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Characteristic Study for Integration of Fixed and Variable Speed Wind Turbines into Transmission Grid

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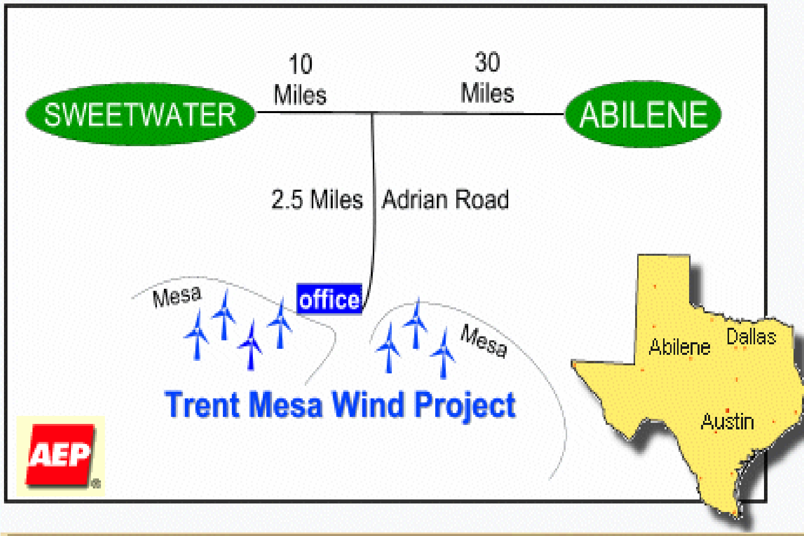
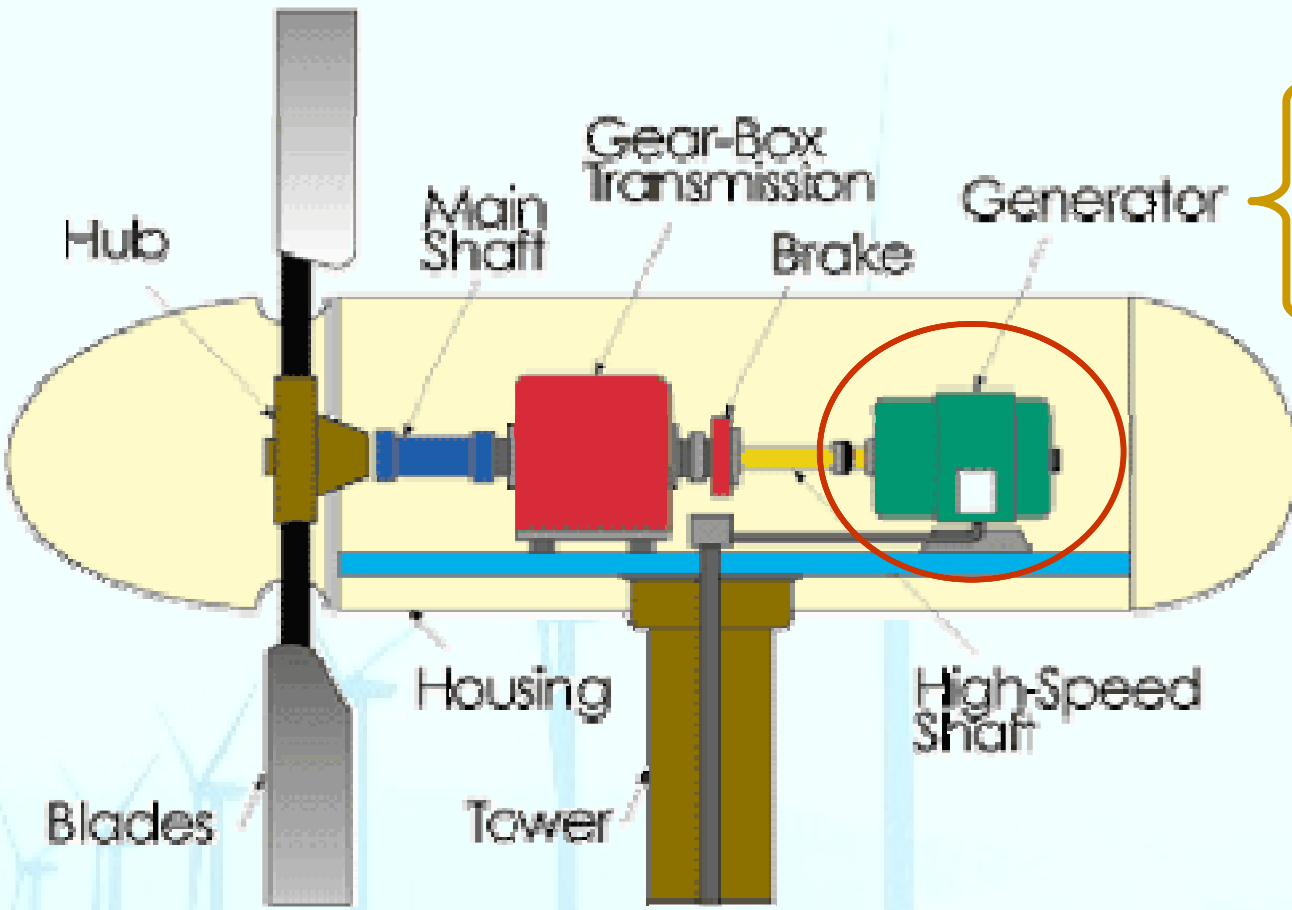
Wind Energy – A Fast Growing Energy Source in Texas



Over 100 1.5 MW DFIG wind turbines for each wind farm

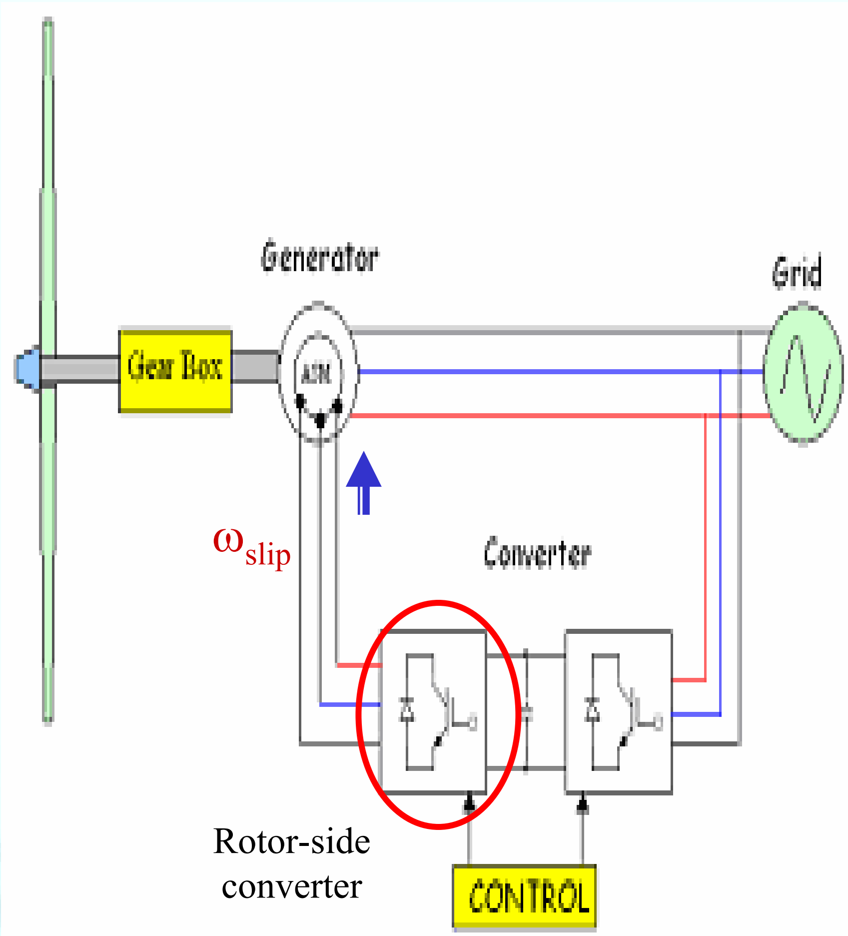
The Wind Turbine

Inside the Wind Turbine



- Fixed-speed Induction Generator
- Double-Fed Induction Generator

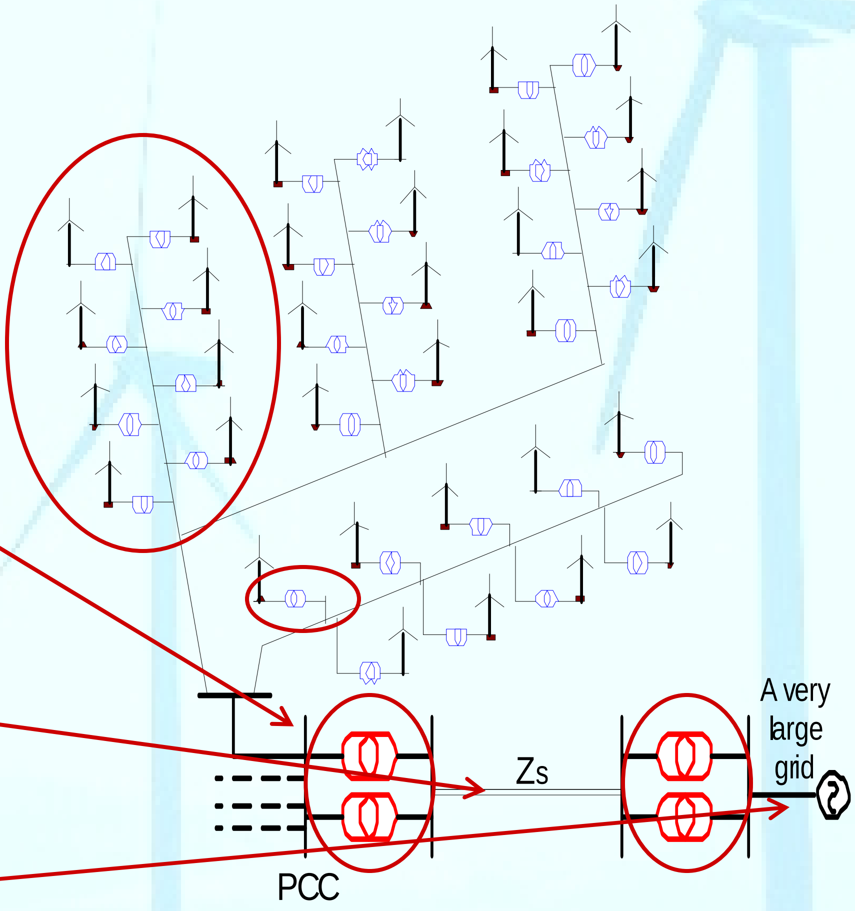
Fixed and Variable Speed Induction Generator Wind Turbines



- **Fixed-speed IG wind turbines**
  - Relatively simple and robust
  - Low energy yield
  - Large mechanical loads
  - Lack of control possibilities of both active and reactive power.
  - Large fluctuations in output power
- **Variable-speed DFIG wind turbines**
  - A higher energy yield.
  - Reduction of mechanical loads.
  - Extensive controllability of both active and reactive power.
  - Easier comply with the requirements of grid companies.
  - Less fluctuations in output power.

Integration of Wind Turbines into Transmission Grid

- A cluster of wind turbines
- Turbine distribution transformer
- The point of common coupling (PCC).
- PCC transmission transformer
- Transmission line
- Grid transformer
- The grid



Issues for Grid Integration of DFIG Wind Turbines

- What are the DFIG characteristics compared to those of fixed-speed IGs?
- How DFIG characteristics and controls are affected as more turbines are added online?
- Will a parallel compensation improve DFIG controls and characteristics?
- How about a series compensation?
- What are the differences between a wind farm using variable-speed DFIGs and fixed-speed IGs?
- What are the integrative characteristics for both situations?

