NETSSWorks Software:
An Extended AC Optimal Power Flow (AC XOPF)
For Managing Available System Resources

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Outline

• Discuss the need for and use of AC XOPF software to manage the power system during operations and planning

• Summarize capabilities of AC XOPF

• Illustrate different voltage optimization options on a simple system (aligning models, physics and decision-making)

• Report experience with large system studies
  - System-wide optimization for normal operation and planning purposes
  -- Corrective actions for contingency management

• Q&A
The need for on-line system management

- Regularly adjust available resources (generation outputs, T&D equipment) as system conditions change (equipment status and/or demand)

- Instead of optimizing just real power dispatch, use all resources; we have shown this keeps the system more reliable and more efficient

- Corrective actions become routine

- Given the power systems complexity this requires software-enabled actions
AC Extended OPF (XOPF) Program

• An AC XOPF not specific to a single performance objective nor control choice could facilitate such system management (therefore, “extended” AC OPF).

• Must be computationally robust to support a variety of performance metrics and decision types.

• Should identify the key decision variables (controls) in the order of their importance for meeting system objectives. This overcomes the major implementation issue associated with AC OPF.

• Should non-iteratively (DC-AC-DC…) optimize the performance metrics of interest (efficiency, cost, reliability and/or emissions).
New features of an AC XOPF

• Should implement on-line partial load shedding and the optimized utilization of generation and T&D equipment.

• Must support voltage optimization to enable:
  – feasible steady-state operation which is difficult to find under some contingencies;
  – enhance power transfer capabilities; and,
  – enable important improvements to system security and reliability, and system efficiency.
Features of NETSS AC XOPF

• One optimization engine with many cost functions: OPF, OQF, OSF, OLD, MXV and OBF.

• Controls include: (1) real generator powers, (2) generator voltages, (3) transformer tap positions (ratio and phase angle), (4) switched-shunt susceptances, (5) DC line powers, and (6) adjustable loads. Each control may be adjusted or kept fixed.

• Provides sensitivities to identify critical controls.

• Can examine trade-offs between objective functions.
Optimizations:

- Optimize real/reactive/apparent power flow (OPF/OQF/OSF)
- Optimize load distribution (OLD)
- Manage extreme voltages (MXV)
- Optimal branch flows (OBF)

Constraints:

- Conserve real and reactive power at all buses
- Satisfy voltage limits at all buses
- Satisfy all real and reactive generation limits
- Satisfy all thermal limits for lines and transformers
- Satisfy all control limits (ratio and phase) for transformers
- Satisfy all control limits for switched shunts and adjustable loads
- Satisfy all control limits for DC lines

Outputs:

- Optimal generation, bus voltages and other controls
- System-wide power flow
- Sensitivities for all constraints
- Marginal price of electricity at all buses (OPF only)
Typical AC XOPF Uses

- Improving system efficiency during operation:
  - traditional economic dispatch and transmission loss minimization (OPF);
  - determine minimum necessary reactive power reserve (OQF);
  - optimize demand-side response (OLD);
  - maximize power transfer through interfaces (OBF)

- Planning studies:
  - import studies and determination of maximum power transfers (OLD);
  - loadability studies for buses and zones (OLD);
  - identify system weaknesses and locate new or improved equipment using sensitivities; assess the economic value of new equipment (All);
  - evaluating the effectiveness of new equipment (All).

- Improving system reliability:
  - make an infeasible system feasible (All);
  - determine operating practices that meet all system constraints (All);
  - maximizing voltage security by minimizing deviations from unity (MXV);
  - look for voltage problems or minimize voltage outliers (MXV);
  - determine realistic safety margins (All);
  - load shedding to arrest evolving blackouts (OLD).
Optimization effects on loadability— an example using NETSSWorks

• Often difficult to relate the results of optimization with the physical constraints and, ultimately, with a quantitative decision making using software results

• In this example we show how NETSSWorks can be used to assess the worst constraints, the locations for improvements and the quantifiable performance enhancements

