Active Damping Control of DFIG Wind Turbines during Fault Ride Through

Hao Xu[1], Honghua Xu[1], Liang Chen[2], Jan Wenske[2]

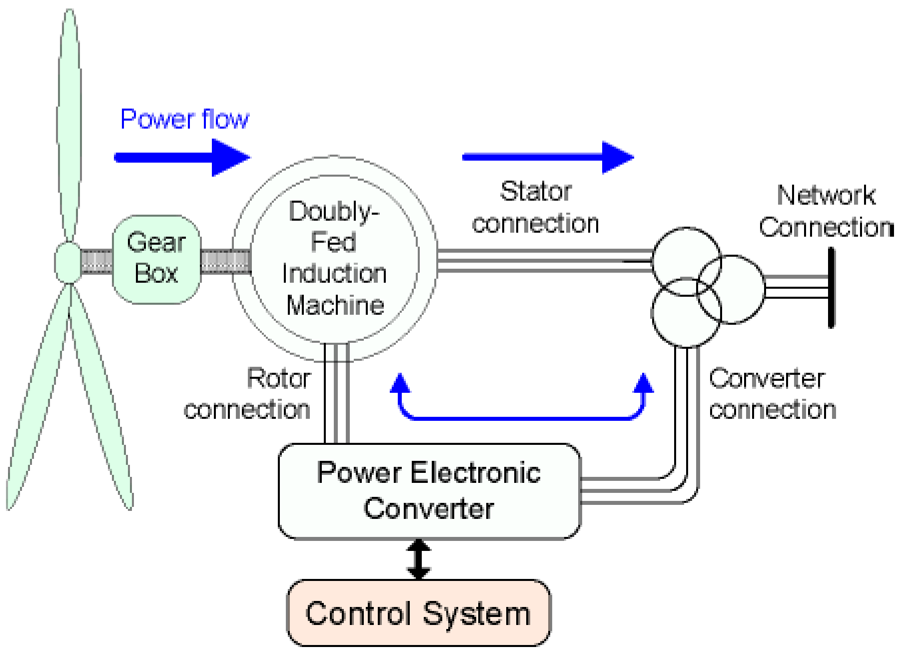
1 Institute of Electrical Engineering, Chinese Academy of Sciences

2 Fraunhofer Institute for Wind Energy and Energy System Technology, Germany

INSTITUTE OF ELECTRICAL ENGINEERING, CHINESE ACADEMY OF SCIENCES

Fraunhofer IWES

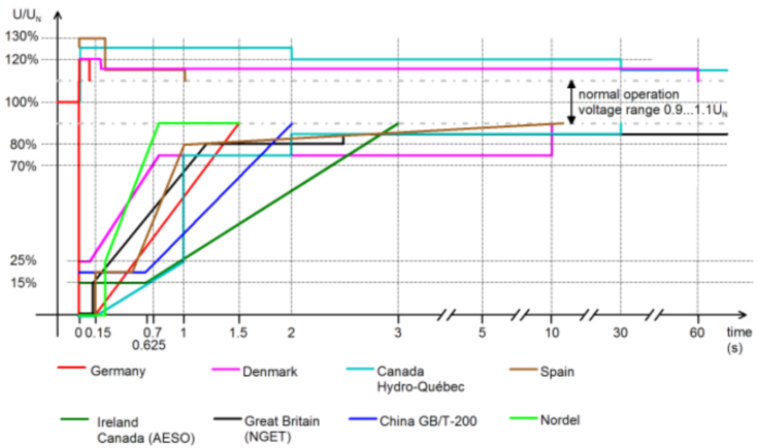
DFIG WT configuration (Type Ⅲ)



