Impact of ACOPF Constraints on Security-Constrained Unit Commitment

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Increasing Market & Planning Efficiency through Improved Software
FERC, 22-24 June 2015

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SCUC with ACOPF Constraints

- Overview
- Motivation
- Methodology
- Case Studies

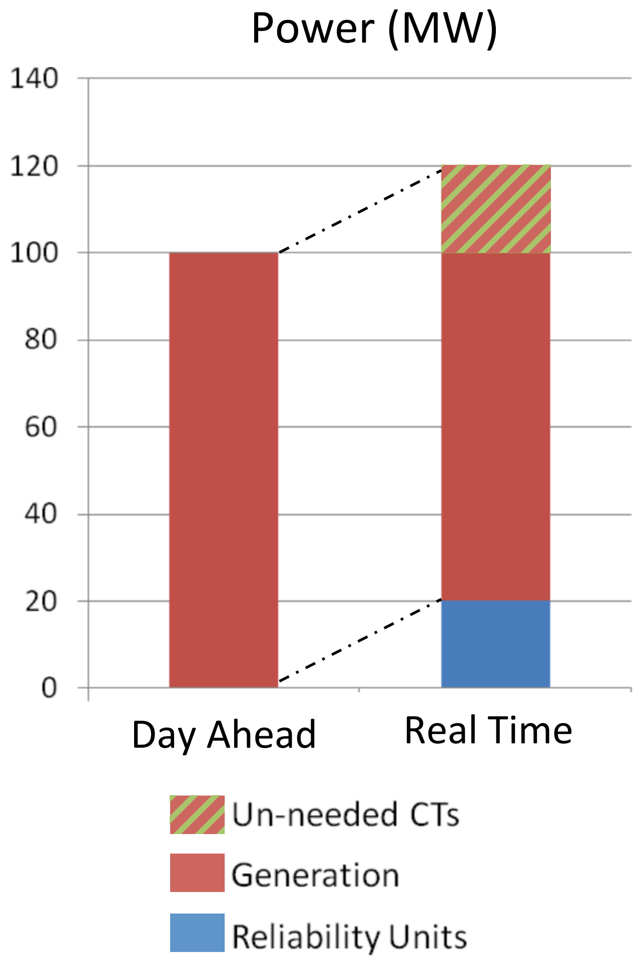
UC Transmission Modeling

Current Practices	Proposed Approach
UC • Copper-plate (no network/single node) • Ignores congestion; requires cutsets to proxy capacity limits on network • Most tractable **SCUC+DCOPF** • Real power flows only (proportional to current) • BΘ (full) or PTDF (compact) approach Extensions: • Accounts for losses (extension) • Incorporates AC feasibility; requires nomograms/cutsets to proxy reliability requirements	**SCUC+ACOPF** • Co-optimizes real and reactive power dispatch • Accounts for commitments needed for blackstart service, reactive support, voltage support, and interface control • Nonlinear, nonconvex on meshed networks (need to approximate)

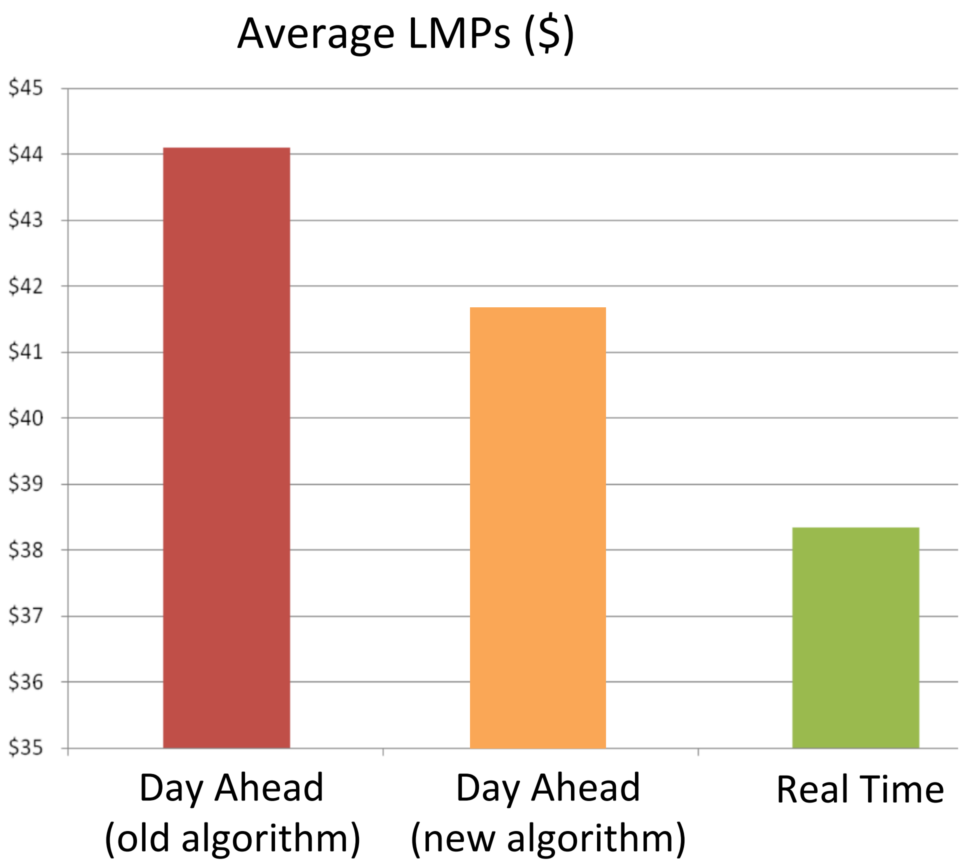
Issues in Day-Ahead Energy Markets

- Operational Challenges
  - Committing Least Cost + Maintaining Reliability
  - Out-of-Merit Reliability Commitments
  - Better convergence between day-ahead and real-time prices
- Algorithmic Challenges
  - Accounting for reliability needs in dispatch and pricing optimization
  - Better physical representation of the generating units and underlying network

Reliability Commitment Example



Load Forecast: 100 MW



PJM
October 3, 2012

Source: PJM “Impact of Reliability Units Being Included in the Day-Ahead Market” (2013)

SCUC+ACOPF: Parameterization

System Parameterizations

Nodal voltage limits
Reserve requirements
Real and reactive power load
Transformer tap ratio and phase-shifters
Thermal line limit and line resistance, reactance, and susceptance
Shunts

Generator Characteristics

Synchronous condensers
Power generated and unit-on state in T0
Minimum/maximum real and reactive power outputs
Minimum up/down time
Ramp up/down limits
Startup/shutdown ramp limits
Startup lags
Startup/shutdown costs

SCUC+ACOPF: MINLP

min Production Costs + Start-up Costs + No-Load Costs

$s.t.$

AC Network Limits[1]
Real power balancing
Reactive power balancing
Voltage magnitude bounds
Thermal line limits
Spinning reserves

Apparent Power Production Limits[2]
Maximum/minimum real power generation
Maximum/minimum reactive power generation
Ramp up/down rates on real power
Minimum up/down time

1. Extends Castillo, Lipka, Watson, Oren, and O'Neill. "A successive linear programming approach to solving the IV-ACOPF," Submitted to *IEEE Trans. On Power Syst*., 2015.
2. Extends Carrion and Arroyo. "A computationally efficient mixed-integer linear formulation for the thermal unit commitment problem," *IEEE Trans. On Sustainable Energy*, vol. 2, no. 1, pp. 69-77, 2011.

