Challenges for Distribution Feeder Voltage Regulation with Increasing Amounts of PV

April 19, 2012
EPRI-NREL-SEPA
Overview

• A Common Issue – Voltage Rise and Voltage Fluctuation on Various Circuits
• Utility Efforts to Accommodate PV
• Three Critical Areas for Higher Penetration Solutions
Pepco Holdings, Inc.
3 states and Washington DC in mid-Atlantic US

648 sq mi (575 in MD)
782,000 cust (528,000 in MD)
4 and 13kV distribution

5,400 sq mi (3,500 in MD)
498,000 cust (199,000 in MD)
4, 12, 25 and 34kV distribution

2,700 sq mi
546,000 cust
4, 12, 23, and 34kV distribution
Active NEM PV MWS By Year

As Of: 3/1/2012

ACE
72.3 MW

DPL
17.5 MW

PEPCO
14.0 MW

TOTAL
103.8 MW
Pending Solar PV NEM (MWS)

PHI Pending NEM PV Generation (MW) By Application Year

As Of: 3/1/2012

ACE
77.5 MW

DPL
16.0 MW

Pepco
2.3 MW

TOTAL
95.8 MW
Solar PV on Express Feeders
Solar PV on Radial Load Serving Feeders
Small Solar – 250 kW or less
Substation Bus Voltage Regulation and Impact of VAR Fluctuation

When the PV stops producing power and absorbing VARs, voltage rises by 2%
Substation Bus Voltage Regulation

- Where there are load serving feeders and an express feeder from a PV site, they both have conflicting interests in the bus voltage – the express feeder tends to have voltage rise out to the large generator and would prefer a lower bus voltage, while the other feeders have voltage decrease over distance as they server load and would need a higher bus voltage.

- Pictured is another issue, when there can be var flow reversals at the substation bus, especially at low load, the voltage of the bus may change discreetly by a significant amount -- ~2.4 volts on a 120V base for the scenario pictured.
Potential Voltage Rise and Fluctuations

- Simulated Voltage Levels for 18 MW PV System (on 120V base)
  - System Off 124.0
  - 0.97 Leading PF 125.9  \(\leftarrow\) setting
  - Unity PF 126.8
  - 0.97 Lagging PF 127.4

- State Reqt: 115.2 – 124.8 V (+/- 4%)
- Feeder Voltage: 12,470 V phase to phase
- Injection to Substation: 9MWs each on 2 feeders
- Substation has 2 other load carrying feeders
Harmonic Issue – Inverter Tripping

● 10 MW Solar System
● Resonant with utility system
● Several times per day it caused some over voltages and unexpected tripping
● Capacitance was added to the inverters to resolve the situation
Impacts to a Distribution Feeder

**Typical Distribution Feeder**

- **Impact severity depends on:**
  - Electrical characteristics looking back into the ACE electric system from the location of the DG
  - Daily load profiles throughout the year
  - Maximum output of DG
  - Substation transformer settings
  - Location and settings of regulators, capacitors, and reclosers

adapted from actual DG customer application
Plot of Feeder Voltage over Distance
Feeder Voltage Regulation

- This feeder is quite long and has 3 sets of voltage regulators besides the voltage regulation of the Load Tap Changer at the substation power transformer.

- Because this is from a load flow, it doesn’t show the minimum or maximum each voltage rise could be – the voltage regulator typically has a bandwidth of 2 volts so where we see 124V it could be 123 to 125V (state voltage reqt is +/-4% instead of +/-5%)

- Notice that because the loading on each phase differs, the voltages are also different – single phase inverter concentrations on different phases can impact these excursions.

- The case we see is peak and the voltage regulators are placed to keep feeder voltage in the required range.
# Voltage Drops (%) @ Peak, Minimum Load & with PV

<table>
<thead>
<tr>
<th></th>
<th>Approximate at PEAK LOAD</th>
<th>Approximate at MINIMUM LOAD</th>
<th>With PV Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Across Line Transformer</td>
<td>- 0.5 – 2%</td>
<td>Negligible</td>
<td>+ 0.3 – 1.3%</td>
</tr>
<tr>
<td>On Secondary</td>
<td>- 0.5 – 1.5%</td>
<td>Negligible</td>
<td>+ 0.2 – 1%</td>
</tr>
<tr>
<td>On Service Drop</td>
<td>- 1 – 1.5%</td>
<td>Negligible</td>
<td>+ 0.5 – 1%</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>- 2.0 – 5.0%</td>
<td>Negligible</td>
<td>+ 1 – 3.3%</td>
</tr>
</tbody>
</table>
Voltage at the Meter

- ANSI 84.1 Guideline: Nominal +/- 5%

- If the voltage delivered to the meter is 126V or +5% over 120V nominal at low load to insure adequate voltage at peak load:
  - As soon as generation output exceeds the load of the premise, the voltage at the meter will begin to rise – and will exceed the ANSI guideline
  - Export is almost guaranteed because solar has such a low capacity factor, it needs to be sized quite large to net out the annual energy use
  - This can be a bigger problem for more than 1 home feeding into the same transformer or for community energy
Voltage on a Radial Feeder

- Voltage declines over distance and based on load level. Utilities must keep voltage in the limits at minimum and peak loading.