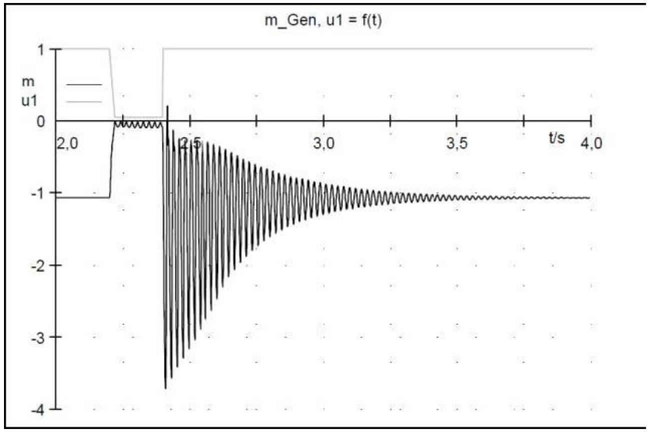
- Less converter cost
- Smaller in weight and dimensions
- No use of raw earth material
- Long track record
- Grid compatibility: crowbar device

➢ **DFIG is still attractive in future (especially on shore wind turbine)**

Power Grid Standards - Fault Ride Through



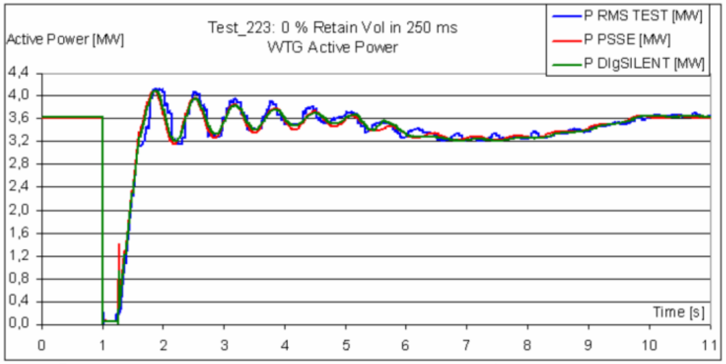
Grid codes(LVRT and HVRT) in different countries



Generator electromagnetic torque during voltage dip

- 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



Active power output of a 3.6 MW WT during and after an FRT-Grid Event

Torsional problem in post-fault period

- **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**
  - **Addtional 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**

Motivations and Aims

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: DIgSILENT, Matlab Powersystem, PSIM
  - Detailed mechanical+simple electrical: Bladed, FAST, HAWC2

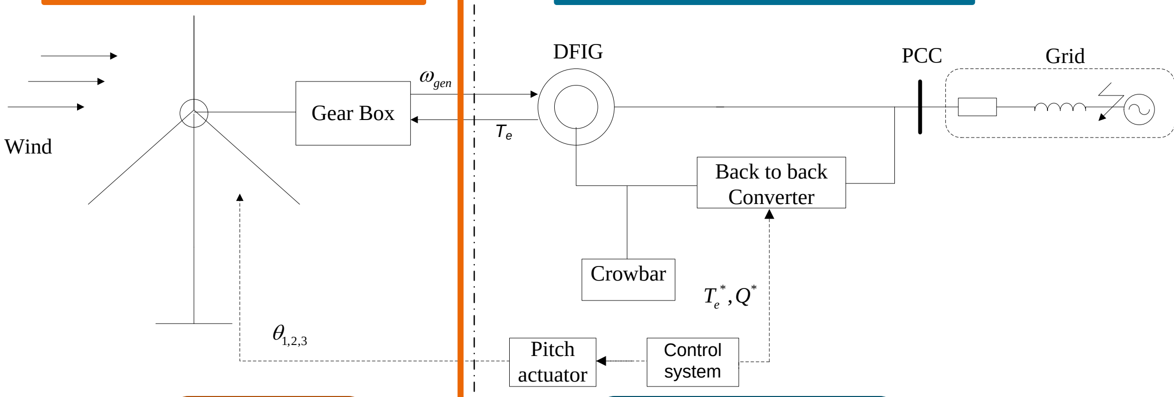
A model based damper is designed to add damping to the torsion modes without energy loss.