SCUC+ACOPF: (Compact) Formulation

$$\min \sum_{i \in I, t \in T} \left(f_{it}^{p}\left(p_{it}\right) + f_{it}^{u}\left(u_{it}\right) \right)$$

s.t.

$$\sum_{i \in I(n)} p_{it} - \left(v_{nt}^{r} i_{nt}^{r} + v_{nt}^{j} i_{nt}^{j} \right) = P_{nt}^{d}, \forall n \in N, t \in T$$

$$\sum_{i \in I(n)} q_{it} + \left(v_{nt}^{r} i_{nt}^{j} - v_{nt}^{j} i_{nt}^{r} \right) = Q_{nt}^{d}, \forall n \in N, t \in T$$

$$\left(V_{n}^{\min}\right)^{2} \le \left(v_{nt}^{r}\right)^{2} + \left(v_{nt}^{j}\right)^{2} \le \left(V_{n}^{\max}\right)^{2}, \forall n \in N, t \in T$$

$$i_{nt}^{r} - \sum_{k(n,\cdot)} i_{k(n,m)t}^{r} = 0, \forall n \in N, t \in T$$

$$i_{nt}^{j} - \sum_{k(n,\cdot)} i_{k(n,m)t}^{j} = 0, \forall n \in N, t \in T$$

$$\left(i_{k(n,m)t}^{r}\right)^{2} + \left(i_{k(n,m)t}^{j}\right)^{2} \le \left(I_{k}^{\max}\right)^{2}, \forall k(\cdot) \in F, t \in T$$

$$i_{k(n,m)t}^{r} = \mathrm{Re}\left(Y_{k(n,m)}^{1,1} v_{nt} + Y_{k(n,m)}^{1,2} v_{mt} \right), \forall k(\cdot) \in F, t \in T$$

$$i_{k(n,m)t}^{j} = \mathrm{Im}\left(Y_{k(n,m)}^{2,1} v_{nt} + Y_{k(n,m)}^{2,2} v_{mt} \right), \forall k(\cdot) \in F, t \in T$$

$$\sum_{i \in I(n)} r_{it} \ge R_{t}, \forall t \in T$$

$$p, q, r, u \in \Omega \ \left(\text{feasible set of apparent power production}\right)$$

$f_{it}^{u}\left(u_{it}\right)$ is the startup and no-load cost

$f_{it}^{p}\left(p_{it}\right)$ is the incremental cost

u_{it} is the commitment status for generator i at time t

p_{it}, q_{it}, r_{it} are the real and reactive power, and reserves for generator i at time t

$\left(v_{nt}^{r}\right)^{2} + \left(v_{nt}^{j}\right)^{2}$ is the nodal voltage magnitude squared for node n

$\left(i_{k(n,m)t}^{r}\right)^{2} + \left(i_{k(n,m)t}^{j}\right)^{2}$ is the directional flow current magnitude squared for network element k

Linearization Constraint Set
MINLP → MIP

Taylor Series Approximation

Real power balancing

Reactive power balancing

Line current magnitude squared

Nodal voltage magnitude squared

$$h\left(x^{k+1}\right)=h\left(x^{k}\right)+\nabla h\left(x^{k}\right)^{T}\left(x^{k+1}-x^{k}\right)$$

Linearization Constraint Set
MINLP → MIP

Slack Variables Penalized in Cost Function

Nodal voltage magnitude bounds
Thermal line limits
Spinning reserves
Load mismatch

$$x^L - \varepsilon^- \le x \le x^U + \varepsilon^+$$

Taylor Series Approximation

Real power balancing
Reactive power balancing
Line current magnitude squared
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$$h\left(x^{k+1}\right) = h\left(x^k\right) + \nabla h\left(x^k\right)^T \left(x^{k+1} - x^k\right)$$

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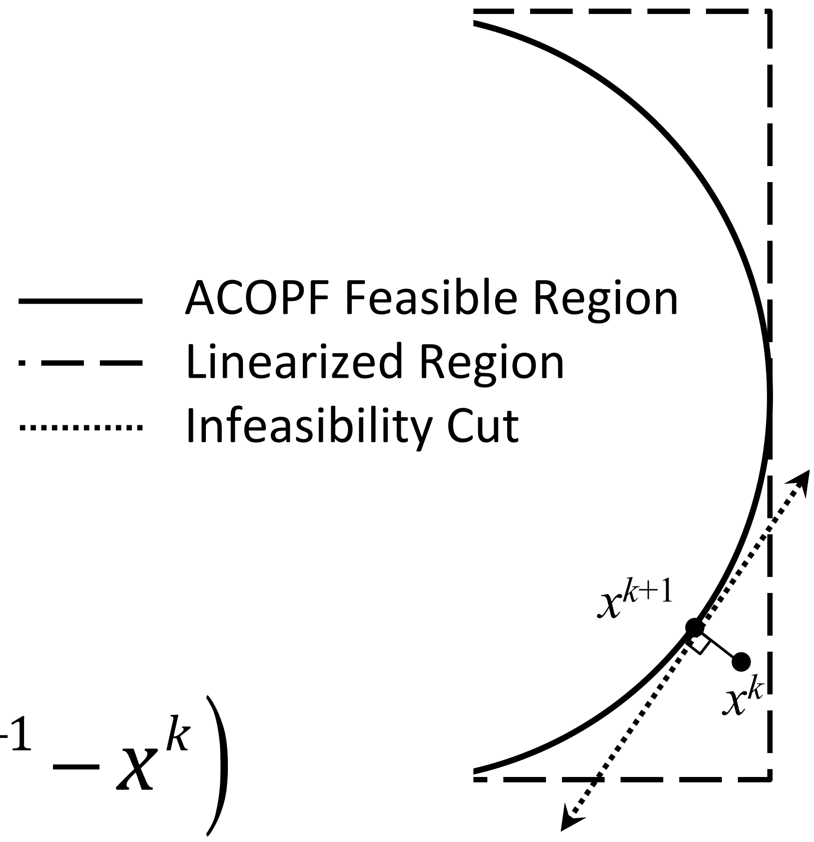
$$x^{L}-\varepsilon^{-}\leq x\leq x^{U}+\varepsilon^{+}$$