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1. Steady-state model in d-q frame
2. Characteristics of a single wind turbine
3. WECS characteristics as multiple turbines are connected online
4. WECS characteristics under parallel compensation
5. WECS characteristics under series compensation
6. Integrated steady-state and transient studies
7. Conclusions

Contents

Induction Machine Transient Model in d-q Frame

- d-q representation (three equations):

Stator voltage equation: $$\begin{pmatrix} v_{sd} \\ v_{sq} \end{pmatrix} = R_s \begin{pmatrix} i_{sd} \\ i_{sq} \end{pmatrix} + \frac{d}{dt}\begin{pmatrix} \lambda_{sd} \\ \lambda_{sq} \end{pmatrix} + \omega_{syn}\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} \lambda_{sq} \\ \lambda_{sd} \end{pmatrix}$$

Rotor voltage equation: $$\begin{pmatrix} v_{rd} \\ v_{rq} \end{pmatrix} = R_r \begin{pmatrix} i_{rd} \\ i_{rq} \end{pmatrix} + \frac{d}{dt}\begin{pmatrix} \lambda_{sd} \\ \lambda_{sq} \end{pmatrix} + \omega_{r}\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} \lambda_{sd} \\ \lambda_{sq} \end{pmatrix}$$

Flux linkage equation: $$\begin{pmatrix} \lambda_{sd} \\ \lambda_{rq} \\ \lambda_{sd} \\ \lambda_{rq} \end{pmatrix} = \begin{pmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{pmatrix}\begin{pmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{pmatrix}$$

- Space vector representation: $\left(\vec{v}_{r\_dq} = v_{rd} + jv_{rq} \;\rightarrow\; \text{injected rotor (control) voltage}\right)$

Stator voltage equation: $$\vec{v}_{s\_dq} = R_s\vec{i}_{s\_dq} + \frac{d}{dt}\vec{\lambda}_{s\_dq} + j\omega_{syn}\vec{\lambda}_{s\_dq}$$

Rotor voltage equation: $$\vec{v}_{r\_dq} = R_r\vec{i}_{r\_dq} + \frac{d}{dt}\vec{\lambda}_{r\_dq} + j\omega_{slip}\vec{\lambda}_{r\_dq}$$

From Transient to Steady-State Model

- Steady-state space vector voltage equations:

$$\text{Stator voltage equation: } \vec{v}_{s\_dq} = R_s\vec{i}_{s\_dq} + \cancel{\frac{d}{dt}\vec{\lambda}_{s\_dq}} + j\omega_{syn}\vec{\lambda}_{s\_dq}$$

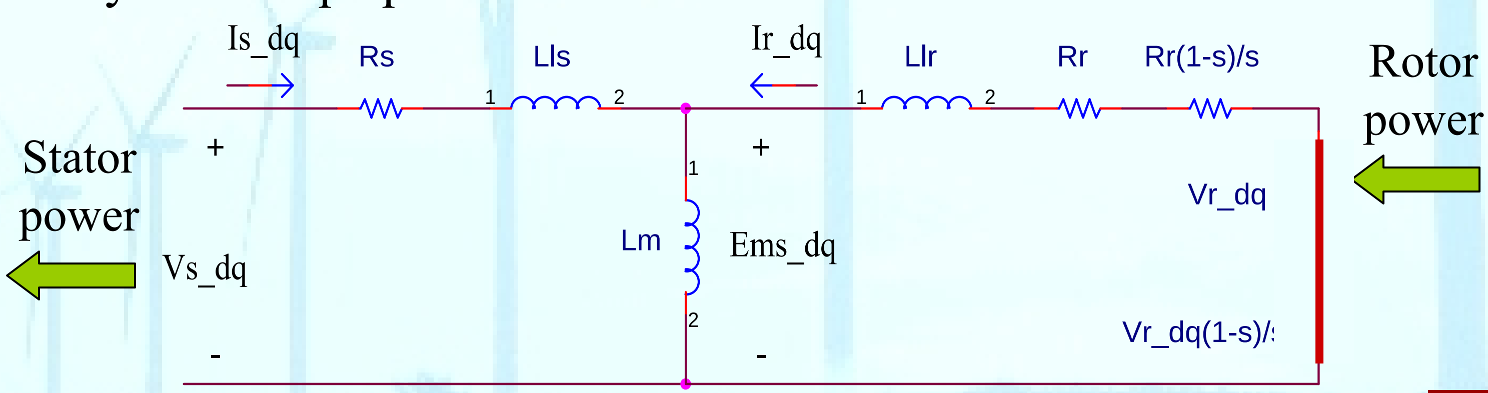
$$\text{Rotor voltage equation: } \vec{v}_{r\_dq} = R_r\vec{i}_{r\_dq} + \cancel{\frac{d}{dt}\vec{\lambda}_{r\_dq}} + j\omega_{slip}\vec{\lambda}_{r\_dq}$$

- Replace flux linkage using stator/rotor currents:

$$\text{Stator steady-state voltage equation: } \vec{V}_{s\_dq} = R_s\vec{I}_{s\_dq} + j\omega_s L_{ls}\vec{I}_{s\_dq} + j\omega_s L_m\left(\vec{I}_{s\_dq} + \vec{I}_{r\_dq}\right)$$

$$\text{Rotor steady-state voltage equation: } \frac{\vec{V}_{r\_dq}}{s} = \frac{R_r}{s}\vec{I}_{r\_dq} + j\omega_s L_{lr}\vec{I}_{r\_dq} + j\omega_s L_m\left(\vec{I}_{s\_dq} + \vec{I}_{r\_dq}\right)$$

- Steady-state d-q equivalent circuit:



Transmission System Models in d-q Frame

- Three-phase voltage balance equation:

$$\underbrace{\begin{bmatrix} v_{ag} \\ v_{bg} \\ v_{cg} \end{bmatrix}}_{Grid\ voltage} = R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \underbrace{\begin{bmatrix} v_{af} \\ v_{bf} \\ v_{cf} \end{bmatrix}}_{PCC\ voltage}$$

- d-q voltage balance equation:

$$\underbrace{\begin{bmatrix} v_{dg} \\ v_{qg} \end{bmatrix}}_{Grid\ \mathrm{dq}\ voltage} = R\begin{bmatrix} i_d \\ i_q \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega_s L\begin{bmatrix} -i_q \\ i_d \end{bmatrix} + \underbrace{\begin{bmatrix} v_{df} \\ v_{qf} \end{bmatrix}}_{PCC\ \mathrm{dq}\ voltage}$$

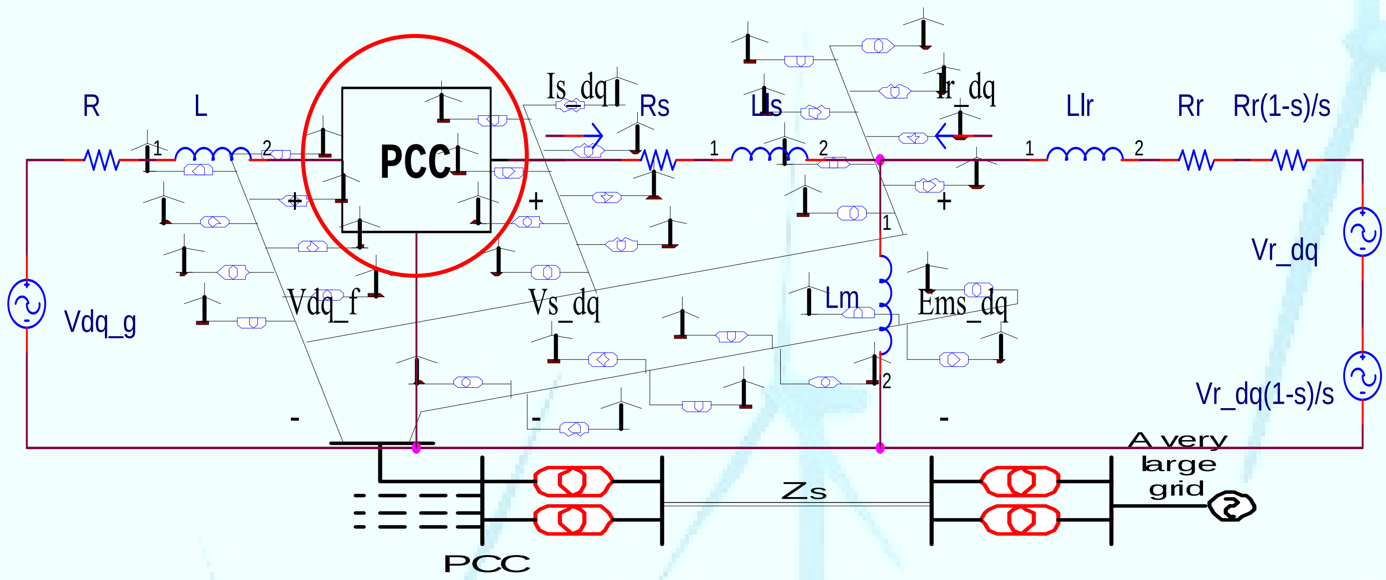
- Space vector equation:

$$\vec{v}_{dq\_g} = R\cdot\vec{i}_{dq} + L\cancel{\frac{d}{dt}\vec{i}_{dq}} + j\omega_s L\cdot\vec{i}_{dq} + \vec{v}_{dq\_f}$$

- Steady-state d-q equation:

$$\vec{V}_{dq\_g} = R\cdot\vec{I}_{dq} + j\omega_s L\cdot\vec{I}_{dq} + \vec{V}_{dq\_f} = \underbrace{\left(R + j\omega_s L\right)}_{Z_S}\cdot\sum_{i=1}^{n}\underbrace{\vec{I}_{dq\_i}}_{turbine\ current} + \vec{V}_{dq\_f}$$

Integrated Wind Farm and Grid Steady-State Equivalent Circuit in d-q Frame



- Voltage transformation from high-voltage side to low-voltage side;
- Current transformation from generator terminal to the line;
- Sum of generator current representing the total current for all the wind turbines;

- Wind turbines are identical and use fixed-speed induction machines.
- Wind speeds at the wind farm are uniform. All wind turbines have the same operating condition.
- The line impedance between each turbine and the PCC is neglected.

