Commercialization of the SuperOPF Framework: Phase III (Theme: Co-optimization Stochastic SuperOPF-renewables)

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Phase I:

1. (support industrial model) A commercial-grade core SuperOPF software supporting various industrial-grade power system models such as

(i) CIM-compliance; and

(ii) PSS/E data format

2. A multi-stage OPF solver with <u>adaptive homotopy-based Interior Point Method</u> for large-scale power systems (PJM: 14,000-bus data)

Results: Efficiency and Robustness (Analytical Jacobian matrices)

Robustness of our method

Loading Conditions	**One-Staged Interior Point Method**	**Multi-Staged Scheme**
1	Succeeded	Succeeded
2	Succeeded	Succeeded
3	Succeeded	Succeeded
4	Succeeded	Succeeded
5	Failed	Succeeded
6	Failed	Succeeded
7	Failed	Succeeded
8	Failed	Succeeded
9	Failed	Succeeded
10	Failed	Succeeded

Challenges

$$\min C(x)$$

Subject to: $h(x) = 0$

$g(x) \le 0$

However, security-constrained OPF can not be expressed as the above analytical form:

i. Power balance equations: $h(x) = 0$

ii. Voltage limit constraints: $\underline{x} \le x \le \overline{x}$

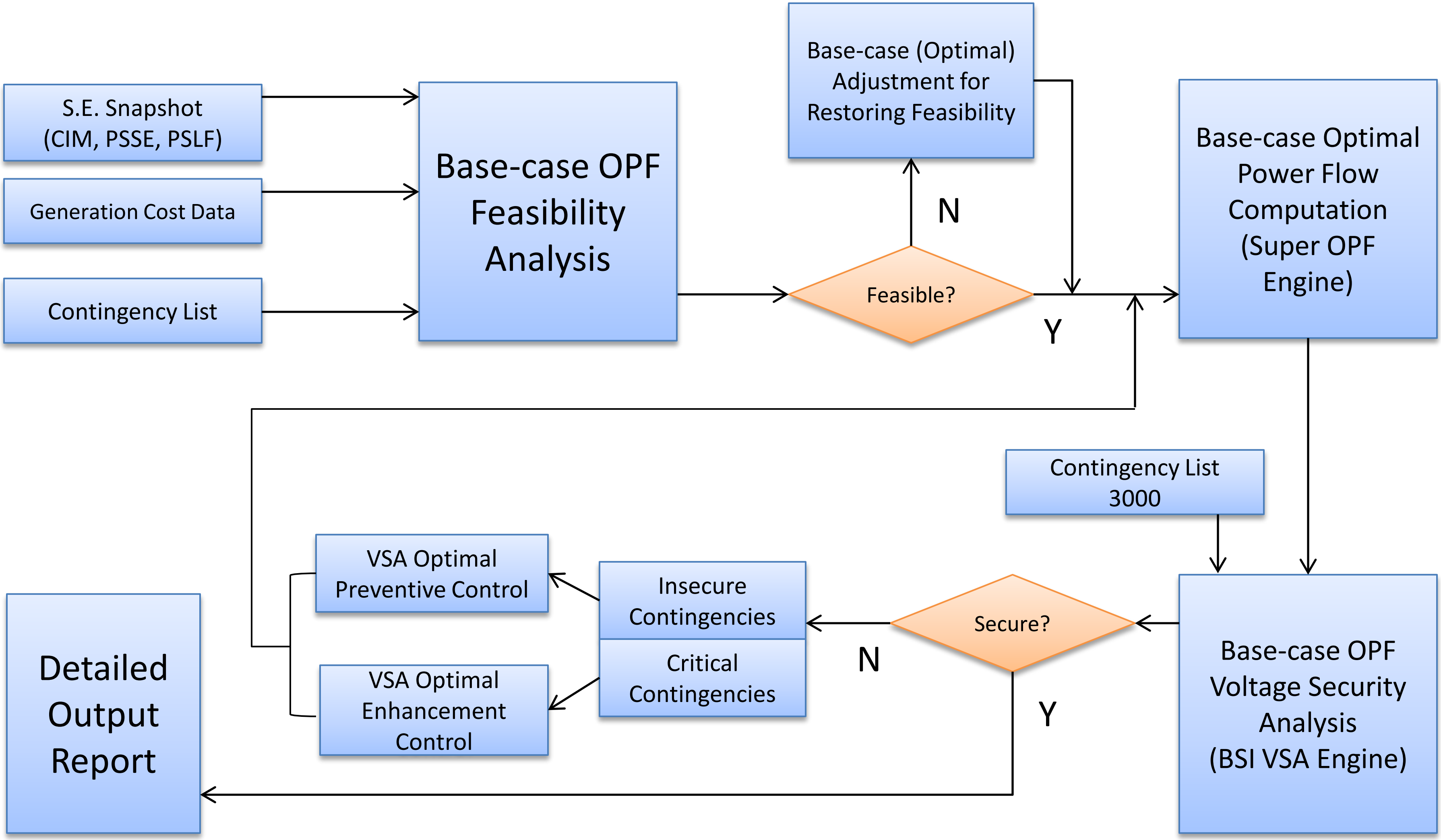
iii. Thermal limit constraints: $g(x) \le 0$

iv. Transient-stability constraints: ???

v. Voltage stability constraints: ???