Infeasibility Handling

Nodal voltage magnitude upperbounds

Thermal line limit



Taylor Series Approximation

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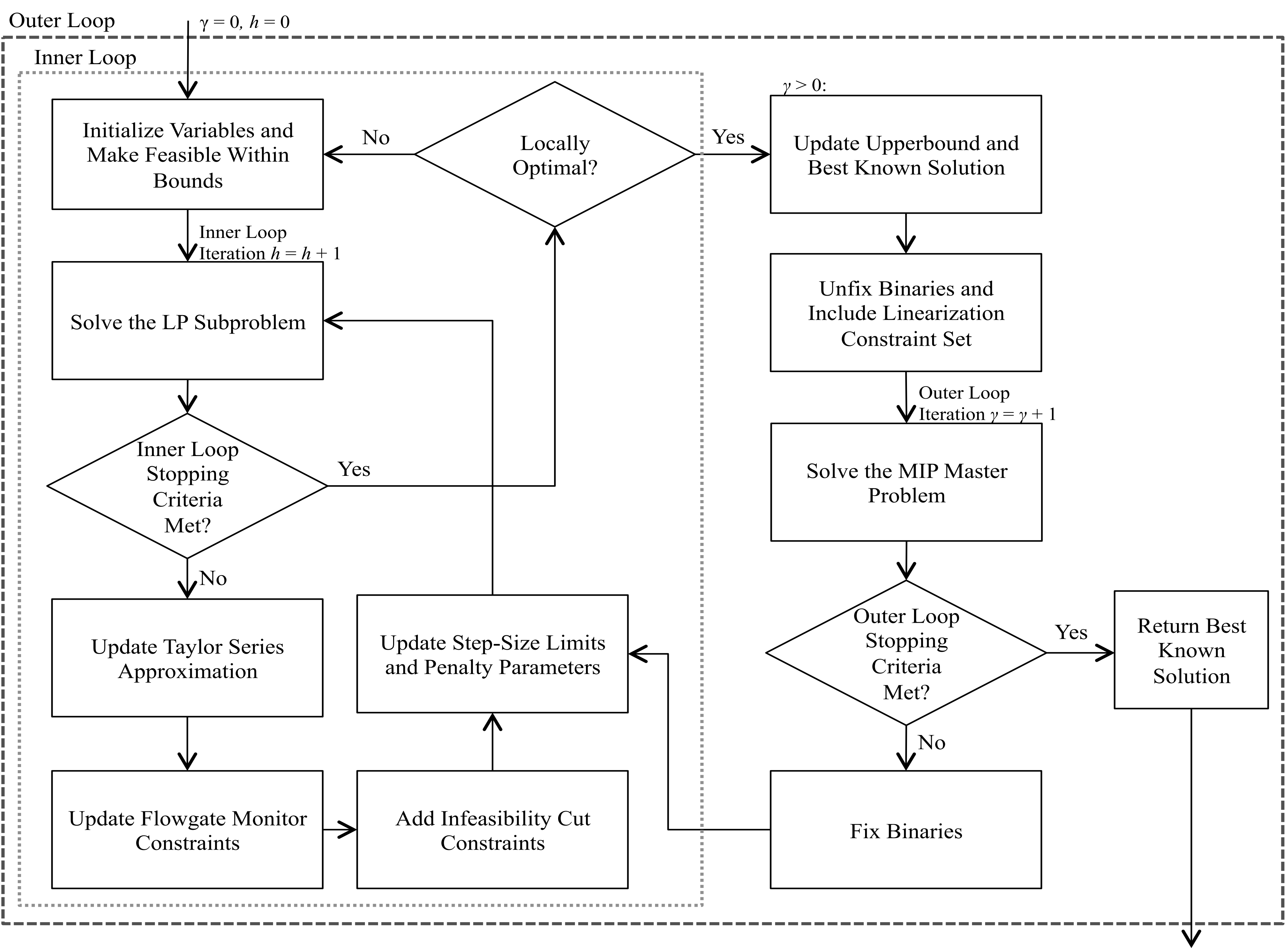
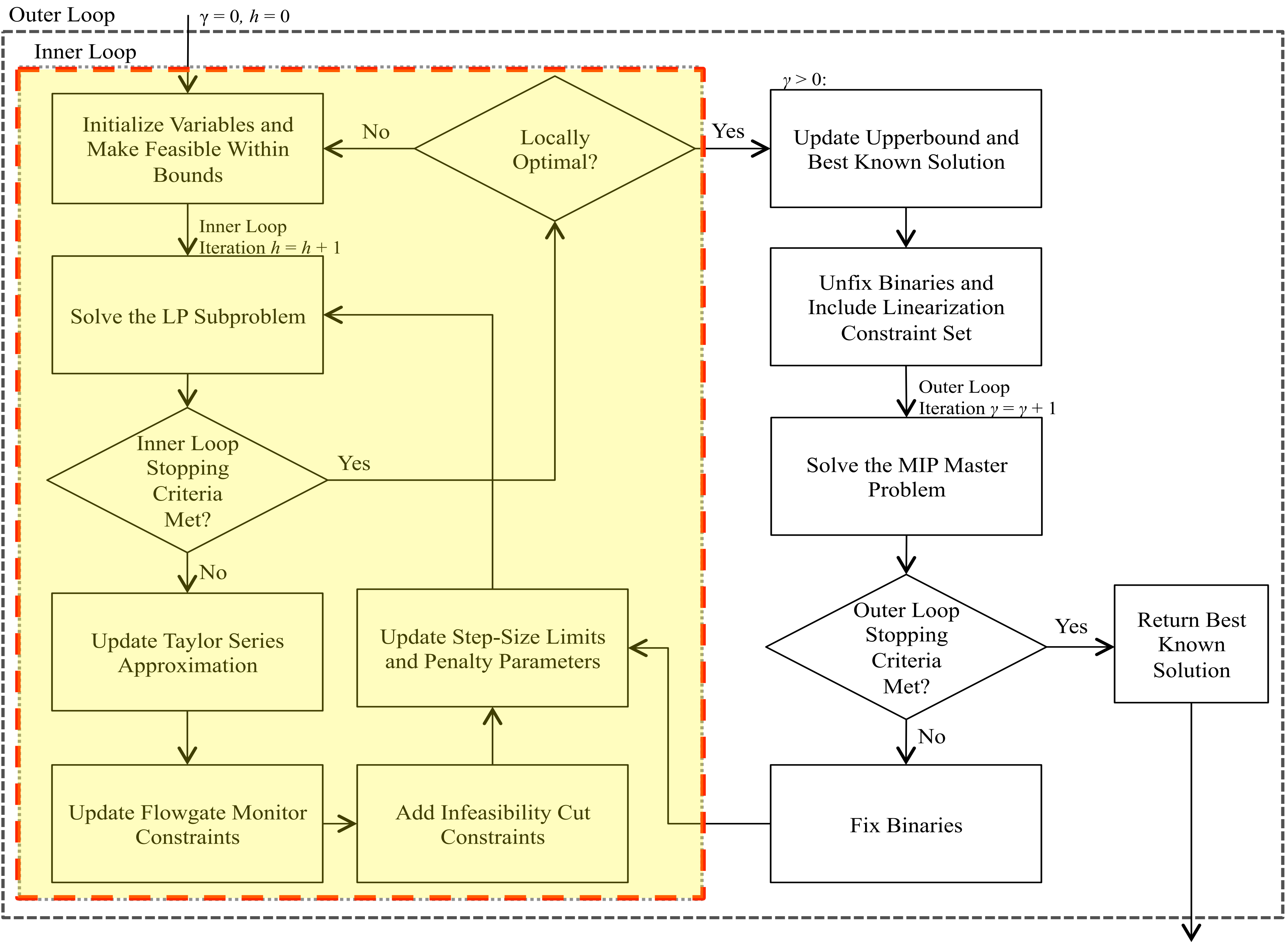


