ECE 566: Grid Integration of Wind Energy Systems

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Reminders and notifications

1. **Mid-term exam scheduled for October 14, 2014**
   - 75-minutes take-home exam 645–8 PM (Mtn time)
   - Closed notes, closed book, etc.
   - Access and submission via RamCT Blackboard

2. **Homework 3 assigned today (9/30/14); due on 10/7/14.**

3. **PE and stability topics in syllabus rearranged**

4. **Course structure: homework; mid-term; project paper; and final exam**
Fixed-speed wind turbines

- Fixed-speed wind turbines have rotor speeds that are fixed and determined by the grid frequency, the gear ratio, and the generator design rather than the wind speed
- Use a squirrel-cage induction machine or wound-rotor induction machine connected directly to the grid
- May require soft starting to avoid impacts of starting currents
- May require capacitor banks for reactive compensation
Generators and power electronics for wind turbines
Requirements for grid connection
Power conditioning
References

Overview/review of wind turbine topologies [1]

Fixed-speed wind turbines

- Fixed-speed wind turbines have rotor speeds that are fixed and determined by the grid frequency, the gear ratio, and the generator design and not determined by than the wind speed

- This implies that they have maximum $\eta$ at one particular wind speed

- To maximize utility of such fixed-speed wind turbines, these machines have 2 winding sets
  1. a higher number of poles (typically, 8) for use in low speeds
  2. a lower number of poles (typically, 4 – 6) for use in high speeds

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### Overview/review of wind turbine topologies [1]

#### Fixed-speed wind turbines

**Advantages**
- Simple design
- Robust and reliable operation
- Low costs of electrical parts

**Disadvantages**
- Uncontrollable reactive power consumption
- Higher mechanical stresses and fluctuations which are reflected on the supply grid; may cause large voltage deviations and line losses
- Limited control of power quality
Overview/review of wind turbine topologies [1]

Variable speed wind turbines

- Variable speed wind turbines are designed to achieve maximum aerodynamic $\eta$ over a range of wind speeds.
- Variable speed operation enables the wind turbine to accelerate or decelerate the rotational speed $\omega$ wrt the wind speed $v$, thus keeping a constant TSR, $\lambda$—this corresponds to the maximum $C_p$.
- Remember that $\lambda = \frac{\omega R}{v}$, where $R$ is the rotor radius.
- Unlike in a fixed-speed wind turbine, generator torque is kept constant and wind speed variations are absorbed by changing the generator speed.
Variable speed wind turbines

- Variable speed wind turbines are equipped with an induction or sync. generator.
- Connected to the grid through power converters that control the generator speed—absorbing the fluctuations in the wind speed.
Overview/review of wind turbine topologies [1]

Variable speed wind turbines

- **Advantages**
  - Increased energy capture
  - Improved power quality
  - Reduced mechanical stresses

- **Disadvantages**
  - Losses in power electronics decreases the $\eta$
  - Uses of more electrical components and power electronics increases costs
Power control concepts

- Power controls are needed to control the aerodynamic forces on the turbine (fixed-speed or variable speed).
- Needed for limiting power during very high wind velocities to prevent damages to the installation.
- Two types of power control: *stall* and *pitch* controls.
Overview/review of wind turbine topologies [1]

Power control: **Stall control**

- Most robust and cheapest control method
- A passive control method in which the wind turbine blades are bolted at a fixed angle to the hub
- Aerodynamics of the rotor will cause the rotor to lose power and stall when high wind speeds are incident
- This limits the aerodynamic power of the blade and thus reduces mechanical stresses
Overview/review of wind turbine topologies [1]

Stall control: Disadvantages

- Lower $\eta$ in low wind speeds
- No assisted start-up (i.e., turbine power cannot be controlled during connection sequence)
- Variations in maximum steady-state power due to variations in air density and grid frequencies
Overview/review of wind turbine topologies [1]

