Transient Stability Analysis with PowerWorld Simulator

T12: Wind Turbine Modeling
Need for Wind Turbine Models

- Over the last decade wind turbine capacity has grown to the point where they need to be explicitly considered in system-wide transient stability studies.

Growth in US Wind Capacity


Wind capacity additions in 2008 were 5538 MW. 12.5 MW of wind power were decommissioned.
Wind Turbine Modeling

• A wind farm usually consists of many small turbines in a collector system
• Each turbine’s voltage is usually less than 1 kV (usually 600 V) with a step-up transformer (usually to 34.5 kV)
• Usually, the wind farm is modeled in aggregate, but how accurate such aggregate models are is an open question
• PowerWorld Simulator provides support of each of the four major types of wind turbine models used in transient stability studies
  – Type 1: Induction generator with fixed rotor resistance
  – Type 2: Induction generators with variable rotor resistance
  – Type 3: Doubly-fed induction generators
  – Type 4: Full converter generators
• New wind turbines are either Type 3 or Type 4
Wind Turbine Modeling: Power Flow Solution

- Wind turbines are represented as generators in the power flow
  - Type 1 and 2 units operate at fixed real/reactive power with the unit supplying real power and consuming reactive power; usually there are compensating capacitors
  - Type 3 and 4 are treated as regular PV buses
Wind Generator Models

• Wind Turbines do not have an “exciter”, “governor”, or “stabilizer”

• However, modeling is very analogous
  – Wind Machine Model = Machine Model
  – Wind Electrical Model = Exciter
  – Wind Mechanical Model = Governor
  – Wind Pitch Control = Stabilizer
  – Wind Aerodynamic Model = Stabilizer

• Simulator will show wind models listed as though they are Exciters, Governors, and Stabilizers
  – Obviously you should not use a synchronous machine exciter in combination with a wind machine model and wind governor!
### Generic Wind Turbine Models

<table>
<thead>
<tr>
<th></th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
<th>Type 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine</td>
<td>WT1G</td>
<td>WT2G</td>
<td>WT3G</td>
<td>WT4G</td>
</tr>
<tr>
<td>&quot;Exciter&quot;</td>
<td>WT1E</td>
<td>WT2E</td>
<td>WT3E</td>
<td>WT4E</td>
</tr>
<tr>
<td>&quot;Governor&quot;</td>
<td>WT1T</td>
<td>WT12T1</td>
<td>WT1T</td>
<td>WT4T</td>
</tr>
<tr>
<td>&quot;Stabilizer&quot;</td>
<td>WT1P</td>
<td>WT12A1</td>
<td>WT3P</td>
<td></td>
</tr>
</tbody>
</table>

- Old Type 1 models as induction machine
  - MOTOR1, GENIND
  - CIMTR1, CIMTR2, CIMTR3, CIMTR4
- GE-specific Type 2 wind turbine model
  - GENWRI, EXWTG1, WNDTRB
- GE-specific Type 3 wind turbine model
  - GEWTG, EXWTGE, WNDTGE
  - Detailed model for GE 1.5, 1.6 and 3.5 MW turbines
Wind Turbine Voltage Control

- Voltage control of wind turbines depends on the type
- Type 1 squirrel cage induction machines - no direct voltage control
- Type 2 - wound rotor induction machines with variable external resistance, no direct voltage control, but external resistance system usually modeled as an exciter
- Type 3 and Type 4 - have the ability to perform voltage or reactive power control, similar to synchronous machines. Common control modes are constant power factor control, coordinated control across a wind farm to maintain a constant interconnection point voltage, and constant reactive power control
Wind Turbine Modeling

- Types 1 and 2 - Induction machine models, stator windings are connected to the rest of the network, rotor currents are induced by the relative motion between the rotating magnetic field due to the stator currents and the rotor.

- Slip is the difference between the synchronous speed and the rotor speed, defined using motor convention as:

\[ S = \frac{n_s - n_r}{n_s} \]

- Synchronous speed is \( n_s \) and rotor speed is \( n_r \), per unit.

Equivalent circuit for a single cage induction machine.