Outer Loop
$\gamma = 0,\ h = 0$
Inner Loop
Initialize Variables and Make Feasible Within Bounds
No
Locally Optimal?
Yes
$\gamma > 0$:
Update Upperbound and Best Known Solution
Inner Loop Iteration $h = h + 1$
Solve the LP Subproblem
Unfix Binaries and Include Linearization Constraint Set
Outer Loop Iteration $\gamma = \gamma + 1$
Inner Loop Stopping Criteria Met?
Yes
Solve the MIP Master Problem
No
Update Taylor Series Approximation
Update Step-Size Limits and Penalty Parameters
Outer Loop Stopping Criteria Met?
Yes
Return Best Known Solution
No
Update Flowgate Monitor Constraints
Add Infeasibility Cut Constraints
Fix Binaries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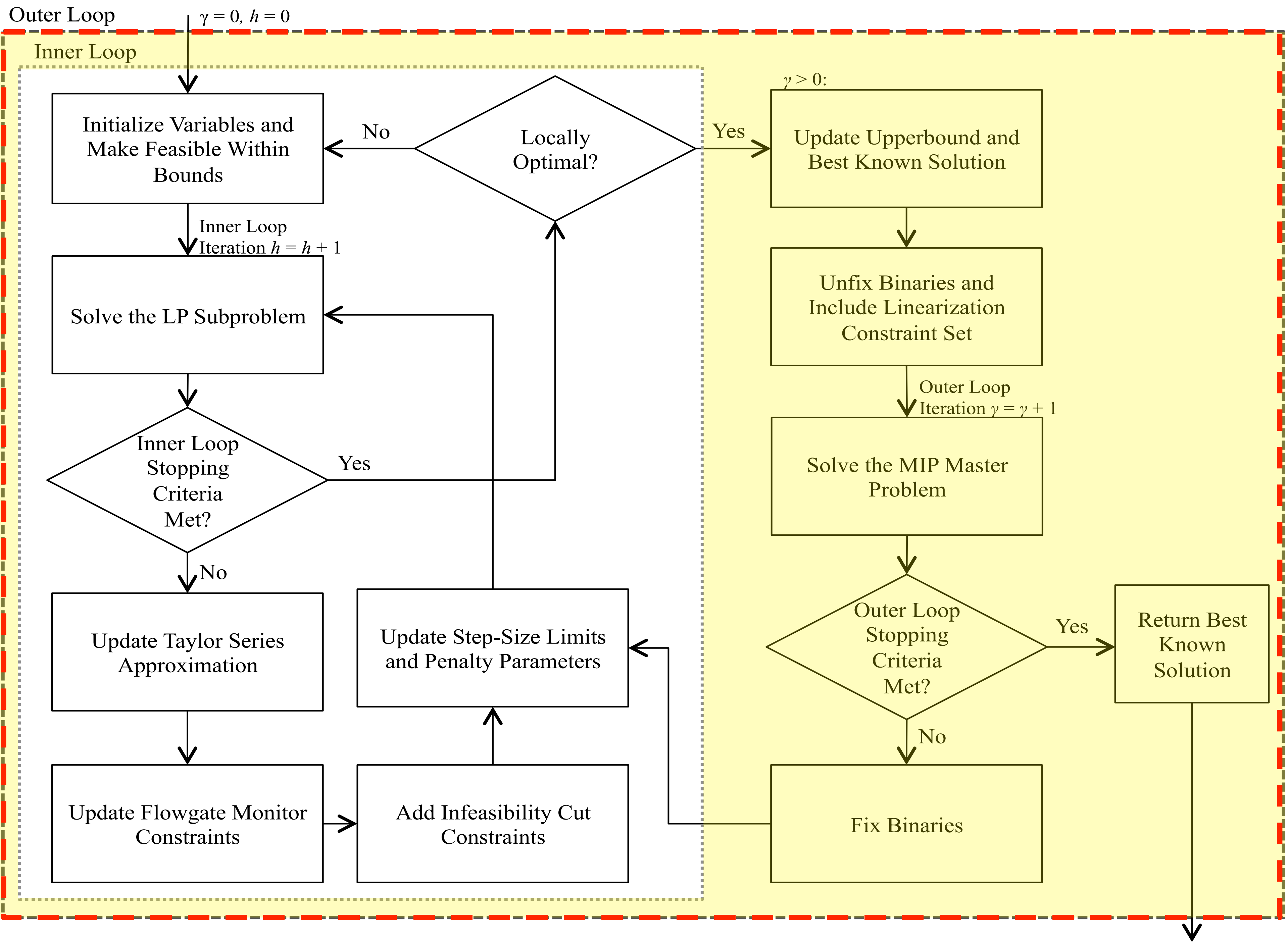

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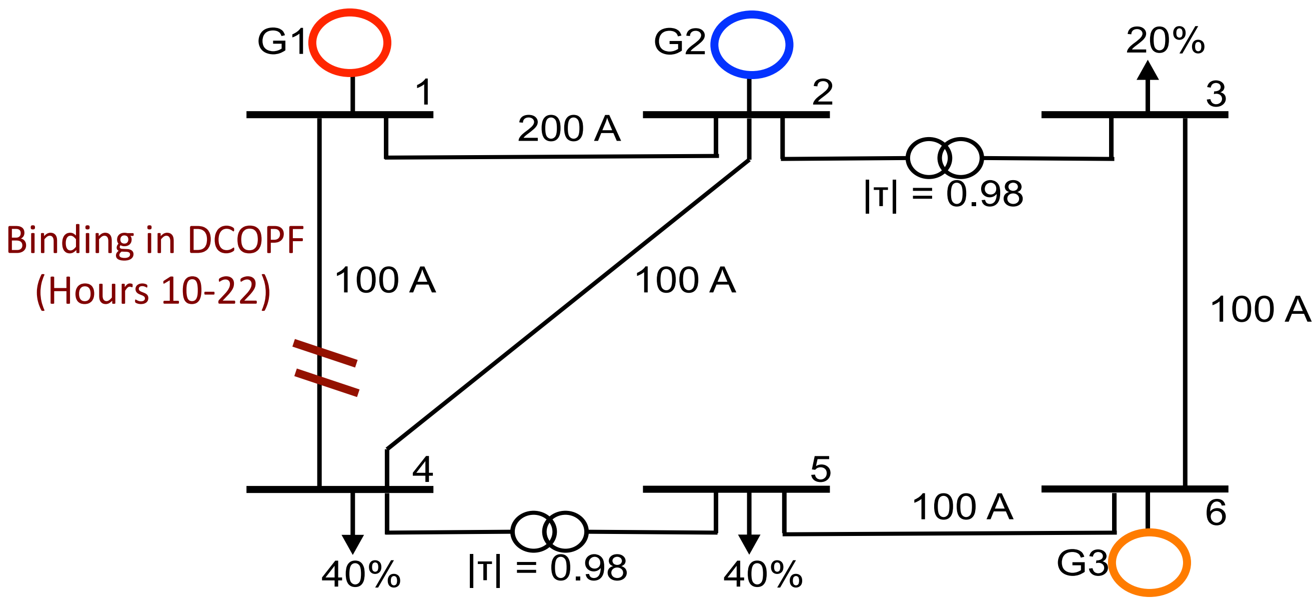
Comparative Case Studies

UC	SCUC+DCOPF	SCUC+ACOPF	SCUC+DCOPF+RUC
No capacity line limits No reactive power dispatch	Capacity line limits determined as $P^{max} = VI^{max}$ where V = 1 p.u. No reactive power dispatch	Capacity line limits determined as thermal line ratings (I^{max}) on the current magnitude *Compared to DCOPF*: V > 1 p.u. → Higher power transfers V < 1 p.u. → Lower power transfers	Initially a SCUC+DCOPF is solved to determine the commitment schedule; if the solution is not AC feasible, then solve the SCUC+ACOPF with the specified commitment schedule in order to determine residual unit (add'l) commitments.

6-Bus Example[1]



G1: $100 \leq p_{it} \leq 220$ MW
Ramp: +/- 55 MW
$-80 \leq q_{it} \leq 200$ MVAr
Min Up/Down Time: 4 Hr

G2: $10 \leq p_{it} \leq 100$ MW
Ramp: +/- 50 MW
$-40 \leq q_{it} \leq 70$ MVAr
Min Up/Down Time: 2/3 Hr

G3: $10 \leq p_{it} \leq 20$ MW
Ramp: +/- 20 MW
$-40 \leq q_{it} \leq 50$ MVAr
Min Up/Down Time: 1 Hr

	Start-Up ($)	**No-Load ($)**	**Production Cost ($/MWh)**
G1	124.69	220.58	$0.0005(p_{it})^2 + 16.83p_{it}$
G2	249.22	161.87	$0.001(p_{it})^2 + 40.62p_{it}$
G3	0	171.23	$0.006(p_{it})^2 + 21.93p_{it}$

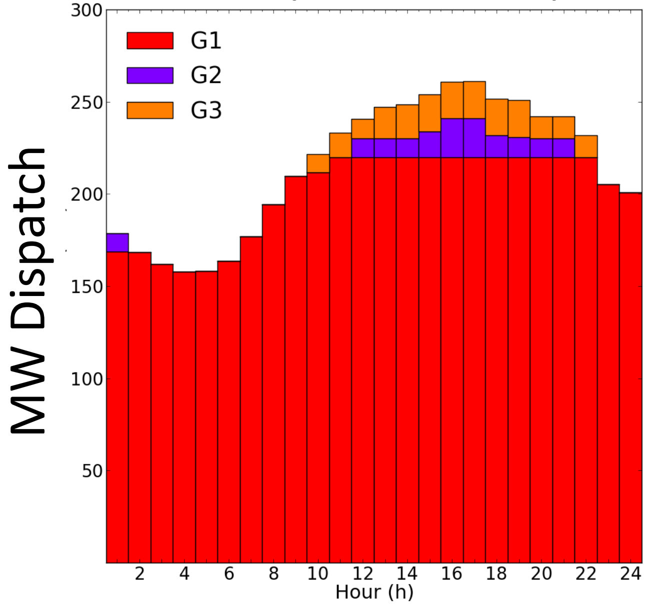
	UC	**SCUC+DCOPF**	**SCUC+ACOPF**
Cost ($)	101,269 (base)	106,987 (+5.8%)	101,762 (+0.5%)
G1 (Hr)	1-24	1-24	1-24
G2 (Hr)	1,12-21	1,11-22	1,12-21
G3 (Hr)	10-22	10-22	10-22

1. Data Source: Fu, Shahidehpour, and Li. "AC Contingency Dispatch Based on Security-Constrained Unit Commitment," IEEE Transactions on Power Systems, vol. 21, no. 2, May 2006.