Power control: Pitch control

- Active control method where the blades are turned into or out of the wind
- As power output crosses a threshold (high or low), the blades are pitched

**Advantages**

1. Efficient power control that keeps the power output close to the rated power of the generator
2. Assisted start-up
3. Emergency stop
Overview/review of wind turbine topologies [1]

Pitch control: Disadvantages

- Complexity in pitch mechanism
- Higher power fluctuations in high winds: this is because the instantaneous power will fluctuate around the mean value of the power in gusts and high wind speeds
Power control: **Active stall control**

- When the stall of the blade is **actively** controlled by pitching mechanism
- In low wind speeds, blades are pitched similar to the standard pitch control of wind turbines for max $\eta$
- In high wind speeds, the blades are stalled deeper by *slightly* pitching into the opposite direction from that of a pitched-controlled turbine
Overview/review of wind turbine topologies [1]

**Power control: Active stall control**

- **Advantages**
  1. Smoother limited power, without high power fluctuations as seen in pitched-controlled machines
  2. Ability to compensate variations in air density
  3. Emergency stop and start up are better enabled using the combination of stall and pitch mechanisms

- **Disadvantages**
  1. Costs
  2. Complexity in control
Overview/review of wind turbine topologies [1]

Classification of wind turbines

- **By speed control:**
  1. Type I
  2. Type II
  3. Type III
  4. Type IV

- **By power control:**
  1. Stall
  2. Pitch
  3. Active stall
### Overview/review of wind turbine topologies [1]

#### Table: Wind turbine control concepts

<table>
<thead>
<tr>
<th>Speed control</th>
<th>Power control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed-speed</td>
<td>Stall</td>
</tr>
<tr>
<td>Type I</td>
<td>Type I0</td>
</tr>
<tr>
<td>Variable speed</td>
<td>Pitch</td>
</tr>
<tr>
<td>Type II (limited VS)</td>
<td>Type I1</td>
</tr>
<tr>
<td>Type III (VS + PLC)</td>
<td>Type I2</td>
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<tr>
<td>Type IV (VS + FLC)</td>
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<tr>
<td></td>
<td>Active stall</td>
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<td></td>
<td>Type II0</td>
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<td>Type II1</td>
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<td>Type IV1</td>
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<td></td>
<td>Type IV2</td>
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</tbody>
</table>

VS: Variable Speed; P/FLC: Partial/Full Load Converter

Text in italics indicate combinations not in use by the wind industry today.
Overview/review of wind turbine topologies [1]

Type I: Fixed-speed wind turbines

- Asynchronous squirrel-cage induction generator (SCIG) directly coupled to grid via transformer
- Uses soft starter for smoother grid connection
- Cap bank provides reactive compensation
Generators

Overview/review of wind turbine topologies [1]

Type I: Fixed-speed wind turbines

- Fluctuations in wind converted to mechanical fluctuations, which are in turn reflected as electric power variations
- When grid is weak, this can cause large voltage variations at point of common coupling
- Because of voltage fluctuations, reactive power drawn by wind turbine from grid will vary causing line losses; hence, the need for a cap bank
- Drawbacks: does not support any speed control; requires a stiff grid; and must be capable of tolerating mechanical stresses
- Power controls: All 3 types (stall, pitch, active stall) are currently available and used in the wind industry.
Overview/review of wind turbine topologies [1]

Type II: Variable speed wind turbines

- Corresponds to limited variable speed wind turbine with variable rotor generator resistance
- E.g.: Vestas OptiSlip® and Suzlon FlexSlip®
Overview/review of wind turbine topologies [1]

Type II: Variable speed wind turbines

- Uses a wound rotor induction generator (WRIG) with additional variable resistance controlled by power electronics.
- Control of rotor resistance allows controlling the slip (s) and the power output of the generator.
- Allows generators to have a variable slip (in a narrow range) from which an optimum value is chosen.
- This reduces the fluctuations in the drive train torque and the output electrical power.
Overview/review of wind turbine topologies [1]

