# Optimization and Control Theory for Smart Grids

## Grid Design

LA-UR 10-04534

**Russell Bent**

**D-4**

# Outline

- Grid Design Overview
- The Transmission Expansion Planning Problem
  - Power flow modeling
  - New Challenges
- Local Search with Simulation
- Branching Heuristics
- Results
- Demo

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# Grid Design Objective and Challenges

- **Determine how to best structure the grid to meet the demands of the 21st century**
  - Smart grid devices
  - Renewable generation
  - Electric vehicles
  - Storage
- **Existing approaches**
  - Don't account for recent advances in technology
  - Rely on power flow modeling approximations for the 20th century
- **Challenges**
  - Intermittent generation
  - Large scale (spatial and temporal)
  - Multi-objective

# References

## Simulation Optimization for Expansion Planning


- L. Toole, M. Fair, A. Berscheid, and R. Bent. *Electric Power Transmission Network Design for Wind Generation in the Western United States: Algorithms, Methodology, and Analysis*. Proceedings of the 2010 IEEE Power Engineering Society Transmission and Distribution Conference and Exposition (IEEE TD 2010), 1-8, April 2010, New Orleans, Louisiana
- R. Bent, A. Berscheid, and G. Loren Toole. *Transmission Network Expansion Planning with Simulation Optimization*. Proceedings of the Twenty-Fourth AAAI Conference on Artificial Intelligence (AAAI 2010), July 2010, Atlanta, Georgia
  - One of 30 papers selected for oral and poster presentation (out of 900+ submissions)


## Non Convex Optimization for Expansion Planning


- J. Johnson and M. Chertkov, *A Majorization-Minimization Approach to Design of Power Transmission Networks*, Proceedings of 49th IEEE Conference on Decision and Control, Decemeber 2010, Atlanta, Georgia


## Locating Battery Swapping Stations


- F. Pan, R. Bent, A. Berscheid, and D. Izraelvitz. *Locating PHEV Exchange Stations in V2G*. Proceedings of the First International Conference on Smart Grid Communications (SmartGridComm 2010), October 2010, Gaithersburg, Maryland

# Our work

- **Simulation Optimization for Expansion Planning**
  - Optimization algorithm that is independent of the power flow model
    - First (that we know of) optimization approach to account for AC power flows
  - Scales to large problems, both temporally and spatially (WECC, 30 years)
  - Multi-objective
  - Integrated resource planning
- **Non Convex Optimization for Expansion Planning**
  - Stochastic planning
  - Integrated resource planning
  - Power flow approximations better suited for today's challenges
  - Modern convex approximation to non-convex problems
- **Locating Battery Swapping Stations**
  - Balancing the needs of the power grid and transportation system
  - Smooth the intermittency of renewable generation

Vastly improved starting solutions (expected)

# Simulation Optimization for Expansion Planning

Russell Bent, Loren Toole, and Alan Berscheid

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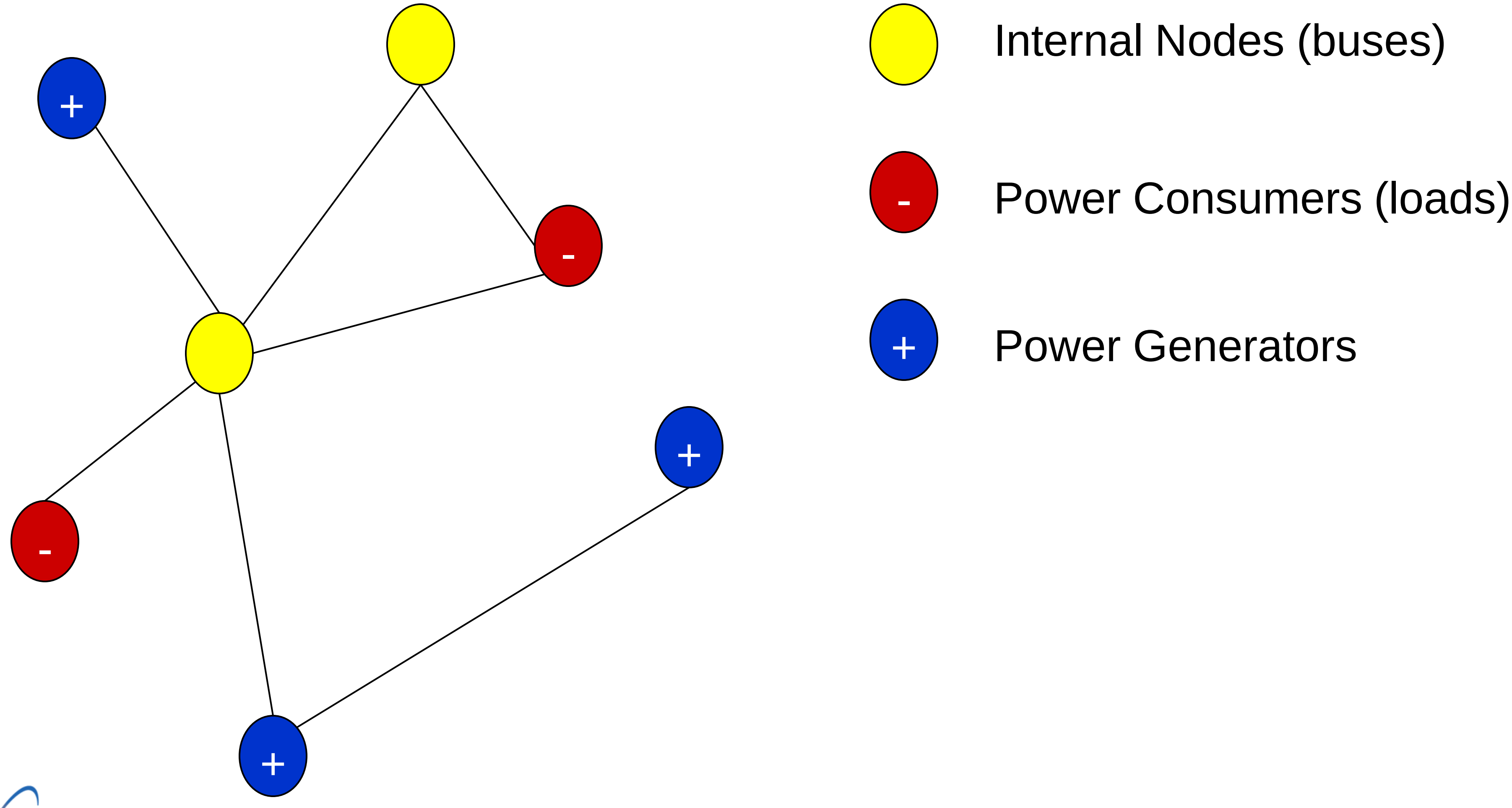
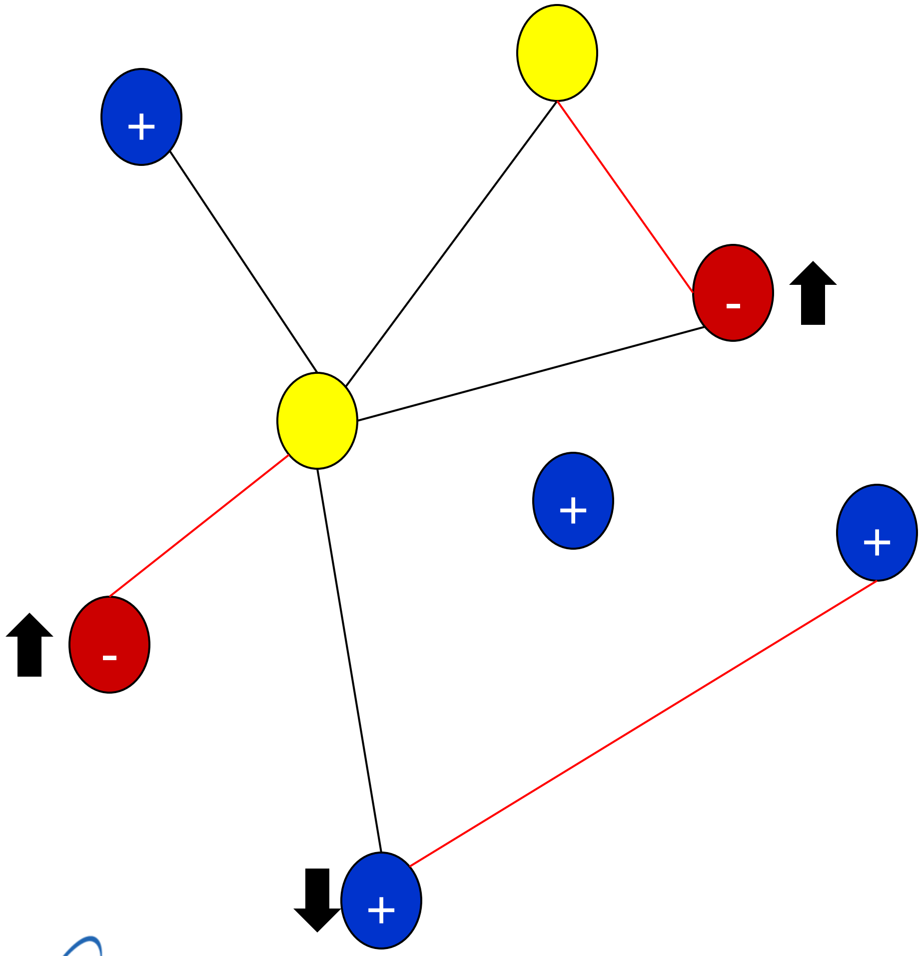
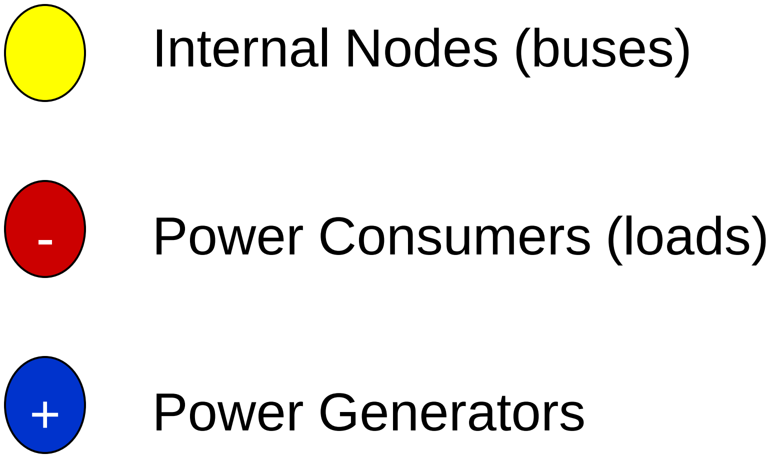
# Transmission Network Expansion Planning (TNEP)



