14TD0543, Evaluating Wind and Solar Plants Harmonics Compliance

David Mueller
EnerNex
FERC Standard Interconnection Agreements and Procedures for Large Generators

Article 9. Operations (From Order No. 2003-C)

9.7 Outages and Interruptions.

9.7.6 Power Quality. Neither Party's facilities shall cause excessive voltage flicker nor introduce excessive distortion to the sinusoidal voltage or current waves as defined by ANSI Standard C84.1-1989, in accordance with IEEE Standard 519, or any applicable superseding electric industry standard. In the event of a conflict between ANSI Standard C84.1-1989, or any applicable superseding electric industry standard, ANSI Standard C84.1-1989, or the applicable superseding electric industry standard, shall control.
ANSI C84.1

• Electric Power Systems and Equipment - Voltage Ratings (60 Hertz)
  – ANSI C84.1 (1989)
  – ANSI C84.1 (2001)
  – ANSI C84.1 (2006)
  – ANSI C84.1 (2011)
IEEE 519

• IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems (1992)
• Draft new standard out for ballot (2014)
UK G5/4 Harmonics Standard

• G5/3 (1973)
• G5/4 (2001) “Planning levels for harmonic voltage distortion and the connection of non-linear equipment to transmission systems and distribution networks in the United Kingdom”
• G5/4-1 (2004)
• G5/5 (In progress)
• From the Nationalgrid’s (UK) Grid Code
  “...harmonic distortion on an Offshore Transmission System will be defined in relevant Bilateral Agreements”
Basic Philosophy of the IEEE 519 Voltage and Current Limits

• The customer is responsible for limiting harmonic currents injected onto the power system.
• The utility is responsible for maintaining quality of voltage waveform.
• In general it wasn’t written for renewable energy sources!
Meeting Harmonics Limits at Wind Plants

• Most interconnection agreements will reference one of the following standards:

• IEEE 1547 basically refers to the limits of IEEE 519

• IEEE 519 includes
  – Voltage Limits
  – Current Limits
# Harmonic Voltage Limits

## Harmonic Voltage Limits - Utility Responsibility

<table>
<thead>
<tr>
<th>Bus Voltage</th>
<th>Maximum Individual Harmonic Component (%)</th>
<th>Maximum THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>69 kV and below</td>
<td>3.0%</td>
<td>5.0%</td>
</tr>
<tr>
<td>115 kV to 161 kV</td>
<td>1.5%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Above 161 kV</td>
<td>1.0%</td>
<td>1.5%</td>
</tr>
</tbody>
</table>
Harmonic Current Limits

Harmonic Current Limits - Customer Responsibility

<table>
<thead>
<tr>
<th>SCR = I_{sc}/I_{L}</th>
<th>&lt;11</th>
<th>11&lt;h&lt;17</th>
<th>17&lt;h&lt;23</th>
<th>23&lt;h&lt;35</th>
<th>35&lt;h</th>
<th>TDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;20</td>
<td>4.0</td>
<td>2.0</td>
<td>1.5</td>
<td>0.6</td>
<td>0.3</td>
<td>5.0</td>
</tr>
<tr>
<td>20 - 50</td>
<td>7.0</td>
<td>3.5</td>
<td>2.5</td>
<td>1.0</td>
<td>0.5</td>
<td>8.0</td>
</tr>
<tr>
<td>50 - 100</td>
<td>10.0</td>
<td>4.5</td>
<td>4.0</td>
<td>1.5</td>
<td>0.7</td>
<td>12.0</td>
</tr>
<tr>
<td>100 - 1000</td>
<td>12.0</td>
<td>5.5</td>
<td>5.0</td>
<td>2.0</td>
<td>1.0</td>
<td>15.0</td>
</tr>
<tr>
<td>&gt;1000</td>
<td>15.0</td>
<td>7.0</td>
<td>6.0</td>
<td>2.5</td>
<td>1.4</td>
<td>20.0</td>
</tr>
</tbody>
</table>