Contents

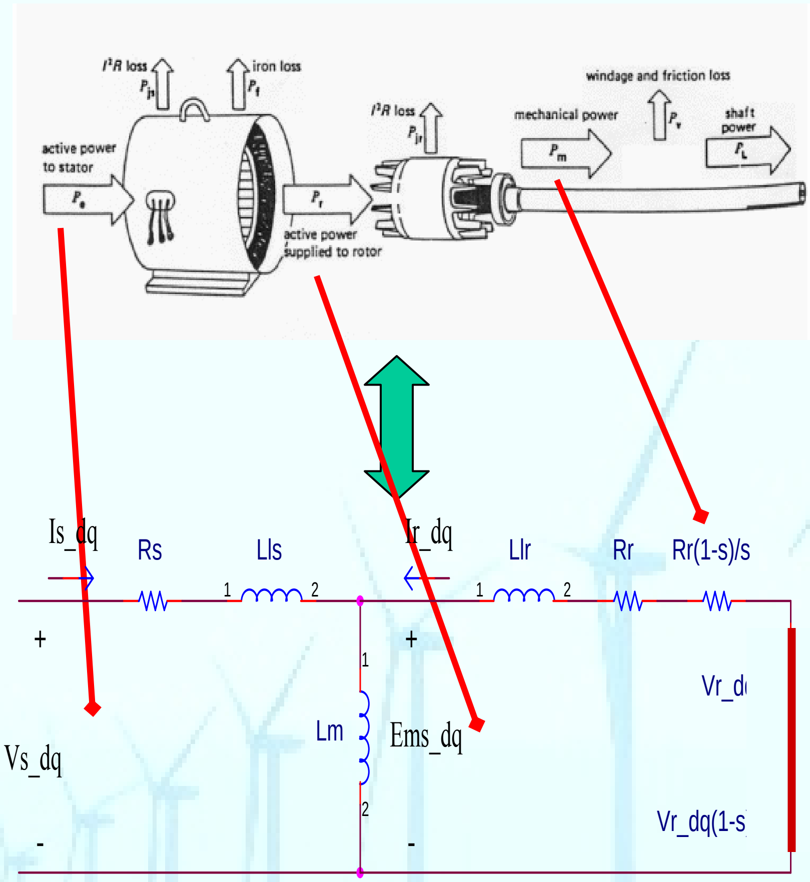
Simulation Mechanism for Characteristic Study

- Based upon the DFIG steady-state model and equivalent circuit
- Grid voltage: constant voltage at 1p.u. for all simulation case $\left(\vec{V}_{dq\_g} = 1 + j0\right)$
- Rotor injected voltage: control voltage from rotor-side converter – variable for each simulation case study

$$\left(\vec{V}_{dq\_r} = V_{rd} + jV_{rq}\right)$$

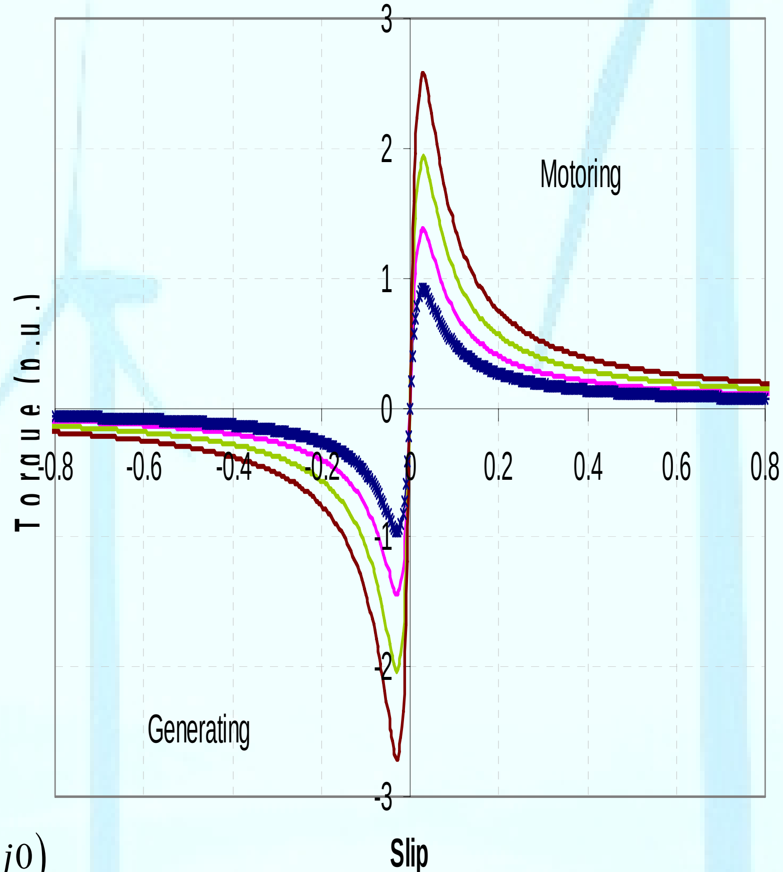
- Characteristics: versus slip obtained for each rotor voltage control condition

Typical Characteristics of Fixed-Speed IG



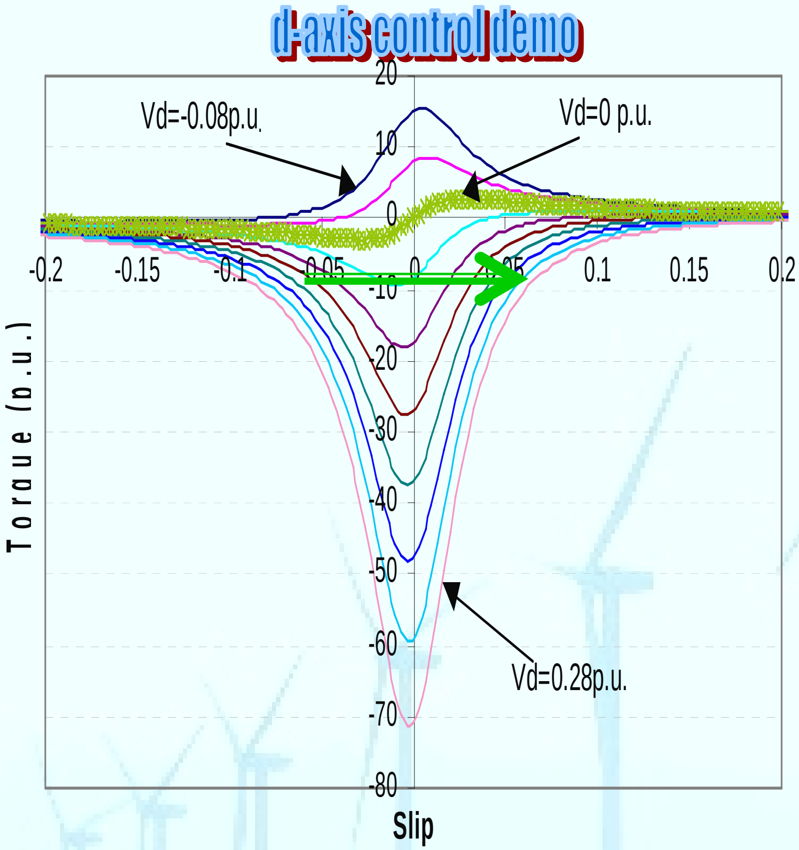
$$\left(\vec{V}_{dq\_r} = 0 + j0\right)$$

V_1 = 0.96, 0.83, 0.71, and 0.58p.u

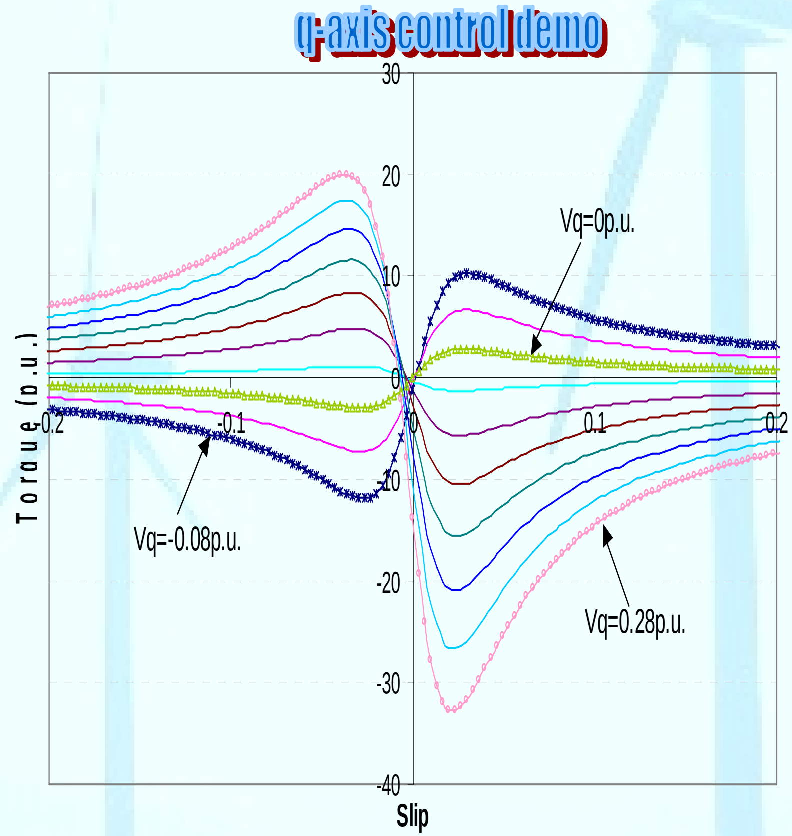


DFIG Torque Characteristics under d-q Control

$$\left(\vec{V}_{dq\_r} = V_{rd} + jV_{rq}\right)$$



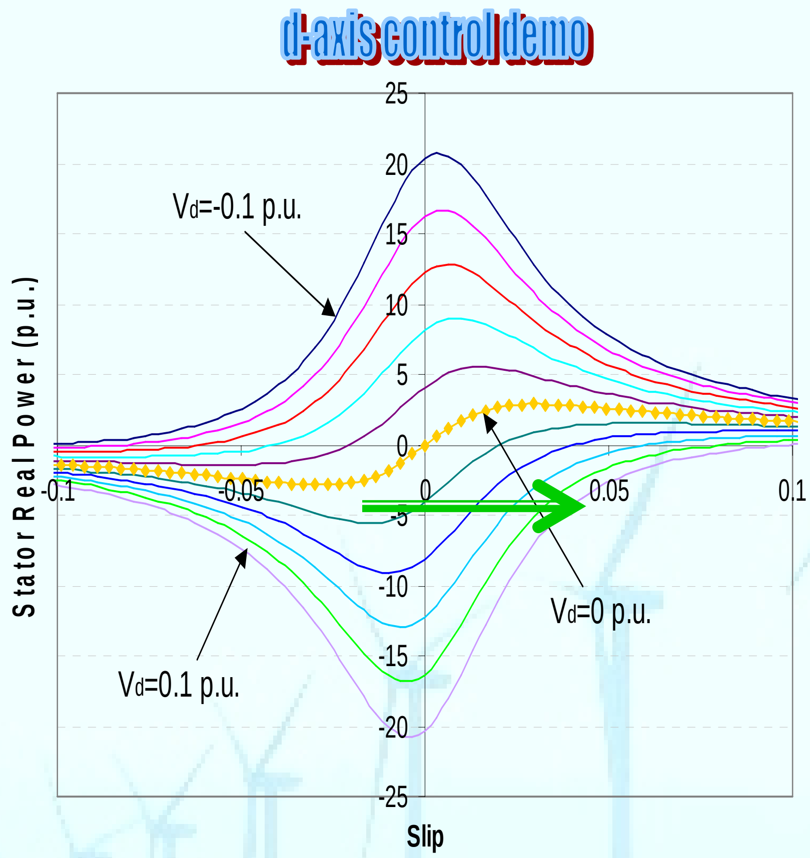
V_{rd} =-0.08 to 0.28 p.u., ΔV_{rd} =0.04 p.u., V_{rq} =0