# Transmission Network Expansion Planning (TNEP)






Upgrade an electric power system to accommodate changes in demand and generation

- Eliminate constraint violations
- Minimize expansion cost

# Power Flow Modeling

- **Very different from traditional network flow models**
- **Power flows are determined by complex, non linear laws of physics**
- **Flows may be controlled only indirectly (modifying generation/demand)**
- **Expansion may *introduce* physical violations (Braess's paradox)**

$$P_i = \sum_{k=1..n} |V_i||V_k|(g_{ik} \cos(\Theta_i-\Theta_k) + b_{ik} \sin(\Theta_i-\Theta_k))$$

$$Q_i = \sum_{k=1..n} |V_i||V_k|(g_{ik} \sin(\Theta_i-\Theta_k) + b_{ik} \cos(\Theta_i-\Theta_k))$$

**$P_i$ = Real power of bus i**

**$Q_i$ = Reactive power of bus i**

**$V_i$ = Voltage of bus i**

**$\Theta_i$ = phase angle of bus**

**$g_{ik}$ = conductance between i,k**

**$b_{ik}$ = susceptance between i,k**

**V and Θ are decision variables. Flow calculated from Δ V and Δ Θ**

**$P_i$, $Q_i$, $g_{ik}$, $b_{ik}$ given**

# Power Flow Modeling in TNEP

- Standard models considered too difficult to use
- Linearized DC model

$$P_i = \sum_{k=1..n} g_{ik} (\Theta_i - \Theta_k)$$

- Still a mixed integer non-linear program

$$P_i = \sum_{k=1..n} g_{ik} \, c_{ik} (\Theta_i - \Theta_k)$$

- $c_{ik}$ is the number of lines with conductance $g_{ik}$ between i and k
- Modeling assumptions
  - Network normally stable
  - Minor changes in V and Θ
  - AC (Q) power a small contributor
  - Controllable generation
- Considered *easy* to modify a TNEP solution to more complex flow representations

# Primary Motivation

Develop an independent assessment of transmission path features of the future western grid, based on "20% Wind Energy by 2030"

***Technical Goals:***
Construct a feasible grid representation (cost of grid upgrades plus operational features) assuming 20% wind penetration

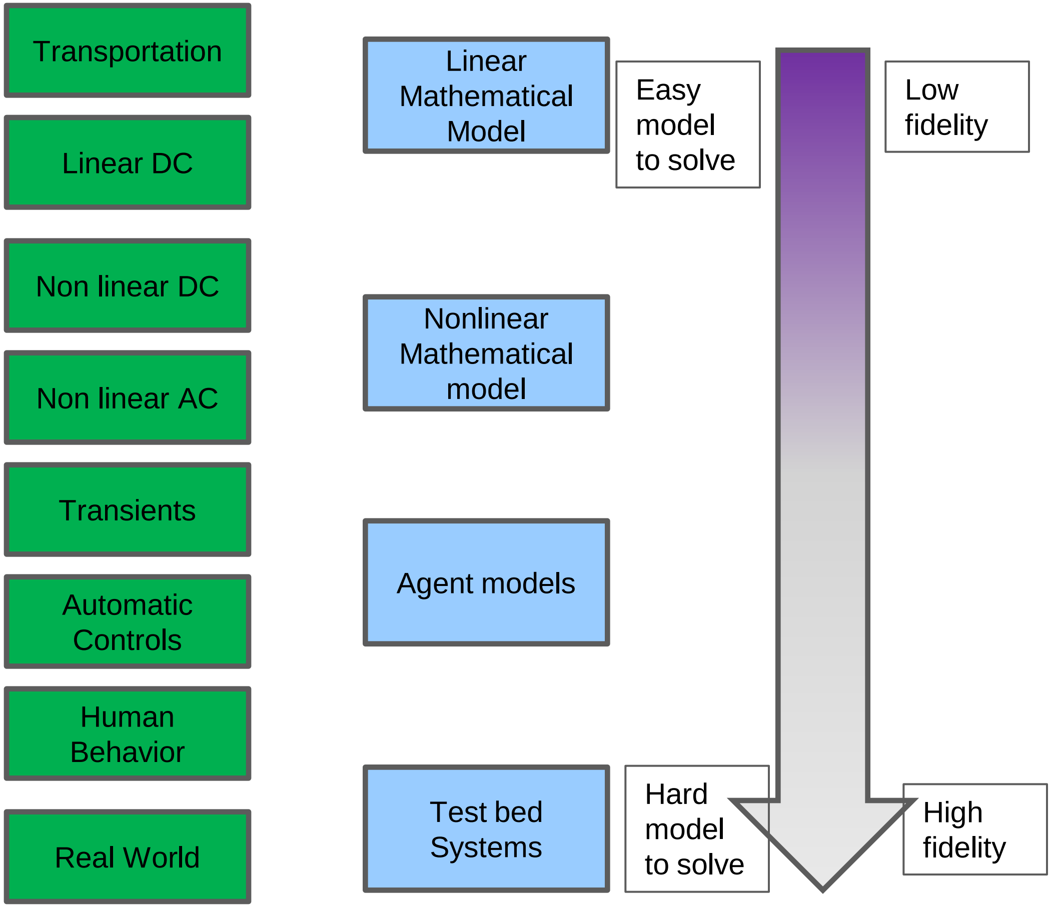
***Ref.*** "20% Wind Energy by 2030: Increasing Wind Energy's Contribution to the U.S. Electricity Supply," DOE/GO-102008-2567, May 2008

# Modeling Assumptions in TNEP

- Network normally stable
  - Generally the case for existing networks, unknown if this holds for expansions
- Minor changes in V and Θ
  - Generally the case for existing networks, unknown if this holds for expansions (esp. large networks)
- AC (Q) power a small contribution
  - Generally the case
- Controllable generation
  - Not with renewable (wind and solar) generation
- Considered *easy* to modify a TNEP solution to more complex flow representations
  - Not anymore…

# Power Flow Modeling Possibilities

- Wide range of possible models to choose from
- TNEP algorithms tailored to specific flow models