• Illustration for maximizing load that can be served
• Demo showing other performance objectives
Example System – Loadability Optimization

Generators (|V| = 1 and Unlimited P & Q)

0.95 \leq |V| \leq 1.05

Otherwise

Scalable Load (P:Q = 5)

& Variable Shunt
Original Optimization – Bus Voltage Sensitivities

\[ |V| = 1.000 \]
\[ \lambda_V = -12.7 \]

\[ |V| = 0.992 \]
\[ \lambda_V = 0 \]

Load = 2.217 \times 44 \text{ MW}

\[ |V| = 0.986 \]
\[ \lambda_V = 0 \]

\[ |V| = 0.966 \]
\[ \lambda_V = 0 \]

\[ |V| = 0.950 \]
\[ \lambda_V = 35.6 \]
## Optimization With Generator Voltage Dispatch

During optimization, $|V| \equiv 1.0$ or $0.95 \leq |V| \leq 1.05$. Bus voltage is as chosen during optimization.

<table>
<thead>
<tr>
<th>$V_{10000}$</th>
<th>$V_{60000}$</th>
<th>Load Scale</th>
<th>Load [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>1.00</td>
<td>2.217</td>
<td>44</td>
</tr>
<tr>
<td>1.05</td>
<td>1.00</td>
<td>2.834</td>
<td>57</td>
</tr>
<tr>
<td>1.00</td>
<td>1.05</td>
<td>3.419</td>
<td>68</td>
</tr>
<tr>
<td>1.05</td>
<td>1.05</td>
<td>3.976</td>
<td>80</td>
</tr>
</tbody>
</table>
Original Optimization – Bus Q-Balance Sensitivities

\[ \lambda_Q = 0 \]

\[ \lambda_Q = -1.28 \]

\[ \lambda_Q = -2.58 \]

\[ \lambda_Q = -6.53 \]

\[ \lambda_Q = -10.53 \]

Load = 2.217 x 44 MW
During optimization, shunt Q is unlimited. Shunt Q is as chosen during optimization.

<table>
<thead>
<tr>
<th>$Q_{30000}$ [MVAR]</th>
<th>$Q_{50000}$ [MVAR]</th>
<th>Load Scale</th>
<th>Load [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>2.217</td>
<td>44</td>
</tr>
<tr>
<td>-154</td>
<td>0</td>
<td>5.302</td>
<td>106</td>
</tr>
<tr>
<td>0</td>
<td>-236</td>
<td>13.433</td>
<td>269</td>
</tr>
<tr>
<td>-385</td>
<td>-340</td>
<td>20.042</td>
<td>401</td>
</tr>
</tbody>
</table>
Load = 2.217 x
= 44 MW

\[ R = 1.000 \]
\[ \lambda_R = -24.8 \]

\[ R = 1.000 \]
\[ \lambda_R = 35.5 \]
During optimization, $R \equiv 1.0$ or $0.8 \leq R \leq 1.2$. Transformer R is as chosen during optimization.

<table>
<thead>
<tr>
<th>$R_{30000-6000}$</th>
<th>$R_{40000-5000}$</th>
<th>Load Scale</th>
<th>Load [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.000</td>
<td>1.000</td>
<td>2.217</td>
<td>44</td>
</tr>
<tr>
<td>1.190</td>
<td>1.000</td>
<td>5.302</td>
<td>106</td>
</tr>
<tr>
<td>1.000</td>
<td>0.886</td>
<td>3.087</td>
<td>62</td>
</tr>
<tr>
<td>1.200</td>
<td>0.860</td>
<td>7.089</td>
<td>142</td>
</tr>
</tbody>
</table>
Experience with Large Scale Systems