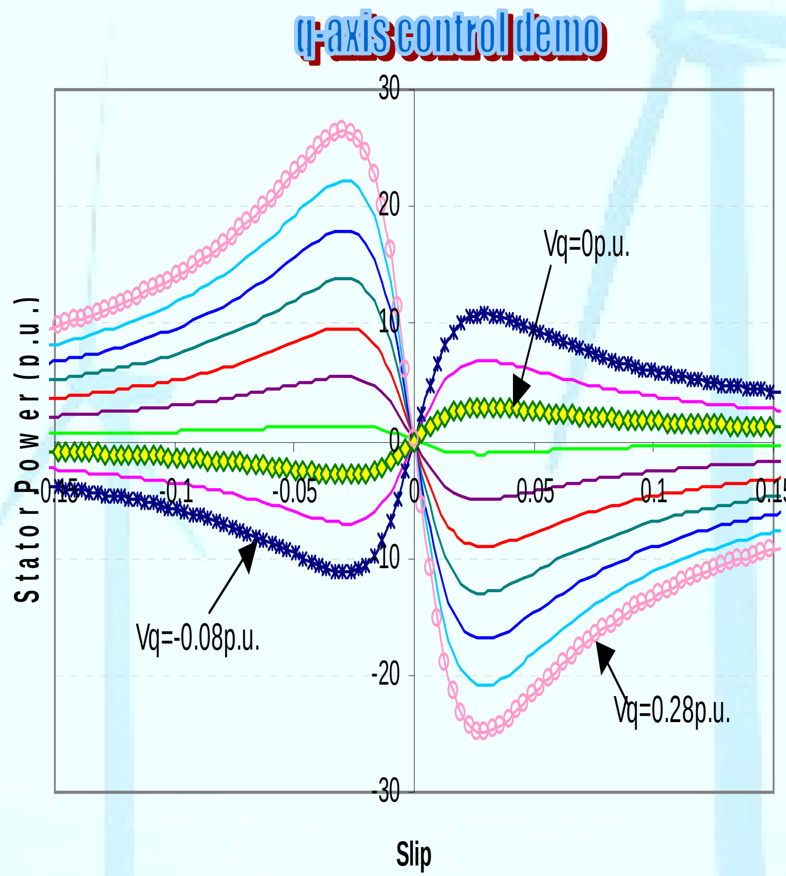


V_{rq} =-0.08 to 0.28 p.u., ΔV_{rq} =0.04 p.u., V_{rd} =0

(V_{rd} – d-axis component of rotor voltage; V_{rq}- q-axis component of rotor voltage)

DFIG Stator Real Power Characteristics





V_{rd} =-0.1 p.u. to 0.1 p.u., ΔV_{rd} =0.01 p.u., V_{rq} =0

V_{rq} =-0.08 to 0.28 p.u., ΔV_{rq} =0.04 p.u., V_{rd} =0

(V_{rd} – d-axis component of rotor voltage; V_{rq}- q-axis component of rotor voltage)

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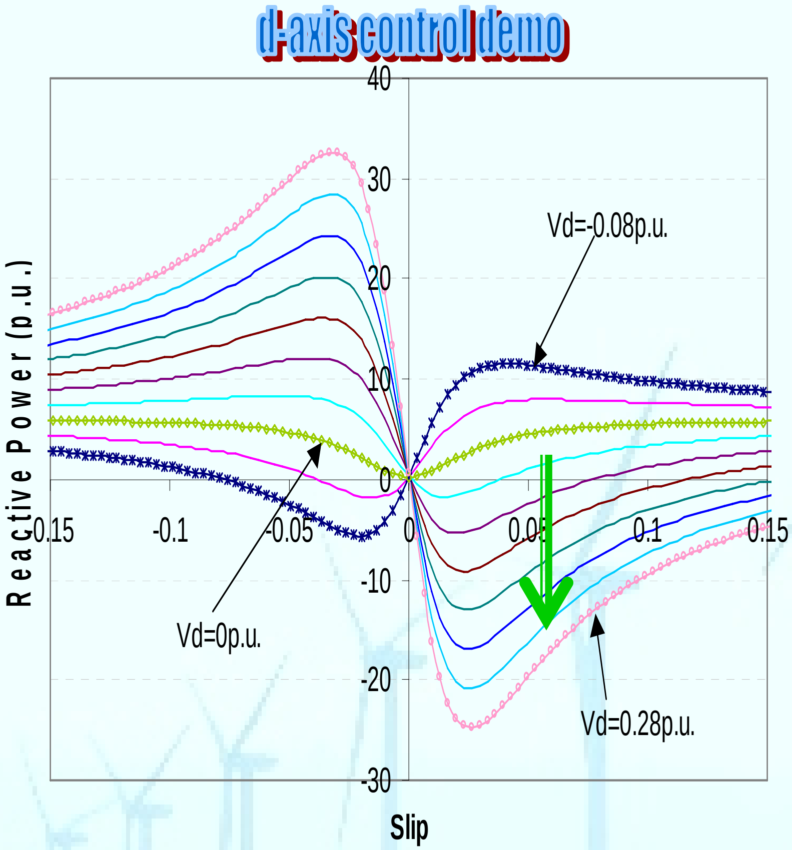
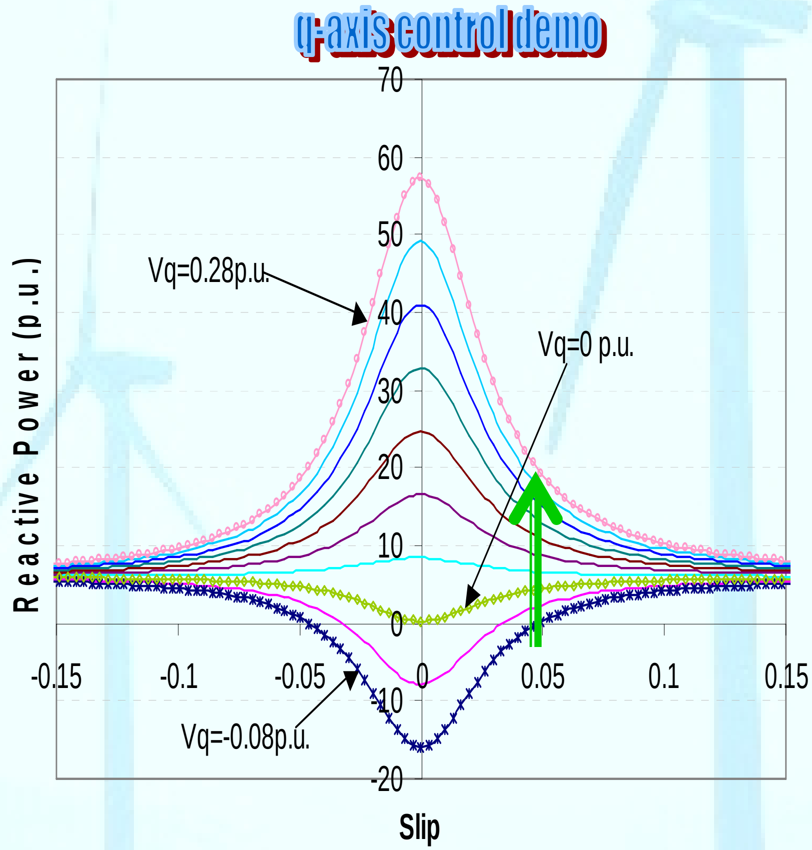
DFIG Stator Reactive Power Characteristics



V_{rd} =-0.08 to 0.28 p.u., ΔV_{rd} =0.04 p.u., V_{rq} =0



V_{rq} =-0.08 to 0.28 p.u., ΔV_{rq} =0.04 p.u., V_{rd} =0

(V_{rd} – d-axis of the rotor voltage; V_{rq}- q-axis component of the rotor voltage)

General Properties of DFIG Wind Turbine

- **Torque characteristics:**
  - generating mode: from over-synchronous to sub-synchronous speed region
  - pushover torque increases; improve DFIG stability.
- **Stator real power characteristics:**
  - similar to the torque characteristics.
  - d-axis voltage is more stable for torque and real power control;
- **Reactive power:**
  - d or q control alone result in excessive reactive power, requiring q or d control to compensate the reactive power.
  - q-axis voltage is more stable for reactive power control.
- **Control coordination between d and q is important:**
  - keep the pushover torque smaller than the generator driving torque
  - maintain stator and rotor power within the rated power limitations.

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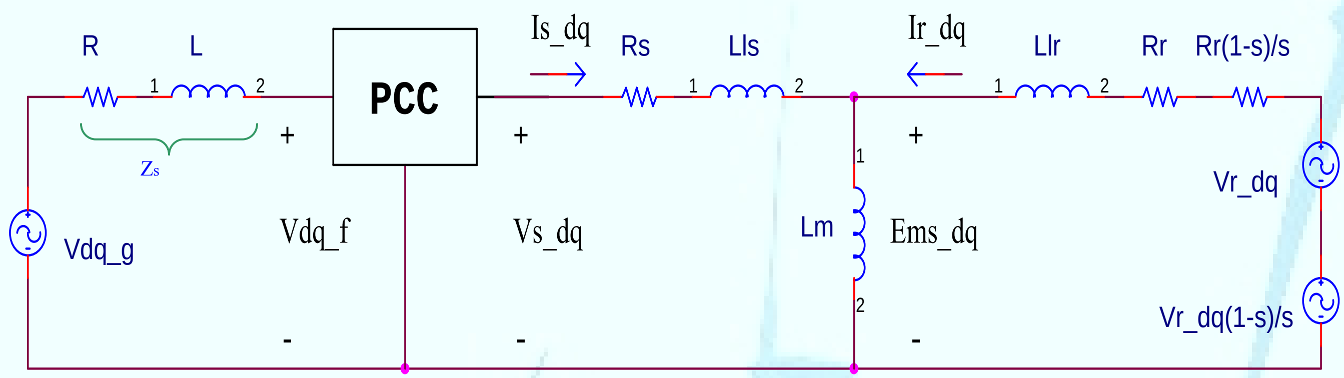
Wind farm Model with Multiple Wind Turbines
(uncompensated)