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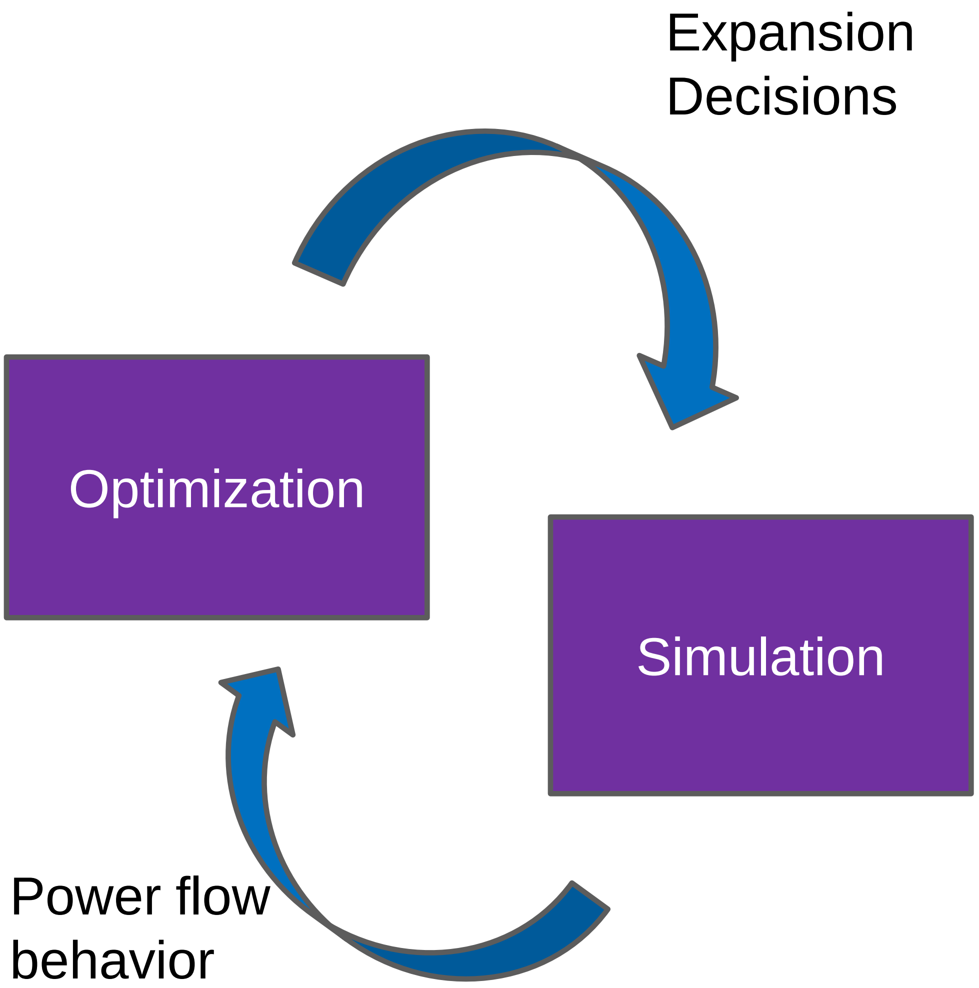
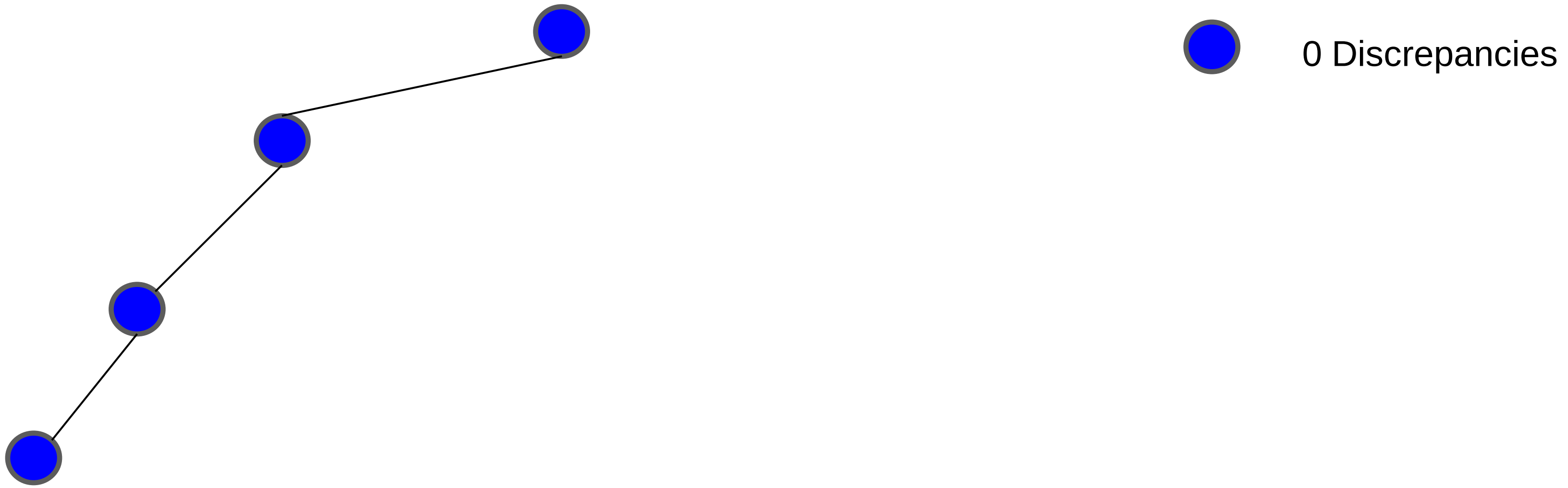
# Simulation Optimization

- Encapsulate models difficult to represent in a *black box (simulation)*
- Typically used only to evaluate objective function or feasibility
- Simulation results inform optimization choices
- Algorithm independence from power flow models



# Local Search Procedure (LS)




- Explore expansion solutions according to a construction heuristic
  - Up to δ discrepancies of the heuristic

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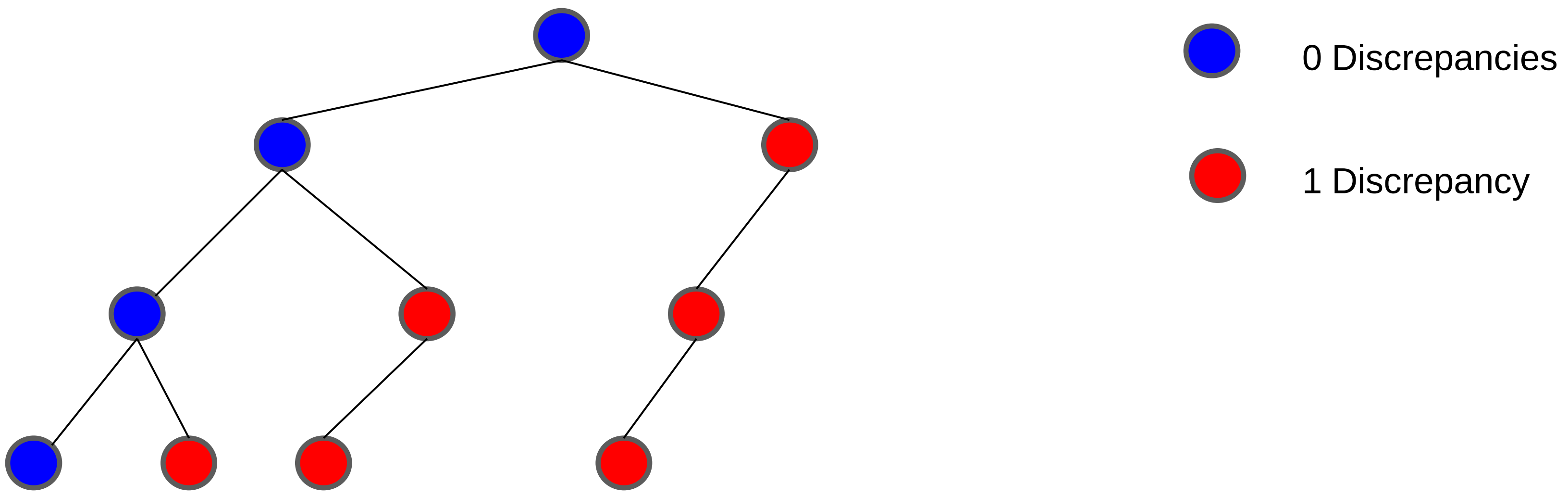


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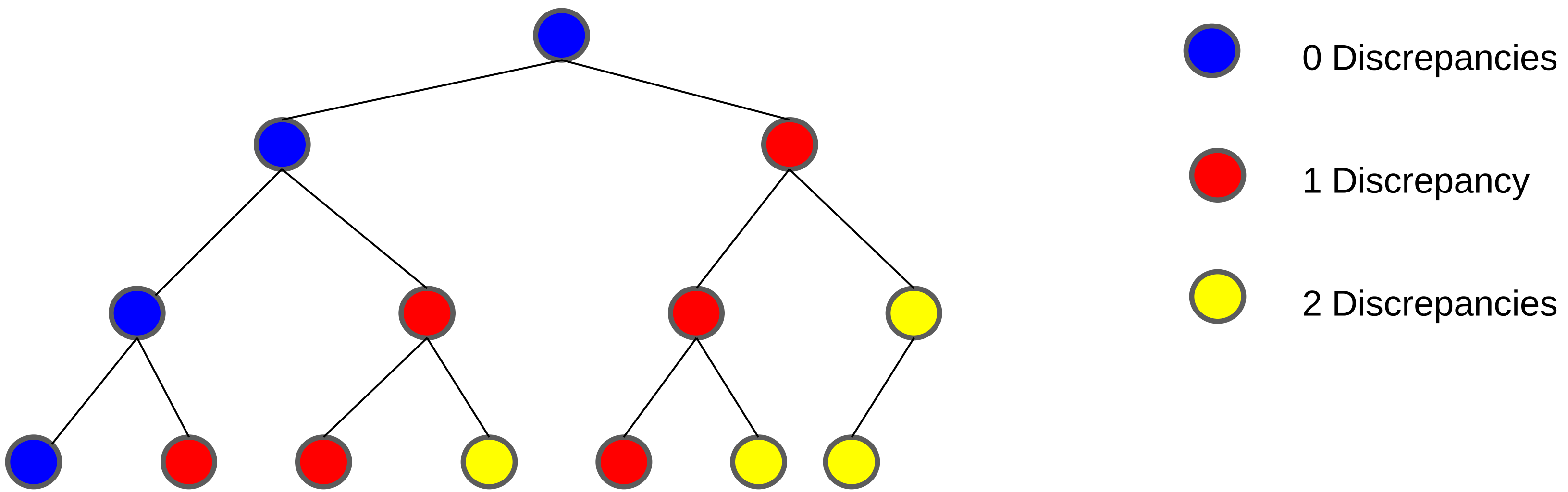