- The smaller the bandwidth a utility maintains for voltage, the closer the voltage regulation or switched capacitor banks must be to each other – more must be used at a higher cost.

- So what is the bandwidth w/o solar and with solar:
  - w/o: At peak. If we can have 5.0% voltage drop between line and meter, that would mean the line must be kept to 119 or 120V to insure the customer receives the minimum of 114V.
  - Since the line can have a 5% voltage drop, between voltage regulation points, it needs to start at 125-126V at regulation points and will decrease to 119V at some distance.
Voltage on a Radial Feeder (cont.)

- Bandwidth with Solar:
  - Voltage on the Feeder Main would need to be the same to accommodate peak load conditions - except higher voltages could be expected on long laterals with reverse flow. Underground cable areas are also vulnerable to high voltage.

- For shorter, “stiffer” feeders with less voltage drop, feeder voltage may not need to be 125-126V at Voltage Regulation devices (feeder voltage bandwidth can be smaller) but for longer rural feeders, it is common use the whole 5% drop as the feeder covers long distances.
Voltage on a Radial Feeder (cont.)

- At the premise: If the premise exports the maximum amount and is connected at a location near a voltage regulator, voltage could be $126 +3.3\% = 130V$ at the meter.

- With very small solar systems the voltage rise would be far smaller. However with some larger systems, possibly from the Community Energy Concept or other virtual arrangements, we may see the higher amounts.

- Higher voltage at premises will have the opposite effect as CVR (Conservation Voltage Reduction), sought by some state PSCs to reduce energy consumption

- SUMMARY – Using +/- 5% Voltage bandwidth at the meter (or less), and up to 5% voltage drop on line transformer, secondary and service, it is a real challenge to accommodate PV
**Hrs/yr where system/feeder is at minimum load and max PV output**

### SUMMARY TABLE: FREQUENCY OF SYSTEM LOADS THAT ARE <= TO A GIVEN PERCENTAGE OF THE SYSTEM PEAK

<table>
<thead>
<tr>
<th>YEAR</th>
<th>SYSTEM PEAK (MW)</th>
<th>35%</th>
<th>40%</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
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<tr>
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<td>10AM - 2PM</td>
<td>7.8%</td>
<td>47.5%</td>
<td>75.2%</td>
<td>87.5%</td>
<td>94.7%</td>
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<tr>
<td></td>
<td>All Hrs</td>
<td>1.6%</td>
<td>9.9%</td>
<td>15.7%</td>
<td>18.2%</td>
<td>19.7%</td>
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</table>

### SUMMARY TABLE: FREQUENCY OF FEEDER LOADS THAT ARE <= TO A GIVEN PERCENTAGE OF THE FEEDER PEAK

<table>
<thead>
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<th>SYSTEM PEAK (MW)</th>
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<td>27</td>
<td>35</td>
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<tr>
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<td>10AM - 2PM</td>
<td>1.5%</td>
<td>7.6%</td>
<td>53.1%</td>
<td>76.8%</td>
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<td>All Hrs</td>
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<td>1.6%</td>
<td>11.1%</td>
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**Hrs/yr where feeder is at minimum load and max PV output**

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</table>
1.9 MW PV System (Feeder Nominal Voltage: 12,470V)

Voltage on 120V base

- Steady State: 125.3
- Fluctuation: at POI: 2.3
- Fluctuation at Voltage Regulator: 1.0
Overvoltage at the Inverter

Source: EPRI Monitoring
Voltage Rise

Electrical Diagram
Solar System
19.4 kW DC
17.1 kW AC
240 V Base

- Outdoor 100 Amp Load Center
- With 6 – 15 Amp 240 VAC breakers for solar and 1 – 20 Amp 120 VAC breaker for outlet
- 2 – 2/0 Al
- 1 – 1/0 Neutral
- 1 – #2 Al Ground
- 100 Amp Breaker
- Disconnect
- Meter
- Junction Box
- House Breaker Panel
- 200 Amp
- Enphase Envoy
- Ground and Surge Protector
- 90 – 215 Watt Panels
- 90 – 190 Watt Microinverters
- #8 Ground to each panel and inverter
- 240 VAC
- 2 – 4/0 Al
- 1 – 4/0 Neutral/Ground
- 73 Amp Max
- 240 V Base
- 200'
- 12/3 and #6 Cu Ground
- 240 VAC
- 2 – 4/0 Al
- 1 – 4/0 Neutral/Ground
- +0.96 Volts
  0.4%
- 12/3 and #6 Cu Ground
- +3.96 Volts
  1.7%
- 90 – 215 Watt Panels
- 90 – 190 Watt Microinverters
- #8 Ground to each panel and inverter
- Ground and Surge Protector
- 240 VAC
- 200'
- 175'
- +2.64 Volts
  1.7%
- 240 VAC
- 2 – 4/0 Al
- 1 – 4/0 Neutral/Ground
- +4.08 Volts
  1.7%
- 240 VAC
- 2 – 4/0 Al
- 1 – 4/0 Neutral/Ground
- 200'
- +0.96 Volts
  0.4%
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- 240 VAC
- 2 – 4/0 Al
- 1 – 4/0 Neutral/Ground
- +4.08 Volts
  1.7%
Voltage Rise Chart
(at max gen and no load)

