Analysis and Mitigation of Subsynchronous Resonance Involving Type-III Wind Turbines

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Outline

• Wind Power Conversion
• Subsynchronous Resonance
• Impedance Models
• Impedance Based Analysis of SSR
• SSR Damping
• Summary
Wind Power Generation

Type-I Wind Turbine
- Fixed Speed
- SCIG

Type-II Wind Turbine
- WRIG

Type-III Wind Turbine
- WRIG

Type-IV Wind Turbine
- PMSG
Type-III System, Detail
ERCOT 2009 SSR

50% Compensation Lines Highlighted

1. Ajo-Nelson Tripped
2. Ajo Wind Farm is Radially Connected to Rio Hondo
3. Voltages Increase Up to 1.95 pu

DFIG Sub-Synchronous Resonance

RSC + Machine
• Most significant turbine component for SSR.
• RSC is also the best prospect of using turbines own controls for reducing SSR.
• Converter interacts with the power grid though induction machine.

Power Grid

GSC
• High impedance compared to RSC
• Not significant for SSR studies or mitigation strategies
DFIG Currents during SSR

Stator Currents

Rotor Currents

Frequency (Hz)

0.88 pu/div

I/I_1 (%)

8 Hz

60 Hz

12 Hz

64 Hz

I/I_1 (%)
Turbine Models

Below fundamental, Positive Sequence

\[
Z^1_p(s) = \frac{s(L_s + L'_r) + \left(R_s + \frac{R'_r}{\sigma_p(s)}\right) + \frac{V_{dc}k_{mr}}{\sigma_p(s)} \left(\frac{N_s}{N_r}\right)^2 (H_{ri}(j\omega_1 - s) + jK_{dr})}{1 - \frac{V_{1r}}{2\sigma_p(s)} G_{PL}(j\omega_1 - s) \left(\frac{N_s}{N_r}\right) \left(V_{dc}k_{mr}(H_{ri}(j\omega_1 - s) + jK_{dr}) \frac{I_{1r}}{V_{1r}} + 1\right)}
\]

Above fundamental, Positive Sequence

\[
Z^2_p(s) = \frac{s(L_s + L'_r) + \left(R_s + \frac{R'_r}{\sigma_p(s)}\right) + \frac{V_{dc}k_{mr}}{\sigma_p(s)} \left(\frac{N_s}{N_r}\right)^2 (H_{ri}(s - j\omega_1) - jK_{dr})}{1 - \frac{V_{1r}^*}{2\sigma_p(s)} G_{PL}(s - j\omega_1) \left(\frac{N_s}{N_r}\right) \left(V_{dc}k_{mr}(H(s - j\omega_1) - jK_{d}) \left(\frac{I_{1r}}{V_{1r}}\right)^* + 1\right)}
\]