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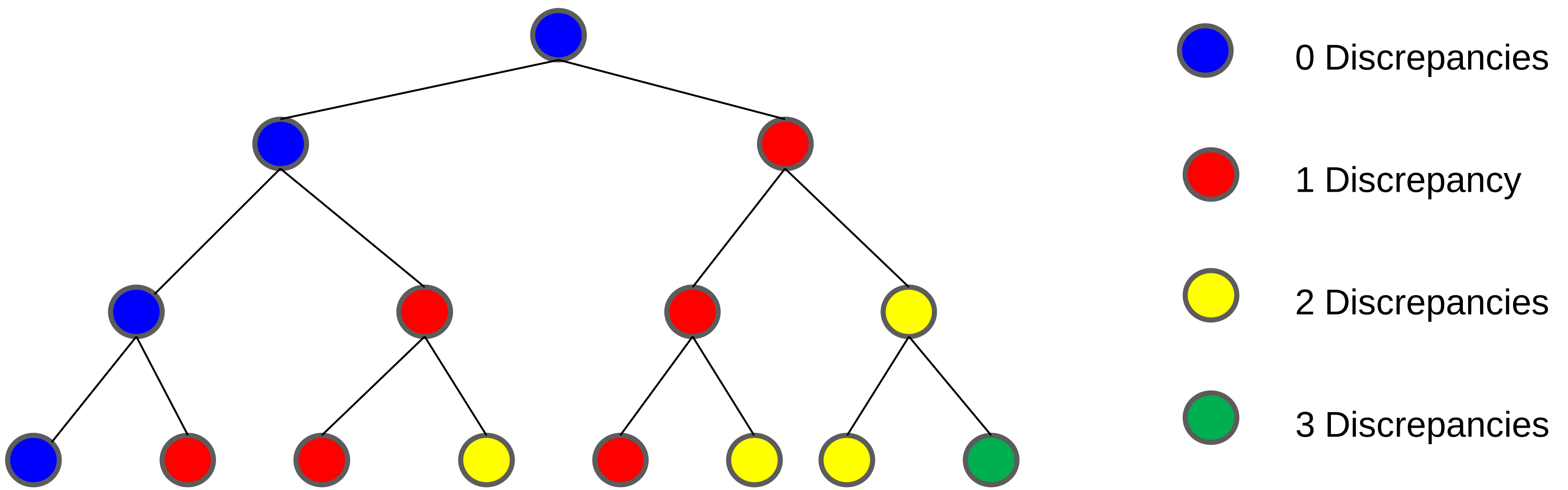
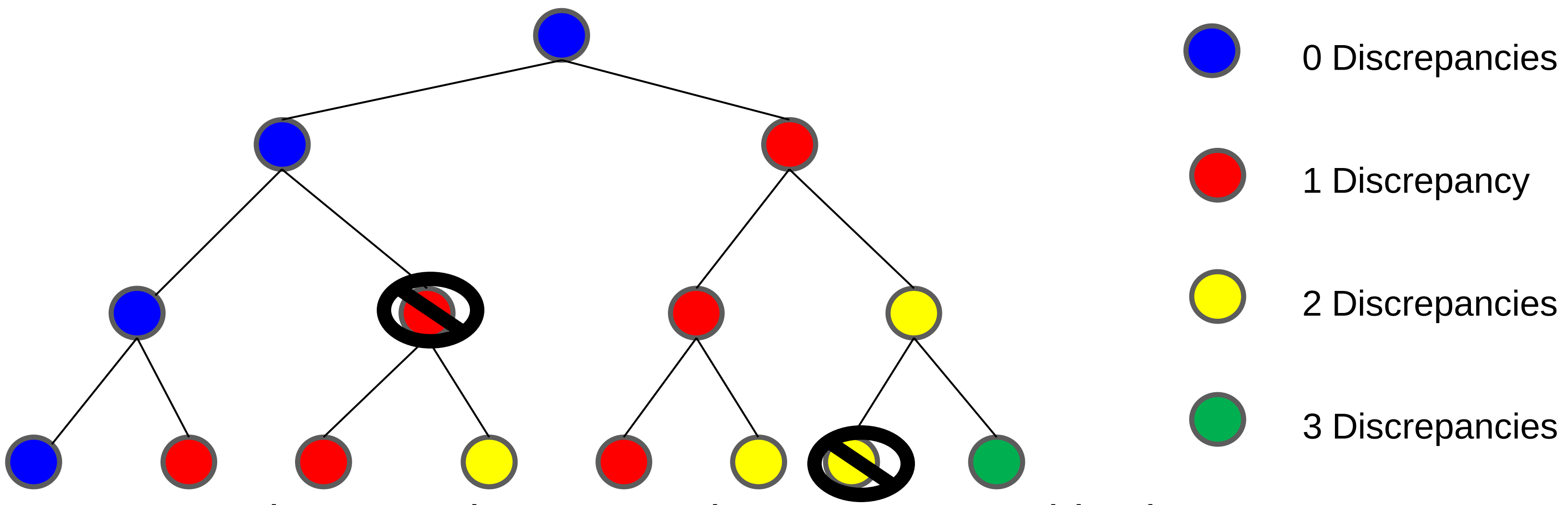


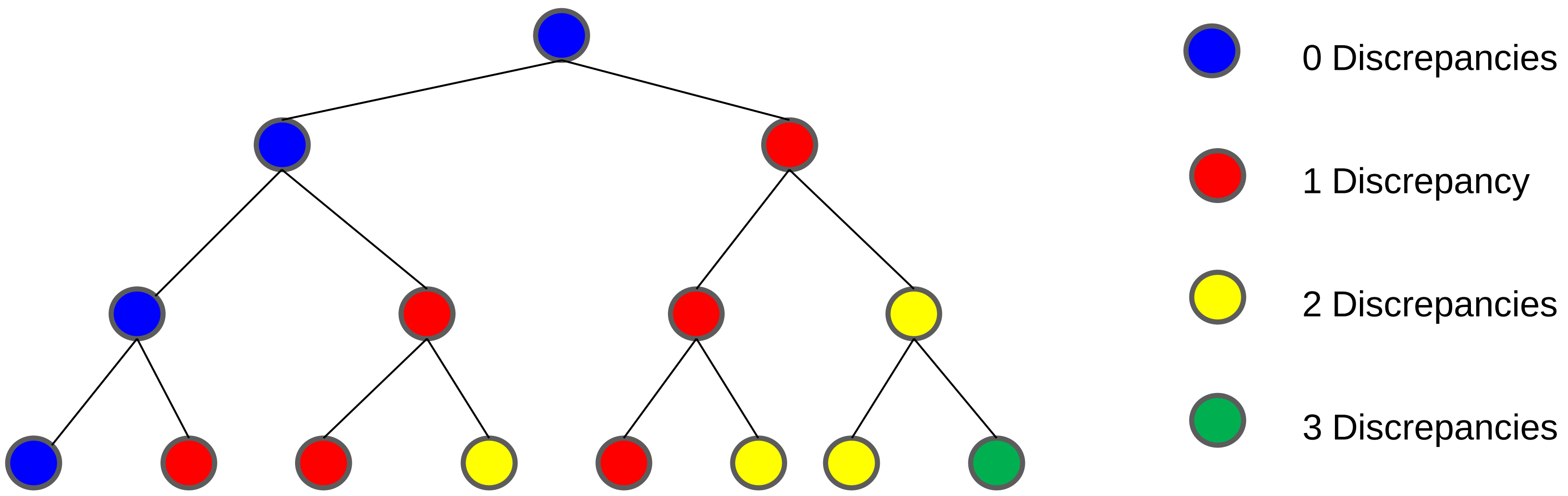

- Explore expansion solutions according to a construction heuristic
  - Up to δ discrepancies of the heuristic
- Explore solutions near the heuristic
- Generalizes many existing TNEP heuristics
- Similar to Limited Discrepancy Search (Harvey and Ginsberg 95)
  - A complete search technique