Values shown are in percent of “average maximum demand load current”
SCR = short circuit ratio (utility short circuit current at point of common coupling divided by customer average maximum demand load current)
TDD = Total Demand Distortion (uses maximum demand load current as the base, rather than the fundamental current)
Harmonic Compliance at a 345kV Connection
Monitoring at the PCC
IEEE 519 Voltage Distortion Limits

- **Table 11-1**
- The limits are applied on a statistical basis ("must be met 95% of the time")

<table>
<thead>
<tr>
<th>Bus Voltage</th>
<th>Maximum Individual Harmonic Component</th>
<th>Maximum THD</th>
</tr>
</thead>
<tbody>
<tr>
<td>69 kV and below</td>
<td>3%</td>
<td>5%</td>
</tr>
<tr>
<td>115 kV to 161kV</td>
<td>1.5%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Above 161kV</td>
<td>1.0%</td>
<td>1.5%</td>
</tr>
</tbody>
</table>
Total Harmonic Voltage Distortion (THDv)

Limit = 1.5 %
Histogram of THDv

- The CP 95% (cumulative probability) value meets the limits!
5th Harmonic Voltage Distortion

From 12/8/2008 8:30:00 AM to 6/14/2009

Limit = 1.0 %
Histogram of $V_{5\%}$

- The individual frequency limit for the 5th harmonic does not meet the limit.
- This will be common for utility transmission limits, with or without wind turbines.
IEEE 519 Harmonic Current Limits

- IEEE 519 Table 10-4
- The limits are applied on a statistical basis ("must be met 95% of the time")

<table>
<thead>
<tr>
<th>Short Circuit Ratio</th>
<th>Individual Harmonic Limits (Odd Harmonics)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 11</td>
<td>11 ≤ h &lt; 17</td>
</tr>
<tr>
<td>I_{SC}/I_L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;20*</td>
<td>2.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Even harmonics are limited to 25% of the odd harmonic limits above.

* All power generation equipment is limited to these values of current distortion, regardless of actual short circuit ratio.

Where

\[ I_L = \text{Maximum demand load current at PCC} \]
Statistical Distribution of 345kV Current

“Relative Probability”

“Cumulative Probability”

From 12/8/2008 8:30:00 AM to 6/14/2009

RP

CP

Electrotek/EPRI

Count 96408
Min 0.1644
Avg 40.79
Max 191.30
Range 191.14
St Dev 44.82
Avg +3 St Dev 175.26
Avg -3 St Dev -93.67
CP01 0.2044
CP05 5.075
CP25 8.598
CP50 18.13
CP75 65.22
CP95 140.94
CP99 171.94
SI Range 28.31

RP CP

Avg[I RMS A] (A), Avg[I RMS B] (A), Avg[I RMS C] (A)

PQView®
Harmonic Current Limits
(Primary Amperes)

<table>
<thead>
<tr>
<th>Primary Current IL</th>
<th>MVA</th>
<th>kV</th>
<th>Amps</th>
</tr>
</thead>
<tbody>
<tr>
<td>102.8</td>
<td>345</td>
<td>172.0</td>
<td></td>
</tr>
</tbody>
</table>

IEEE 519 (1992) Table 10-5 -- Current Distortion Limits for General Transmission Systems

<table>
<thead>
<tr>
<th>&gt;161kV</th>
<th>&lt;11</th>
<th>11=&lt;h&lt;17</th>
<th>17=&lt;h&lt;23</th>
<th>23=&lt;h&lt;35</th>
<th>35=&lt;h</th>
<th>TDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limits (Percent)</td>
<td>2.0%</td>
<td>1.0%</td>
<td>0.75%</td>
<td>0.3%</td>
<td>0.15%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Limits (Primary Current Amps)</td>
<td>3.4</td>
<td>1.7</td>
<td>1.3</td>
<td>0.5</td>
<td>0.3</td>
<td>4.3</td>
</tr>
</tbody>
</table>
Total Harmonic Current Trend