Type II: Variable speed wind turbines

**Advantages**

1. Simple; reliable; cost-effective way to attain load reductions and steadier outputs
2. Improved operating speed compared to SCIG
   - Slip in Vestas OptiSlip® is 10%
   - Slip in Suzlon FlexSlip® is 16%

**Disadvantages**

1. Needs a soft-starter and reactive compensation via cap banks
2. Limited speed range; poor control of active/reactive powers; slip power dissipated in variable resistance losses
Overview/review of wind turbine topologies [1]

Type III: Variable speed with partial-scale frequency converter

- Also known as doubly-fed induction generator (DFIG)
- Uses WRIG with a partial-scale frequency converter (rated at approx. 30% of nominal generator power) on rotor circuit
Overview/review of wind turbine topologies [1]

Type III: Variable speed with partial-scale frequency converter

- **Advantages**
  1. No need for soft-starter or reactive compensation via cap banks; partial-scale freq. converter will do these tasks
  2. Wider dynamic range than Vestas OptiSlip® and Suzlon FlexSlip®
     - Depends on converter rating
     - Typical range is in −40% to +30%
  3. Smaller converter makes it economically attractive

- **Disadvantages**
  1. Still more expensive than Type I and Type II topologies
  2. Additional protection in the case of grid faults
  3. Use of slip rings for making electrical connection to the rotor
Overview/review of wind turbine topologies [1]

Type IV: Variable speed with full-scale frequency converter

- Instead of partial-scale, a full-scale frequency converter is used
- Uses WRIG, or wound-rotor synchronous generator (WRSG), or permanent magnet synchronous generator (PMSG)
- WRSG uses electrical excitation and PMSG uses magnetic excitation
Overview/review of wind turbine topologies [1]

Type IV: Variable speed with full-scale frequency converter

Advantages

1. Provides control of both active and reactive powers delivered to the grid
2. Smooth grid connection
3. No gear box needed (see dotted line in figure); a direct-driven multi-pole generator with a large diameter is used (e.g., Enercon, Made, and Lagerwey)

Disadvantages

1. Expensive
2. More losses in power conversion
Overview/review of wind turbine topologies [1]

Figure: World share of yearly installed wind power for different wind turbine concepts from 48 manufacturers [1]
Global market share of the world’s leading wind turbine manufacturers in 2013, based on sales in GW

Figure: Global market share of the world’s leading wind turbine manufacturers in 2013, based on sales in GW [2]
Transfer of electric energy to the grid depends on differentiating between the following two types:

1. Systems with connection to a weak grid
2. Systems with connection to a stiff grid

WECS must operate reliably in both the application areas.

Stiff grid can be considered as an infinite inertia system.

Low-level energy supplies like WECS regard the stiff grid as an infinite sink of constant voltage and frequency.
Requirements for grid connection [3]

- Usually, WECS are installed in remote areas with limited supply options.
- Use of long, radial, and dead-end feeders may form a weak interconnection to the grid.
- For large WECS, output may match the grid transfer capacity, such that mutual influences start playing key roles.
- Hence, special requirements and equipment are needed for interconnection of WECS.
Grid connection is governed primarily by a grid code. According to [4]: “A grid code is a technical specification which defines the parameters a facility connected to a public electric network has to meet to ensure safe, secure and economic proper functioning of the electric system.”
“Typically a grid code will specify the required behavior of a connected generator during system disturbances. These include:

1. voltage regulation
2. power factor limits and reactive power supply
3. response to a system fault (short-circuit)
4. response to frequency changes on the grid, and
5. requirement to "ride through" short interruptions of the connection
Grid code in the US: FERC Orders 661 and 661-A