<table>
<thead>
<tr>
<th>System</th>
<th>Buses</th>
<th>Generator Buses</th>
<th>AC Lines</th>
<th>Xformers</th>
<th>DC Lines</th>
<th>Switched Shunts</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>303</td>
<td>53</td>
<td>359</td>
<td>85</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>II</td>
<td>1447</td>
<td>348</td>
<td>2352</td>
<td>507</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>III</td>
<td>5249</td>
<td>531</td>
<td>4301</td>
<td>1943</td>
<td>2</td>
<td>320</td>
</tr>
<tr>
<td>IV-EMS</td>
<td>2003</td>
<td>371</td>
<td>1921</td>
<td>877</td>
<td>0</td>
<td>31</td>
</tr>
<tr>
<td>IV-OPS</td>
<td>7678</td>
<td>761</td>
<td>6505</td>
<td>3221</td>
<td>0</td>
<td>472</td>
</tr>
</tbody>
</table>

- The system characteristics are measured after the reduction of breakers. Only variable switched shunts are listed.

- Typical starting “solved” power flow case always has voltages outside the acceptable limits. This is not physically implementable, but it is a direct result of power flow runs which do not observe voltage limits. Also, sometimes the real power generation is outside the acceptable limits, as power flow does not check for this.
• Employ an optimization that quadratically penalizes voltages outside the range of 0.95-1.05 puV.

• Consider normal operating conditions.

• First, examine what can be accomplished through real power dispatch alone.

• Next, examine what can be accomplished by varying all available controls: generator voltages and real power, and transformer settings.

• Finally, examine what can be accomplished with additional equipment such as controllable shunts. This is a planning exercise, but could ultimately be used for operations.
Voltage security under normal conditions. Controls include generator voltages and real power, and transformer settings.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Solution</th>
<th>Controls</th>
<th>Outliers</th>
<th>Worst-Case Outliers (Min, Max) [puV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>Original</td>
<td>Original.</td>
<td>318</td>
<td>0.891, 1.152</td>
</tr>
<tr>
<td>A</td>
<td>NETSS</td>
<td>Fixed except for real power generation.</td>
<td>65</td>
<td>0.907, 1.096</td>
</tr>
<tr>
<td>B</td>
<td>NETSS</td>
<td>Variable.</td>
<td>38</td>
<td>0.917, 1.069</td>
</tr>
<tr>
<td>C</td>
<td>NETSS</td>
<td>Same as Run B with 240 and 15 MVAR capacitive shunts at buses 282 and 600.</td>
<td>30</td>
<td>0.950, 1.058</td>
</tr>
</tbody>
</table>

Note: System I had no voltage security issues. All voltages as given were within the limits of 0.95-1.05 puV.
Voltage Security – System II
Voltage Security – System III

Voltage security under normal conditions. Controls include generator voltages and real power, transformer settings and DC lines.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Solution</th>
<th>Controls</th>
<th>Outliers</th>
<th>Worst-Case Outliers (Min, Max) [puV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>Original</td>
<td>Original.</td>
<td>600</td>
<td>0.806, 1.113</td>
</tr>
<tr>
<td>D</td>
<td>NETSS</td>
<td>Fixed except for real power generation.</td>
<td>273</td>
<td>0.810, 1.108</td>
</tr>
<tr>
<td>E</td>
<td>NETSS</td>
<td>Variable.</td>
<td>73</td>
<td>0.810, 1.106</td>
</tr>
</tbody>
</table>

Note that Runs D and E exhibit many bus voltages just outside the desired range of 0.95-1.05 puV. They could be brought within the desired range by using a tighter optimization penalty.
Voltage Security – System III

Bus Voltages

- Original
- Run A
- Run B

Bus Voltage [puV]