Nominal Voltages: 120V or 240V
Max Voltage at Meter: 126V or 252V (per ANSI)

<table>
<thead>
<tr>
<th>Electrical Segment</th>
<th>Voltage Rise @ 120V</th>
<th>Voltage Rise @ 240V</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microinverter String to End</td>
<td>2.0</td>
<td>4.0</td>
<td>1.7</td>
</tr>
<tr>
<td>Connection to PV Breaker Panel</td>
<td>0.5</td>
<td>1.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Line to PV Disconnect (2/0 Al)</td>
<td>2.0</td>
<td>4.0</td>
<td>1.7</td>
</tr>
<tr>
<td><strong>Sub-total</strong></td>
<td><strong>4.5</strong></td>
<td><strong>9.0</strong></td>
<td><strong>3.8</strong></td>
</tr>
<tr>
<td>Service Drop</td>
<td>1.3</td>
<td>2.6</td>
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<tr>
<td>Line Transformer</td>
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<td>0.6</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>6.6</strong></td>
<td><strong>13.2</strong></td>
<td><strong>5.5</strong></td>
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</tbody>
</table>

Note: The microinverter voltage measurement accuracy is +/- 2.5%
Power vs. Time

Solar Output

Net at Line Transformer

House Load

Turned PV System Off
Voltage vs. Time

Difference between blue and yellow line is voltage difference between Line Trans. and Generator

Substation transformer adjusting voltage
Voltage Drop vs. House Load
Unity Power Factor

Change in Voltage (120 volt base)

House Load (kW)
Voltage Regulation Issues/Thoughts

● There are several directions utilities are generally headed: CVR (Conservation Voltage Reduction), IVVC (Integrated Volt/Var Control) – what is needed is a strategy and general voltage guidelines that will lay the ground work for smart inverters to participate, as well as work with the reasons CVR and IVVC are being implemented – especially if we are to create a national standard for how inverters are to do autonomous control.

● The above needs to consider rural long feeders as well as short stiff feeders generally found in urban locations. It also needs to envision different paths that utilities are taking to upgrade or implement “Smart Grid” solutions
Voltage Regulation Issues/Thoughts (cont.)

- The ANSI voltage bandwidth of +/- 5% may need to be revisited. Germany appears to use +/- 10%.

- Going to a flatter feeder voltage is nice, but can be costly because it may add many more voltage regulation zones to the feeder. Need guidelines where to possibly use a regulating transformer.

- It has been difficult for utilities to quantify and mitigate extra operations of voltage regulators and switched caps due to PV but this needs to be taken into consideration.

- Smart Load Control options also need to be considered as part of the voltage regulation solution.
# Smart Energy

## Smart Grid
- ISO (Independent Sys. Operator)
  - Bulk Generation
  - Bulk Transmission
    - Synchrophasors
- LDC (Local Distribution Co.)
  - Transmission
  - Substation
    - Power Transformers
  - Feeders
    - Distributed Automation
    - Conductors, ALE
    - Line Transformers
    - Advanced Fdr Mgmt
- AMI
  - Outage Mgmt
  - Load Profile Info
  - HAN (Home Area Network)
    - Price and other comm.

## Smart Inverter
- Low Voltage Ride Thru
- Ramp Rate Control
- Autonomous & Centralized Control
  - VAR/PF Control
    - Fixed/Dynamic
    - Algorithm based
  - Curtailment
  - Remote Trip
- With Battery
  - Premium Power
  - Voltage Control
  - Frequency Regulation
  - Spinning Reserve
  - Arbitrage (TOU or Real Time Pricing)
  - Demand Side Mgmt
  - Pk Demand Mgmt.

## Smart Premise
- HEMS (Home Energy Mgmt System)
  - Pricing Signal Response
  - Peak Load Control
- DER (Distributed Energy Resource)
- Smart Thermostat
- Smart Appliances
- Smart HVAC
  - Thermal Storage
- EV
  - Controllable Charging
- Remote Access and Control
- Energy Efficiency Controls
  - Turn off Phantom Loads
  - Vacant space mgmt.
- Direct Use of DC

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Pepco Holdings, Inc.
Steve Steffel, PE
Mgr, Distributed Energy Resources Planning and Analytics

Steve.Steffel@pepcoholdings.com

Thank You!