Negative Sequence

\[
Z_n(s) = \frac{s(L_l + L'_r) + \left(R_s + \frac{R'_r}{\sigma_n(s)}\right) + \frac{V_{dc}k_{mr}}{\sigma_n(s)} \left(\frac{N_s}{N_r}\right)^2 (H_{ri}(s + j\omega_1) + jK_{dr})}{1 - \frac{V_{1r}^*}{2\sigma_n(s)} G_{PL}(s + j\omega_1) \left(\frac{N_s}{N_r}\right) \left(V_{dc}k_{mr}(H_{ri}(s + j\omega_1) + jK_{dr}) \frac{I_{1r}}{V_{1r}} + 1\right)}
\]
# System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_s$</td>
<td>690 V</td>
<td>$V_{dc}$</td>
<td>1500 V</td>
</tr>
<tr>
<td>$f$</td>
<td>60 Hz</td>
<td>$R_s$</td>
<td>0.929 mΩ</td>
</tr>
<tr>
<td>$I_s$</td>
<td>3740</td>
<td>$R_R$</td>
<td>5.8 mΩ</td>
</tr>
<tr>
<td>Turns Ratio</td>
<td>0.34:1</td>
<td>$L_{ls}$</td>
<td>54.7 µH</td>
</tr>
<tr>
<td>Pole Pairs</td>
<td>3</td>
<td>$L_{lr}$</td>
<td>462 µH</td>
</tr>
<tr>
<td>Mac. Speed</td>
<td>2160 RPM</td>
<td>$L_M$</td>
<td>1.6 mH</td>
</tr>
<tr>
<td>$K_{pr}$</td>
<td>0.0518</td>
<td>$K_d$</td>
<td>$-8.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>$K_{ir}$</td>
<td>3.8462</td>
<td>$k_{mr}$</td>
<td>$2.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>$K_{pp}$</td>
<td>0.7886</td>
<td>$K_ip$</td>
<td>2495</td>
</tr>
<tr>
<td>RSC BW</td>
<td>100 Hz</td>
<td>RSC PM</td>
<td>60°</td>
</tr>
<tr>
<td>PLL BW</td>
<td>50 Hz</td>
<td>PLL PM</td>
<td>45°</td>
</tr>
<tr>
<td>$L_{grid}$</td>
<td>0.5 pu</td>
<td>Compensation</td>
<td>50%</td>
</tr>
</tbody>
</table>
DFIG Model for SSR

\[
Z^1_\text{p}(s) = \frac{s(L_s + L'_r) + \left(R_s + \frac{R'_r}{\sigma_p(s)}\right) + \frac{V_{dc} k_{mr}}{\sigma_p(s)} \left(\frac{N_s}{N_r}\right)^2 \left(H_{ri}(j\omega_1 - s) + j K_{dr}\right)}{1 - \frac{V_{1r}}{2\sigma_p(s)} G_{PL}(j\omega_1 - s) \left(\frac{N_s}{N_r}\right) \left(V_{dc} k_{mr} \left(H_{ri}(j\omega_1 - s) + j K_{dr}\right) I_{1r} \frac{V_{1r}}{V_{1r}} + 1\right)}
\]

Red: Positive Sequence Turbine
Purple: Grid Impedance
Black: Negative Sequence Turbine
Dots: Measured
Line: Model

Magnitude (db)

Phase (deg)

Frequency

1 Hz 10 Hz 100 Hz 1 kHz

1 Hz 10 Hz 100 Hz 1 kHz

~0°
Impedance Ratio Nyquist Plot

\[ \frac{Z_g(s)}{Z_{P1}(s)} \]

\(~0°\) Phase Margin

Stator Currents
DFIG Model Analysis

- In the SSR range machine inductance dominates.
- SSR falls into converter control bandwidth:
  - Turbine impedance can be modified through RSC controls.
SSR Damping Methods

• Static Var Compensator at wind farm terminals
  – (H. Xie and M. Oliveira, 2014)

• STATCOM damping at wind farm terminals
  – (A. Moharana, R. Varma and R. Seethapathy, 2014)

• Damping through power electronics controls
  – GSC damping using series capacitor voltage
    (H. Mohammadpour and E. Santi, 2015)
  – RSC damping using $dq$-axis rotor voltages
    (A. Leon and J. Solsona, 2015)
Hailian Xie, “Mitigation of SSR in Presence of Wind Power and Series compensation by SVC”, 2014 POWERCON, Chengdu

- Controls susceptance based on local variables, e.g. line power
- Susceptance response is non linear, and depends on operating conditions
- Needs the installation TSC
- With enough information, its effective over a wide power and wind speed spectrum.
STATCOM SSR Damping

- STATCOM is tuned to stabilize electrical modes of the complete system.
- Requires detailed knowledge of the wind farm parameters and operating conditions.
- Fine-tuning of parameters is done by hand using EMT simulations.
- STATCOM gives a lot of flexibility to adjust system eigenvalues and stabilize it.

Obtain chosen control signals.