- Decrease the fatigue and ultimate loads
- Works in both normal operation and fault operation

Modeling of DFIG WT system

Aerodynamic & Mechanical

Electrical parts& Controller



FAST

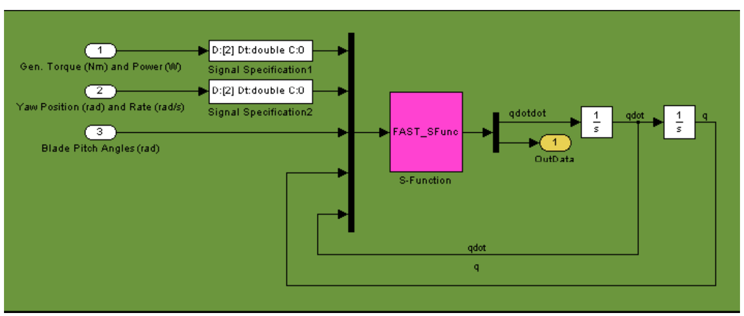
Simulink

	Detailed Approaches
Aerodynamic parts	BEM theory
Mechanical parts	16 DOFs
Electrical parts	DFIG, Back-to-Back VSC, crowbar
Controller	pitch controller, torque controller

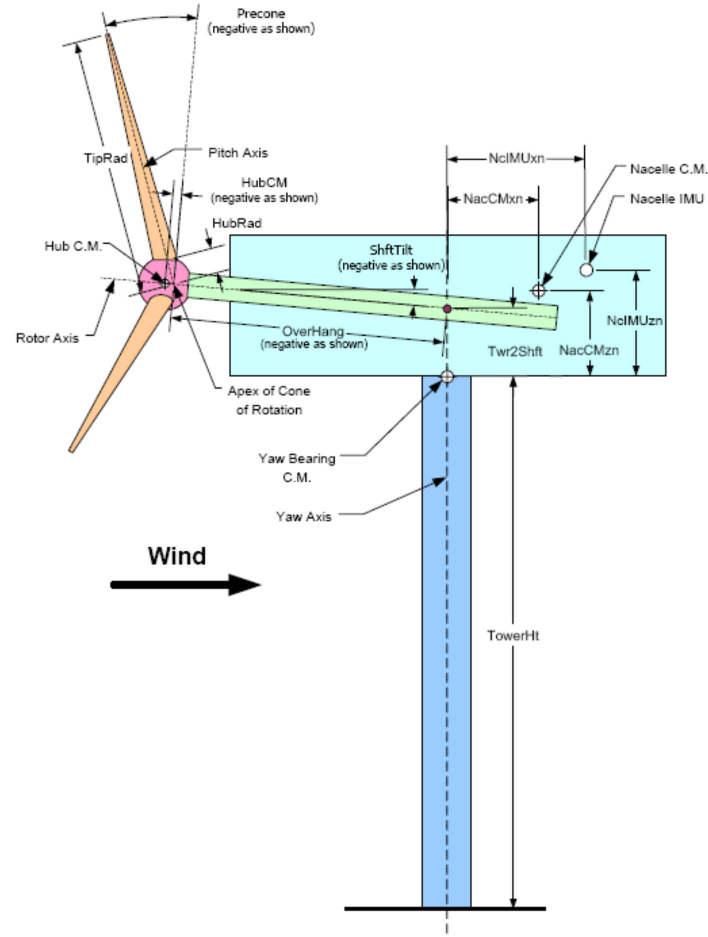
FAST(Fatigue, Aerodynamics, Structure, Turbulence)

- 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 block in Simulink



Source: FAST user's guide, NREL

DFIG model

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

$$v_{ds} = R_s i_{ds} + \dot{\lambda}_{ds} - \omega_s \lambda_{qs}$$
$$v_{qs} = R_s i_{qs} + \dot{\lambda}_{qs} + \omega_s \lambda_{ds}$$
$$v_{dr} = R_r i_{dr} + \dot{\lambda}_{dr} - (\omega_s - \omega_r)\lambda_{qr}$$
$$v_{qr} = R_r i_{qr} + \dot{\lambda}_{qr} + (\omega_s - \omega_r)\lambda_{dr}$$