From 12/8/2008 8:30:00 AM to 6/14/2009

Limit = 4.3 A
5th Harmonic Current Trend

From 12/8/2008 8:30:00 AM to 6/14/2009

Limit = 3.4 A
<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Limit</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>CP95%</td>
</tr>
<tr>
<td>THD</td>
<td>1.5</td>
<td>1.42</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>0.01</td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
<td>0.16</td>
</tr>
<tr>
<td>4</td>
<td>1.0</td>
<td>0.01</td>
</tr>
<tr>
<td>5</td>
<td>1.0</td>
<td>1.33</td>
</tr>
<tr>
<td>6</td>
<td>1.0</td>
<td>0.01</td>
</tr>
<tr>
<td>7</td>
<td>1.0</td>
<td>0.65</td>
</tr>
<tr>
<td>11</td>
<td>1.0</td>
<td>0.14</td>
</tr>
<tr>
<td>13</td>
<td>1.0</td>
<td>0.06</td>
</tr>
<tr>
<td>23</td>
<td>1.0</td>
<td>0.04</td>
</tr>
<tr>
<td>24</td>
<td>1.0</td>
<td>0.04</td>
</tr>
<tr>
<td>25</td>
<td>1.0</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Harmonic Current Summary

Statistical Summary of Current TDD and Harmonics

- CP05
- Average
- CP95

TDD and Individual Harmonics

Current (A)

TDD

1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0

PQView®

IEEE PES

Power & Energy Society®
<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Limit (A)</th>
<th>Measured Limit CP95% (A)</th>
<th>TDD</th>
<th>Pass/Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.85</td>
<td>0.19</td>
<td>4.3</td>
<td>Pass</td>
</tr>
<tr>
<td>3</td>
<td>3.40</td>
<td>0.4</td>
<td></td>
<td>Pass</td>
</tr>
<tr>
<td>4</td>
<td>0.85</td>
<td>0.06</td>
<td></td>
<td>Pass</td>
</tr>
<tr>
<td>5</td>
<td>3.40</td>
<td>0.64</td>
<td></td>
<td>Pass</td>
</tr>
<tr>
<td>6</td>
<td>0.85</td>
<td>0.07</td>
<td></td>
<td>Pass</td>
</tr>
<tr>
<td>7</td>
<td>3.40</td>
<td>1.28</td>
<td></td>
<td>Pass</td>
</tr>
<tr>
<td>11</td>
<td>1.70</td>
<td>0.19</td>
<td></td>
<td>Pass</td>
</tr>
<tr>
<td>13</td>
<td>1.70</td>
<td>0.37</td>
<td></td>
<td>Pass</td>
</tr>
<tr>
<td>23</td>
<td>0.50</td>
<td>0.14</td>
<td></td>
<td>Pass</td>
</tr>
<tr>
<td>24</td>
<td>0.13</td>
<td>0.14</td>
<td></td>
<td>Fail</td>
</tr>
<tr>
<td>25</td>
<td>0.50</td>
<td>0.07</td>
<td></td>
<td>Pass</td>
</tr>
</tbody>
</table>
IEEE 519 Evaluation Conclusions

- The Wind Plant meets the harmonic current limits of IEEE 519, with the exception of the 24th harmonic current that slightly exceeds the limits. The small amount of 24th harmonic current should not present any practical concern.

- The total harmonic voltage distortion meets the IEEE 519 limits. However, the 5th harmonic voltage distortion exceeds the IEEE-519 single frequency limit of 1.0%, with the CP95% value of 1.33%.