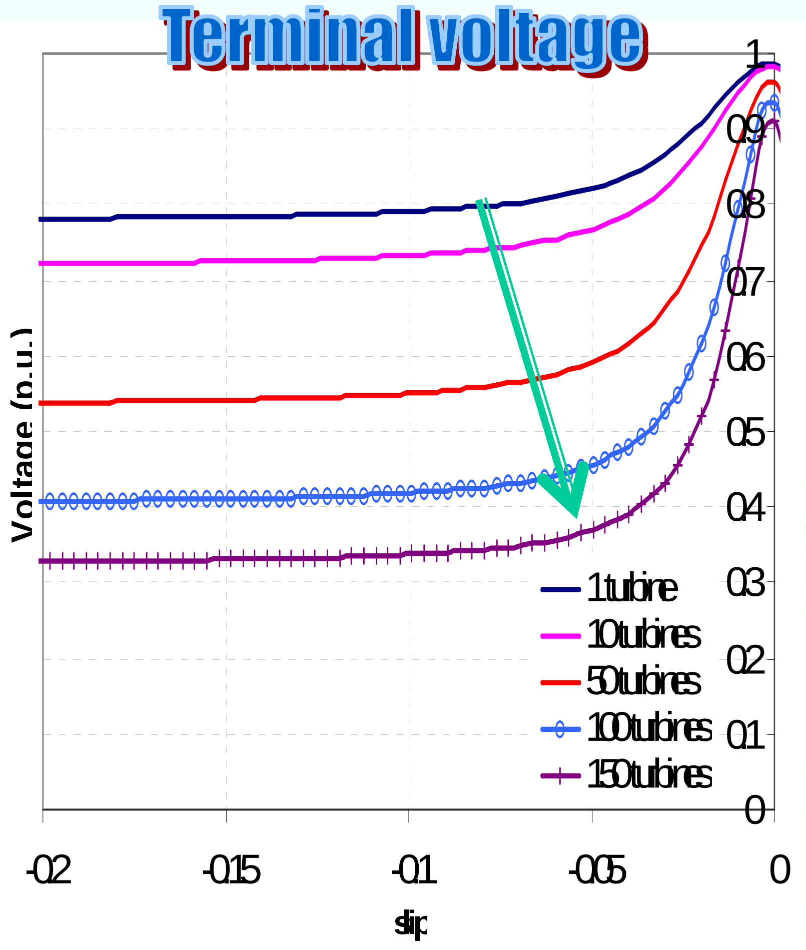
- **<u>Voltage balance equation:</u>**

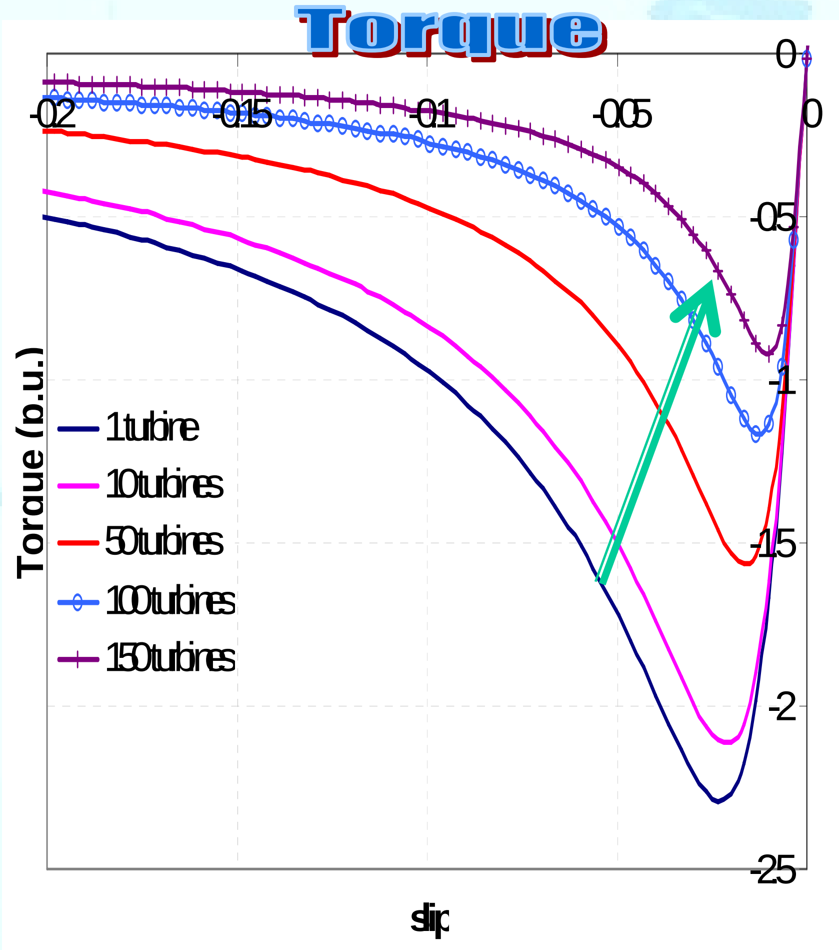
One turbine only: $\vec{V}_{dq\_f} = \vec{V}_{dq\_g} - \vec{I}_{dq1} \cdot Z_s$

n turbines: $\underline{\vec{V}_{dq\_f}} = \vec{V}_{dq\_g} - \left(\vec{I}_{dq1} + \cdots + \vec{I}_{dqn}\right) \cdot Z_s$

$$= \vec{V}_{dq\_g} - n\vec{I}_{dq1} \cdot Z_s = \vec{V}_{dq\_g} - \vec{I}_{dq1}\underline{\left(n \cdot Z_s\right)}$$

Wind Farm using Fixed-Speed IGs





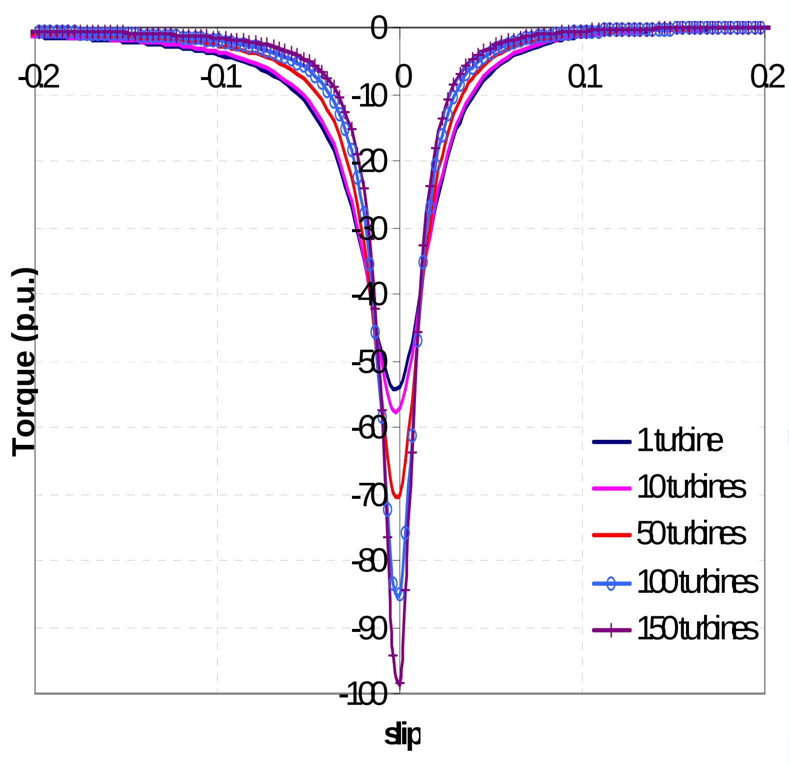
Properties of Fixed-Speed IG Wind Farm

(as number of turbines added to the wind farm increases)

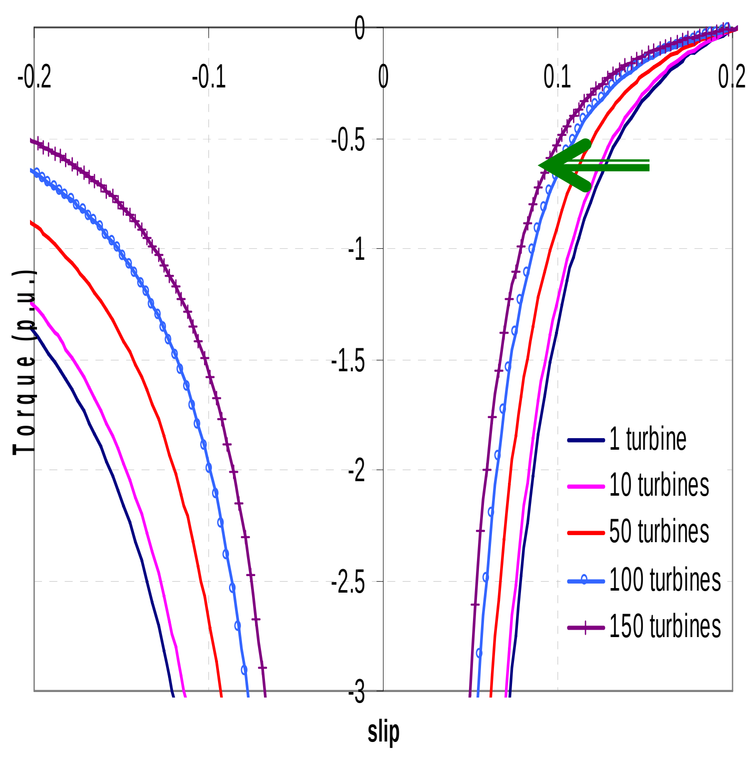
- Generator terminal voltage drops.
- Torque characteristics of a wind turbine shrink (also true for output power-speed characteristics).
- Both terminal voltage drop and equivalent line impedance changes cause the torque characteristics to shrink.
- Stability of a fixed-speed wind turbine is reduced.

Wind Farm using variable-Speed DFIGs

complete view



close look



(V_{rd} =0.2 p.u., V_{rq} =0 p.u.)

Properties of Variable-Speed DFIG Wind Farm

(as number of turbines added to the wind farm increases)

- **Around the synchronous slip:**
  - more reactive power generation
  - higher generator terminal voltage
  - pushover torque increases rather than decreases (also true for stator real power characteristics)
  - DFIG becomes more stable.
- **Away from the synchronous speed:**
  - voltage boost effect drops quickly.
  - the effectiveness of the speed control is reduced.
  - a larger voltage control signal is needed for the same speed control effect
  - the rotor-side converter is more fragile to get into the converter nonlinear modulation mode.

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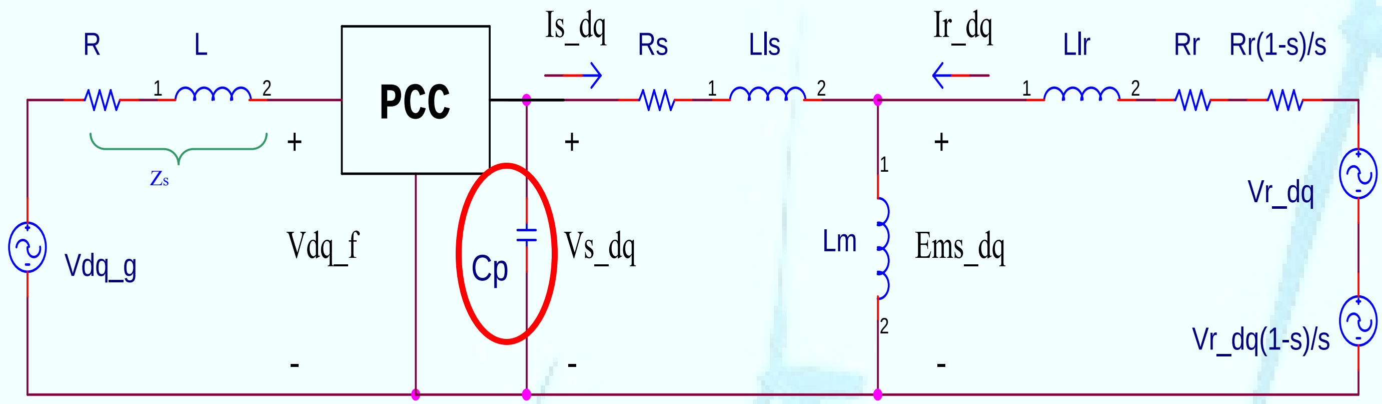
Wind farm Model with Multiple Wind Turbines

(parallel compensated)



- **Voltage balance equation:**

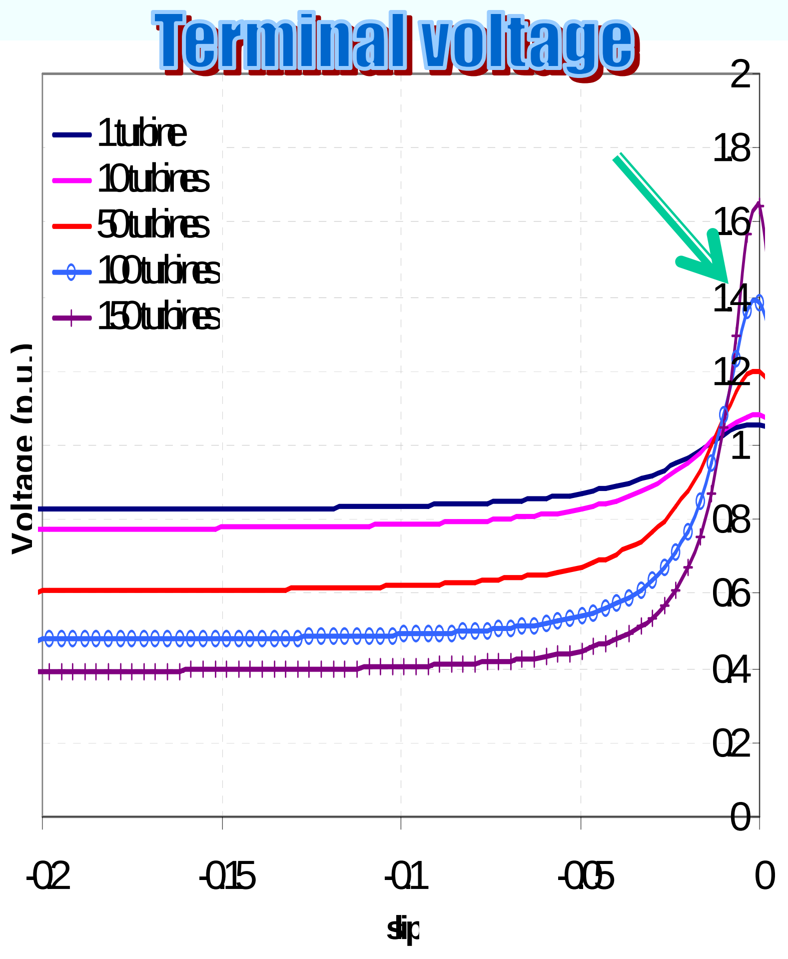
One turbine only:

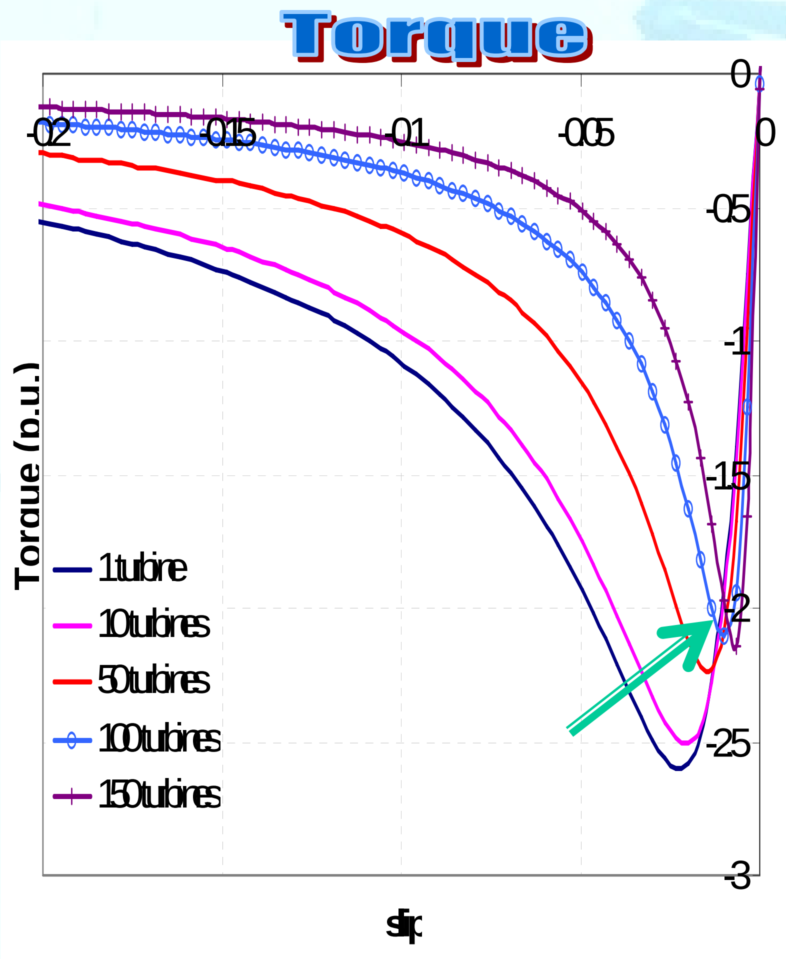
$$\vec{V}_{dq\_f} = \vec{V}_{dq\_g} - \left(\vec{I}_{dq1} + \vec{I}_{dq\_cp1}\right)\cdot Z_s; \quad \vec{I}_{dq\_cp1} = jX_{cp}\cdot\vec{V}_{dq\_f}$$

n turbines:

$$\vec{V}_{dq\_f} = \vec{V}_{dq\_g} - \left(\vec{I}_{dq1} + \vec{I}_{dq\_cp1}\right)\cdot\left(nZ_s\right); \quad \vec{I}_{dq\_cp1} = jX_{cp}\cdot\vec{V}_{dq\_f}$$

Wind Farm using Fixed-Speed IGs





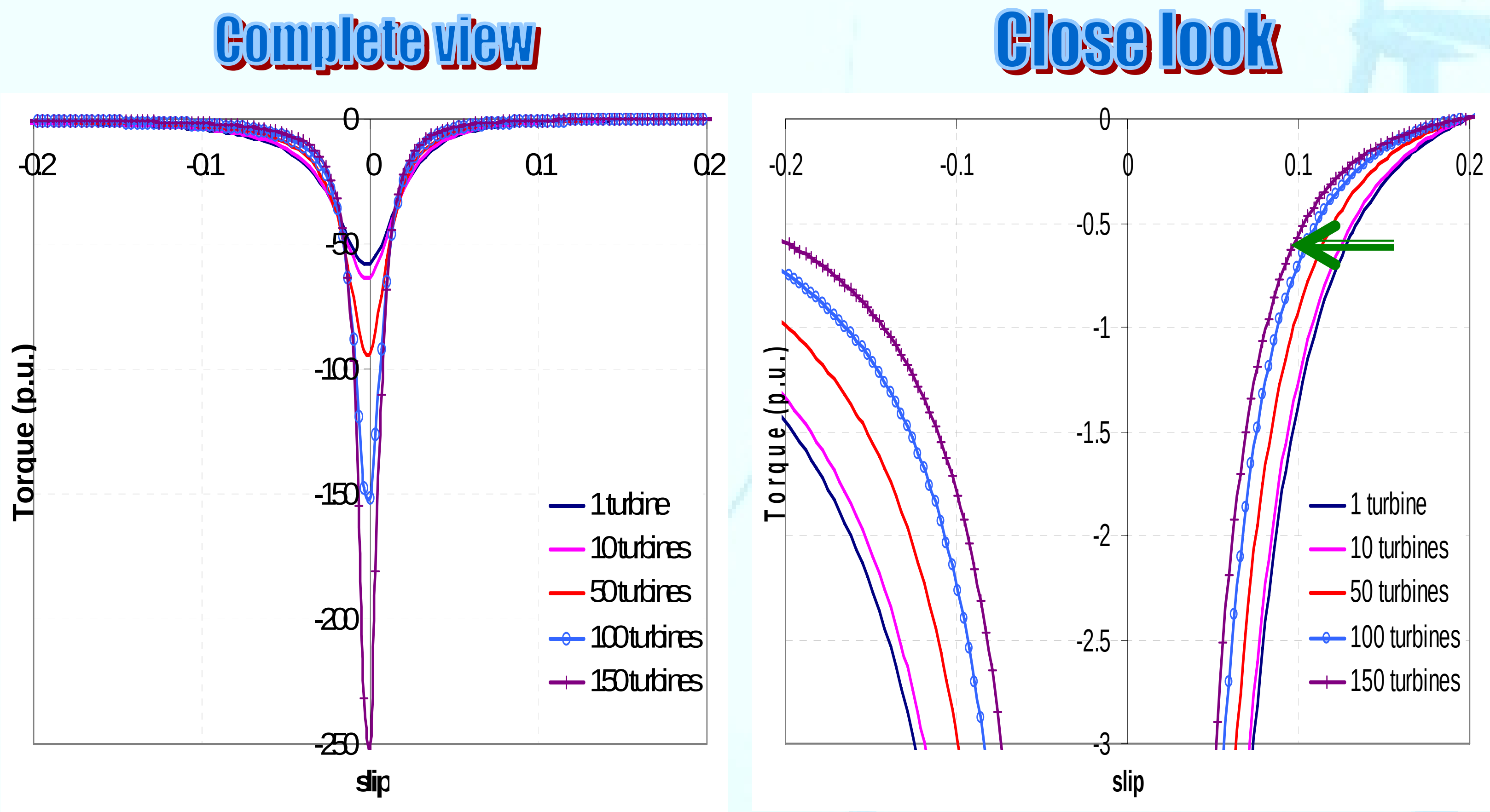
Properties of Parallel Compensated Fixed-Speed IG Wind Farm

(as number of turbines added to the wind farm increases)

- **A properly selected parallel capacitor:**
  - generator terminal voltage is boosted
  - pushover torque is improved
  - at the price of a high over-voltage
- **To avoid a high over-voltage:**
  - Either a thyristor controlled parallel compensation or a smaller parallel capacitor
  - A smaller parallel capacitor → torque characteristics of a fixed-speed IG still shrink considerably

Wind Farm using variable-Speed DFIGs

Complete view / Close look



(V_{rd} =0.2 p.u., V_{rq} =0 p.u.)

Properties of Parallel Compensated Variable-Speed DFIG Wind Farm

(as number of turbines added to the wind farm increases)

- **Around the synchronous slip:**
  - more reactive power generation
  - higher generator terminal voltage
  - pushover torque increases rather than decreases (also true for stator real power characteristics)
  - DFIG becomes more stable.

- **Away from the synchronous speed:**
  - voltage boost effect drops quickly.
  - the effectiveness of the speed control is reduced.
  - a larger voltage control signal is needed for the same speed control effect
  - the rotor-side converter is more fragile to get into the converter nonlinear modulation mode.

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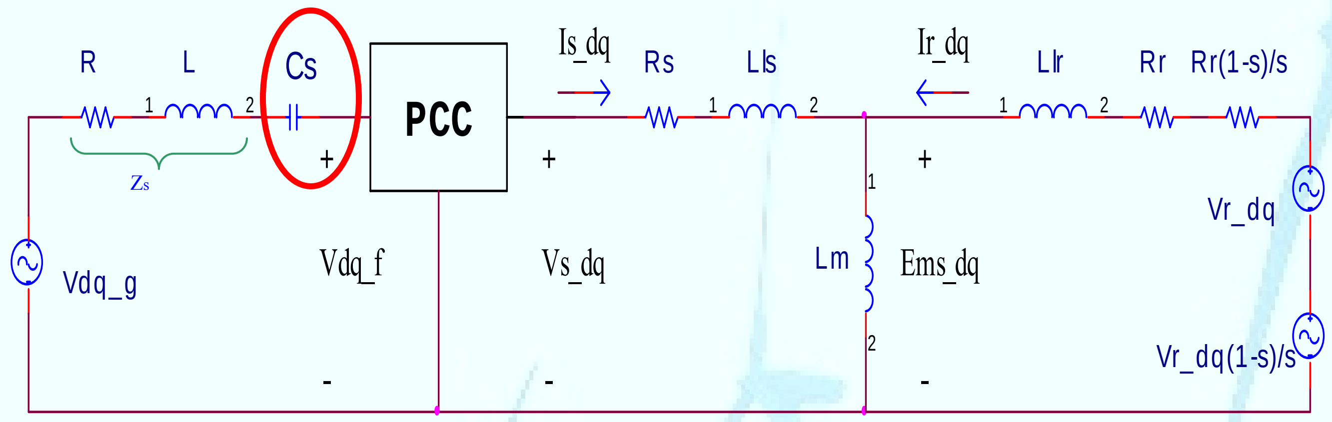
Wind farm Model with Multiple Wind Turbines

(series compensated)



- **Voltage balance equation:**

One turbine only:

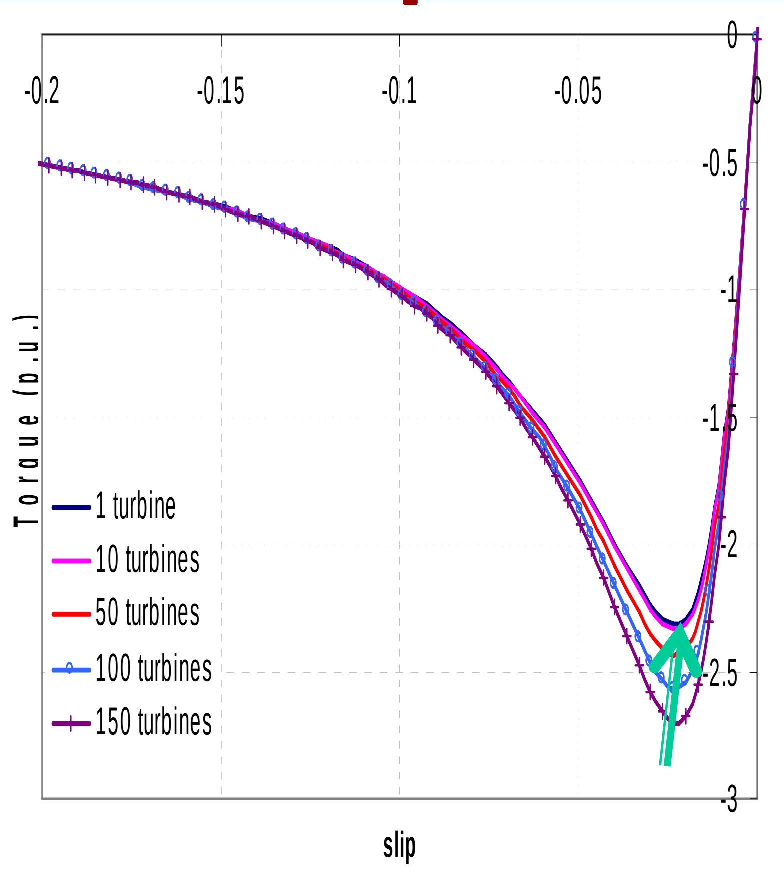
$$\vec{V}_{dq\_f} = \vec{V}_{dq\_g} - \vec{I}_{dq1} \cdot \left(Z_s - X_{Cs} \right)$$

n turbines:

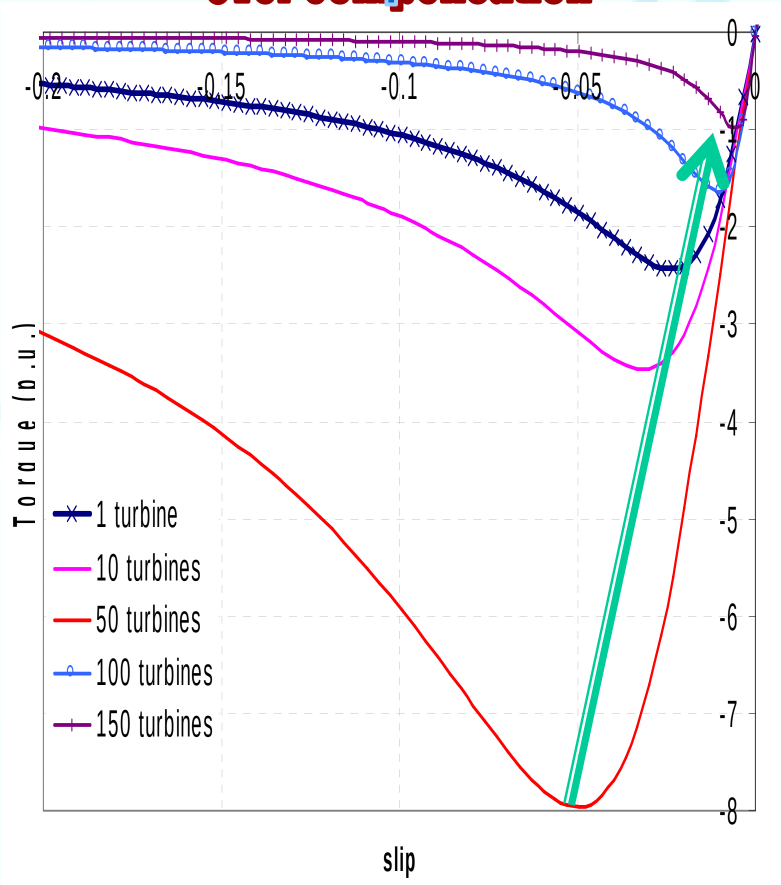
$$\vec{V}_{dq\_f} = \vec{V}_{dq\_g} - \vec{I}_{dq1} \cdot n\left(Z_s - X_{Cs} \right)$$

Wind Farm using Fixed-Speed IGs

Perfect compensation



Over compensation



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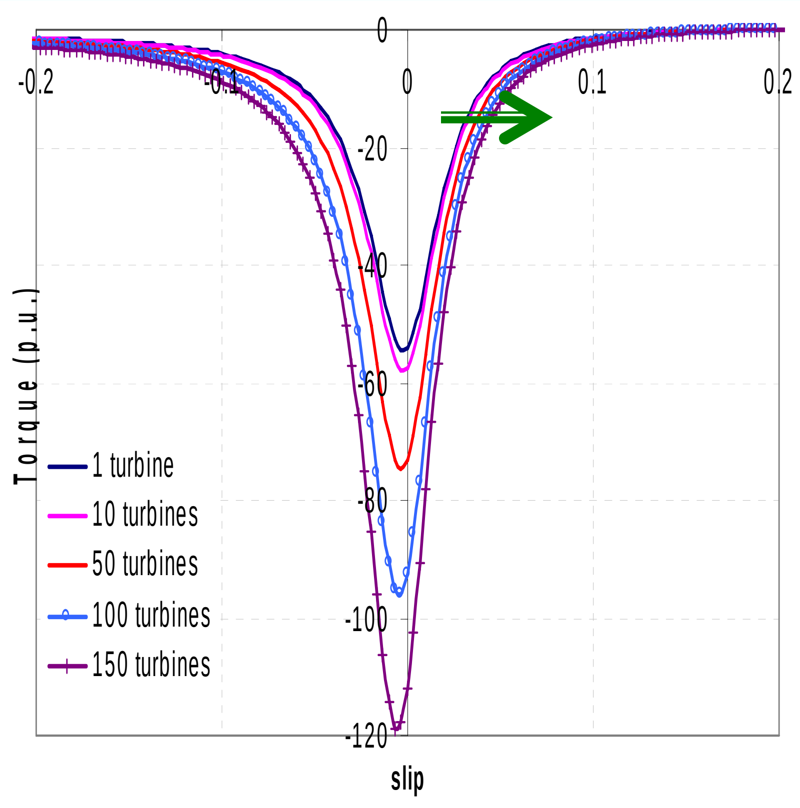
Properties of Series Compensated Fixed-Speed IG Wind Farm

(as number of turbines added to the wind farm increases)

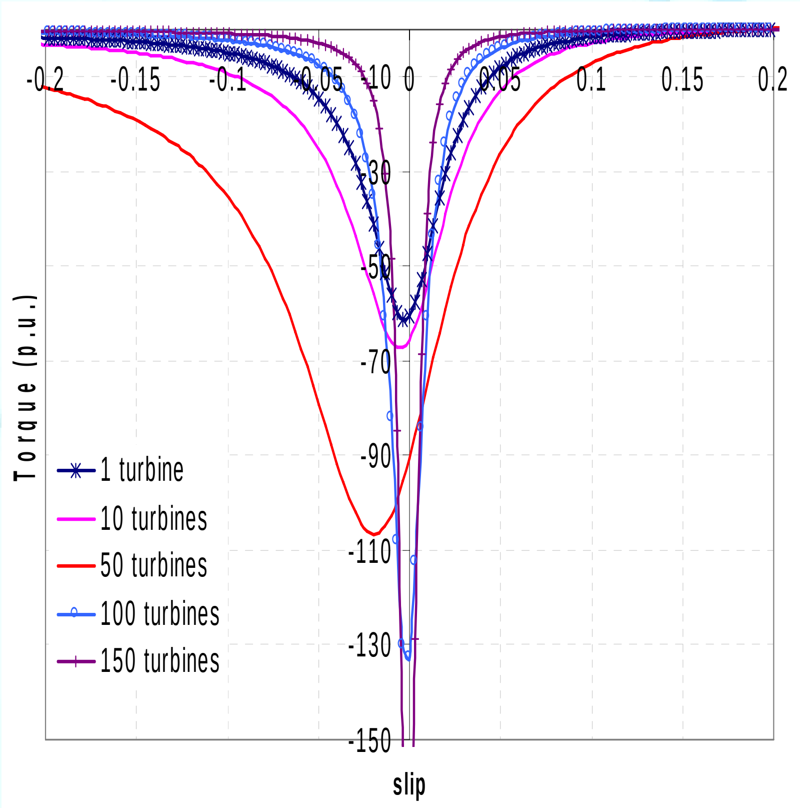
- **<u>A properly selected series capacitor:</u>**
  - voltage regulation is greatly reduced
  - generator torque characteristics and stability are improved
  - usually requires a large capacitor
- **<u>Over compensation:</u>**
  - A low series capacitance
  - a high generator terminal voltage
  - significant drop of generator torque characteristics
  - affect proper and/or stable operation of fixed-speed wind turbines.

Wind Farm using variable-Speed DFIGs

Perfect compensation



Over compensation



(V_{rd} =0.2 p.u., V_{rq} =0 p.u.)

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Properties of Series Compensated Variable-Speed DFIG Wind Farm

(as number of turbines added to the wind farm increases)

- **A properly selected series capacitor:**
  - Equivalent line impendence is much smaller.
  - Total reactive power generation increases at low speed.
  - Torque characteristics expand
  - Voltage control signal is smaller than that without a series compensation for the same speed control effect
  - Converter has larger margin toward its nonlinear modulation mode.
- **Over compensation:**
  - high generator terminal voltage
  - considerable distortion of DFIG characteristics
  - affect operation, efficiency and effective control of DFIG wind turbines on the wind farm.

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6. **Integrated steady-state and transient studies**
7. Conclusions

Integrated Simulation Environment

- **d-q control of the rotor-side controller affect machine operating data simultaneously**:
  - Torque & speed
  - Stator real and reactive power
  - Rotor real and reactive power
  - Stator/rotor d and q currents.
- **Integrative study**:
  - examine input/output power, torque, and other parametric data **concurrently**
  - evaluate various practical constraints
    - rated power of the stator and rotor windings
    - acceptable slip
    - converter linear modulation requirement.

Integrated Steady-State Study Using MathCAD

$n := 1$ $\quad Z_s := Z_{s0} + Z_{st} + n \cdot Z_t$ $\quad Z_{th} := \dfrac{Z_m \cdot Z_s}{Z_m + Z_s}$ $\quad V_{th\_dq} := V_{g\_dq} \cdot \dfrac{Z_m}{Z_s + Z_m}$

- **Injected rotor voltage**

$V_{rd} := \sqrt{3} \cdot 99V$ $\quad V_{rq} := \sqrt{3} \cdot 7.15V$ $\quad V_{r\_dq} := V_{rd} + j \cdot V_{rq}$

- **Find operating slip and rotor speed**

Given

$$\mathrm{Re}\left[\left[\frac{V_{th\_dq} - \dfrac{V_{r\_dq}}{s_1}}{Z_{th} + Z_r + R_r \cdot \dfrac{(1-s_1)}{s_1}} \cdot \left[R_r \cdot \frac{(1-s_1)}{s_1}\right] + \frac{V_{r\_dq} \cdot (1-s_1)}{s_1}\right] \cdot \overline{\left(\frac{V_{th\_dq} - \dfrac{V_{r\_dq}}{s_1}}{Z_{th} + Z_r + R_r \cdot \dfrac{(1-s_1)}{s_1}}\right)}\right] = P_{drive} + P_{rot}$$

$s_{slip} := \mathrm{Find}(s_1)$ $\quad s_{slip} = 0.235673$ $\quad \omega_m := \omega_{syn} \cdot (1 - s_{slip})$ $\quad \omega_m = 120.06\,\mathrm{Hz}$

- **Input drive torque** $\quad \tau_{in} := \dfrac{P_{drive}}{\omega_m}$ $\quad \tau_{in} = -4997.5\,\mathrm{N \cdot m}$
- **Converted power** $\quad P_{conv} := P_{rot} + P_{drive}$ $\quad P_{conv} = -595\,\mathrm{kW}$
- **Air gap power**

$Z_{rt} := Z_{th} + Z_r + R_r \cdot \dfrac{(1 - s_{slip})}{s_{slip}}$ $\quad I_{r\_dq} := \dfrac{\dfrac{V_{r\_dq}}{s_{slip}} - V_{th\_dq}}{Z_{rt}}$