  - Flux equations

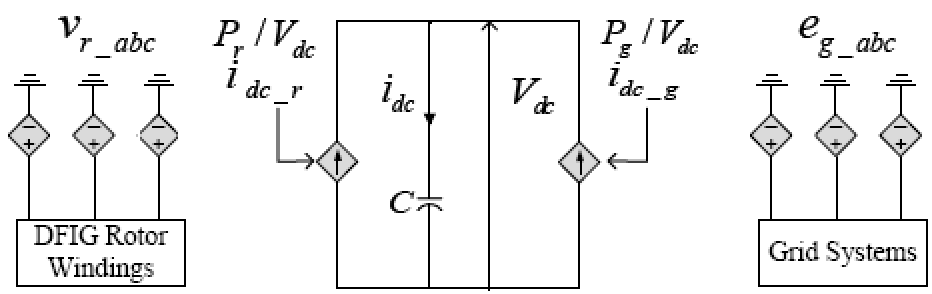
$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr}$$
$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr}$$
$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds}$$
$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs}$$

  - Electromagnetic torque

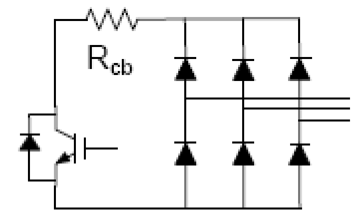
$$T_e = 1.5p(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds})$$