No damping

Capacitor voltage compensation Injected at GSC voltage regulator

Virtual Impedance Damping

• Approach:
  – Use rotor $dq$-axis currents (already measured)
  – Obtain voltage drop for currents through an equivalent impedance.
    \[ V_{dq} = I_{dq} \cdot Z_d(s) \]
    – Inject voltage terms into controller output.

• Modify turbine impedance to add phase margin
• Does not need eigenvalue analysis of turbine system
• Impedance of systems with complex/unknown controls can be scanned instead of modelled
• Virtual impedance can be filtered and narrowed to not affect fundamental or higher frequencies
Virtual Rotor Impedance Damping

\[ V_{dc} \]

\[ Z_d \]

\[ R_r \]

\[ L_{lr} \]

\[ L_{ls} \]

\[ R_s \]

\[ \Sigma \]

\[ \Sigma \]

\[ K_{pr} + K_{ir}/s \]

\[ K_{pr} + K_{ir}/s \]

\[ \omega_1 \]

\[ \omega_2 \]

\[ Z_d(s) = \frac{s R}{\omega_1 \left(1 + \frac{s}{\omega_1}\right) \left(1 + \frac{s}{\omega_2}\right)} \]

\[ \text{Magnitude (dB)} \]

\[ -20 \]

\[ -30 \]

\[ -40 \]

\[ -50 \]

\[ -60 \]

\[ -70 \]

\[ -80 \]

\[ 1 \text{ Hz} \]

\[ 10 \text{ Hz} \]

\[ 100 \text{ Hz} \]

\[ 1 \text{ kHz} \]

\[ 10 \text{ kHz} \]
Damped Impedance

Turbine impedance with a negative virtual resistance as damping

Red: Positive Sequence Turbine
Purple: Grid Impedance
Black: Negative Sequence Turbine
Dots: Measured
Line: Model
Virtual Stator Impedance

\[ Z_d(s) = \sigma_p(s) \frac{s R}{\omega_1 \left( 1 + \frac{s}{\omega_1} \right) \left( 1 + \frac{s}{\omega_2} \right)} \]

\[ V_{dc} \]

\[ R_r \]
\[ L_{lr} \]
\[ L_s \]
\[ R_s \]
\[ Z_d \]

\[ I_{dr} \]
\[ I_{qr} \]
\[ I_{dr}^{\text{ref}} \]
\[ I_{qr}^{\text{ref}} \]
\[ K_p + K_i / s \]
\[ K_p + K_i / s \]

\[ \theta_{PL} - \theta_r \]
\[ K_d \]

\[ Z_d(s) \]
Undamped Resonance, Zoomed

Total Output Currents (2kA/div)

Strong grid  Fault  Compensated weak grid

10 Hz Resonance

Current (A)

Time (s)
Undamped Resonance

Total Output Currents (2kA/div)

Current (A) vs. Time (s) during a fault event.
Damped Resonance

Total Output Currents (2kA/div)

Fault

Time (s)

Current (A)
The SSR phenomenon is present also when the generator operates below synchronous speed.

Red: Positive Sequence Turbine  
Purple: Grid Impedance  
Black: Negative Sequence Turbine  
Line: Model
Damped Simulation, SuperS Oper.

Total Output Currents (2kA/div)

18 Hz Resonance

Time (s)

Current (A)

SSR Control OFF

SSR Control ON

CFES Annual Conference 02-26-2015
SSR Control $d$-axis Output

SSR Control output when connected to an ideal grid (no resonance)

Steady-state output: 211V
Damping Stator Impedance

Shaping stator impedance is more drastic, but to implement it, controls needs to consider machine airgap.

Red: Virtual Rotor Resistance

Black: Virtual Stator Resistance

Purple: Grid Impedance
Summary

• SSR in type-III wind turbines was explained and analyzed using turbine impedance.
• Turbine impedance was modified through controllers to damp the resonance.
• Future Work:
  – More robust control actions that can emulate impedances on rotor or stator side
  – Use damping as part of stability studies in heavily compensated weak grids.

End of Presentation

This work is supported in part by the National Science Foundation under Award #ECCS-1002265