- The technical requirements for wind generation facilities of capacity $\geq 20$MW were issues in FERC Order 661.
- Requirements included:
  1. low voltage ride through (LVRT) capability
  2. power factor design criteria
  3. supervisory control and data acquisition (SCADA) capability
  4. self-study of interconnection feasibility
Upon studies by the transmission provider showing the need for maintaining the power factor (between a range) by the wind farm, the facility is expected to provide operation in the following range: 0.95 capacitive (leading) to 0.95 inductive (lagging), measured at the high-side of the substation transformer [6].
Requirements for grid connection [5]

Grid code in the US: FERC Orders 661 and 661-A

- SCADA capability
  1. Wind farms must have SCADA capability to receive instructions from the transmission provider
  2. Transmission providers cannot control the wind farm
  3. Specific SCADA capability is flexible for negotiation between the wind power plant and the transmission provider depending on the specific needs at the specific location

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Grid code in the US: FERC Orders 661 and 661-A

- **Self-study of interconnection feasibility**

  “The wind developer is permitted to satisfy the requirements of the interconnection request by providing a set of preliminary electrical design specifications depicting the wind plant as a single equivalent generator after which the plant may enter the queue and receive the base case data as is provided for all large generators. No more than six months following the submittal, the wind plant is required to submit completed detailed design specifications and other data needed to allow the transmission provider to complete its system impact study” [5].
Requirements for grid connection

Low voltage ride through (LVRT) capability [7]

- During system faults, the voltages may dip and fault currents may increase
- Low voltages may cause generators—especially permanent magnet machines—to trip due to loss of field
- Loss of generation will create further lower voltages, which may in turn cause more generators to trip and exacerbate the situation to a cascading failure
- To prevent such a cascade, wind generators are particularly required to ride through low voltages and faults.
Requirements for grid connection

Low voltage ride through (LVRT) capability [7]

- Depending on the code, they may
  - a. disconnect momentarily, then reconnect and continue to supply
  - b. stay connected throughout the fault
  - c. stay connected and provide reactive support
Requirements for grid connection [5]

Grid code in the US: FERC Orders 661 and 661-A

- LVRT in Order 661
  - Based on results supported from system studies, Order 661 “required wind generators to stay connected to the grid for voltage drops of 15 percent of nominal network voltage levels at the point of interconnection” [5].

- LVRT requirements were modified in Order 661-A based on input from the North American Electric Reliability Corporation (NERC) and the American Wind Energy Association (AWEA)
Grid code in the US: FERC Orders 661 and 661-A

- LVRT in Order 661-A
  - "Wind plants (following the transition period) are required to ride through low voltage events down to a 0 voltage level for location specific clearing times up to a maximum of 9 cycles. Also called ZVRT (for zero-voltage ride through).
  - If the fault on the transmission system remains after the clearing time, the wind plant is permitted to disconnect from the system.
  - LVRT capability is required for all new wind plant interconnections, not just those flagged by the system impact study.
Requirements for grid connection [5]

Grid code in the US: FERC Orders 661 and 661-A

- LVRT in Order 661-A
  - The point of measurement for the requirement is at the high side of the wind plant step-up transformer and no longer at the point of interconnection
  - Variations to the LVRT provisions are only permitted on an interconnection-wide basis.” [5].

- LVRT requirements were modified in Order 661-A based on input from the North American Electric Reliability Corporation (NERC) and the American Wind Energy Association (AWEA)
Figure from [8]
Figure from [9]

Data points for older LVRT and newer ZVRT specifications.
Fault analysis

\[ F = \text{fault} \]
\[ I_F = \text{fault current} \]
Fault analysis

\[ I_F^k = \frac{V_{TH}}{(Z_{TH} + Z_F)} \]  
\[ V_F^k = V_{TH} - (Z_{TH} \cdot I_F^k) \]  
\[ V_F^k = \frac{V_{TH} \cdot Z_F}{(Z_{TH} + Z_F)} \]
LVRT example

