Operating beyond PV curves

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with contributions by

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Main messages

• Impact of optimal voltage dispatch in today’s practice:
  - PV curves better with voltage dispatch since maximum power transfer always higher
  - DC OPF accounts for voltage with PV curve limits; more efficient with voltage dispatch
  - Region-to-region PV curves in large systems “similar” to point-to-point PV curves

• Recommended future practice—Beyond PV curves (**the issue: selection of interface limits**)
  - Use AC OPF for the entire system without observing net interface limits; much more efficient with voltage dispatch
  - AC OPF enables both economic and physical efficiency

• Demonstration of extended AC OPF with voltage dispatch for systems up to 30,000 buses

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Study systems

• IEEE 14 bus
• ERCOT planning case from August 2013 (6,355 buses)
• PJM operations case from November 2012 (13,940 buses)
• PJM planning case (34,171 buses obtained by truncating half of PJM FERC 715)
IEEE 14 bus system
Set up for PV curve –IEEE 14 bus system

• Maximizing transfer from
  – Generator at bus 2 to load at bus 14
  – Bus 1 is slack
• PV curve is generated
  – Through incremental increase of load at bus 14 by 10% at each step (both P and Q of the load are scaled)
  – While real power output of generator at bus 2 is increased by the same amount (10% of Pl at bus 14) at each time step
• Voltage collapse happens when no feasible AC power flow solution is found
Constraints

- Thermal AC line limits are ignored
- Thermal transformer limits are ignored
- Generation Q limits are both ignored or observed in different scenarios
- No limits on real and reactive power of the slack generator
Types of PV curves

• Power flow PV curve
  – All set points of generators are fixed (P and V) (*current practice*)
• PV curve with voltage optimization
  – Voltage set points of generators are optimized
• PV curve with optimization of real power
  – Real power outputs of generators are optimized
• PV curve with optimization of both voltage and real power
  – Real power outputs and voltage set points of generators are optimized
Creating PV Curve With Fixed Generator Voltages

Slack generation balances $P$ loses

Increase load by $\Delta P$

Increase generation by $\Delta P$

Minimum System Voltage

$\Delta P$
Creating PV Curve With **Variable** Generator Voltages

Slack generation balances P loses

Increase load by $\Delta P$

Increase generation by $\Delta P$

Minimum System Voltage

Varying $V_G$ over $V_{G_{Min}} \leq V_G \leq V_{G_{Max}}$ yields a feasible band.

Select the $V_G$ for each $\Delta P$ via optimization. For example, loss minimization will also tend to push the minimum system voltage higher and permit greater transfer.
Optimization Setup: All Fixed—Similar to current practice

- **Optimization objective:**
  - Loss minimization (feasible space is a single point)
  - Cost of all generators is $100/MWh

- **Constraints:**
  - Voltage magnitude limits are equal to
    - Generator set points at generator regulated buses
    - $V_{\text{min}}= 0.3\text{pu}$, $V_{\text{max}}=2\text{pu}$ at all other buses
  - Real power generation limits are equal to
    - Real power generated (except for slack)
  - Reactive power generation limits are
    - Observed/Ignored in two different scenarios
  - All AC and transformer thermal limits are ignored

- For each point on PV curve this optimization is executed after increasing source generation by $X$ MW and the sink load by $X$ MW
Optimization Setup: Vg variable

- Optimization objective:
  - Loss minimization (tends to raise receiving voltages)
  - Cost of all generators is $100/MWh
- Constraints:
  - Voltage magnitude limits are equal to
    - $V_{\text{min}}=0.9\text{pu}$ and $V_{\text{max}}=1.1\text{pu}$ at generator regulated buses
    - $V_{\text{min}}=0.3\text{pu}$, $V_{\text{max}}=2\text{pu}$ at all other buses
  - Real power generation limits are equal to
    - Real power generated (except for slack)
  - Reactive power generation limits are
    - Observed/Ignored in two different scenarios
  - All AC and transformer thermal limits are ignored
- For each point on PV curve this optimization is executed after increasing source generation by $X$ MW and the sink load by $X$ MW
Optimization Setup: Pg variable

• Optimization objective:
  – Loss minimization
  – Cost of all generators is $100/MWh

• Constraints:
  – Voltage magnitude limits are equal to
    • Generator set points at generator regulated buses
    • Vmin= 0.3pu, Vmax=2pu at all other buses
  – Real power generation limits are equal to
    • Originally specified real power generation limits
  – Reactive power generation limits are
    • Observed/Ignored in two different scenarios
  – All AC and transformer thermal limits are ignored

• For each point on PV curve this optimization is executed after increasing source generation by X MW and the sink load by X MW
Optimization Setup: Pg and Vg variable