- Generator rotational motion has been involved in FAST model

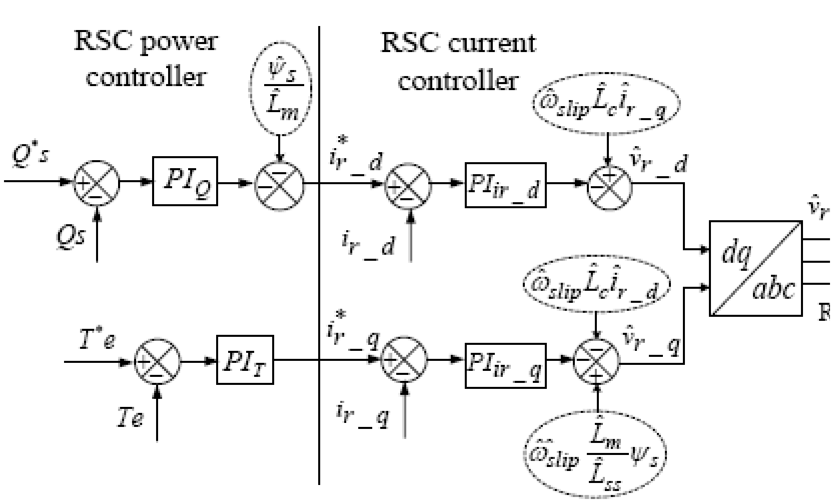
Back-to-back converter model



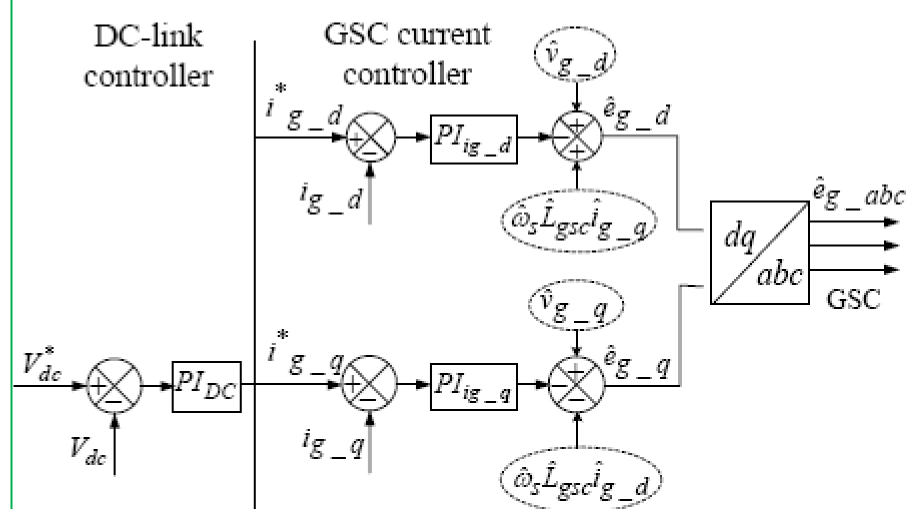
- Crow bar circuit



- RSC controller



- GSC controller

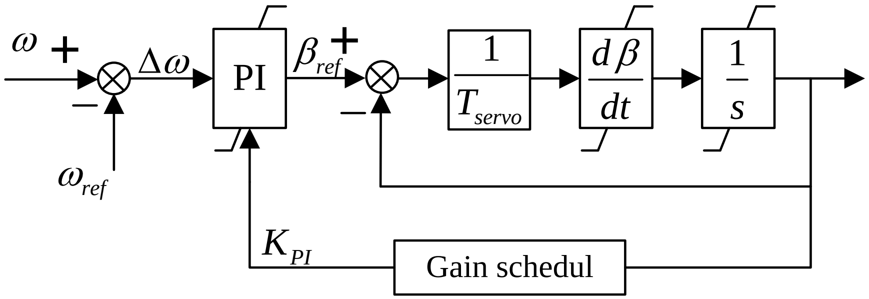


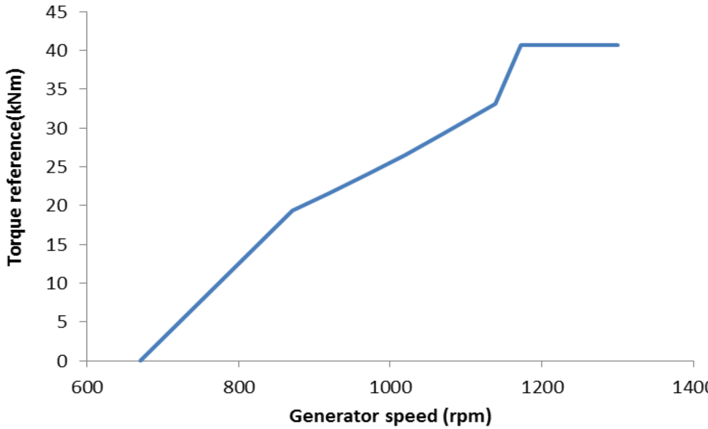
Baseline controller

- 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





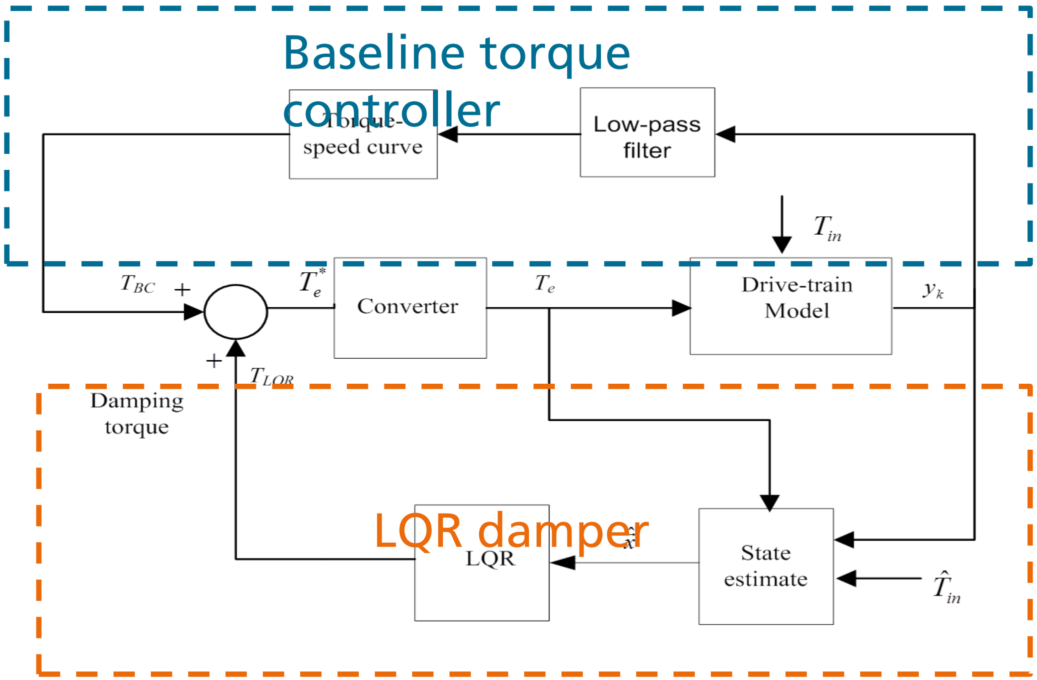
Torque ref vs. Generator speed

- 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

Active damping controller via torque control

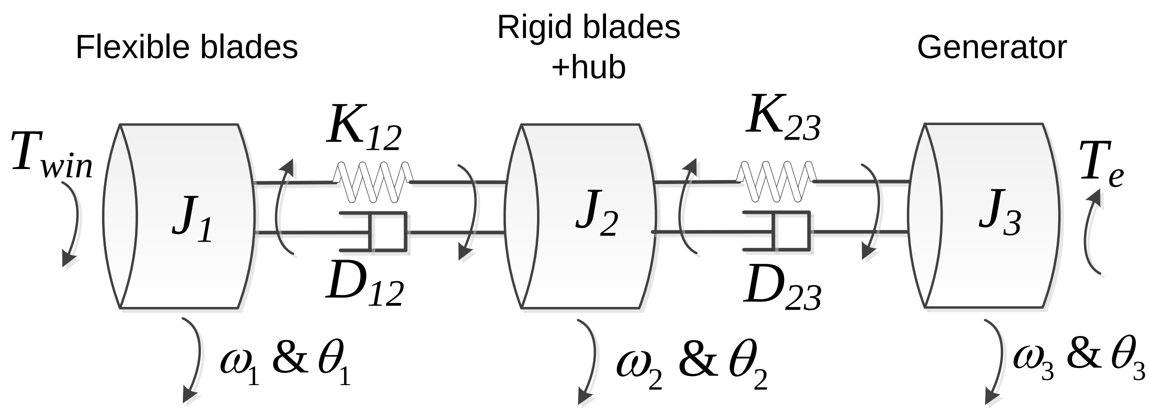
The proposed drive train control



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

Controller design

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



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

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

Controller design

- System identification

$$f_1 = \frac{1}{2\pi}(-\frac{b}{2} - \frac{\sqrt{b^2 - 4c}}{2})^{0.5},\ f_2 = \frac{1}{2\pi}(-\frac{b}{2} + \frac{\sqrt{b^2 - 4c}}{2})^{0.5}$$

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

- In this case, f_1=1.7Hz, f_2=4Hz, and k_{23},J_1+J_2,J_3 are known
- From above

J_1 [kgm^2]	J_2 [kgm^2]	J_3 [kgm^2]	K_{12} [Nm/rad]	K_{23} [Nm/rad]
3.09×10^7	4.54×10^6	5.03×10^6	1.39×10^9	8.68×10^9

Linear-quadratic regulator (LQR)