# Local Search Procedure (LS)




- Expansions can decrease or increase some objectives
  - Minimize physical violations
- Simulation may be fail to deliver a solution
- Introduce parameters to prune search tree
  - α limits the # of successive solutions that degrade objective
  - β limits the # of successive solutions that are not solvable

# Branching Heuristics




- Most challenging part of benchmarks is minimizing physical violations (over capacity lines)
- Branching heuristics focus on reducing violations
- Simulation results provide flow behavior that is used by the heuristics

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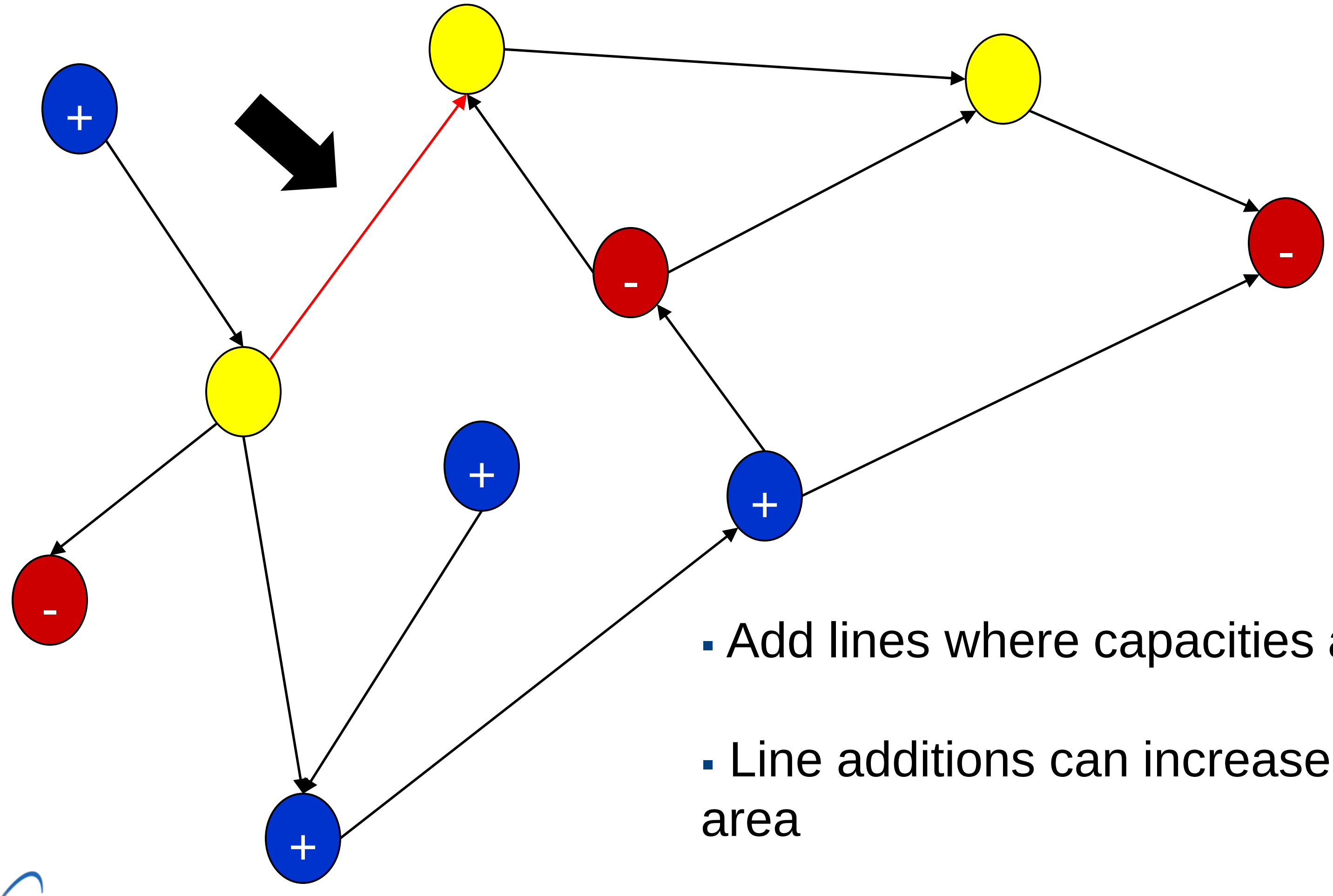
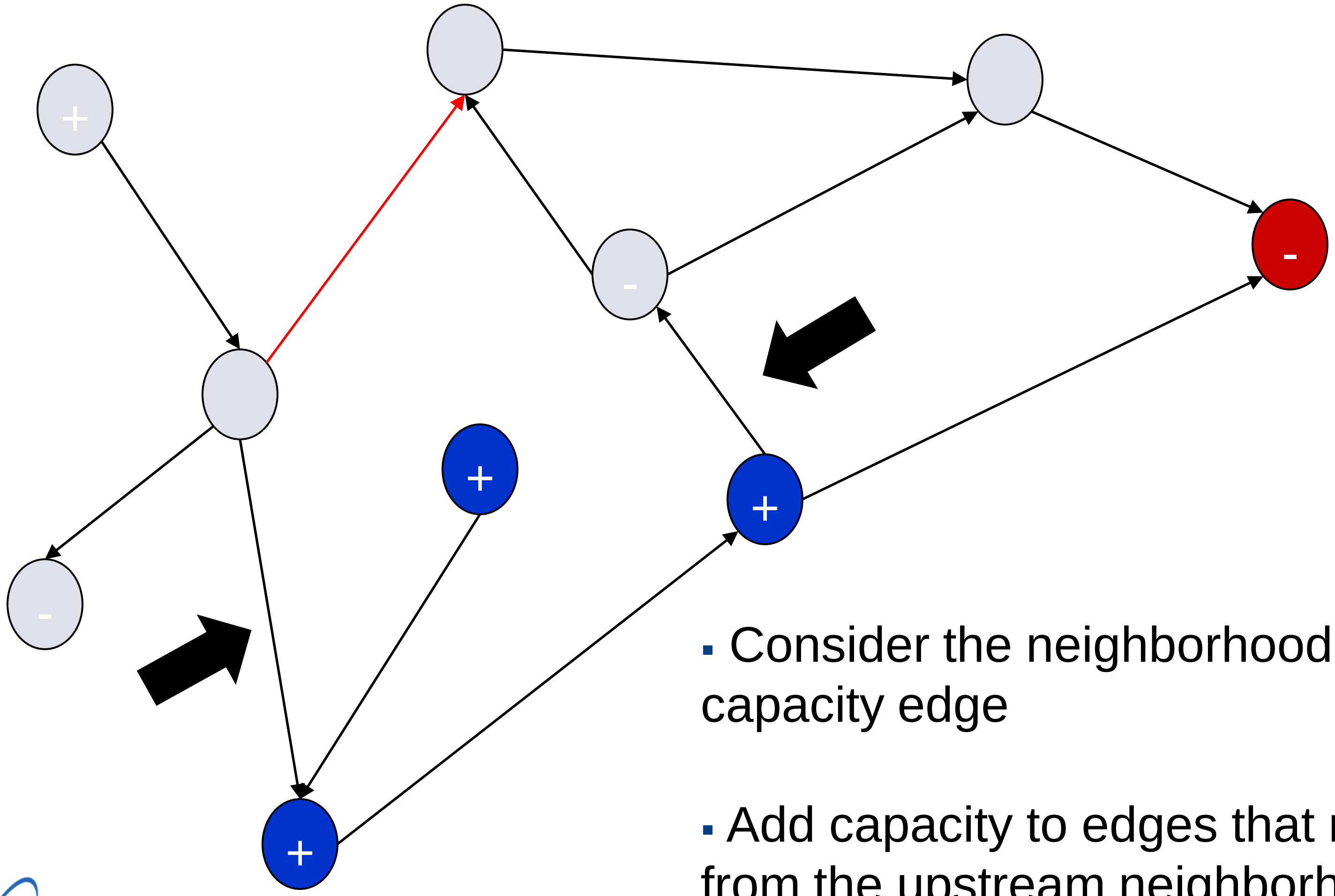
# Branching Heuristics: Max Utilization (MU)




- Add lines where capacities are violated
- Line additions can increase flow in the area

