Active Damping Control of DFIG Wind Turbines during Fault Ride Through

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DFIG WT configuration (Type Ⅲ)

- Less converter cost
- Smaller in weight and dimensions
- No use of raw earth material
- Long track record
- Grid compatibility: crowbar device

➢ DFIG is still attractive in future (especially on shore wind turbine)
Grid codes (LVRT and HVRT) in different countries

- Grid disturbances (LVRT, HVRT) leads to high level vibrational excitation of the drive train during operation of wind turbines
- Especially in a worst-case scenario the turbine is loaded with rated torque before a FRT grid event

Generator electromagnetic torque during voltage dip

Active power output of a 3.6 MW WT during and after an FRT-Grid Event
The torsional problem in DFIG drive-train caused by:

- Highly dynamic electrical torque
- Modes transition when Crowbar on and off
- Soft shaft
- Little damping
- Fluctuating wind

Which result in:

- Additional load in the drive train and all mechanically coupled systems (such as rotor blades, nacelle and tower)
- Long time electrical oscillation (power recovery slowly)
- Emergency stop
To study the structural loads of wind turbines during FRT, a whole model including both mechanical and electrical parts should be constructed.

- Commonly used simulation tools:
  - Simple mechanical+detailed electrical: DlgSILENT, Matlab Powersystem, PSIM
  - Detailed mechanical+simple electrical: Bladed, FAST, HAWC2

A model based damper is designed to add damping to the torsion modes without energy loss.

- Decrease the fatigue and ultimate loads
- Works in both normal operation and fault operation
Modeling of DFIG WT system

Aerodynamic & Mechanical

- Gear Box
- Back to back Converter
- Crowbar
- Fast Simulink
- Wind
- \( \omega_{\text{gen}} \)
- \( \theta_{1,2,3} \)

Electrical parts & Controller

- DFIG
- Back to back Converter
- Crowbar
- Control system
- \( T_v' \), \( Q' \)
- Pitch actuator
- Simulink
- PCC
- Grid

Detailed Approaches

- Aerodynamic parts: BEM theory
- Mechanical parts: 16 DOFs
- Electrical parts: DFIG, Back-to-Back VSC, crowbar
- Controller: pitch controller, torque controller
16 degree of freedom (DOF)

- 1st and 2nd flapwise blade mode (6)
- Edgewise blade mode (3)
- 1st and 2nd tower fore-aft bending mode (2)
- 1st and 2nd tower side-side bending mode (2)
- Drive-train rotational flexibility (1)
- Yaw angle (1)
- Generator azimuth angle mode (1)

**FAST (Fatigue, Aerodynamics, Structure, Turbulence)**

**Source:** FAST user’s guide, NREL
DFIG model

- The DFIG generator model is expressed in a DQO-dqo synchronously rotating reference Frame

  - Voltage equations
    \[
    \begin{align*}
    v_{ds} &= R_s i_{ds} + \dot{\lambda}_{ds} - \omega_s \lambda_{qs} \\
    v_{qs} &= R_s i_{qs} + \dot{\lambda}_{qs} + \omega_s \lambda_{ds} \\
    v_{dr} &= R_r i_{dr} + \dot{\lambda}_{dr} - (\omega_s - \omega_r) \lambda_{qr} \\
    v_{qr} &= R_r i_{qr} + \dot{\lambda}_{qr} + (\omega_s - \omega_r) \lambda_{dr}
    \end{align*}
    \]

  - Flux equations
    \[
    \begin{align*}
    \dot{\lambda}_{ds} &= L_s i_{ds} + L_m i_{dr} \\
    \dot{\lambda}_{qs} &= L_s i_{qs} + L_m i_{qr} \\
    \dot{\lambda}_{dr} &= L_r i_{dr} + L_m i_{ds} \\
    \dot{\lambda}_{qr} &= L_r i_{qr} + L_m i_{qs}
    \end{align*}
    \]