• Optimization objective:
  – Loss minimization
  – Cost of all generators is $100/MWh

• Constraints:
  – Voltage magnitude limits are equal to
    • $V_{min}=0.9pu$ and $V_{max}=1.1pu$ at generator regulated buses
    • $V_{min}=0.3pu$, $V_{max}=2pu$ at all other buses
  – Real power generation limits are equal to
    • Originally specified real power generation limits
  – Reactive power generation limits are
    • Observed/Ignored in two different scenarios
  – All AC and transformer thermal limits are ignored

• For each point on PV curve this optimization is executed after increasing source generation by $X$ MW and the sink load by $X$ MW
IEEE 14 bus PV curves without Q limits
## IEEE 14 bus-Dependence of DC OPF efficiency on PV-curves

<table>
<thead>
<tr>
<th>Case</th>
<th>PV curve voltage dispatch</th>
<th>Int. Defn.</th>
<th>Voltages</th>
<th>PG 2 (MW); PL 14 (MW)</th>
<th>Line flows (MW)</th>
<th>Interface flow (MW)</th>
<th>DC OPF cost with PV curve ($/hour)</th>
<th>Power loss (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No</td>
<td>2-3; 2-4; 2-5; 1-5</td>
<td>VL,14 = .585; VG,1 = 1.06; VG,2 = 1.045; VG,3 = 1.01; VG,6 = 1.07; VG,8 = 1.09</td>
<td>PG,2 = .3999; QG,2 = 2.61; PL,14 = 1.356; QL,14 = .455</td>
<td>P2,1 = -3.91; P2,3 = .975; P2,4 = .984; P2,5 = .775</td>
<td>Pint,1 = .399</td>
<td>$7650</td>
<td>0 MW</td>
</tr>
<tr>
<td>2</td>
<td>No</td>
<td>14-13; 14-9</td>
<td>VL,14 = .585; VG,1 = 1.06; VG,2 = 1.045; VG,3 = 1.01; VG,6 = 1.07; VG,8 = 1.09</td>
<td>PG,2 = .3999; QG,2 = 2.61; PL,14 = 1.356; QL,14 = .455</td>
<td>P14,13 = -.58; P14-9 = -.775</td>
<td>Pint,2 = 1.356</td>
<td>$7650</td>
<td>0 MW</td>
</tr>
<tr>
<td>3</td>
<td>Yes</td>
<td>2-3; 2-4; 2-5; 1-5</td>
<td>VL,14 = .606; VG,1 = 1.10; VG,2 = 1.10; VG,3 = 1.09; VG,6 = 1.10; VG,8 = 1.10</td>
<td>PG,2 = .399; QG,2 = 2.848; PL,14 = 1.4485; QL,14 = .4860</td>
<td>P2,1 = -4.07; P2,3 = 1.016; P2,4 = 1.003; P2,5 = .788</td>
<td>Pint,1 = .399</td>
<td>$7650</td>
<td>0 MW</td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>14-13; 14-9</td>
<td>VL,14 = .606; VG,1 = 1.10; VG,2 = 1.10; VG,3 = 1.09; VG,6 = 1.10; VG,8 = 1.10</td>
<td>PG,2 = .399; QG,2 = 2.848; PL,14 = 1.4485; QL,14 = .4860</td>
<td>P14,13 = -.83; P14-9 = -.616</td>
<td>Pint,2 = 1.448</td>
<td>$7650</td>
<td>0 MW</td>
</tr>
</tbody>
</table>
New net load  (PL,14=1.40; QL,14=.5)

• Could happen either because of load increase or loss of (coal) plant
• Thermal limits of lines 1
• DC OPF not feasible with V=1
IEEE 14 bus-Dependence of DC OPF efficiency on PV-curves (new load at 14)

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<th>PV curve voltage dispatch</th>
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<td>P2,1=-3.91; P2,3=.975; P2,4=.984; P2,5=.775</td>
<td>Pint,1=.399</td>
<td>Fails</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>No</td>
<td>14-13; 14-9</td>
<td>VL,14=.585; VG,1=1.06; VG,2=1.045; VG,3=1.01; VG,6=1.07; VG,8=1.09</td>
<td>PG,2=.3999; QG,2=2.61; PL,14=1.356; QL,14=.455</td>
<td>P14,13=-.58; P14-9=-.775</td>
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<td>P14,13=-.83; P14-9=-.616</td>
<td>Pint,2=1.448</td>
<td>Fails</td>
<td></td>
</tr>
</tbody>
</table>
Beyond PV curves--New load can be served with AC OPF!!!