Glover, Sarma, Overbye, *Power System Analysis and Design*
Type 1 generators usually operate with a small negative slip since the wind turbine causes the machine to spin slightly faster than synchronous speed.
Type 2 Wind Models

- Type 2 models augment Type 1 by allowing for variable rotor resistance control in the wound rotor induction generator.
- By using turbine speed and electrical power output as inputs to the control system, the wind turbine can provide a more steady power output during wind variation.

![Graph showing real power output for different slips with external resistances of 0.05 and 0.99 pu.](image)

- External resistance = 0.05
- External resistance = 0.99 pu
Type 3 Wind Models

- Models Doubly-Fed Asynchronous Generators (DFAGs) or Doubly-Fed Induction Generators (DFIGs)
- In addition to the stator windings, rotor windings are connected to the AC network through a converter
- Allows separate control of both real and reactive power
- Allows a much wider speed range
- No electrical coupling with the turbine dynamics
- The DFAG dynamics are well approximated as a voltage-source converter (VSC)

Type 3 DFAG Model, Voltage Source Converter (VSC)

Glover, Sarma, Overbye, *Power System Analysis and Design*
Type 3 Wind Models

• Physically, these models usually consist of a wound rotor induction machine coupled with a voltage-source converter AC excitation system.

• Electrical performance is dominated by the converter which acts on a much faster time scale than transient stability level dynamics.
  – Machine model consists of a synthesized voltage behind a reactance.
  – Rotor dynamics are not important electrically.

• Modeling
  – Represents the generator by a machine model.
  – Reactive power control by an exciter model.
  – Mechanical control by a governor model.
  – Blade pitch control by a stabilizer model.
Type 3 Wind Model Example

- **Generator 3** will be modeled using a GEWTG machine, which models a 85 MW aggregation of GE 1.5 MW DFIGs
- **Exciter model EXWTGE** will be used to model the reactive power control of the wind turbine
- **Governor model WNTDGE** will be used to model the inertia of the wind turbine and its pitch control
- **Generators 1 and 2** remain unchanged
- **Open the case which has these settings,** wscc_9bus_Type3WTG.pwb
Type 3 Wind Model Example

- Set up Plot Definitions as desired
- Click “Run transient Stability”

Voltage recovery

Wind turbine MW Mechanical input and terminal output

Generator 3 EXWTGE states
Type 3 Wind Model Example

- During the fault the wind turbine terminal bus voltage will be quite low. This will cause the turbine’s Low Voltage Power Logic (LVPL) to reduce the real power current to zero.

- This will cause the wind turbine pitch control system to begin to pitch the blades to reduce the mechanical power into the rotor. This pitch control occurs slowly.

- Once the fault is cleared, this current is ramped back up, subject to a rate limit.
The way load dynamics are modeled often has a significant impact on the results of transient stability studies.

So far, we have mostly been looking at generator models, but many load models are also available in Simulator.

The default (global) models are specified on the Options, Power System Model page as constant impedance loads:
- Used when no other model is specified
- Discussed in the Transient Stability Basics section

Simulator makes it very easy to add complex load models.

More detailed models are added by selecting “Stability Case Info” from the ribbon, then Case Information, Load Characteristics Models.

Models can be specified for the entire case (system), or individual areas, zones, owners, buses or loads.

To insert a load model, right-click and select “Insert” to display the Load Characteristic Information dialog.
Complex Load Example

- Add a CLOD model to the system
  - Go to the Load Characteristic page in Model Explorer
  - Right-click and choose “insert” to open the Load Characteristic information dialog
- In the dialog, click “System” in the Element Type box to apply the load model to all buses in the system
- Click “Insert” to select the model type. Use CLOD (see [1]), which models the load as a combination of large and small induction motors, constant power and discharge lighting loads

Complex Load Example

- The case with these settings is `wscc_9bus_Type3WTG_CLOD`
- Run the simulation
- Compare the plots obtained with and without the CLOD load model

Plots after inserting system-level CLOD model
Complex Load Example

- On the Simulation page, increase the time for when the line is opened from 1.12 seconds to 1.155 seconds
- Open the Events tab on the Results page
- The Transient Contingency events are there, but there are also under voltage load trip events present
Complex Load Example

- In the PowerWorld CLOD model, under-voltage motor tripping may be set by the following parameters:
  - $V_i =$ voltage at which trip will occur (default = 0.75 pu)
  - $T_i$ (cycles) = length of time voltage needs to be below $V_i$ before trip will occur
- In the example, under voltage trips occurred at bus 5 and bus 8 when the fault clearing time was increased to 1.155
- Verify that increasing the clearing time further to 1.2 causes additional under-voltage trips of loads at buses 6, and an over-frequency trip of Generator 2
Complex Load Example

Plots when fault is cleared at 1.2 seconds

Large and Small Induction Motor Loads experience under voltage trips at buses 5, 6, and 8 at about 2 seconds after the line opens.