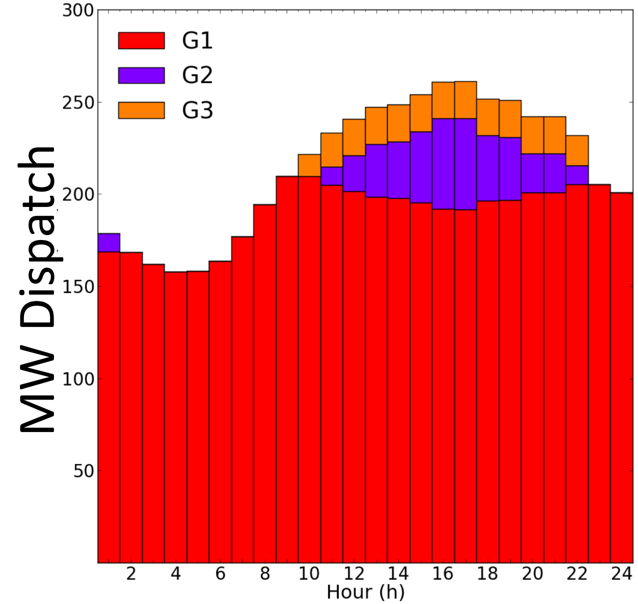
6-Bus Dispatch Stacks

UC commitments and dispatch equivalent to SCUC+ACOPF (minus losses)

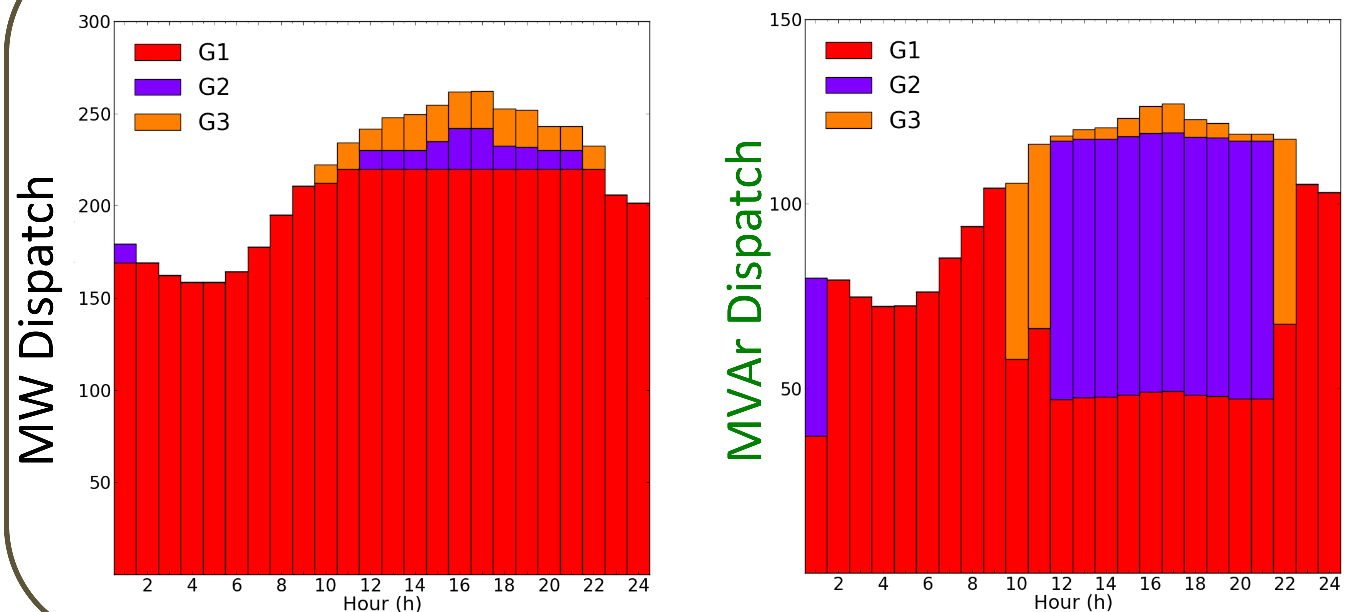
UC (no network)



SCUC+DCOPF



SCUC+ACOPF



6-Bus Dispatch Stacks

UC commitments and dispatch equivalent to SCUC+ACOPF (minus losses)

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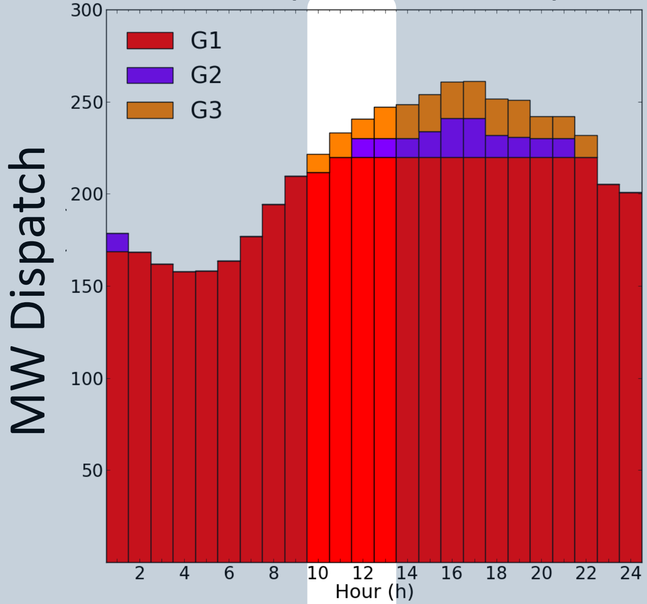
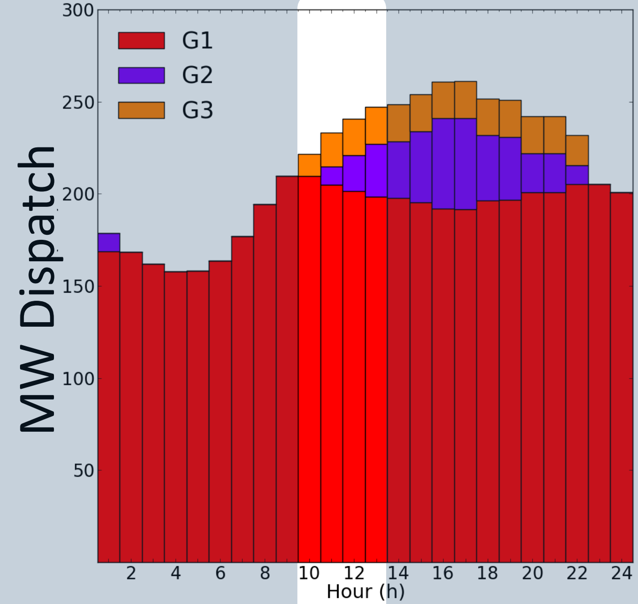