• Voltages found which make the delivery feasible
• No load shedding required
• Critical in the future when plants retire and new come on
• AC OPF makes the system feasible by adjusting voltages!!!
Economic efficiency comparison of DC OPF with PV curve line limits and AC OPF

• The case of initial load.
• Generation cost appears to be lower with DC OPF
• Misleading because there are marginal costs associated with voltage limits and reactive power balancing
• Without enforcing these, the system is not physically implementable
• AC OPF more efficient with voltage dispatch (easy to show): cost = $9911 with $V_g = 1.05$; cost = $8126$ with $V_g \leq 1.05$.
• Must have market for AC OPF
ERCOT PV CURVE SETUP
Optimization Setup: All Fixed

• Optimization objective:
  – Loss minimization
  – Cost of all generators is $100/MWh

• Constraints:
  – Voltage magnitude limits are equal to
    • Generator set points at generator regulated buses
    • Vmin= 0.3pu, Vmax=2pu at all other buses
  – Real power generation limits are equal to
    • Real power generated (except for slack buses: 5920, 6103, 86101, 110015)
  – Reactive power generation limits are observed
  – All AC and transformer thermal limits are ignored
    – All transformers and shunts are fixed

• For each point on PV curve this optimization is executed after increasing
  – source generation (wind in the west) by 200 MW proportional to capacity of each generator
  – the sink (NCEN) loads by 200 MW evenly across loads
Optimization Setup: Vg variable

- Optimization objective:
  - Loss minimization
  - Cost of all generators is $100/MWh
- Constraints:
  - Voltage magnitude limits are equal to
    - \( V_{\text{min}} = 0.95\text{pu} \) and \( V_{\text{max}} = 1.05\text{pu} \) at generator regulated buses
    - \( V_{\text{min}} = 0.3\text{pu} \), \( V_{\text{max}} = 2\text{pu} \) at all other buses
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    - Real power generated (except for slack buses: 5920, 6103, 86101, 110015)
  - Reactive power generation limits are observed
  - All AC and transformer thermal limits are ignored
  - All transformers and shunts are fixed
- For each point on PV curve this optimization is executed after increasing
  - source generation (wind in the west) by 200 MW proportional to capacity of each generator
  - the sink (NCEN) loads by 200 MW evenly across loads
Optimization Setup: Pg variable

• Optimization objective:
  – Loss minimization
  – Cost of all generators is $100/MWh

• Constraints:
  – Voltage magnitude limits are equal to
    • Generator set points at generator regulated buses
    • V_{\text{min}} = 0.3\text{pu}, V_{\text{max}} = 2\text{pu} at all other buses
  – Real power generation limits are equal to
    • Originally specified real power generation limits
  – Reactive power generation limits are observed
  – All AC and transformer thermal limits are ignored
  – All transformers and shunts are fixed

• For each point on PV curve this optimization is executed after increasing
  – source generation (wind in the west) by 200 MW distributed in proportion to capacity of each generator
  – the sink (NCEN) loads by 200 MW evenly across loads
Optimization Setup: Pg and Vg variable

• Optimization objective:
  – Loss minimization
  – Cost of all generators is $100/MWh

• Constraints:
  – Voltage magnitude limits are equal to
    • Vmin=0.95pu and Vmax=1.05pu at generator regulated buses
    • Vmin=0.3pu, Vmax=2pu at all other buses
  – Real power generation limits are equal to
    • Originally specified real power generation limits
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  – the sink (NCEN) loads by 200 MW evenly across loads
ERCOT PV curves with Qg limits
## PJM OPS case EAST Interface

<table>
<thead>
<tr>
<th>Case</th>
<th>PJM voltage limits</th>
<th>Generator Voltage dispatch</th>
<th>Contingency</th>
<th>Received load (MW)</th>
<th>Interface Flow (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>N/A</td>
<td></td>
<td>None</td>
<td>10,584 (+0)</td>
<td>1,309</td>
</tr>
<tr>
<td>1</td>
<td>Normal</td>
<td>Yes</td>
<td>None</td>
<td>16,766 (+6,182)</td>
<td>4,881</td>
</tr>
<tr>
<td>2</td>
<td>Emergency</td>
<td>Yes</td>
<td>None</td>
<td>17,626 (+7,042)</td>
<td>5,369</td>
</tr>
<tr>
<td>3</td>
<td>Emergency</td>
<td>Yes</td>
<td>ALBURTIS-JUANITA</td>
<td>17,368 (+6,784)</td>
<td>4,628</td>
</tr>
<tr>
<td>4</td>
<td>Emergency</td>
<td>Yes</td>
<td>ALBURTIS-WESCOSVI</td>
<td>17,617 (+7,035)</td>
<td>4,744</td>
</tr>
<tr>
<td>5</td>
<td>Emergency</td>
<td>Yes</td>
<td>PEACHBOT-LIMERICK</td>
<td>16,931 (+6,347)</td>
<td>3,645</td>
</tr>
<tr>
<td>6</td>
<td>Normal</td>
<td>No</td>
<td>None</td>
<td>11,467 (+883)</td>
<td>1,730</td>
</tr>
</tbody>
</table>
## Economic Dispatch for PJM