The Taiban Mesa Wind Farm plant in the WECC interconnection is located at Bus C. If a far away fault occurs in the WECC interconnection that produces a voltage sag at Bus C which lasts for a period of 200 cycles, determine if the wind farm is required to remain on-line or not?
Power conditioning [1]

Role of power electronics

- Power electronic systems are required in standard variable-speed turbines to control voltage and frequency prior to grid connection.
- Power electronics have 2 strong attractive features:
  1. Controllable frequency - important for the turbine
  2. Power plant characteristics - important for the grid
Power conditioning [1]

Role of power electronics: Controllable frequency

- Advantages
  - Optimal energy operation
  - Reduced loads on gears and drive train, as the rotor speed changes absorbs wind speed variations
  - Load control, as life-consuming loads can be avoided
  - Gearless operation of wind turbines, since the power electronics replace the mechanical gearbox
  - Reduced noise at low wind speeds

- Disadvantages
  - Costs!
  - Additional losses
Power conditioning [1]

Role of power electronics: Power plant characteristics

- Advantages
  - Provides the possibility of the wind farm becoming an active element in the grid
  - Provision of controls for active and reactive power controls
  - Wind farm can serve as a local reactive power source and participate in voltage regulation services
  - Improvement in wind farm PQ characteristics: reduced flicker, filtered out low harmonics, limiting the short-circuit power.

- Disadvantages
  - Higher harmonics may be present in the system due to the higher switching power electronics
Power electronics devices in a wind turbine and wind farm may include a variety of devices.
Power electronics devices in a wind turbine and wind farm may include a variety of devices

- Capacitor bank controls
Power electronics devices in a wind turbine and wind farm may include a variety of devices:
- Capacitor bank controls
- Soft starters
Power electronics devices in a wind turbine and wind farm may include a variety of devices:

- Capacitor bank controls
- Soft starters
- Rectifiers
Power electronics devices in a wind turbine and wind farm may include a variety of devices:

- Capacitor bank controls
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- Rectifiers
- Inverters
Power electronics devices in a wind turbine and wind farm may include a variety of devices:
- Capacitor bank controls
- Soft starters
- Rectifiers
- Inverters
- Frequency converters
Power electronics [1]

- Basic elements of power converters are *diodes* and *electronic switches*
- Diodes are uncontrollable valves that conduct current in one direction while blocking the current in the reverse direction when voltage polarity changes
- Electronic switches are controllable valves that will allow precise control of turning on and off of the switching element to conduct current
- Examples of electronic switches: Thyristors, integrated gate commutated thyristor (IGCT), bipolar junction transistor, metal oxide semiconductor field effect transistors (MOSFETs) and insulated gate bipolar transistor (IGBT)
### Power electronics [3]

<table>
<thead>
<tr>
<th>Maximum output rating</th>
<th>IGBT</th>
<th>MOSFET</th>
<th>GTO</th>
<th>IGCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (V)</td>
<td>6500</td>
<td>1200</td>
<td>6000</td>
<td>6000</td>
</tr>
<tr>
<td>Current (A)</td>
<td>3600</td>
<td>700</td>
<td>6000</td>
<td>6000</td>
</tr>
<tr>
<td>Output (kVA)</td>
<td>4000</td>
<td>70</td>
<td>24000</td>
<td>24000</td>
</tr>
<tr>
<td>Turn-off time (µs)</td>
<td>1–4</td>
<td>0.3–0.5</td>
<td>10–25</td>
<td>10–15</td>
</tr>
<tr>
<td>Freq. rang (kHz)</td>
<td>2–20</td>
<td>5–100</td>
<td>0.2–1</td>
<td>1–2</td>
</tr>
<tr>
<td>Drive req.</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>
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Power conditioning
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R. Piwko et al. “Penetrating Insights: Lessons Learned from Large-Scale Wind Power Integration”. In: Power and Suryanarayanan ECE 566 Lecture/Week 6.
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