Bus Index

0 1000 2000 3000 4000 5000 6000
Voltage Security – System IV- EMS

Voltage security under normal conditions. Controls include generator voltages and real power, and transformer settings in System IV alone.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Solution</th>
<th>Controls</th>
<th>Outliers</th>
<th>Worst-Case Outliers (Min, Max) [puV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>Original</td>
<td>Original.</td>
<td>17</td>
<td>None, 1.250</td>
</tr>
<tr>
<td>20</td>
<td>NETSS</td>
<td>Fixed except for real power generation.</td>
<td>5</td>
<td>None, 1.244</td>
</tr>
<tr>
<td>21</td>
<td>NETSS</td>
<td>Same as Run 20 except for control voltage adjustment at Bus 92.</td>
<td>2</td>
<td>None, 1.244</td>
</tr>
<tr>
<td>22</td>
<td>NETSS</td>
<td>Variable.</td>
<td>2</td>
<td>None, 1.170</td>
</tr>
<tr>
<td>23</td>
<td>NETSS</td>
<td>Same as Run 22 with 100 MVAR inductive shunts at buses 434 and 435.</td>
<td>0</td>
<td>None, None</td>
</tr>
</tbody>
</table>

Three generators were originally scheduled to control the voltage at Bus 92 to 1.054 puV. These voltage controls were released for Run 21.
Voltage security under normal conditions. Controls include generator voltages and real power, and transformer settings in System IV alone.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Solution</th>
<th>Controls</th>
<th>Outliers</th>
<th>Worst-Case Outliers (Min, Max) [puV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>Original</td>
<td>Original.</td>
<td>9</td>
<td>0.941, 1.052</td>
</tr>
<tr>
<td>24</td>
<td>NETSS</td>
<td>Fixed except for real power generation.</td>
<td>8</td>
<td>0.944, 1.052</td>
</tr>
<tr>
<td>25</td>
<td>NETSS</td>
<td>Variable.</td>
<td>0</td>
<td>None, None</td>
</tr>
</tbody>
</table>
• Employ an optimization that maximizes load within security limits. Use a single load scale factor, as opposed to priorities. (Priorities could be used given local knowledge.)

• Consider normal operating conditions.

• First, examine what can be accomplished through real power dispatch alone.

• Next, examine what can be accomplished by varying all available controls: generator voltages and real power, and transformer settings.

• Next, identify critical controls.

• Finally, examine what can be accomplished with new equipment such as controllable shunts. This is a planning exercise.
Loadability under normal conditions. Controls include generator voltages and real power, and transformer settings.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Solution</th>
<th>Controls</th>
<th>Load Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>NETSS</td>
<td>Fixed except for real-power generation.</td>
<td>3.4 %</td>
</tr>
<tr>
<td>27</td>
<td>NETSS</td>
<td>Same as Run 26 except for voltage adjustment at Bus 3917, and a tap adjustment for the transformer at Buses 6310-6313.</td>
<td>6.5 %</td>
</tr>
<tr>
<td>28</td>
<td>NETSS</td>
<td>Same as Run 27 except for voltage adjustment at Bus 254.</td>
<td>8.2 %</td>
</tr>
<tr>
<td>29</td>
<td>NETSS</td>
<td>Variable.</td>
<td>15.2 %</td>
</tr>
</tbody>
</table>
Loadability – System I