<table>
<thead>
<tr>
<th>Voltaages</th>
<th>Generation Cost [$]</th>
<th>Generator Revenue [$]</th>
<th>Load Charge [$]</th>
<th>Merchandise Surplus [$]</th>
<th>PJM Losses [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>2,560,232</td>
<td></td>
<td></td>
<td></td>
<td>1113</td>
</tr>
<tr>
<td>Fixed</td>
<td>2,455,262</td>
<td>4,587,644</td>
<td>3,656,729</td>
<td>-930,915</td>
<td>1105</td>
</tr>
<tr>
<td>Variable</td>
<td>2,292,642</td>
<td>3,512,257</td>
<td>3,242,615</td>
<td>-269,642</td>
<td>991</td>
</tr>
</tbody>
</table>

\[(2,455,262 - 2,292,642) \times 24 \times 365 \approx 1.4 \text{ B} \text{ value of voltage dispatch in PJM}\]

- PJM OPS case from 20 November 2010 at 10 AM
- Voltages maintained within normal operating limits
- Flows maintained within normal operating thermal limits
- Zonal LMPs within PJM used as the generation bids within the corresponding zones
  - LMPs taken from the corresponding date and time
  - $34.51 \$/MW-Hr \leq \text{Bid} \leq 48.15 \$/MW-Hr (approximately the fuel cost of coal)
Loss minimization for PJM

<table>
<thead>
<tr>
<th>PJM Voltages</th>
<th>Load [MW]</th>
<th>Loss [MW]</th>
<th>Loss/Load [%]</th>
<th>Savings [MW-Hr/Yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>62167</td>
<td>1113</td>
<td>1.79</td>
<td></td>
</tr>
<tr>
<td>Fixed</td>
<td>62167</td>
<td>1098</td>
<td>1.77</td>
<td>131400</td>
</tr>
<tr>
<td>Variable</td>
<td>62167</td>
<td>1047</td>
<td>1.68</td>
<td>578160</td>
</tr>
</tbody>
</table>

- PJM OPS case from 20 November 2010 at 10 AM
- Voltages maintained within normal operating limits
- Flows maintained within normal operating thermal limits
- PJM generator real power (and voltage) dispatched to minimize losses

PJM estimates that they save 220,000 MW-Hr/year for a savings of $17M.
## Interface Transfer Study Using PJM Planning Case

<table>
<thead>
<tr>
<th>Case</th>
<th>PJM VG</th>
<th>External VG</th>
<th>PJM Bus Voltage Limits</th>
<th>Total Sink Load [MW]</th>
<th>Increase [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>Fixed</td>
<td>Fixed</td>
<td>Not Used</td>
<td>23524</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>Fixed</td>
<td>Fixed</td>
<td>Not Used</td>
<td>23665</td>
<td>141</td>
</tr>
<tr>
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<td>Fixed</td>
<td>Variable</td>
<td>Not Used</td>
<td>23978</td>
<td>454</td>
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<tr>
<td>3</td>
<td>Variable</td>
<td>Fixed</td>
<td>Not Used</td>
<td>25444</td>
<td>1920</td>
</tr>
<tr>
<td>4</td>
<td>Variable</td>
<td>Fixed</td>
<td>Normal</td>
<td>24581</td>
<td>1057</td>
</tr>
<tr>
<td>5</td>
<td>Variable</td>
<td>Variable</td>
<td>Normal</td>
<td>27439</td>
<td>3915</td>
</tr>
</tbody>
</table>

- Study PJM EAST Interface
  - Optimization objective is to increase the net load in the receiving region
  - Power increase is supplied only by generators in the sending region
  - Examine importance of voltage dispatch; voltage limited only as specified
  - Thermal flow limits are ignored
- PJM (FERC-715) planning case for 2017 truncated to 34171 buses
Electricity Prices With Fixed VG in PJM

Prices in $ / 100 MW-Hr
Electricity Prices With Variable VG in PJM

Prices in $ / 100 MW-Hr
Conclusions

- Voltage dispatch plays major role in both physical delivery (feasibility and efficiency) and in economic efficiency
- Often variable voltage more valuable than line
- Prices less volatile with variable voltage dispatch
- Planning case closer to non-feasible condition than operations cases (higher loading conditions, less room for transfer increase)
- Market incentives are needed to reap benefits from voltage dispatch