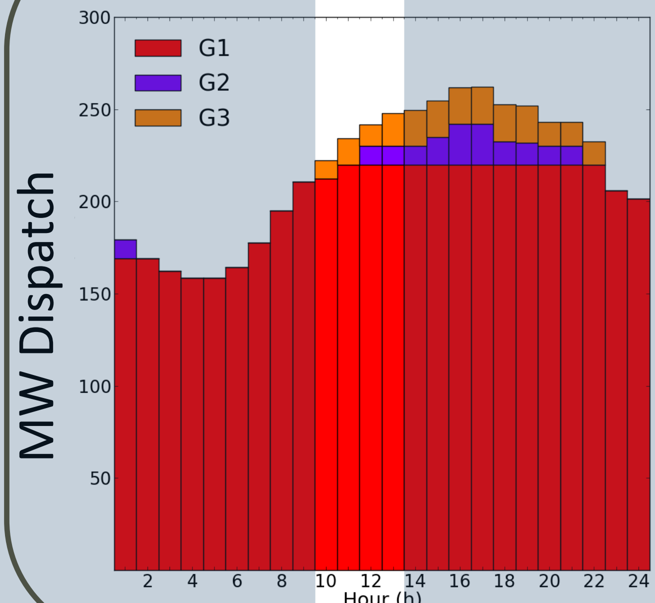
SCUC+DCOPF

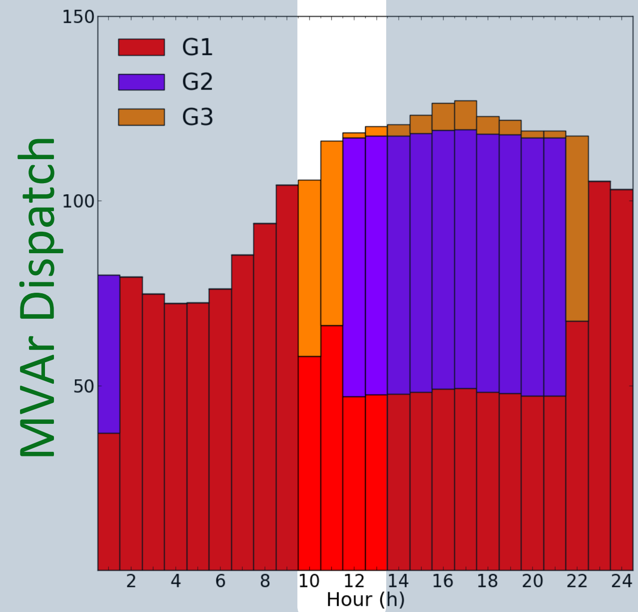


SCUC+DCOPF congestion begins in hour 10

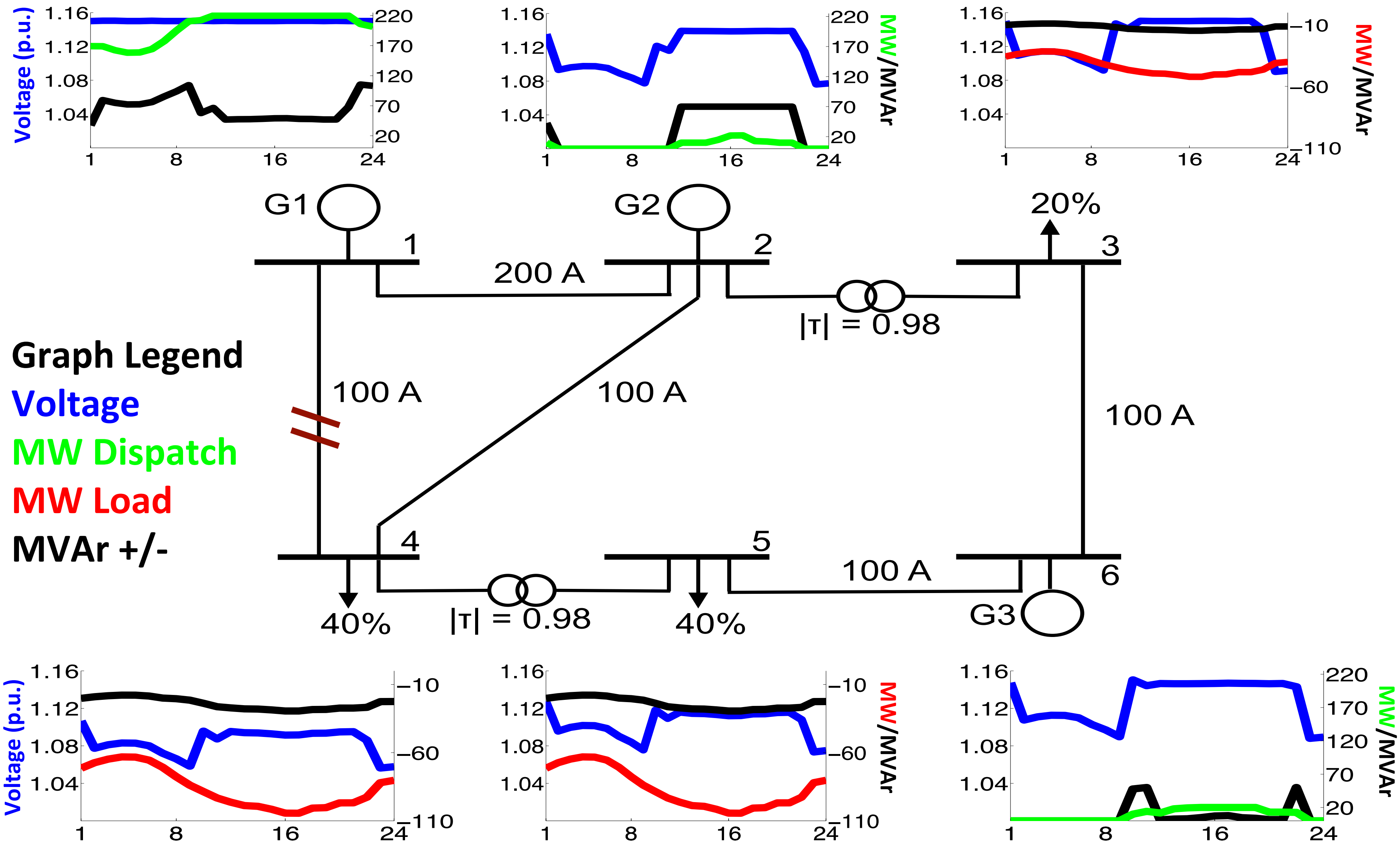
More VAr from G2 and G3 starting in hours 10-12 in SCUC +ACOPF