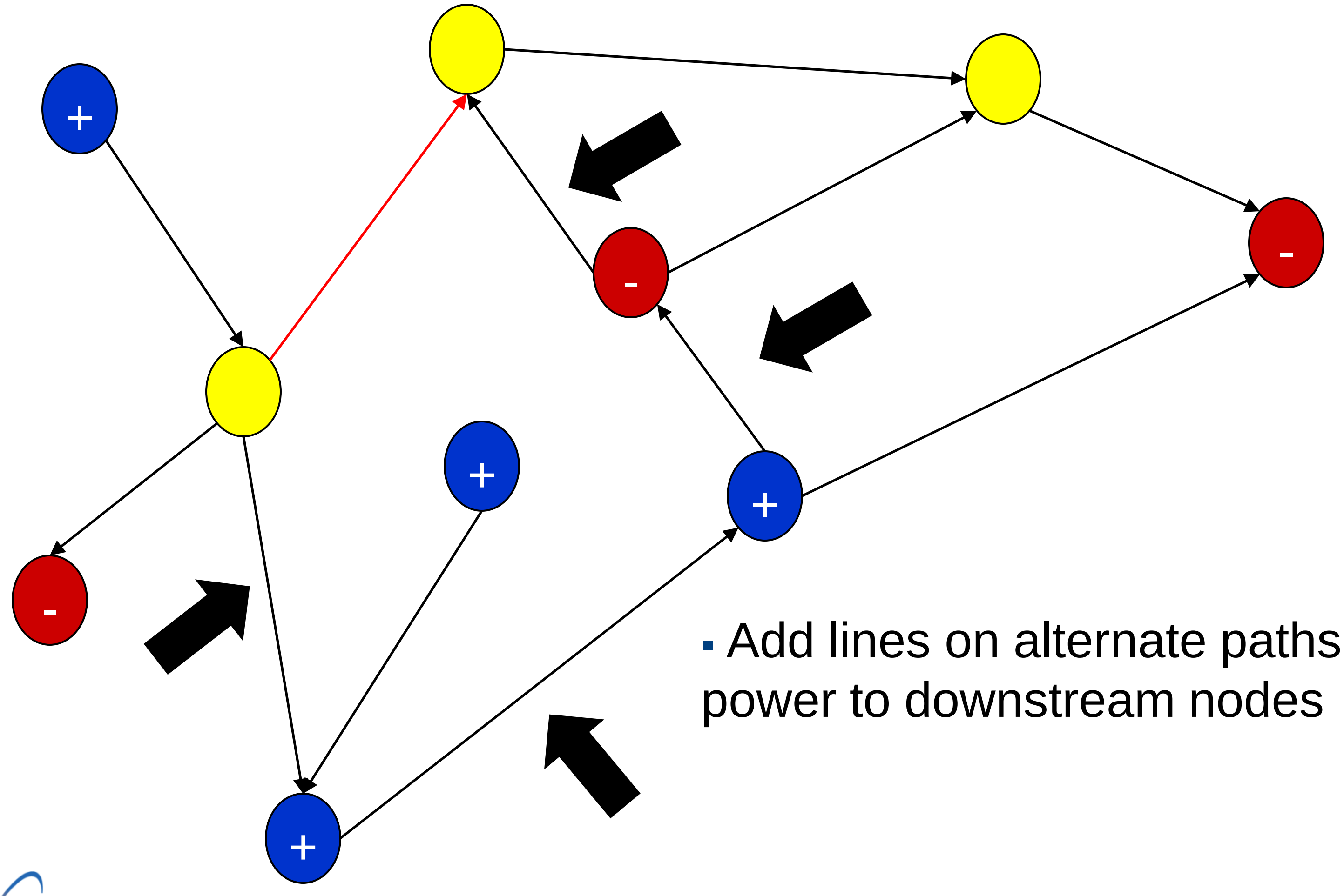
# Branching Heuristics: Flow Diversion (FD)




- Consider the neighborhood of an over-capacity edge

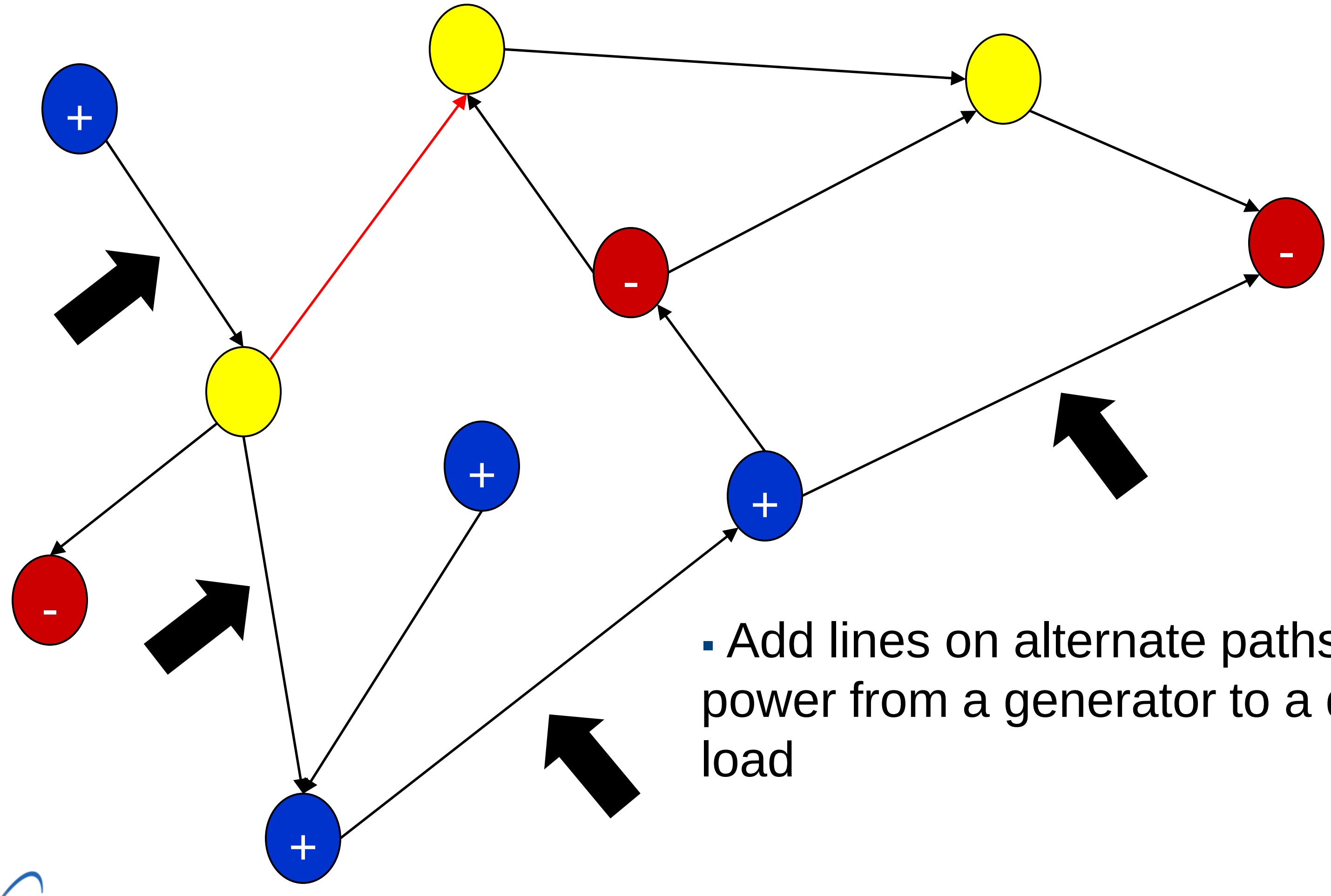
- Add capacity to edges that remove power from the upstream neighborhood or add power downstream

# Branching Heuristics: Alternate path (AP)




- Add lines on alternate paths that bring power to downstream nodes

# Branching Heuristics: Alternate path around (APA)




- Add lines on alternate paths that bring power from a generator to a downstream load

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# IEEE Benchmarks (Feng and Hill, 2003)

- **Grew Loads and Generation of IEEE RTS-79 by 200-300%**
- **24 buses, 41 transmission corridors**
- **Test the hypothesis that it is easy and cost efficient to modify a DC-based expansion plan**

| | Problem | Total Generation | # Line Overloads | Total Overload |
|---|---|---|---|---|
| Romero et al. 2005 | G1 | 8550 MW | 8 | 450.47 MVA |
| | G3 | 8550 MW | Divergent | Divergent |
| Feng and Hill 2003 | G1 | 8550 MW | 6 | 346.37 MVA |
| | G2 | 8550 MW | 7 | 403.37 MVA |
| | G3 | 8550 MW | 7 | 510.40 MVA |
| | G4 | 8550 MW | 4 | 177.47 MVA |

# IEEE Benchmarks (Feng and Hill, 2003)

- **Grew Loads and Generation of IEEE RTS-79 by 200-300%**
- **24 buses, 41 transmission corridors**
- **Test the hypothesis that it is easy and cost efficient to modify a DC-based expansion plan**

| | Problem | DC Cost | MU | FD | AP | APA |
|---|---|---|---|---|---|---|
| Romero et al. 2005 | G1 | 438K | 1072K | 1499K | 1422K | 1517K |
| | G3 | 218K | 631K | 1356K | 1141K | 784K |
| Feng and Hill 2003 | G1 | 454K | 913K | 1491K | 1908K | 1460K |
| | G2 | 451K | 786K | 1510K | 1842K | 2078K |
| | G3 | 292K | 1729K | 1308K | 988K | 1097K |
| | G4 | 376K | 867K | 1213K | 1833K | 1325K |