- The harmonic voltage limits of IEEE 519 are extremely conservative, and it is not unusual for transmission systems to exceed those limits, particularly at the 5th harmonic voltage. The voltage distortion should not be expected to cause any practical problems, but the conditions deserve some further monitoring.
Turbine Controls Resonance Interactions
Interharmonics

• Based on 200 msec windows

IEC 61000-4-30 Subgroups
Another Example of Controls Interaction with Resonance Conditions at a Wind Plant
Third Example: Interharmonic Voltages at a Wind Plant
New IEEE 519 (2014 ?)

• IEEE 519 was due to be “administratively withdrawn”, but it was extended to the end of 2012 to allow extra time for the new draft standard to be balloted and approved.

• As of the Joint Technical Committee Meeting in New Orleans, in January 2014
  – Currently on the third round of balloting to resolve minor technical editing issues.
  – Expected to be approved “soon”
Proposed Revisions to IEEE 519

• Draft versions remove much of the tutorial information, and is mostly concerned with the limits.
• Introduces a new Vthd < 8% limit for LV systems.
• Introduces a section with limits on subharmonics and interharmonics.
• Improves procedures for compliance monitoring.
• Proposes very stringent harmonic current limits for wind and solar plants connected above 161 kV
IEEE 519 Draft

- Improved compliance measurement guidelines:

The limits in this sub-clause apply to users connected to systems where the rated voltage at the PCC is 120 V to 69 kV. At the PCC, users should limit their harmonic currents as follows:

- Daily 99\textsuperscript{th} percentile very short time (3 s) harmonic currents should be less than 2.0 times the values given in Table A-2.

- Weekly 99\textsuperscript{th} percentile short time (10 min) harmonic currents should be less than 1.5 times the values given in Table A-2.

- Weekly 95\textsuperscript{th} percentile short time (10 min) harmonic currents should be less than the values given in Table A-2.
IEEE 519 Draft

• Revised Voltage Distortion Limits

<table>
<thead>
<tr>
<th>Bus Voltage V at PCC</th>
<th>Individual Harmonic (%)</th>
<th>Total Harmonic Distortion THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V ≤ 1.0 kV</td>
<td>5.0</td>
<td>8.0</td>
</tr>
<tr>
<td>1 kV &lt; V ≤ 69 kV</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>69 kV &lt; V ≤ 161 kV</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>161 kV &lt; V</td>
<td>1.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

NOTE: High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.
IEEE 519 (Draft Revision)

Table 5-4 – Current Distortion Limits for Systems Rated > 161 kV

<table>
<thead>
<tr>
<th>I_{sc}/I_L</th>
<th>&lt;11</th>
<th>11 \leq h &lt; 17</th>
<th>17 \leq h &lt; 23</th>
<th>23 \leq h &lt; 35</th>
<th>35 \leq h</th>
<th>TDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;25*</td>
<td>1.0</td>
<td>0.5</td>
<td>0.38</td>
<td>0.15</td>
<td>0.1</td>
<td>1.5</td>
</tr>
<tr>
<td>25&lt;50</td>
<td>2.0</td>
<td>1.0</td>
<td>0.75</td>
<td>0.3</td>
<td>0.15</td>
<td>2.5</td>
</tr>
<tr>
<td>\geq50</td>
<td>3.0</td>
<td>1.5</td>
<td>1.15</td>
<td>0.45</td>
<td>0.22</td>
<td>3.75</td>
</tr>
</tbody>
</table>

Even harmonics are limited to 25% of the odd harmonic limits above.

Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

*All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L

Where

\( I_{sc} \) = maximum short-circuit current at PCC.
\( I_L \) = maximum demand load current (fundamental frequency component) at PCC under normal load operating conditions.
Summary

• In general, wind turbines and solar inverters are very slight sources of harmonics.
• Resonance, caused from the extensive underground cabling or capacitor banks, is the main concern in large plants.
• The worst problems have been caused by controls interactions with the grid resonant frequency.
• The IEEE 519 recommended guidelines are very restrictive. I recommend that they are used to resolve serious harmonic issues, and not to create petty problems. 😊😊
Thank You!

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