems

- Subsynchronous oscillations
- Harmonic amplification
- Voltage stability
- Controller interaction

Interaction of wind generators and their control systems with the grid and devices connected to the grid
Phenomena in wide-area systems

- Subsynchronous oscillations
  - Subsynchronous resonance occurs in synchronous generators connected to series compensated transmission lines

- The natural oscillation of the series LC circuit is seen by the synchronous generator rotor as two natural oscillations of subsynchronous and supersynchronous frequencies respectively

\[
f_{1,2} = f_0 \pm f_n
\]

\[
f_n = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi} \sqrt{\frac{X_C}{X_L}}
\]
Phenomena in wide-area systems

- Subsynchronous oscillations
  - The frequency of the subsynchronous oscillation may be close to a torsional frequency of the rotor making it unstable
  - The subsynchronous frequency may be unstable itself resulting in induction generator behaviour
Phenomena in wide-area systems

- Harmonic amplification
  - Harmonic sources
  - Power electronic converters

\[ h = \sqrt{\frac{X_C}{X_L}} = \frac{1}{\sqrt{X_L B_C}} = \sqrt{\frac{S_{cc}}{Q_C}} \]
Phenomena in wide-area systems

- Voltage stability
  - Maximum power delivered by a line

\[ P_{\text{max}} = \frac{EV}{X} \]

\[ E = E \angle \theta \quad V = V \angle 0 \]
**Phenomena in wide-area systems**

- Controller interaction
  - A statcom connected at MV busbar of the wind farm can provide reactive power compensation and improve the transient voltage response as well
Test cases

- Subsynchronous oscillations

Interaction between the wind farm and the series compensated transmission line

- Harmonic amplification

Interaction between the wind farm and the resonant circuit of the shunt capacitor and line inductance
Test cases

- Voltage stability

Maximum transmitted power

- Controller interaction

Interaction between a wind farm and a statcom
Simulation models

• Modeling options
  o Electromagnetic transient
  o Network transients
  o Electromechanical transients (transient stability)
Simulation models

- Subsynchronous oscillations
Simulation models

- Harmonic amplification
Simulation models

- Voltage stability
Simulation models

- Controller interaction
Analysis techniques

• Non-linear model

\[
\dot{x} = F(x, u, \eta) \\
y = G(x, u, \eta) \\
0 = F(x_0, u_0, \eta)
\]
Analysis techniques

• Linear model

\[
\begin{align*}
\Delta x &= \left. \frac{\partial F(x, u, \eta)}{\partial x} \right|_{x_0, u_0} \Delta x + \left. \frac{\partial F(x, u, \eta)}{\partial u} \right|_{x_0, u_0} \Delta u \\
\Delta y &= \left. \frac{\partial G(x, u, \eta)}{\partial x} \right|_{x_0, u_0} \Delta x + \left. \frac{\partial G(x, u, \eta)}{\partial u} \right|_{x_0, u_0} \Delta u \\
\Delta \dot{x} &= A \Delta x + B \Delta u \\
\Delta y &= C \Delta x + D \Delta u
\end{align*}
\]
Analysis techniques

- Eigenvalue analysis
  - Eigenvalues and eigenvectors

\[
\begin{align*}
\mathbf{A}v_i &= v_i \lambda_i \\
\mathbf{w}_i^T \mathbf{A} &= \lambda_i \mathbf{w}_i^T \\
\mathbf{w}_i^T v_i &= 1
\end{align*}
\]

\[
\Delta \mathbf{x} = \mathbf{V} e^{\mathbf{A}t} \mathbf{W} \Delta \mathbf{x}(0) = \sum_{i=1}^{N} v_i e^{\lambda_i t} \left[ \mathbf{w}_i^T \Delta \mathbf{x}(0) \right]
\]

- Participacion factors

\[
p_{ji} = v_{ji} w_{ij}
\]
Analysis techniques

• Frequency response

\[
\frac{\Delta y(\omega)}{\Delta u(\omega)} = c^T (j\omega I - A)b + d
\]
Analysis techniques

Model

Calculation of operating point

Calculation of the linear model
  - Eigenvalue analysis
  - Frequency response

Time domain simulation of the non-linear model
Results

- Subsynchronous oscillations

\[ R = 0.01X \quad X = 0.15 \quad R = 0.01X \quad X = 0.2X_C = -FC \cdot X \]

Wind generator and wind farm step-up transformers

Series compensated line

All parameters are in per unit of the MVA base of the wind generator
Results

- Subsynchronous oscillations
  - Natural frequency in case of 20% compensation factor
    \[
    f_n = f_0 \sqrt{\frac{X_C}{X_L}} = f_0 \sqrt{\frac{FC \cdot X_\ell}{X_s + X_r + X_t + X_\ell}}
    \]
    \[
    = 50 \sqrt{\frac{0.2 \cdot 0.2}{0.15 + 0.15 + 0.15 + 0.2}} = 12.4 \text{Hz}
    \]
  - Supersynchronous oscillation
    \[
    f_0 + f_n = 62.4 \text{Hz}
    \]
  - Subsynchronous oscillation
    \[
    f_0 - f_n = 37.6 \text{Hz}
    \]
Results

- Subsynchronous oscillations
  - Root locus when compensation factor changes

The supersynchronous mode is stable no matter the compensation factor is.