# IEEE Benchmarks (Feng and Hill, 2003)

- **Branching Heuristic Performance (δ = 5, α = 2, β = 2)**
- **Smaller tree indicates pruning due to α,β**
  - Heuristic directing search into bad areas of the search space

| | Problem | MU Overloads | MU Tree Size | FD Overloads | FD Tree Size | AP Overloads | AP Tree Size | APA Overloads | APA Tree Size |
|---|---|---|---|---|---|---|---|---|---|
| Romero et al. 2005 | G1 | 81.36 MVA | 1045 | 38.15 MVA | 5408 | 42 MVA | 3830 | 12.25 MVA | 12006 |
| | G3 | 124.07 MVA | 535 | 96.6 MVA | 1767 | 68.6 MVA | 1254 | 119 MVA | 247 |
| Feng and Hill 2003 | G1 | 81.9 MVA | 520 | 54.6 MVA | 3747 | 37.1 MVA | 3118 | 54.25 MVA | 1088 |
| | G2 | 127.75 MVA | 640 | 78.05 MVA | 2272 | 94.15 MVA | 1485 | 45.85 MVA | 18327 |
| | G3 | 113.4 MVA | 1638 | 68.25 MVA | 4783 | 68.25 MVA | 4109 | 32.02 MVA | 25936 |
| | G4 | 125.65 MVA | 184 | 92.05 MVA | 723 | 72.1 MVA | 1476 | 84 MVA | 2052 |

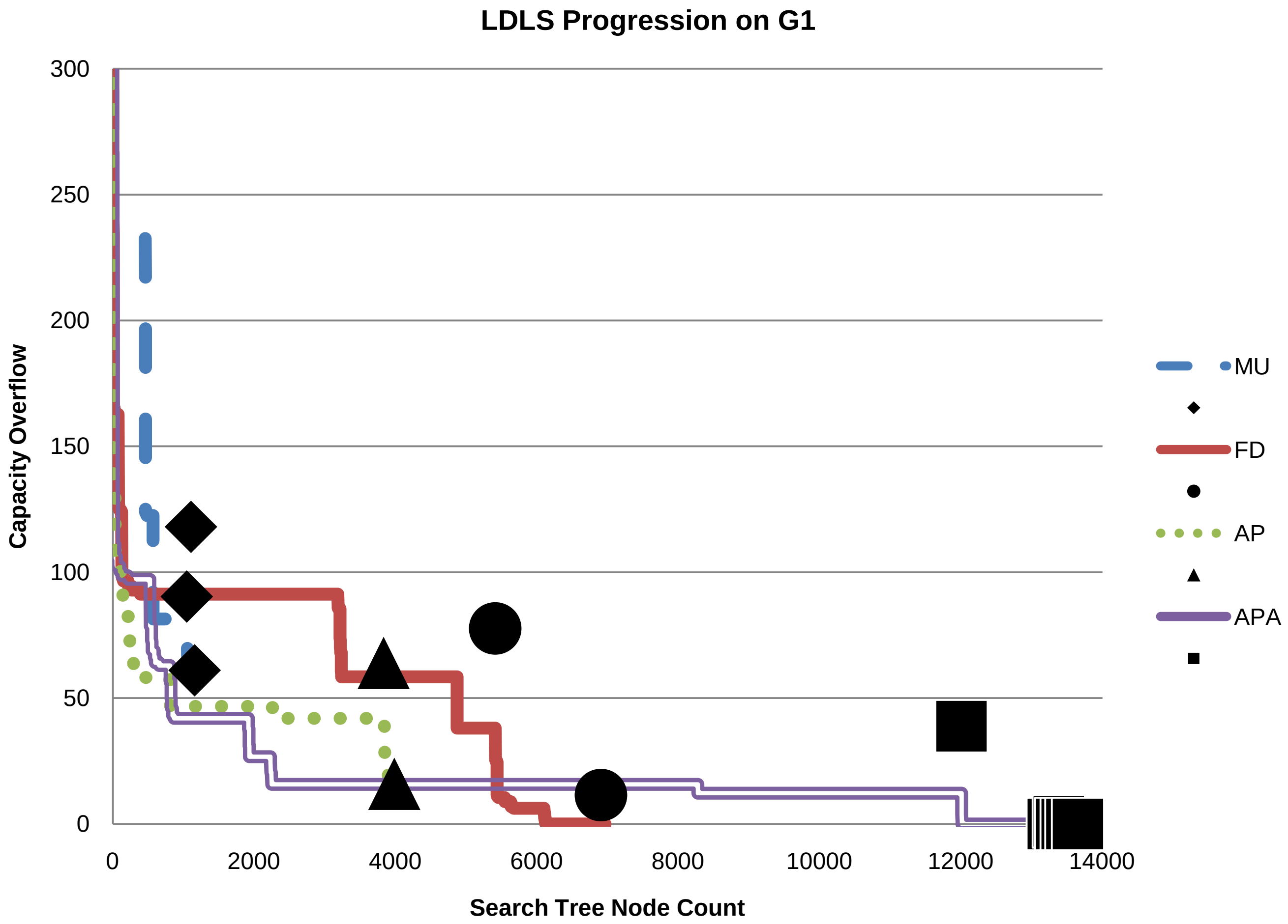
# IEEE Benchmarks (Feng and Hill, 2003)

- **Iteratively restart LS from best solution discovered**
- **Smaller tree indicates pruning due to α,β**
  - Heuristic directing search into bad areas of the search space

| | Problem | MU Overloads | MU Tree Size | FD Overloads | FD Tree Size | AP Overloads | AP Tree Size | APA Overloads | APA Tree Size |
|---|---|---|---|---|---|---|---|---|---|
| Romero et al. 2005 | G1 | 54.25 MVA | 1189 | 0.0 MVA | 6964 | 14.7 MVA | 4010 | 0.0 MVA | 13665 |
| | G3 | 124.07 MVA | 655 | 19.78 MVA | 2709 | 33.25 MVA | 1756 | 107.5 MVA | 553 |
| Feng and Hill 2003 | G1 | 81.9 MVA | 554 | 1.4 MVA | 4674 | 4.2 MVA | 6956 | 30.97 MVA | 1379 |
| | G2 | 127.75 MVA | 738 | 33.08 MVA | 4296 | 42.88 MVA | 5202 | 0.0 MVA | 20547 |
| | G3 | 12.95 MVA | 4559 | 12.6 MVA | 5254 | 58.1 MVA | 4216 | 26.95 MVA | 26010 |
| | G4 | 125.65 MVA | 246 | 39.72 MVA | 1832 | 36.4 MVA | 5167 | 33.78 MVA | 2695 |

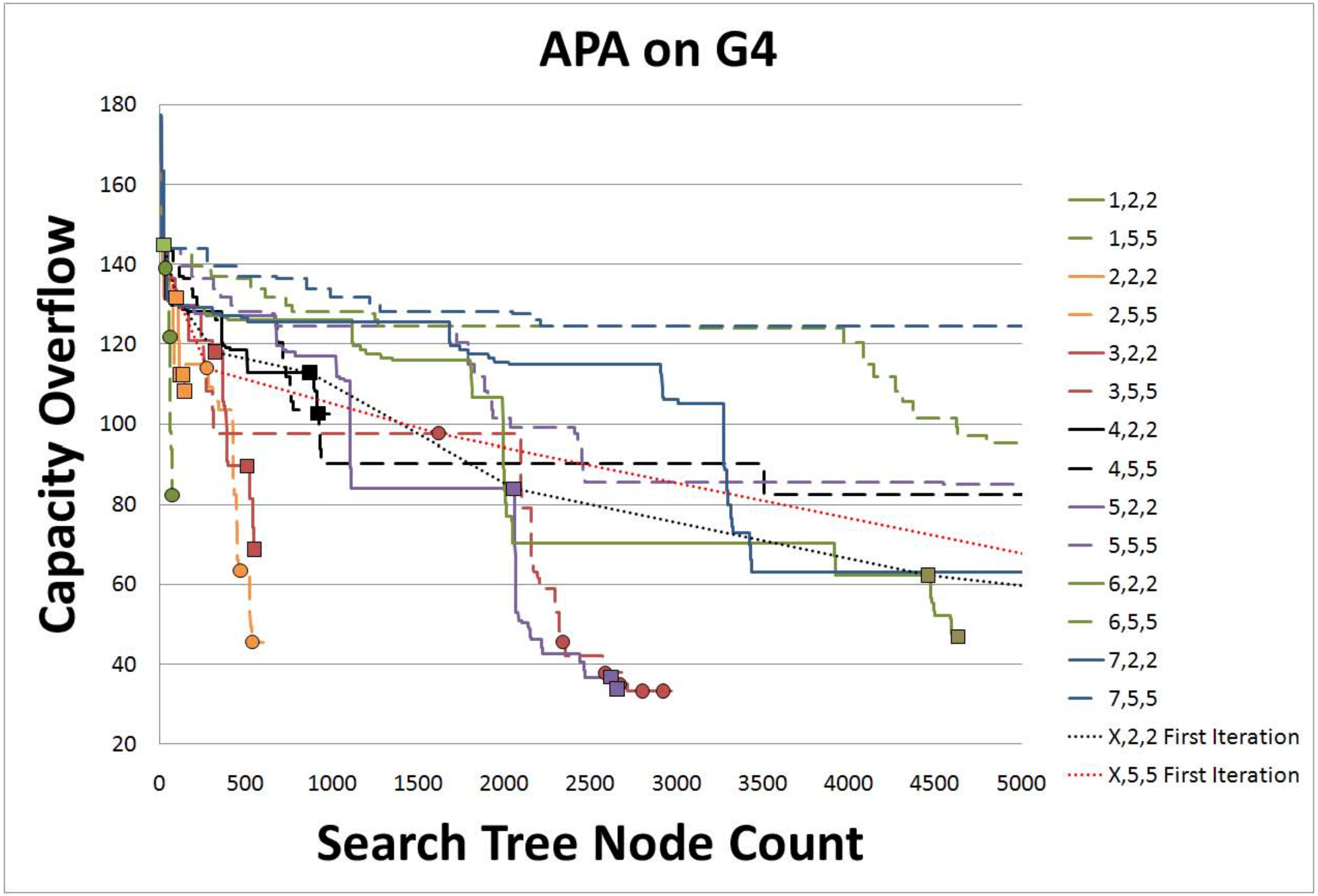
# IEEE Benchmarks (Feng and Hill, 2003)