For a continuous-time linear system described by

$$\dot{x} = Ax + Bu$$

with a cost functional defined as

$$J = \int_0^\infty \left(x^T Q x + u^T R u\right) dt$$

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

$$u = -Kx$$

where is given by

$$K = R^{-1} B^T P$$

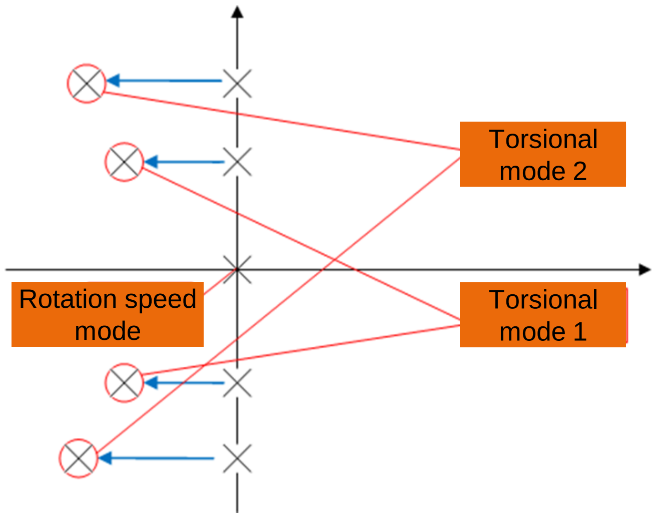
and is found by solving the continuous time algebraic Riccati equation

$$A^T P + PA - PBR^{-1}B^T P + Q = 0$$

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;

$$\begin{cases} \dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + L(y(t) - \hat{y}(t)) \\ \hat{y}(t) = C\hat{x}(t) \end{cases}$$



Closed-loop pole locations

Simulations

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

Power rating	5 MW
Rotor	3-bladed, upwind
Rotor diameter	126m
Hub height	90m
Rated rotor speed	12.1rpm
Total rotor inertia(J_1+J_2)	3.09×10^7 kgm^2
Generator inertia($_{J3}$)	5.03×10^6 kgm^2
Gearbox ratio	97:1
Equivalent shaft stiffness(K_{23})	8.676×10^8 Nm/rad

- 5-MW DFIG parameters

U_s [V]	R_s [mΩ]	L_s [mH]	R_r [mΩ]	L_r [mH]	L_m [mH]	R_{cr} [Ω]
960	2.1	0.153	2.1	0.149	4.26	0.11