- Electromagnetic torque
  \[
  T_e = 1.5p(\lambda_{ds}i_{qs} - \lambda_{qs}i_{ds})
  \]

- Generator rotational motion has been involved in FAST model
Back-to-back converter model

- Crow bar circuit

- RSC controller

- GSC controller
Baseline controller

- Baseline torque controller
  \[ T_{BC} = \begin{cases} 
  K_{opt} \omega_g^2, & \omega_g < \omega_{rate} \\
  T_{rate}, & \omega_g \geq \omega_{rate} 
  \end{cases} \]

- Baseline pitch controller

  - For below-rated region, the optimal power control is realized through the maximum power point tracking (MPPT)
  - For above-rated region, the generator torque is held constant at the rated torque and the rotor speed is controlled by limiting the aerodynamic torque by varying the pitch angle
  - Active damping controller is required for above-rated area

![Torque ref vs. Generator speed](chart.png)
Active damping controller via torque control

The proposed drive train control

- Model-based damper
- Add damping to torsional modes
- Without energy yield lost
Controller design

- 3-mass drive-train model considering both shaft flexibility and blades flexibility

![Diagram of a 3-mass drive-train model]

- Supposing $D_{12}=D_{23}=0$

\[
\begin{bmatrix}
\dot{\omega}_{12} \\
\dot{\theta}_{12} \\
\omega_{23} \\
\dot{\theta}_{12} \\
\dot{\omega}_{3}
\end{bmatrix} =
\begin{bmatrix}
0 & -\frac{K_{12}}{J_1} & -\frac{K_{12}}{J_2} & 0 & \frac{K_{23}}{J_2} & 0 \\
1 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{K_{12}}{J_2} & 0 & -\frac{K_{23}}{J_2} & -\frac{K_{23}}{J_3} & 0 \\
0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{K_{23}}{J_3} & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\omega_{12} \\
\theta_{12} \\
\omega_{23} \\
\theta_{12} \\
\omega_{3}
\end{bmatrix} +
\begin{bmatrix}
0 \\
0 \\
-\frac{N}{J_3}
\end{bmatrix}
\]
Controller design

- System identification

\[ f_1 = \frac{1}{2\pi} \left( -\frac{b}{2} - \sqrt{\frac{b^2 - 4c}{2}} \right)^{0.5}, \quad f_2 = \frac{1}{2\pi} \left( -\frac{b}{2} + \sqrt{\frac{b^2 - 4c}{2}} \right)^{0.5} \]

\[ b = -\left[ K_{12}\left( \frac{1}{J_1} + \frac{1}{J_2} \right) + K_{23}\left( \frac{1}{J_2} + \frac{1}{J_3} \right) \right], \quad c = K_{12}K_{23}\left( \frac{J_1 + J_2 + J_3}{J_1J_2J_3} \right) \]

- In this case, \( f_1 = 1.7 \text{Hz}, \ f_2 = 4 \text{Hz}, \) and \( k_{23}, J_1+J_2, J_3 \) are known

- From above

<table>
<thead>
<tr>
<th>( J_1 ) [kgm²]</th>
<th>( J_2 ) [kgm²]</th>
<th>( J_3 ) [kgm²]</th>
<th>( K_{12} ) [Nm/ rad]</th>
<th>( K_{23} ) [Nm/ rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 3.09 \times 10^7 )</td>
<td>( 4.54 \times 10^6 )</td>
<td>( 5.03 \times 10^6 )</td>
<td>( 1.39 \times 10^9 )</td>
<td>( 8.68 \times 10^9 )</td>
</tr>
</tbody>
</table>
Linear-quadratic regulator (LQR)

