Modelling of Wind Turbines For Power System Analysis

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Introduction and Outline

• Modelling for Power System Analysis
• Modelling of Wind Generators
  – Main characteristics
  – Types of wind generators
  – Modelling for Power Flow Analysis
  – Modelling for Short Circuit Analysis
  – Modelling for Dynamic Analysis
  – Aggregated Models (Wind Farms)
Modelling for Power System Analysis

• Not a unique model (system or element).
• Simple models (fundamental frequency model) because large number of components.
• Requirements of the study
  – Power Flow (Powers and voltages)
  – Short Circuit (Level of fault currents)
  – Others.
Models for Wind Generators

Include models of complex subsystems.

- Wind modelling.
- Aerodynamics.
- Mechanical components (gears, shaft)
- Electrical components (generator, control systems, power electronic converters)

- Most models too complex for power system analysis.
Models for Wind Generators

– New models available.
  • Quasi-static models (simplified) for some subsystems.
  • Some losses and magnetic saturation are neglected.
  • Stator voltages and currents are sinusoidal.
  • Voltage control converters are modeled as current sources.
  • Mechanical representation of shaft and rotating mass is modeled as one simple element.

– Models available in commercial software (in some cases verified by manufacturers).

– Institutions and associations are working on new models (IEEE, UWIG, WECC, etc.)
Wind Generation Characteristics

Mechanical power (Translation)  Mechanical power (Rotation)  Electrical power
Wind Generation Differences

- Wind generators are usually based on different generator technologies than conventional synchronous generators.
- Wind turbines (prime movers) cannot be controlled and fluctuates randomly.
- Typical size of wind turbine is much lower than conventional power plant (wind farm).
- Wind resources are usually at different locations than conventional power stations.
- Wind generators are usually connected to lower voltage levels than conventional power stations.
Types of Wind Generators [1, 2, 3, 4, 5, 6]

Squirrel Cage Induction Generator
(Old Machines)

Doubly Fed Induction Generator
(Current Machines)

Direct Drive
Synchronous Generator
(Future Machines)
### Types of Wind Generators [1, 2, 3, 4, 5, 6]

<table>
<thead>
<tr>
<th>Squirrel Cage Induction</th>
<th>Doubly Fed Induction</th>
<th>Direct Drive Synchronous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple and Robust</td>
<td>Less mechanical stress</td>
<td>Less mechanical stress</td>
</tr>
<tr>
<td>Less expensive</td>
<td>Less noisy</td>
<td>Less noisy</td>
</tr>
<tr>
<td>Electrically efficient</td>
<td>Aerodynamically efficient</td>
<td>Aerodynamically efficient</td>
</tr>
<tr>
<td>Standard generator</td>
<td>Standard generator</td>
<td>No gearbox</td>
</tr>
<tr>
<td>Small converter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerodynamically less efficient</td>
<td>Electri</td>
<td>Electrically less efficient</td>
</tr>
<tr>
<td>Gearbox included</td>
<td>Gearbox included</td>
<td>Large converter</td>
</tr>
<tr>
<td>Mechanical stress</td>
<td>Expensive</td>
<td>Expensive</td>
</tr>
<tr>
<td>Noisy</td>
<td></td>
<td>Complex, heavy and large generator</td>
</tr>
</tbody>
</table>
Types of Wind Generators \([1, 2, 3, 4, 5, 6]\)

Constant Speed

Variable Speed
Types of Wind Generators

![Diagram showing wind speed vs. active power for different wind speed intervals: cut-in, rated/nominal, cut-out.]

- **Cut-in wind speed**: No generation.
- **Rated/nominal wind speed**: Maximize rotor efficiency, nominal power, reduce rotor efficiency.
- **Cut-out wind speed**: No generation.

Wind speed [m/s] vs. Active power [p.u.]

Oct. 2006 CREDP - Wind Farm Operation and Grid Integration
Load Flow Analysis

• Knowledge of basic electrical properties.
  – Line and transformer impedances.
  – Power consumed and generated.
  – Generators: PV buses (slack).
  – Requirements: input of active and reactive power
Load Flow Analysis \([1, 2, 6]\)

- Squirrel cage induction generator in constant speed turbines
  - It has a fixed relation between rotor speed, active power, reactive power and terminal voltage.
  - Cannot affect its terminal voltage. Additional equipment such as capacitor banks, SVCs or STATCOMs is required for voltage control.
Load Flow Analysis [1, 2, 6]

• Variable speed turbines
  – Have the capability of varying the reactive power at given active power, rotor speed and terminal voltage.
  – Range of control of reactive power depends on size of the power of the power electronic converter.
Load Flow Analysis [1, 2, 6]

• Usual practice to model wind generators as a PQ bus (as a negative load).
  – Generated real power set at a momentary value.
  – Estimate reactive power based on terminal voltage and parameters of the induction generator (macro programs) for squirrel cage machines.
  – Variable speed machines have reactive power controllability, fix value of Q.