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

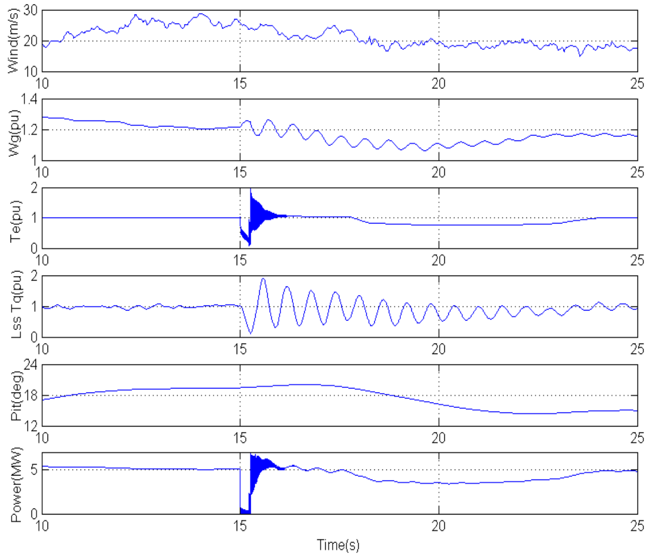
•Generator speed

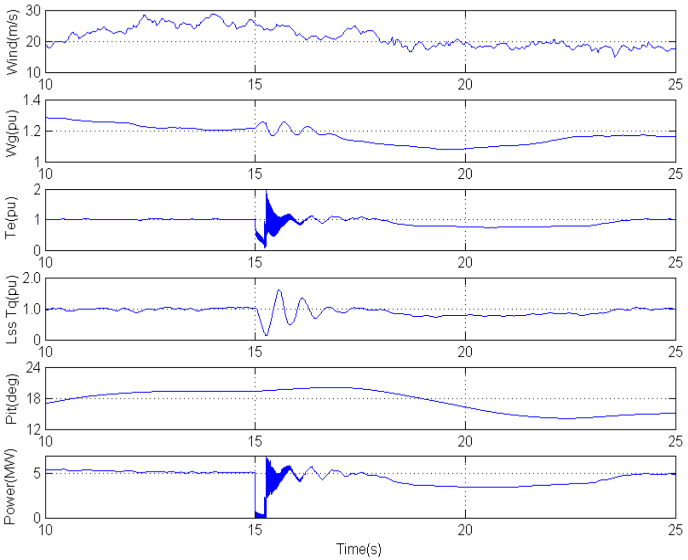
•Generator torque

•Shaft torque

•Pitch angle

•Active power

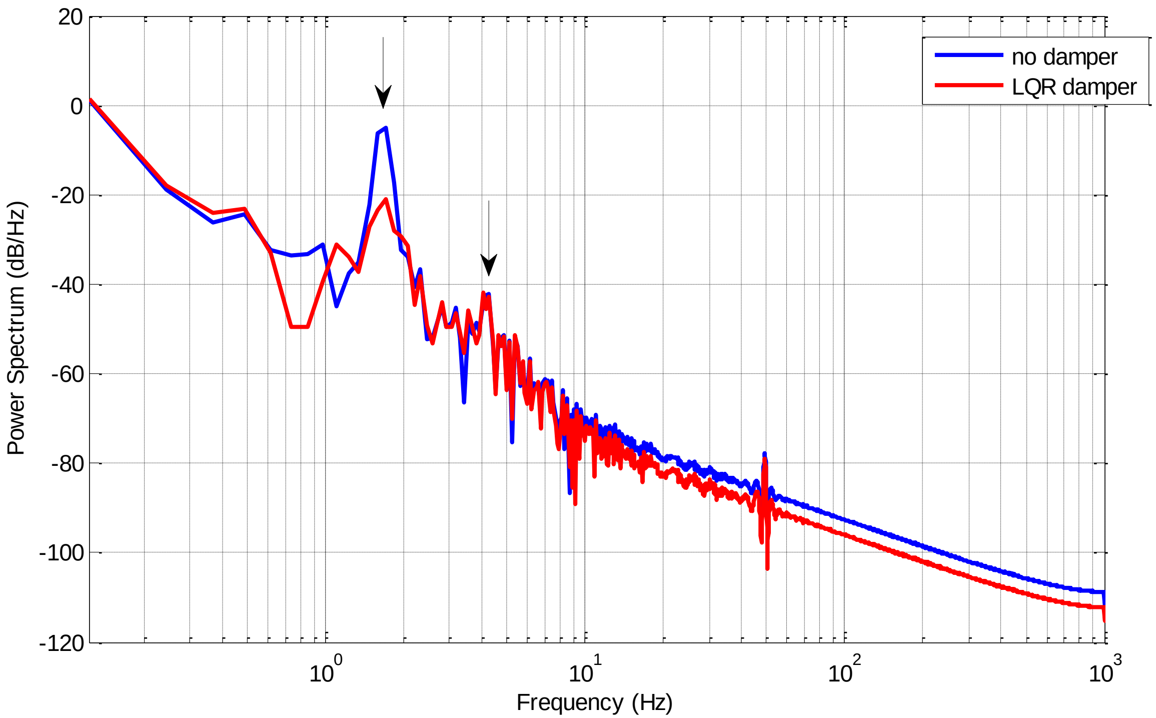




- Before FRT event, almost steady with active damping controller
- After FRT event,
- Peak load decreased by 0.2 pu;
- Osillations will be damped in 3 seconds;
- Quick active power recovery;
- Over loading(<10%), it could be tolerated by power converters in short time

Simulation results-frequency domain

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



Powe spectrum density of shaft load

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!

xuhaocas@gmail.com

INSTITUTE OF ELECTRICAL ENGINEERING,
CHINESE ACADEMY OF SCIENCES

Fraunhofer
IWES