Super-OPF-VS (Voltage Stability) (Phase II)

1. Input 2. Feasibility Check 3. Ensuring Feasibility 4. Computation Engine



S.E. Snapshot (CIM, PSSE, PSLF)

Generation Cost Data

Contingency List

Base-case OPF Feasibility Analysis

Feasible?

N

Y

Base-case (Optimal) Adjustment for Restoring Feasibility

Base-case Optimal Power Flow Computation (Super OPF Engine)

Contingency List 3000

Base-case OPF Voltage Security Analysis (BSI VSA Engine)

Secure?

N

Y

Insecure Contingencies

Critical Contingencies

VSA Optimal Preventive Control

VSA Optimal Enhancement Control

Detailed Output Report

7. Output Report 6. VSA Enhancement 5. VSA Check

Super-OPF Contingency Analysis

CAISO 6534-Bus System

Initial Power Flow

Super-OPF Solution

BSI VSA Preventive Control

CAISO System
1062 N-1
Contingencies

0	0	3010.028	-20.088	0	3010.028
1	21	-0.305	-0.305	3	0.000
2	34	-0.218	-0.218	6	0.000
3	691	-0.100	-0.100	17	0.000
4	8	-0.066	-0.066	1	0.000
5	35	-0.060	-0.060	5	0.000
6	24	-0.056	-0.056	2	0.000
7	36	-0.015	-0.015	4	0.000
8	639	1353.153	-9.031	12	2347.311
9	281	1884.894	-12.579	10	1397.252
10	282	1884.894	-12.579	11	1397.252
11	491	2715.639	-18.123	14	2481.276
12	492	2715.639	-18.123	13	2481.276
13	561	2716.463	-18.129	15	2485.825
14	521	2730.695	-18.224	16	2503.604
15	572	2789.834	-18.619	41	2789.834
16	864	2791.814	-18.632	42	2791.814
17	863	2791.814	-18.632	43	2791.814
18	628	2805.778	-18.725	44	2805.778
19	690	2807.721	-18.738	18	2619.026
20	684	2822.604	-18.837	47	2822.604

Load margin: 3010MW
Objective (loss):
2793.6MW
7 insecure contingencies

0	0	4840.000	-32.301	0	4840.000
1	21	-0.285	-0.285	3	0.000
2	34	-0.253	-0.253	5	0.000
3	35	-0.071	-0.071	4	0.000
4	8	-0.050	-0.050	1	0.000
5	24	-0.042	-0.042	2	0.000
6	561	4373.778	-29.189	16	4304.356
7	491	4386.839	-29.276	15	4284.000
8	492	4386.839	-29.276	14	4284.000
9	691	4404.315	-29.393	20	4404.315
10	521	4407.446	-29.414	17	4316.588
11	690	4437.187	-29.612	23	4437.187
12	281	4494.606	-29.996	18	4381.087
13	282	4494.606	-29.996	19	4381.087
14	639	4508.597	-30.089	21	4413.366
15	428	4544.092	-30.326	25	4483.436
16	432	4544.092	-30.326	26	4483.436
17	431	4544.092	-30.326	27	4483.436
18	430	4544.092	-30.326	28	4483.436
19	429	4544.092	-30.326	29	4483.436
20	501	4555.107	-30.399	30	4511.405

Load margin: 4840MW
Objective (loss):
1642.8MW
5 insecure contingencies

0	0	4840.161	-32.302	0	4840.161
1	561	4376.021	-29.204	23	4303.308
2	492	4389.094	-29.291	22	4282.792
3	491	4389.094	-29.291	21	4282.792
4	521	4409.681	-29.429	24	4315.462
5	690	4436.558	-29.608	25	4436.558
6	691	4509.283	-30.094	6	2244.418
7	431	4546.083	-30.339	26	4482.817
8	430	4546.083	-30.339	27	4482.817
9	429	4546.083	-30.339	28	4482.817
10	428	4546.083	-30.339	29	4482.817
11	432	4546.083	-30.339	30	4482.817
12	501	4556.994	-30.412	31	4510.822
13	509	4564.158	-30.460	32	4514.185
14	281	4571.971	-30.512	14	2416.908
15	282	4571.971	-30.512	15	2416.908
16	506	4577.873	-30.551	33	4534.745
17	662	4580.186	-30.567	38	4550.269
18	663	4580.186	-30.567	39	4550.269
19	456	4585.097	-30.599	34	4536.546
20	455	4585.097	-30.599	35	4536.546