SCUC+ACOPF



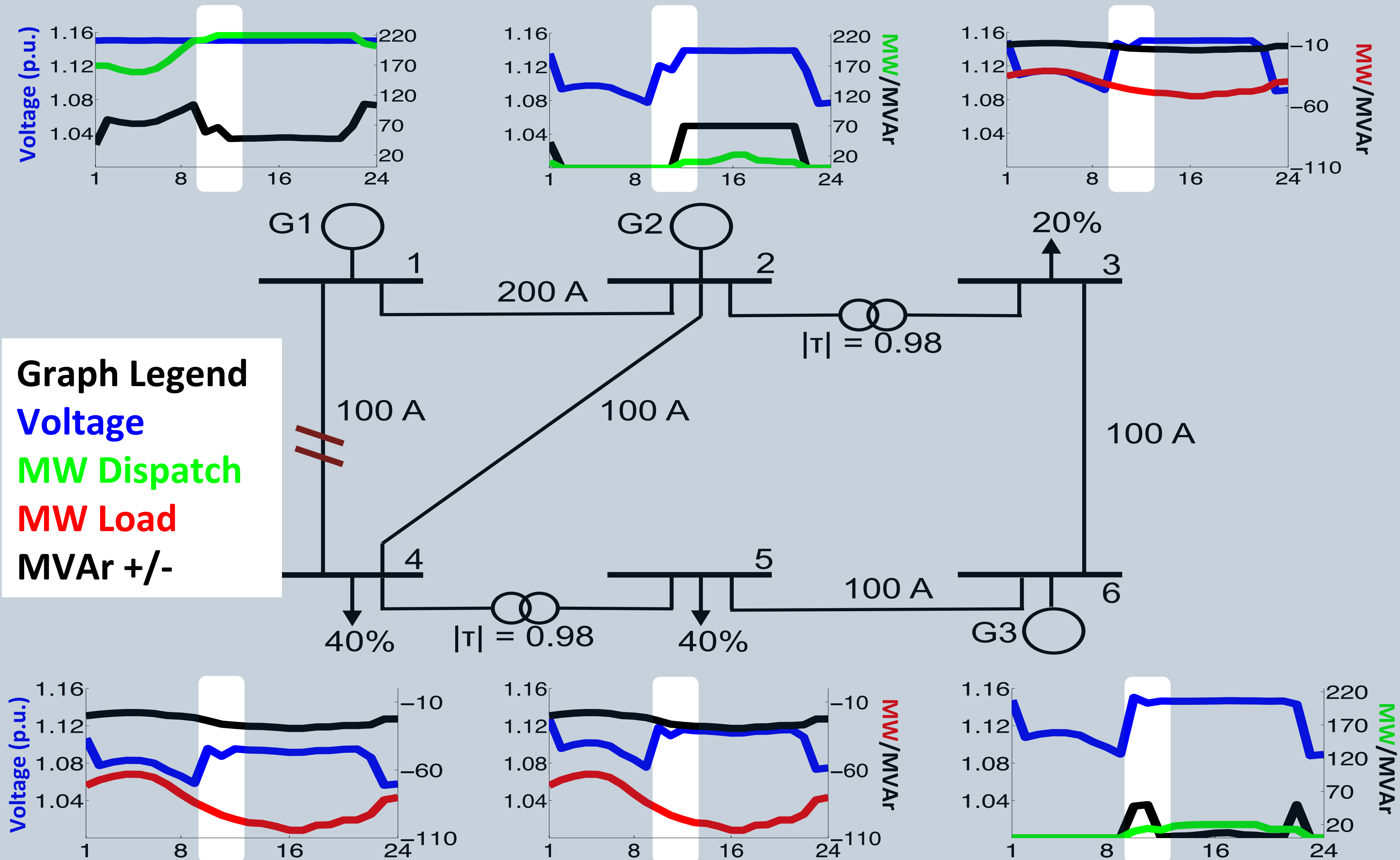


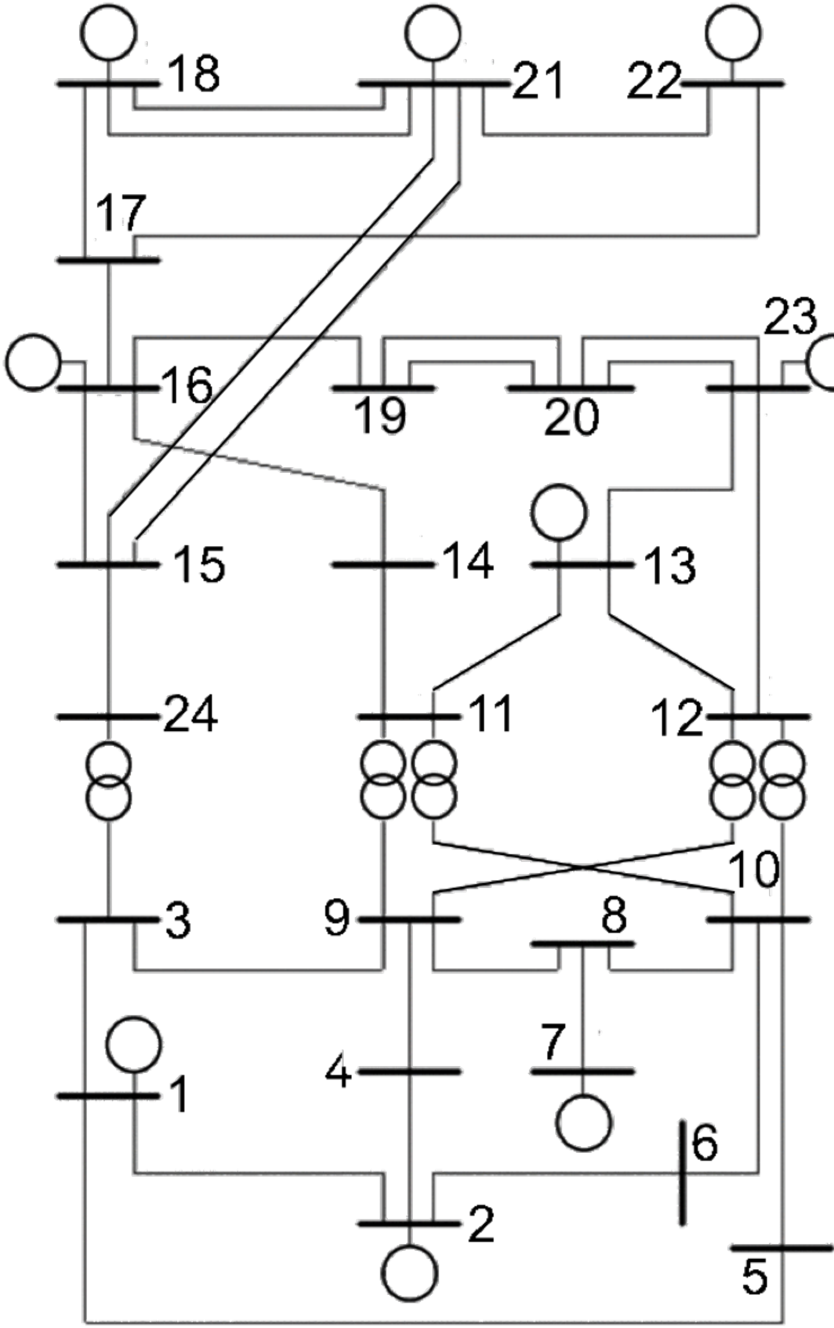
6-Bus Nodal Voltage Profiles and Dispatch