For a continuous-time linear system described by

\[ \dot{x} = Ax + Bu \]

with a cost functional defined as

\[ J = \int_0^\infty (x^T Q x + u^T R u) \, dt \]

the feedback control law that minimizes the value of the cost is

\[ u = -K x \]

where \( K \) is given by

\[ K = R^{-1} B^T P \]

and \( P \) is found by solving the continuous time algebraic Riccati equation

\[ A^T P + PA - PBR^{-1}B^T P + Q = 0 \]
Controller performance

- Full state feedback;
- Add damping to the drive-train torsion mode and blade in-plane symmetrical mode;
- A trade-off between control performance (Q large) and low power ripple (R large);
- A Kalman Filter is used for state estimate;

\[
\begin{align*}
\dot{x}(t) &= A\hat{x}(t) + Bu(t) + L(y(t) - \hat{y}(t)) \\
\hat{y}(t) &= C\hat{x}(t)
\end{align*}
\]
Simulations

To define a typical onshore wind turbine, we use properties from the NREL 5-MW baseline model

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power rating</td>
<td>5 MW</td>
</tr>
<tr>
<td>Rotor</td>
<td>3-bladed, upwind</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>126m</td>
</tr>
<tr>
<td>Hub height</td>
<td>90m</td>
</tr>
<tr>
<td>Rated rotor speed</td>
<td>12.1rpm</td>
</tr>
<tr>
<td>Total rotor inertia</td>
<td>$3.09 \times 10^7$ kgm$^2$</td>
</tr>
<tr>
<td>Generator inertia</td>
<td>$5.03 \times 10^6$ kgm$^2$</td>
</tr>
<tr>
<td>Gearbox ratio</td>
<td>97:1</td>
</tr>
<tr>
<td>Equivalent shaft stiffness</td>
<td>$8.676 \times 10^8$ Nm/rad</td>
</tr>
</tbody>
</table>

5-MW DFIG parameters

<table>
<thead>
<tr>
<th>$U_s$ [V]</th>
<th>$R_s$ [mΩ]</th>
<th>$L_s$ [mH]</th>
<th>$R_r$ [mΩ]</th>
<th>$L_r$ [mH]</th>
<th>$L_m$ [mH]</th>
<th>$R_{cr}$ [Ω]</th>
</tr>
</thead>
<tbody>
<tr>
<td>960</td>
<td>2.1</td>
<td>0.153</td>
<td>2.1</td>
<td>0.149</td>
<td>4.26</td>
<td>0.11</td>
</tr>
</tbody>
</table>
Simulations

- **Load case:**
  
  In order to show the impact of voltage sag on drive-train, we considered the worst-case scenario. (the turbine is loaded with rated torque within the drive-train before a FRT grid event.)

- **Wind speed:**
  
  Three dimensional turbulent wind has been used for simulating inflow turbulence environments which is produced by **Turbsim**

- **Voltage dip:**
  
  In this study, the 3 phase voltage dip is simulated by a voltage step of the voltage source in the grid model at t=15s, with duration 200ms, which causes stator voltage sags to 20%
Simulation results - time domain

- Wind speed
- Generator speed
- Generator torque
- Shaft torque
- Pitch angle
- Active power

- Before FRT event, almost steady with active damping controller
- After FRT event,
  - Peak load decreased by 0.2 pu;
  - Oscillations will be damped in 3 seconds;
  - Quick active power recovery;
  - Over loading(<10%), it could be tolerated by power converters in short time
Simulation results-frequency domain

- Dominate frequencies around 1.7 Hz and 4 Hz have be totally damped
Conclusions and future work

Co-simulation of FAST and Simulink are used to model the mechanical and electrical aspects of a 5-MW doubly-fed induction generator (DFIG) based wind turbine respectively.

A LQR controller with state estimate is proposed to reduce the torque oscillations and improve drive-train reliability.

Simulation results show the effectiveness of the proposed control strategy.

Because no extra sensors are added, the controller can be easily implemented to the commercial wind turbine.

Future work should include impact of different grid parameters on wind turbine loads and Hardware-in-the-loop test.
Questions?

Thank you for your Attention!

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