Generator 2 opens due to over frequency at 4.2 seconds after the line recloses.

Results from RAM

<table>
<thead>
<tr>
<th>Contingency Name</th>
<th>Time (Seconds)</th>
<th>Object</th>
<th>Model Type</th>
<th>Description</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0000</td>
<td>Branch 'y' 'y' 'y'</td>
<td>TXLine</td>
<td>Apply Solid Fault</td>
<td>Info</td>
</tr>
<tr>
<td>2</td>
<td>1.5000</td>
<td>Branch 'y' 'y' 'y'</td>
<td>TXLine</td>
<td>Open</td>
<td>Info</td>
</tr>
<tr>
<td>3</td>
<td>2.0003</td>
<td>Load '5' '1'</td>
<td>TXLoadObject</td>
<td>Large Induction Motors Under Voltage Trip: Op1Info</td>
<td>Info</td>
</tr>
<tr>
<td>4</td>
<td>2.0003</td>
<td>Load '5' '1'</td>
<td>TXLoadObject</td>
<td>Large Induction Motors Under Voltage Trip: Op2Info</td>
<td>Info</td>
</tr>
<tr>
<td>5</td>
<td>2.0003</td>
<td>Load '6' '1'</td>
<td>TXLoadObject</td>
<td>Small Induction Motors Under Voltage Trip: Op3Info</td>
<td>Info</td>
</tr>
<tr>
<td>6</td>
<td>2.0003</td>
<td>Load '6' '1'</td>
<td>TXLoadObject</td>
<td>Small Induction Motors Under Voltage Trip: Op4Info</td>
<td>Info</td>
</tr>
<tr>
<td>7</td>
<td>2.0003</td>
<td>Load '8' '1'</td>
<td>TXLoadObject</td>
<td>Large Induction Motors Under Voltage Trip: Op5Info</td>
<td>Info</td>
</tr>
<tr>
<td>8</td>
<td>2.0003</td>
<td>Load '8' '1'</td>
<td>TXLoadObject</td>
<td>Large Induction Motors Under Voltage Trip: Op6Info</td>
<td>Info</td>
</tr>
<tr>
<td>9</td>
<td>2.0000</td>
<td>Bus '1' '1'</td>
<td>TXBus</td>
<td>Generator Over Frequency: Open</td>
<td>Info</td>
</tr>
<tr>
<td>10</td>
<td>4.2000</td>
<td>Bus '2' '1'</td>
<td>TXBus</td>
<td>Generator Over Frequency: Open</td>
<td>Info</td>
</tr>
</tbody>
</table>
Complex Load Example

- CLOD model under-voltage tripping can be turned off by setting its parameter $V_i$ to zero
- Re-open the CLOD dialog, and set $V_i$ to zero
- Run the simulation, clearing the fault at 1.2 seconds
- Compare the plots

Set to zero to turn off under-voltage tripping

Voltages with under-voltage tripping turned OFF

Voltages with under-voltage tripping turned ON (default)
Type 4 Wind Models

• Completely asynchronous by design, called a “full converter model”
• The wind turbine’s output is completely decoupled from the network using an AC-DC-AC converter
• This decoupling allows considerable freedom in selecting what type of electric machine is used
  – Machine could be a conventional synchronous generator, permanent magnet synchronous generator, or squirrel cage induction machine
  – No electrical coupling with the turbine dynamics
• Represented as a VSC, like Type 3, but with $I_p$ and $I_q$ as direct control variables and without effective reactance
• Modeled
  – Machine/Exciter combination WT4G1/WT4E1 (PSSE)
  – Machine/Exciter/Governor WT4G, WT4E, and WT4T (PSLF)