The subsynchronous mode becomes unstable for high compensation factors.
Results

- Subsynchronous oscillations
  - Effect of the compensation and the wind speed

The damping of the subsynchronous mode reduces as the compensation factor increases. The wind speed does not affect to the damping of the subsynchronous mode.
Results

• Subsynchronous oscillations
  ◦ Effect of the bandwidth of the converter regulators

The damping of the subsynchronous model is affected by the bandwidth of the rotor side converter regulators.
Results

- Subsynchronous oscillations
  - Conclusions
    - The stability is determined by the subsynchronous mode.
    - The damping of the subsynchronous mode depends on the line compensation factor. It does not depend on the wind speed.
    - The damping of the subsynchronous mode depends on the bandwidth of the regulators of the rotor side converter. Higher bandwidth results in undamped mode.
    - In case of a compensation factor of 30% and a wind speed of 10 m/s, the mode becomes unstable if the bandwidth is 32.5 rad/s.
    - The bandwidth of the regulators of the grid side converter does not affect the damping of the subsynchronous mode.
Ingeteam

This work is a result of a joint effort with
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Results

- Harmonic amplification

\[ R_t = 0.01X_t \quad X_t = 0.15 \]

\[ X_{\ell} \quad R_{\ell} = 0.01X_{\ell} \]

\[ B_C = 0.05 \]

All parameters are in per unit of the MVA base of the wind generator.

\[ f = f_0 \frac{1}{\sqrt{X_e B_C}} \]

\[ X_e = \frac{1}{\frac{1}{X_s + X_r + X_t} + \frac{1}{X_{\ell}}} \]

The resonant frequency corresponds to the 11th harmonic if the line reactance is 0.2612pu.
Results

- Harmonic amplification

Resonant frequency at 11th harmonic: the resonant frequency is the average of the two frequency peaks

Frequency response between the grid side converter voltage and the point of common coupling voltage
Results

- Harmonic amplification
  - Resonant frequency as a function of the line reactance for several shunt capacitor banks

Amplification at the 11th harmonic

0.2612 pu
Resultados

- Harmonic amplification
  - Effect of the line reactance and the bandwidth of the grid side converter regulators of the resonant frequency

The bandwidth of the grid side converter regulator does not affect to the resonant frequency.
Results

- Harmonic amplification
  - Conclusions
    - The resonant frequency calculated using a simplified model agrees with the frequency determined using a detailed model.
    - The resonance at the 11th harmonic occurs at a high value of the line reactance (low short circuit ratio).
    - The resonant frequency is not affected by the bandwidth of the regulators of the converters.
Results

• Voltage stability

The normalized active power is changed by changing the line reactance

\[ R_t = 0.01X_t \]
\[ X_t = 0.15 \]
\[ R_{\ell} = 0.01X_{\ell} \]

Wind generator and wind farm step-up transformers

All parameters are in per unit of the MVA base of the wind generator
Results

• Voltage stability
  o Root locus as the line reactance increases from 0.15 to 0.45 pu
    Complex mode at the synchronous frequency in a reference frame rotating at synchronous speed. It becomes a real mode in a stationary reference frame.

The eigenvalues move to right as the line reactance increases
Results

- Voltage stability
  - Normalized voltage as the line reactance increases from 0.15 to 0.45 pu
Results

- Voltage stability
  - Voltage variation when the wind speed increases 1%

La constante de tiempo de la respuesta aumenta al aumentar la reactancia de la línea ya que el modo tiene parte real menor.
Resultados

- Voltage stability
  - Effect of the line reactance and the bandwidth of the grid side converter regulators on the time constant of the slowest real mode

The bandwidth of the regulators of the grid side converter does not affect to the time constant of the slowest real mode.
Results

- Voltage stability
  - Conclusions
    - Voltage stability is characterized by negative real eigenvalue (decreasing monotonic behavior). As the system approaches to the point of voltage instability, the time constant increases.
    - Voltage stability is not affected by the bandwidth of the regulators of the grid side converter.
Results

- Controller interaction

\[ R_t = 0.01X_t \]
\[ X_t = 0.06 \]

\[ R_\ell = 0.01X_\ell \]
\[ X_\ell = 0.09 + 0.5 \]

Wind generator

Wind generator step-up transformer

Wind farm step-up transformer and line

Statcom

All parameters are in per unit of the MVA base of the wind generator.
Results

• Controller interaction
  - Root locus as the bandwidth of the statcom regulators increases

If the bandwidth of the statcom regulators increases, the natural frequency of associated modes increases whereas the damping remains.
Results

- Controller interaction
  - Effect of the bandwidth of the statcom regulators and grid side converter regulators of DFIG

The bandwidth of the regulators of the grid side converter does not affect to the minimum damping.
Results

• Controller interaction
  ○ Conclusions
    • No adverse interactions amongs wind generator controls and Statcom controls have been found.
Summary

• Subsynchronous oscillations
  o Subsynchronous instability arises when both the compensation factor and the bandwidth of the regulators of the rotor side converter.

• Harmonic amplification
  o Resonance at the 11th harmonic arises in high impedance grids.

• Voltage stability
  o The stability limit decreases as the line reactance increases.

• Controller interaction
  o No adverse interactions among wind generator controls and Statcom controls have been found.