$E_{ms} := -I_{r\_dq} \cdot \left[Z_r + R_r \cdot \dfrac{(1 - s_{slip})}{s_{slip}}\right] + \dfrac{V_{r\_dq}}{s_{slip}}$ $\quad P_{air} := \mathrm{Re}\left(E_{ms} \cdot \overline{-I_{r\_dq}}\right)$ $\quad P_{air} = -778.463\,\mathrm{kW}$

- **Generator terminal voltage**

$I_{ms\_dq} := \dfrac{E_{ms}}{Z_m}$ $\quad I_{s\_dq} := I_{ms\_dq} - I_{r\_dq}$ $\quad V_{s\_dq} := E_{ms} + I_{s\_dq} \cdot Z_{s0}$ $\quad |V_{s\_dq}| = 694.715\,\mathrm{V}$

- **Stator real and reactive power**

$P_{stator} := \mathrm{Re}\left(V_{s\_dq} \cdot \overline{I_{s\_dq}}\right)$ $\quad P_{stator} = -777.126\,\mathrm{kW}$ $\quad Q_{stator} := \mathrm{Im}\left(V_{s\_dq} \cdot \overline{I_{s\_dq}}\right)$ $\quad Q_{stator} = -162.483\,\mathrm{kW}$

- **Rotor real and reactive power**

$P_{rotor} := \mathrm{Re}\left(V_{r\_dq} \cdot \overline{I_{r\_dq}}\right)$ $\quad P_{rotor} = 186.303\,\mathrm{kW}$ $\quad Q_{rotor} := \mathrm{Im}\left(V_{r\_dq} \cdot \overline{I_{r\_dq}}\right)$ $\quad Q_{rotor} = 196.889\,\mathrm{kW}$

- **Efficiency**

$$\eta(P_r) := \begin{cases} \dfrac{P_{stator}}{P_{in} - P_r} & \text{if } P_r \geq 0 \\ \dfrac{P_{stator} - P_r}{P_{in}} & \text{if } P_r < 0 \end{cases}$$

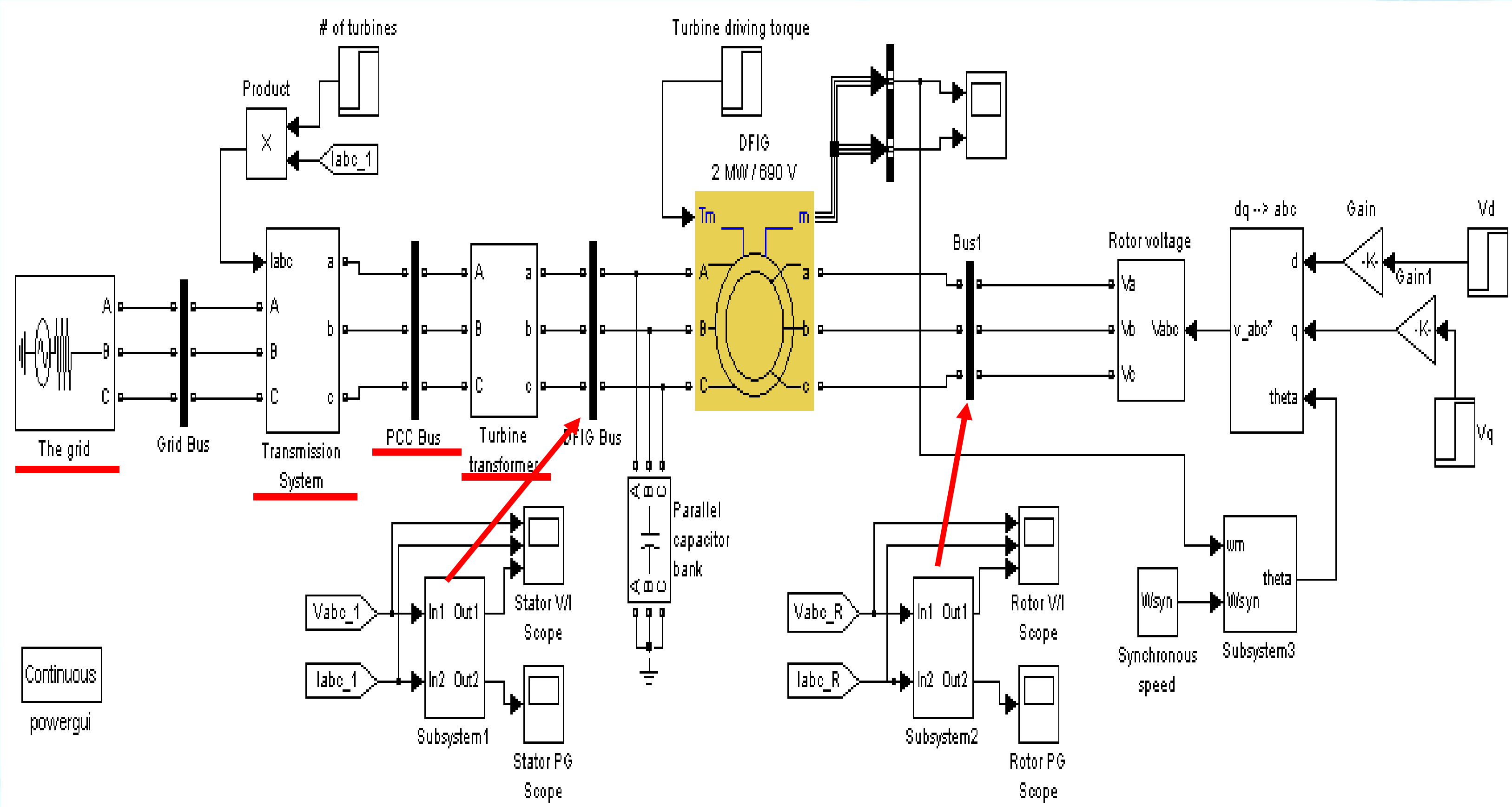
$\eta(P_{rotor}) = 98.833\,\%$

Integrative power generation and control study

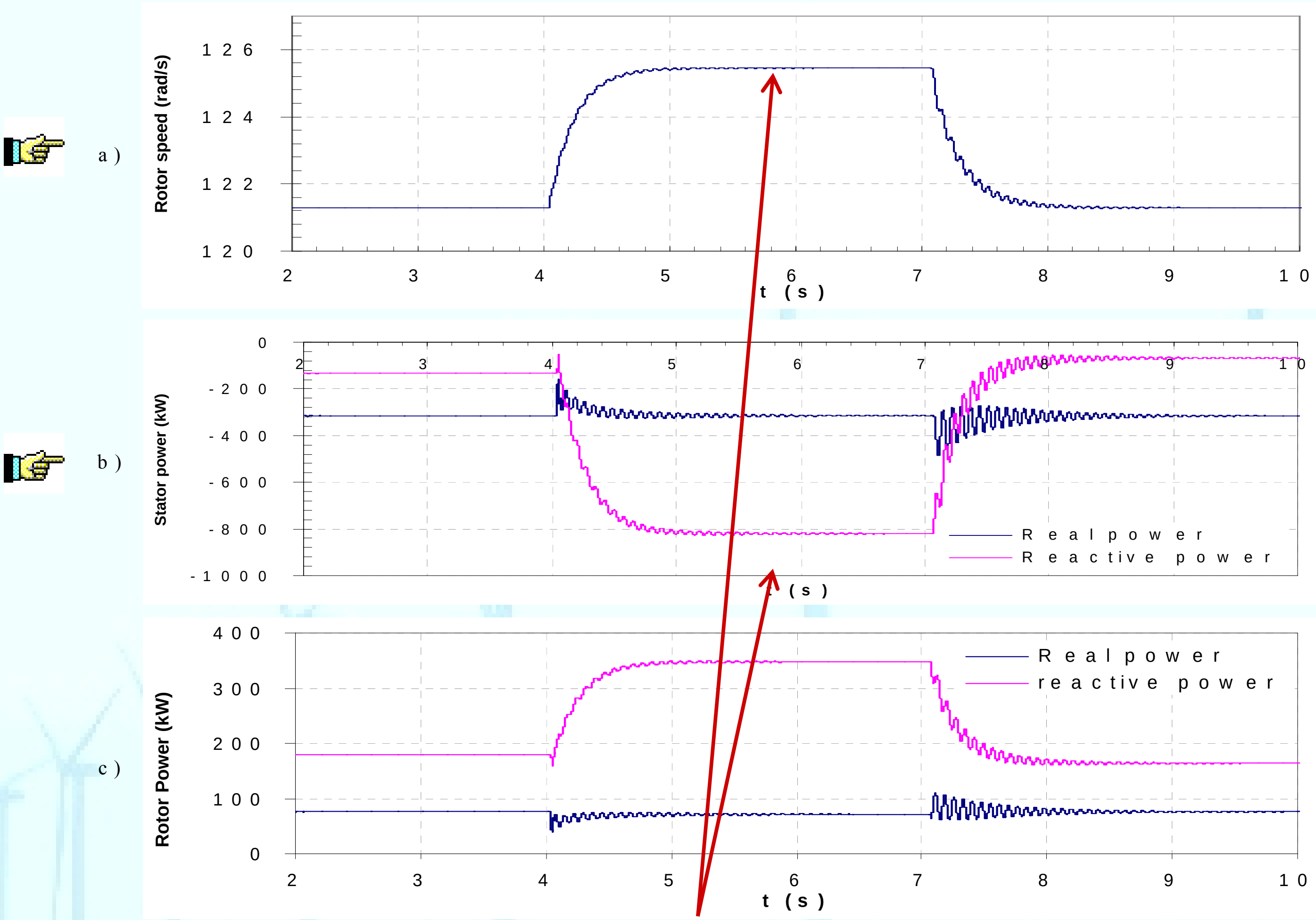
(Turbine drive power: 600kW; Turbine rotational speed: 120rad/s)

No. of wind turbines	Uncompensated		Parallel		Series	
	1	**150**	**1**	**150**	**1**	**150**
Stator line voltage (V)	694.7	707.5	732.7	715.8	692.9	700
Stator real power (kW)	-777.1	-777.5	-777	-761	-777.4	-777.3
Resultant reactive power (kVar)	-162.5	-101.7	-2650.9	-174.3	-54.6	64.2
Rotor real power (kW)	186.3	186.4	185.1	197.2	186.2	185.7
Rotor reactive power (kVar)	196.9	185.9	31.3	-426.7	168	139.9
V_{rd} control (V)	171.5	171.5	171.5	133.4	169.7	169.7
V_{rq} control (V)	12.4	31.4	11.38	31.35	12.6	13.3
Generator Efficiency (%)	98.8	98.9	99	95.5	98.9	98.9

Integrated Transient Study Using SimPowerSystems



DFIG transient simulation under constant turbine driving torque



When stable, transient results match steady-state results perfectly.

Conclusions

As the number of turbines online increases

- **Uncompensated wind park:**
  - Fixed-speed WECS: torque characteristics shrinks obviously.
  - Variable-speed DFIG WECS:
    - DFIG stability increases as more turbines are connected online
    - A higher voltage control signal may be needed to get the same speed control effect
- **Parallel compensated wind park:**
  - Fixed-speed WECS:
    - Enhances the generator torque characteristics
    - Over-voltage may become a critical problem.
  - Variable-speed DFIG WECS:
    - DFIG stability is reinforced
    - A higher voltage control signal may still be needed to achieve the same speed control effect.
- **Series compensated wind park:**
  - Properly designed series compensation improves the generator profiles for both fixed and variable speed induction generators.
  - A high overcompensation may derogate fixed-speed wind turbine characteristics and distort the DFIG characteristics significantly.

THANK YOU!