Short Circuit Modeling for Inverter-Based Resources

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Motivation, Challenges & Needs

- Continuously increasing penetration level of inverter interfaced resources, predominantly renewables (Type III, Type IV WTGs & PVs)
- Complex fault response
  - Differs significantly from synchronous short-circuit current contribution (SCC)
- Accurate short-circuit models for protection/planning studies
- Performance of legacy protection schemes (distance protection etc)

Impact on System Protection

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Inverter Based Resources Fault Response Characteristics

Synchronous Generator

- SCC close to nominal load current (typically 1.1-1.5 pu)
- Typically low/zero negative sequence contribution
- No zero sequence contribution
- Fault response depends on WTG/PV inverter control scheme
Inverter Based Resources Short-Circuit Modeling

Limitations

Synchronous generator classical short circuit model (voltage source behind an impedance) is not applicable

Recognized Industry Gap

IEEE PSRC WG C24 “Modification of Commercial Fault Calculation Programs for Wind Turbine Generators”
WTG (Type III & Type IV) and Solar/PV phasor domain short circuit model:

- Voltage controlled current source
- Iterative solution (nonlinear behavior)
  - considers the impact of controls (reactive power/voltage control) on the short circuit response
  - respects converter current limits
Iterative Solution

Load Flow (Optional)

Wind SC Model Parameters Initialization

Apply Fault

SC Network Solution

Update IBR SC Model Current Injections

SC Network Solution

Convergence?

Yes

End

No

Matlab code provided to vendors
# Inverter Control Mode Options

<table>
<thead>
<tr>
<th>Function</th>
<th>Control Mode</th>
<th>Performance/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactive power/voltage control during ride-through</td>
<td>Constant power factor</td>
<td>Allows for inverter injection/absorption of reactive power based on a desired power factor</td>
</tr>
<tr>
<td></td>
<td>Constant Q</td>
<td>Allows for inverter fixed desired value of reactive power injection/absorption</td>
</tr>
<tr>
<td></td>
<td>V Control</td>
<td>Allows for inverter control of voltage to desired value</td>
</tr>
<tr>
<td></td>
<td>Dynamic reactive current control based on reference curve</td>
<td>Allows for reactive current injection based on a reference curve (e.g. grid code)</td>
</tr>
</tbody>
</table>

1) Control mode defines desired active & reactive current
2) Then current limiter is applied (P or Q priority)
## Current Limiter - PQ Priority - Examples

### Example 1:

**Assume:**
- Active Power: 1 p.u.
- Post fault voltage: 0.7 pu
- Control mode: Reference curve with slope 2
- Q priority
- Ilimit = 1.1 pu

**Desired Currents:**
- Iactive = 1/0.7 = 1.43 p.u
- Ireactive = 2(1-0.7) = 0.6 p.u
- Itotal = 1.55 pu (exceeds limit)

**Upon current limiter:**
- Iactive = 0.92 (reduced to satisfy limit)
- Ireactive = 0.6 p.u
- Itotal = 1.1 pu

### Example 2:

**Assume:**
- Active Power: 1 p.u.
- Post fault voltage: 0.4 pu
- Control mode: Reference curve with slope 2
- Q priority
- Ilimit = 1.1 pu

**Desired Currents:**
- Iactive = 1/0.4 = 2.5 p.u
- Ireactive = 2(1-0.4) = 1.2 p.u
- Itotal = 2.77 pu (exceeds limit)

**Upon current limiter:**
- Iactive = 0 (reduced to satisfy limit)
- Ireactive = 1.1 p.u (reduced to satisfy limit)
- Itotal = 1.1 pu
Model Non-Convergence Cases

• For some scenarios (typically close-in three-phase faults with no other source of fault current between converter and fault) the desired current power factor calculated by the controller cannot be imposed due to violation of physics laws (the network impedance phase angle has to be satisfied)
• Issue is related to converter synchronization to the grid which in reality is provided by the PLL
• Solution: Fix power factor based on network impedance

Source: Charlie Henville "Power factor of electronic sources under normal and fault conditions" presentation at the PSRC WG C24
Demonstrating Results

- Type IV WTG/Solar model assumes zero negative sequence current contribution
- Type III WTG has negative sequence current contribution due to the DFIG stator connection to the grid
Vendor Engagement

• Goal: Vendor engagement and implementation of the models in commercial platforms (CAPE, ASPEN, CYME, PSS/E, Powerfactory, etc).

• ASPEN & Electrocon have started implementing a beta version of the models and EPRI is providing technical support

• Present Status: Testing and benchmarking of the models with vendors using benchmark systems and databases provided by EPRI members.
CAPE Implementation - Electrocon

Update

- Electrocon has implemented so far the Type IV WTG/Solar model
- Type III WTG model is under development
- EPRI and Electrocon are benchmarking the Type IV WTG model
- Resolved issue with non-convergence for close-in faults
- No fault contribution for voltages above 0.9pu (load current) – based on a suggestion by a CAPE user
- Technical paper was presented at the CAPE UGM - June 2018
OneLiner Implementation - ASPEN

**Update**

- ASPEN has implemented the Type IV WTG/Solar model with FRT control mode (v14)
- Voltage Controlled Current Source model
- Tentative implementation as a V-I-pf table (v14)
- Model with no tabular input and GUI with FRT function settings already implemented. It will be available in OneLiner v15
- Type III WTG model has been also implemented and will be available in OneLiner v15
- EPRI and ASPEN have benchmarked both Type III and Type IV WTG model using a 9 bus test system
- ASPEN has documented the model implementation and contributed the write-up to the PSCR WG C24 report