Bus Voltage Sensitivities

- Sensitivity
- Bus Index

Uncontrolled Voltage
Controlled Voltage
Transformer Ratio Sensitivities

Sensitivity vs Transformer Index

Points at indices 6310-6313 have sensitivity values.
Loadability – System I

Bus Voltage Sensitivities

Sensitivity

Bus Index

Uncontrolled Voltage
Controlled Voltage
Loadability under normal conditions. Controls include generator voltages and real power, and transformer settings.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Solution</th>
<th>Controls</th>
<th>Load Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>NETSS</td>
<td>Fixed except for real-power generation.</td>
<td>0 %</td>
</tr>
<tr>
<td>G</td>
<td>NETSS</td>
<td>Variable.</td>
<td>1.1 %</td>
</tr>
<tr>
<td>H</td>
<td>NETSS</td>
<td>Same as Run G with the placement of a 75 MVAR capacitive shunt at Bus 113.</td>
<td>8.4 %</td>
</tr>
<tr>
<td>I</td>
<td>NETSS</td>
<td>Same as Run G with the placement of a 110 MVAR capacitive shunt at Bus 113 and a 330 MVAR capacitive shunt at Bus 282.</td>
<td>10.9 %</td>
</tr>
<tr>
<td>J</td>
<td>NETSS</td>
<td>Same as Run G with the placement of a 150 MVAR capacitive shunt at Bus 113, a 390 MVAR capacitive shunt at Bus 282, and a 70 MVAR capacitive shunt at Bus 341.</td>
<td>24.5 %</td>
</tr>
</tbody>
</table>
Loadability under normal conditions. Controls include generator voltages and real power, transformer settings, and DC lines.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Solution</th>
<th>Controls</th>
<th>Load Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>NETSS</td>
<td>Fixed except for real-power generation</td>
<td>0.4 %</td>
</tr>
<tr>
<td>L</td>
<td>NETSS</td>
<td>Variable</td>
<td>0.8 %</td>
</tr>
</tbody>
</table>

System III notes: this is a heavy winter case with all lines and equipment in service but with very high load, 11300 MW including losses.
Loadability under normal conditions. Controls include generator voltages and real power, and transformer settings in System IV alone.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Solution</th>
<th>Controls</th>
<th>Load Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>NETSS</td>
<td>Fixed except for real-power generation.</td>
<td>8.9 %</td>
</tr>
<tr>
<td>31</td>
<td>NETSS</td>
<td>Variable.</td>
<td>9.0 %</td>
</tr>
<tr>
<td>32</td>
<td>NETSS</td>
<td>Same as Run 31 except for the placement of a 285 MW real-power generator at Bus 2245.</td>
<td>22.4 %</td>
</tr>
<tr>
<td>33</td>
<td>NETSS</td>
<td>Same as Run 31 except for a strengthened line between Buses 2242-2245.</td>
<td>22.4 %</td>
</tr>
</tbody>
</table>
Loadability under normal conditions. Controls include generator voltages and real power, and transformer settings in System IV alone.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Solution</th>
<th>Controls</th>
<th>Load Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>NETSS</td>
<td>Fixed except for real-power generation.</td>
<td>0.8 %</td>
</tr>
<tr>
<td>35</td>
<td>NETSS</td>
<td>Variable.</td>
<td>3.4 %</td>
</tr>
<tr>
<td>36</td>
<td>NETSS</td>
<td>Same as Run 35 except for the placement if a 210 MW real-power generator at Bus 73704.</td>
<td>4.4 %</td>
</tr>
</tbody>
</table>
Summary on Large System Studies

- Representative examples of different optimizations supported by the NETSS AC XOPF have been shown.
- The effectiveness of optimization sensitivities for identifying key controls has been illustrated.
- The software converged for all examples, applying minimized load shedding for infeasible systems.
- The software is fast, typically taking between 30 seconds and several minutes to complete an optimization.
- GUI supported use of software for selecting performance metrics, decisions, etc.
Experiences with Large Systems

- NETSS greatly appreciates the opportunity given to work with industry on testing the software.
- The results presented here are based on the real systems cases and were discussed and approved by the sponsors.
- The names of specific companies are not given.
- Here only the optimization results for normal conditions presented; the second presentation includes corrective actions as the basis for implementing flexible operation in Smart Grids.
Overall Summary

• It is becoming necessary to enable system operators and market makers with system management software capable of exploring many options to manage complex power systems.

• An AC XOPF program which is a carefully designed software not specific to single performance objective or control choice could serve as such enabler.

• In particular, AC XOPF can be used to determine when load shedding is and is not required to maintain system-wide security.

• Voltage dispatch greatly reduces the need for load shedding.

• When load shedding is required, the AC XOPF program can determine the minimum load shedding required to maintain system-wide security.
Major Open Questions

• Economic and environmental implications of not using AC XOPF

• The NETSS AC XOPF always produces stable LMPs (June 24 presentation).

• How to align the market and operations objectives

• Work with industry on using AC XOPF for more frequent adjustments of interface limits; this would have major impact on market efficiency

• Voltage/reactive power support pricing methods