- **MU drifts into bad search regions easily**
- **APA stays out of bad search regions, but may take longer to find high quality solutions**
- **FD and AP have a good balance between efficiency and search space exploration**



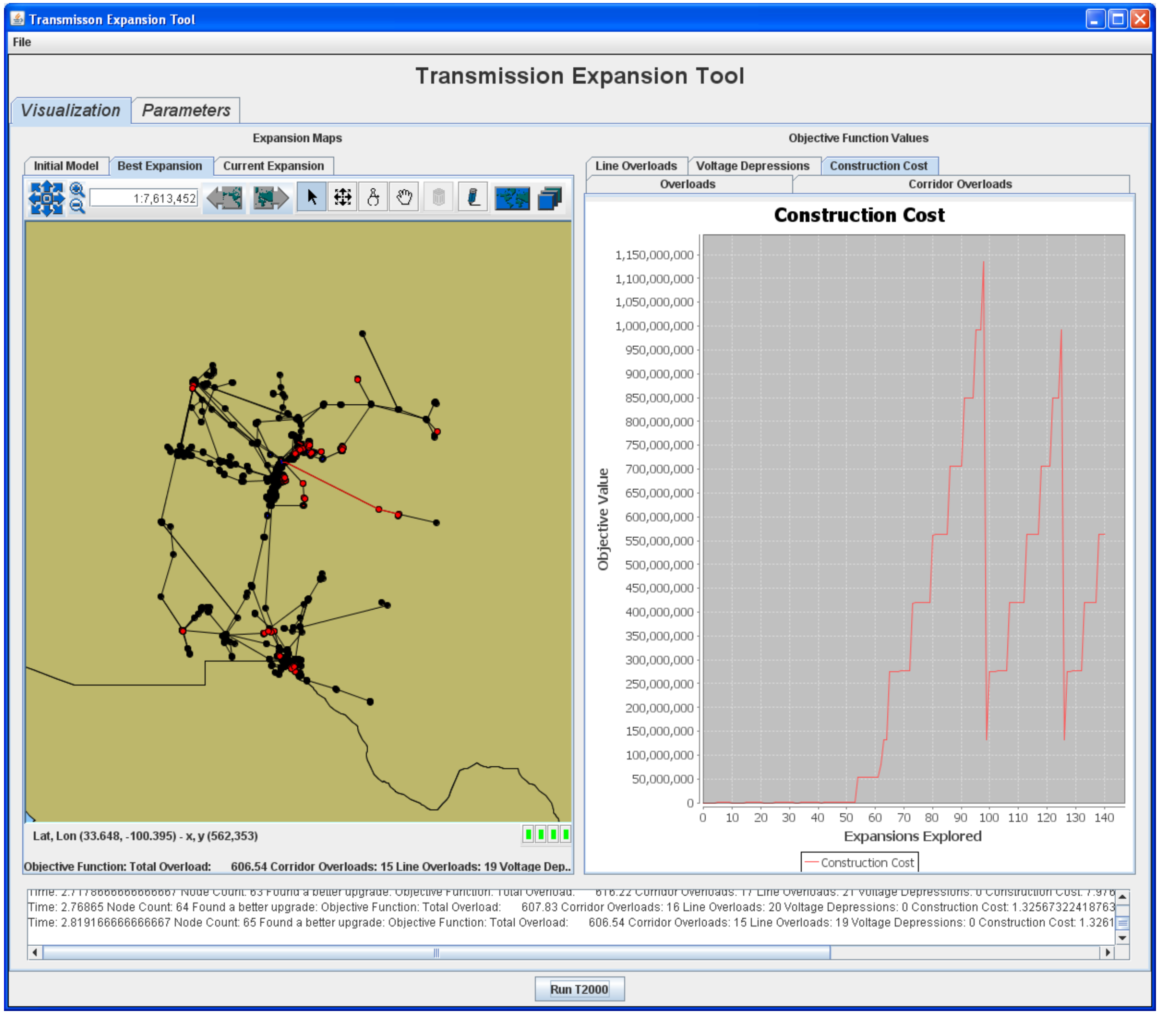
# IEEE Benchmarks (Feng and Hill, 2003)

- **Evaluation complete search**
- **Find higher quality solutions more quickly by inserting a restart strategy between successive increments of δ**
- **Large α, β have limited benefit**



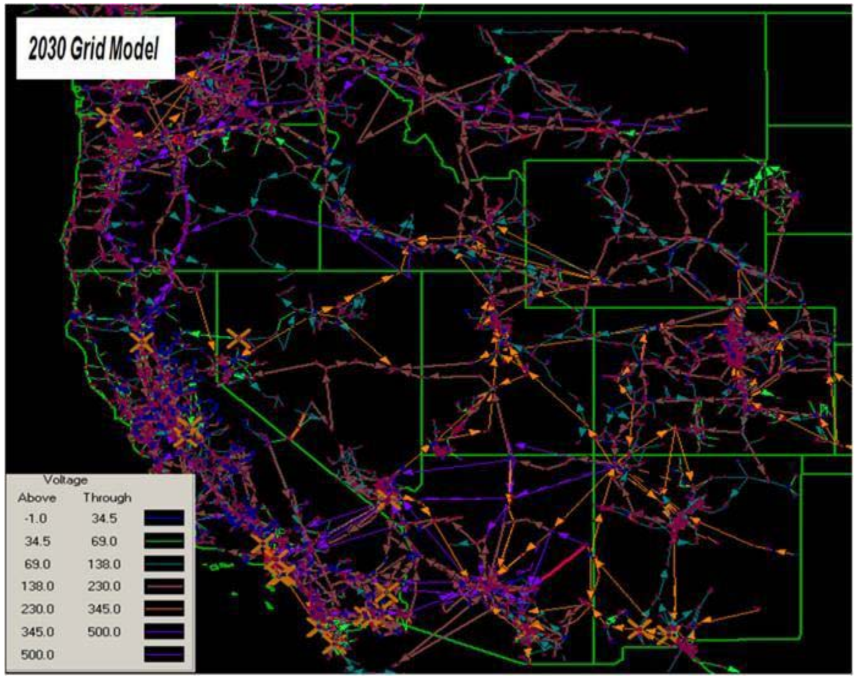
# Real Instances

- **Department of Energy generation and demand predictions for 2016.**
- **66 Transmission corridors over capacity**
- **53 new power lines in existing corridors required to resolve problems**



# Real Instances

- Department of Energy generation and demand predictions for 2030.
- > 2200 transmission corridors over capacity
- > 3300 new power lines in existing and new corridors required to resolve problems (cost of 10.5 billion)




| Option | <100kV | 100-230kV | >230kV | Capacity | Unit |
|---|---|---|---|---|---|
| Line Uprate | 34,761 | 362,975 | 33,410 | 431,146 | MVA |
| Line Shunt | 7,587 | 67,762 | 27,133 | 126,036 | MVAR |
| Transformer | 31,141 | 60,312 | 1,132 | 69,030 | MVA |

# Demo

# Future Work

- **Integrating with Jason's research**
  - Plans based on existing power flow approximations far from optimal
  - Better starting solutions for this approach
- **Locating renewable generation (in progress)**
- **Robust expansion planning**
- **Stochastic expansion planning**
- **Adaptive simulation (in progress)**