**Type III WTG - SLG Fault Bus 3**

<table>
<thead>
<tr>
<th>WTG Variables</th>
<th>EPRI</th>
<th>ASPEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vpgc_pos (pu)</td>
<td>0.877 (20.6)</td>
<td>0.883 (20.0)</td>
</tr>
<tr>
<td>Ipgc_pos(pu)</td>
<td>1.058 (5.6)</td>
<td>1.052 (5.5)</td>
</tr>
<tr>
<td>Positive sequence pf angle</td>
<td>-15.0</td>
<td>-14.5</td>
</tr>
<tr>
<td>Vpgc_neg (pu)</td>
<td>0.112 (178.0)</td>
<td>0.124 (178.6)</td>
</tr>
<tr>
<td>Ipgc_neg(pu)</td>
<td>0.221 (-82.9)</td>
<td>0.243 (-82.4)</td>
</tr>
<tr>
<td>Negative sequence pf angle</td>
<td>99.1</td>
<td>99.0</td>
</tr>
</tbody>
</table>
PSRC WG C24 “Modification of Commercial Fault Calculation Programs for Wind Turbine Generators”

- Chair: Dr. Sukumar Brahma (NMSU), Vice-Chair: Evangelos Farantatos (EPRI)
- Scope:
  - 1) To survey WTG manufacturers to determine what parameters they could provide that could be used by steady state short circuit program developers in various time frames.
  - 2) Use the result of this survey to prepare a report that can be used by steady state program developers to refine their models.
- EPRI has a leading role to the WG. Members include WTG manufacturers (Siemens, Vestas, GE) and software vendors (Electrocon, ASPEN, ETAP)
- WG has proposed a voltage controlled current source model with iterative solution
- Input model data:
  - Algorithms for generic converter control schemes (EPRI proposal)
  - Tabular format (suggested to be provided by manufacturers with non generic converter control scheme)

<table>
<thead>
<tr>
<th>Time Frame (cycles)</th>
<th>Positive sequence voltage (p.u)</th>
<th>Positive sequence current (p.u)</th>
<th>Negative sequence current (p.u)</th>
<th>Power factor of positive sequence current</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Model Validation – 3 Approaches

1. Generic EMT Models

<table>
<thead>
<tr>
<th>FC variable</th>
<th>EMTP-RV</th>
<th>Complete model</th>
<th>Iterative solution</th>
<th>Iterative solution</th>
<th>Absolute difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(pu)</td>
<td>1.011</td>
<td>1.003</td>
<td>1.003</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>(deg.)</td>
<td>14.4</td>
<td>15.1</td>
<td>15.1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>(pu)</td>
<td>0.941</td>
<td>0.942</td>
<td>0.942</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>(deg.)</td>
<td>20.2</td>
<td>19.9</td>
<td>19.9</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>(pu)</td>
<td>0.002</td>
<td>0.002</td>
<td>0</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>(deg.)</td>
<td>-150.1</td>
<td>-167.3</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>(pu)</td>
<td>0.057</td>
<td>0.058</td>
<td>0.057</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>(deg.)</td>
<td>-70.6</td>
<td>-71.8</td>
<td>-71.6</td>
<td>0.2</td>
</tr>
</tbody>
</table>

2. Manufacturer EMT Models

3. Fault Recorded Measurements
**Type-III WTG Wind Park Connected to a 230-kV Substation**

Unfiltered phase voltage on the line side of the collector substation

Unfiltered phase current from the wind plant

### Phasor Model Results

<table>
<thead>
<tr>
<th>Variable</th>
<th>POI - pu</th>
<th>EMTP-RV</th>
<th>Phasor Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{I}_+$</td>
<td>0.825 (-39.7)</td>
<td>0.810 (-56.4)</td>
<td></td>
</tr>
<tr>
<td>$\bar{V}_+$</td>
<td>0.509 (1.5)</td>
<td>0.509 (0.6)</td>
<td></td>
</tr>
<tr>
<td>$\bar{I}_-$</td>
<td>0.858 (105.8)</td>
<td>0.862 (98.4)</td>
<td></td>
</tr>
<tr>
<td>$\bar{V}_-$</td>
<td>0.488 (0.4)</td>
<td>0.486 (0.1)</td>
<td></td>
</tr>
</tbody>
</table>

- Wind farm with 66x1.5MW type-III wind turbine generators
- B-C phase to phase fault on the tie line to the POI substation
Solar Model Validation with Recorded Data

- Three-phase fault in adjacent line
- Close match between simulation results and recorded data
Existing North American Standards for Inverter-Based Generating Resources and Gaps

<table>
<thead>
<tr>
<th>Performance</th>
<th>Test &amp; Verification &amp; Model Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>• FERC Orders</td>
<td>• NERC compliance monitoring &amp; enforcement</td>
</tr>
<tr>
<td>• NERC Reliability Standards &amp; Guidelines</td>
<td>• Not available</td>
</tr>
<tr>
<td>• Not available</td>
<td>• Not available</td>
</tr>
<tr>
<td>BES¹</td>
<td>BPS</td>
</tr>
</tbody>
</table>

IEEE P2800

IEEE P2800.1

• IEEE Std 1547-2018 ✓
• IEEE P1547.1
• UL 1741 (SA)
• IEEE ICAP

DER²

Work in Progress

¹ NERC definition of Bulk Electric System: ≥100 kV with gross individual / aggregate nameplate rating greater than 20 MVA / 75 MVA
² DER connected at typical (radial) primary and secondary voltage levels
Together…Shaping the Future of Electricity