• Variable speed turbines could be modelled as PV buses (voltage control, reactive power limits).
Probabilistic Load Flow Analysis [7]

• Probabilistic Load Flow Analysis
  – Load and generation can be described by probabilistic density functions.
  – Wind resource is usually characterized by PDF.

Figure 4. Probability Density Distribution of the Reactive Power Supplied (a) without WT's, (b) without WT's, (c) with WT's and Compensation.

Figure 5. Probability Density of Voltage (a) without and (b) with WT's in Operation.
Short Circuit Analysis [1, 2, 6]

• Constant speed turbines contribute to the fault current and rely on conventional protection schemes (Overcurrent, overspeed, over- and undervoltage, over- and underfrequency).

• Turbines based on the doubly fed induction generator also contribute to the fault current. Control system of the power electronics converter measures the voltage grid at a very high sampling rate (several kHz). A fault is detected very quickly. Turbine disconnected very quickly.

• Direct drive generator turbines hardly contribute to the fault current at all, because power electronic converter can not carry a fault current.
Short Circuit Analysis \[1, 2, 6\]

- Constant speed machine should be represented by the induction machine model.
- Doubly fed induction generators represented by the induction machine neglecting the converter.
- For machines with full converters the generator is decoupled from the grid. Proper representation of the converter should be used.
Dynamic Analysis

• Behaviour of the electrical system in the time domain (transient behaviour).

• Different aspects:
  – Rotor angle stability (Transient stability).
  – Frequency stability.
  – Voltage stability.

• Models are more complex and involved additional elements such as control elements, relays, mechanical parts of rotating machines, etc.
Dynamic Analysis

- Detailed model allows
  - examination of interaction between turbine and grid
  - electrical & mechanical quantities
  - good understanding of turbine behaviour
  - thorough insight in mechanical and electrical behaviour of turbine/grid
  - simulation of ‘heavy’ transients
  - help to set up connection requirements
Dynamic Analysis
Constant Speed Wind Turbine [3, 4, 5, 6]
Model Direct Drive Synchronous

Wind speed model or measured sequence → Wind speed

Rotor model → Mechanical power

Model of direct drive synchronous generator

Active and reactive power → Stator currents

Converter and protection system

Active and reactive power → Voltage and frequency

Fundamental frequency grid model

Pitch angle

Pitch angle controller

Rotor speed → Rotor speed set point

Active power set point

Terminal voltage controller

Reactive power set point
Response of Models [3, 4, 5, 6]
Farm (Aggregated) Models \[3, 4, 5, 6\]

- Aggregated wind park models
  - High penetration (several farms with many wind turbines).
  - Adequate representation of the behaviour during normal operation and disturbances.
  - Exchange of real and reactive power and voltage at point of common coupling (PCC).
  - Wind speed model:
    - No turbulence.
    - Layout of the farm and wind front, arrival times.
Farm (Aggregated) Models [3, 4, 5, 6]

Model of a single CS wind turbine or of n simplified variable speed wind turbine models

Turbine transformer impedance divided by n

Grid connection and park transformer impedance
Farm (Aggregated) Model \([3, 4, 5, 6]\)

Constant Speed Turbines – possible to aggregate at the level of the mechanical power.
Farm (Aggregated) Model [3, 4, 5, 6]

Comparisons under Normal Operation.

(Solid lines – detailed Model
Dashed lines – aggregated Model)
Comparisons under Fault Conditions.

(Solid lines – detailed model
Dashed lines – aggregated model)
Farm (Aggregated) Model \([3, 4, 5, 6]\)

Variable Speed Turbines – assume constant performance coefficient, reduction of the order of some of the control models, the electrical machine and the converter.
Comparisons under Normal Operation.

(Solid lines – detailed Model
Dashed lines – aggregated Model)
Farm (Aggregated) Model \([3, 4, 5, 6]\)

Comparisons under Fault Conditions.

(Solid lines – detailed model
Dashed lines – aggregated model)
Models for Wind Generators

- Future developments:
  - Better equipment and control techniques.
  - Manufacturers more involved on modelling.
  - Better models (more accurate, various levels of detail).
References