Graph Legend
Voltage
MW Dispatch
MW Load
MVAr +/-

6-Bus Nodal Voltage Profiles and Dispatch





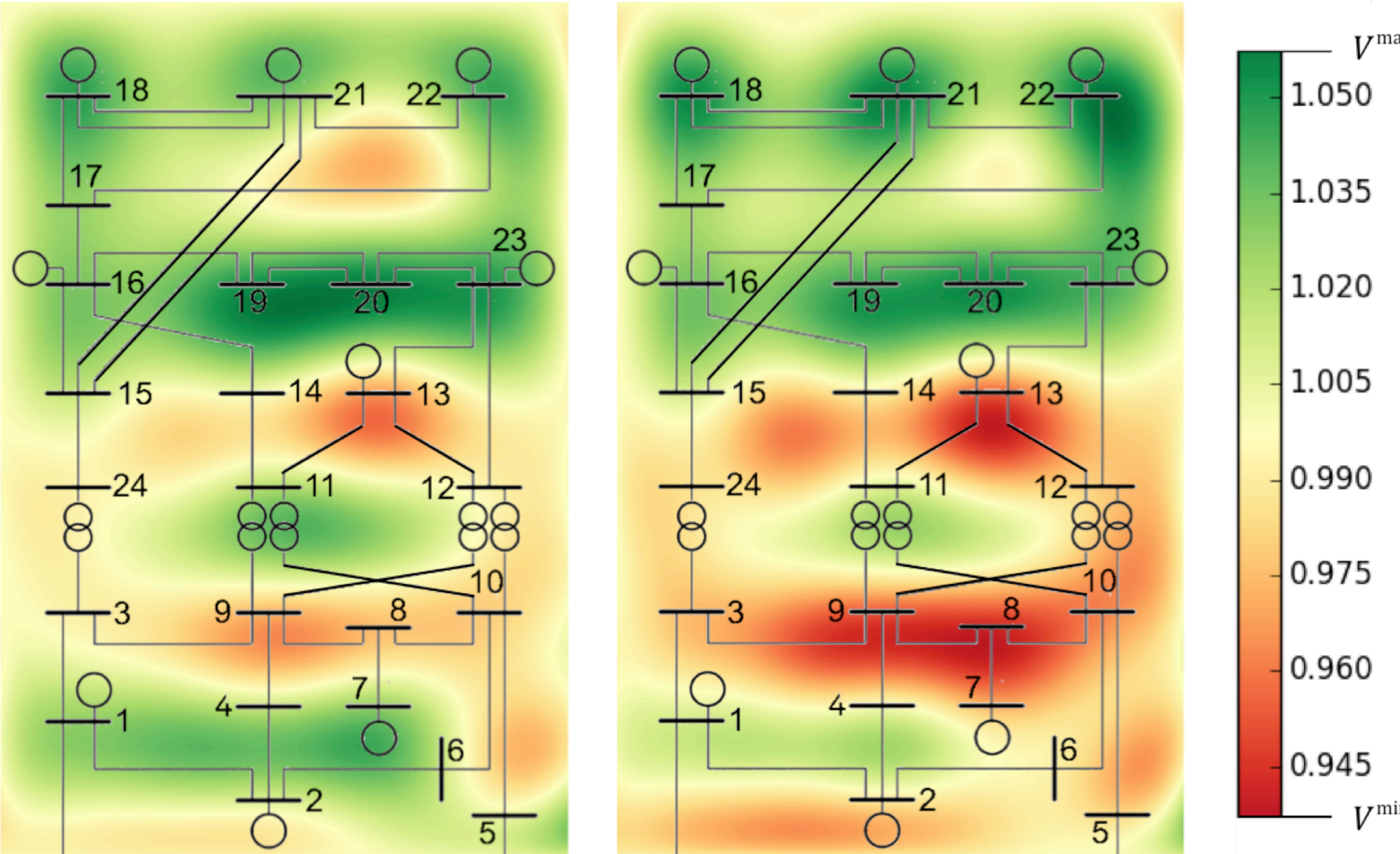
RTS-96[1]

24 nodes
32 generators
17 loads
1 synchronous condenser
38 network elements/lines

	Cost ($)	AC Feasible?
UC	822,977 (base)	NO
SCUC+DCOPF	823,648 (+0.1%)	NO
SCUC+ACOPF	873,984 (+5.8%)	YES
SCUC+DCOPF+RUC	879,751 (+6.5%)	YES

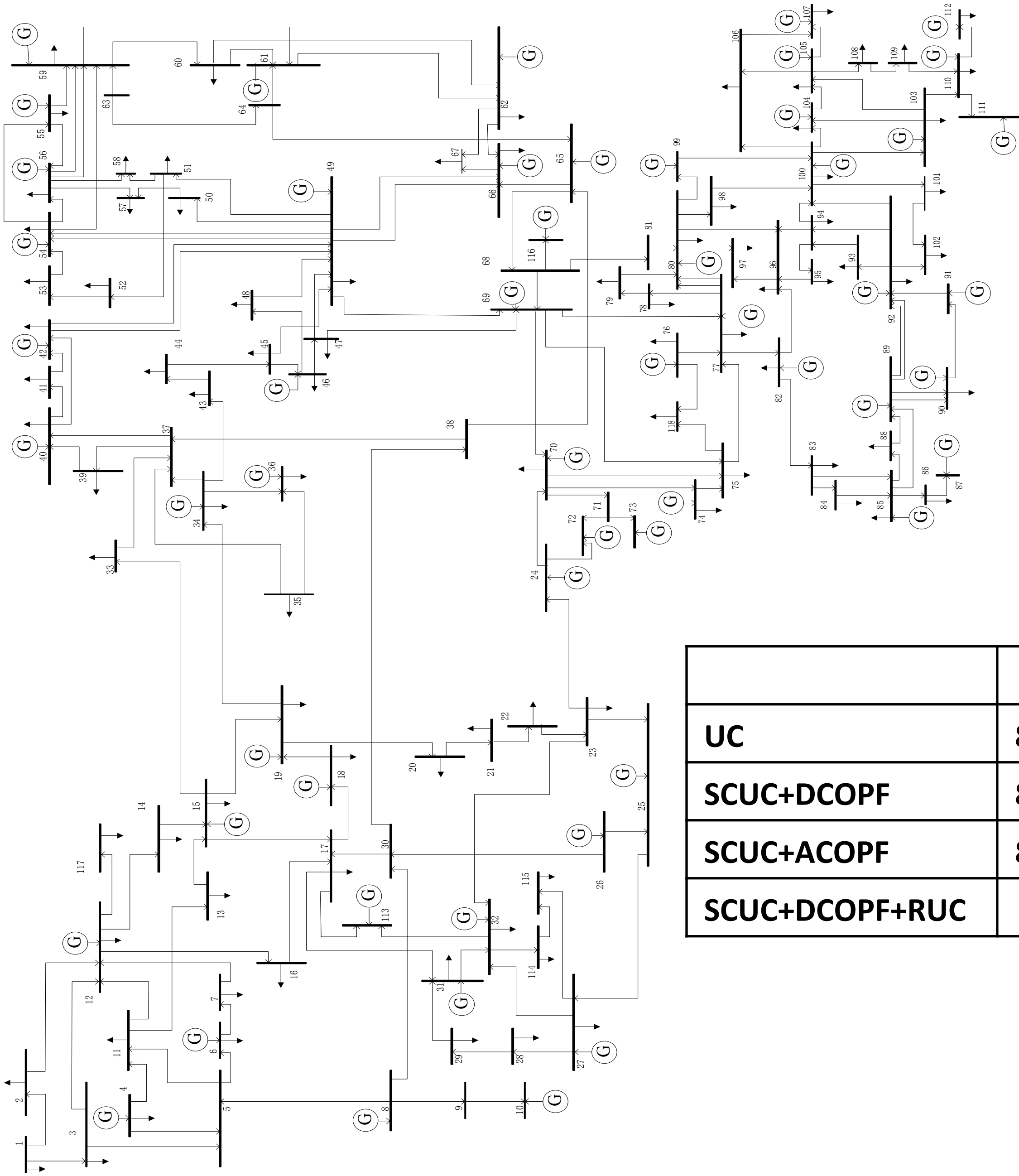
1. Data Source: Reliability Test System Task Force, “The IEEE reliability test system -- 1996,” IEEE Trans. on Power Syst., vol. 14, no. 3, 1999.

RTS-96 Voltage Levels



SCUC+ACOPF **(ACOPF FEASIBLE)**

SCUC+DCOPF **(LOAD MISMATCH)**



IEEE-118[1]

118 nodes
54 generators
91 loads
186 network elements/lines

	Cost ($)	AC Feasible?
UC	812,369 (base)	NO
SCUC+DCOPF	814,703 (+0.41%)	NO
SCUC+ACOPF	845,983 (+3.97%)	YES
SCUC+DCOPF+RUC	-	-

1. Data Source: Fu, Shahidehpour, and Li. "AC Contingency Dispatch Based on Security-Constrained Unit Commitment," IEEE Transactions on Power Systems, vol. 21, no. 2, May 2006.

Conclusions

- Findings
  - The SCUC+ACOPF can result in a different commitment schedule compared to current practices
  - The residual commitments to make current models AC feasible can be expensive
- Preliminary Stats (CPLEX 12.6.2)
  - Linearized ACOPF solves 3.4k node network (Polish, 1 time period) in ~ 60 seconds
  - SCUC+ACOPF solves RTS-96 (24 time period) in ~ 136 seconds (47% in SLP, 53% in MIP)
  - SCUC+ACOPF solves IEEE-118 (24 time period) in ~ 15-20 minutes (SLP << MIP time)
- Next Steps…
  - Improve scalability
  - Parameterize solver options and algorithm defaults
  - Incorporating models of controllable network devices (transformers, phase-shifters, FACTS, etc.)