Load margin: 4840MW
Objective (loss):
1674.6MW
No insecure contingency

Super-OPF Contingency Analysis

PJM 13183-Bus System


Initial Power Flow

Super-OPF Solution

BSI VSA Preventive Control

PJM System 6894
N-1 Contingencies

```
 0     0   4900.904  1143.944   0   4900.904
 1  2708     -0.200    -0.200  15      0.000
 2  3628     -0.134    -0.134   4      0.000
 3  1742     -0.126    -0.126   7      0.000
 4  3528     -0.120    -0.120  14      0.000
 5  1757     -0.119    -0.119  10      0.000
 6  6096     -0.100    -0.100   8      0.000
 7  5756     -0.100    -0.100   2      0.000
 8  5162     -0.094    -0.094  13      0.000
 9  2228     -0.064    -0.064   3      0.000
10  2025     -0.049    -0.049   9      0.000
11  2453     -0.038    -0.038   1      0.000
12  3619     -0.038    -0.038   5      0.000
13  4877     -0.034    -0.034  12      0.000
14  1999     -0.030    -0.030   6      0.000
15  3599     -0.021    -0.021  19      0.000
16  1543     -0.015    -0.015  11      0.000
17  3917   4385.884  1023.731  24    790.538
18   124   4870.774  1136.912  34   7034.131
19  2238   4895.449  1142.671  27   4047.664
20  2806   4895.868  1142.769  29   4657.256
```

Load margin: 4901MW
Objective (loss):
5589.3MW
16 insecure contingencies

```
 0     0   4305.851  1005.050   0   4305.851
 1  3628     -0.098    -0.098   3      0.000
 2  1742     -0.097    -0.097   6      0.000
 3  1757     -0.079    -0.079   8      0.000
 4  3528     -0.078    -0.078   9      0.000
 5  1999     -0.061    -0.061   5      0.000
 6  3619     -0.030    -0.030   4      0.000
 7  2025     -0.030    -0.030   7      0.000
 8  2228     -0.025    -0.025   2      0.000
 9  3599     -0.011    -0.011   1      0.000
10   238   4150.848   968.870  23   6278.033
11   380   4203.134   981.074  22   6117.726
12   527   4265.406   995.609  28   6835.490
13   718   4267.237   996.037  27   6796.001
14   124   4294.967  1002.509  25   6677.155
15  1630   4299.961  1003.675  13    498.673
16  5142   4301.633  1004.065  11    232.497
17  5143   4301.634  1004.065  10    232.497
18   648   4302.521  1004.272  29   6846.455
19  1214   4303.292  1004.453  16   2873.253
20  2015   4303.294  1004.453  14   1537.550
```

Load margin: 4306MW
Objective (loss):
3293.0MW
9 insecure contingencies

```
 0     0   4298.985  1003.447   0   4298.985
 1  1742     -0.049    -0.049   1      0.000
 2  5952   4117.302   961.040  11   3280.010
 3   238   4138.999   966.104  16   6337.589
 4   380   4191.245   978.299  15   6162.814
 5  6563   4201.527   980.699  25   6925.380
 6   527   4255.147   993.215  21   6852.554
 7   718   4256.856   993.614  19   6810.427
 8   667   4274.275   997.680  24   6906.906
 9   317   4274.946   997.836  26   6958.633
10   124   4287.687  1000.810  18   6719.880
11  5142   4293.659  1002.204   4    232.497
12  5143   4293.663  1002.205   3    232.497
13  2015   4293.894  1002.259   6   1535.457
14  3628   4295.075  1002.534   5    621.551
15  1214   4295.432  1002.618   8   2871.496
16   568   4299.906  1003.662  28   6970.977
17   647   4301.207  1003.966  17   6697.015
18   648   4304.292  1004.686  22   6893.834
19   639   4304.703  1004.782  30   6990.219
20  6468   4307.001  1005.318   2    232.497
```

Load margin: 4299MW
Objective (loss):
3293.8MW
1 insecure contingencies

This phase is focused on the following enhancements

Topicss

Co-optimization over multiple scenario(functions)

Commercial-grade packages (applications)

Outreach and Market feedbacks

Enhancements

(i) deal with multiple base-cases (i.e., co-optimize multiple base-cases)

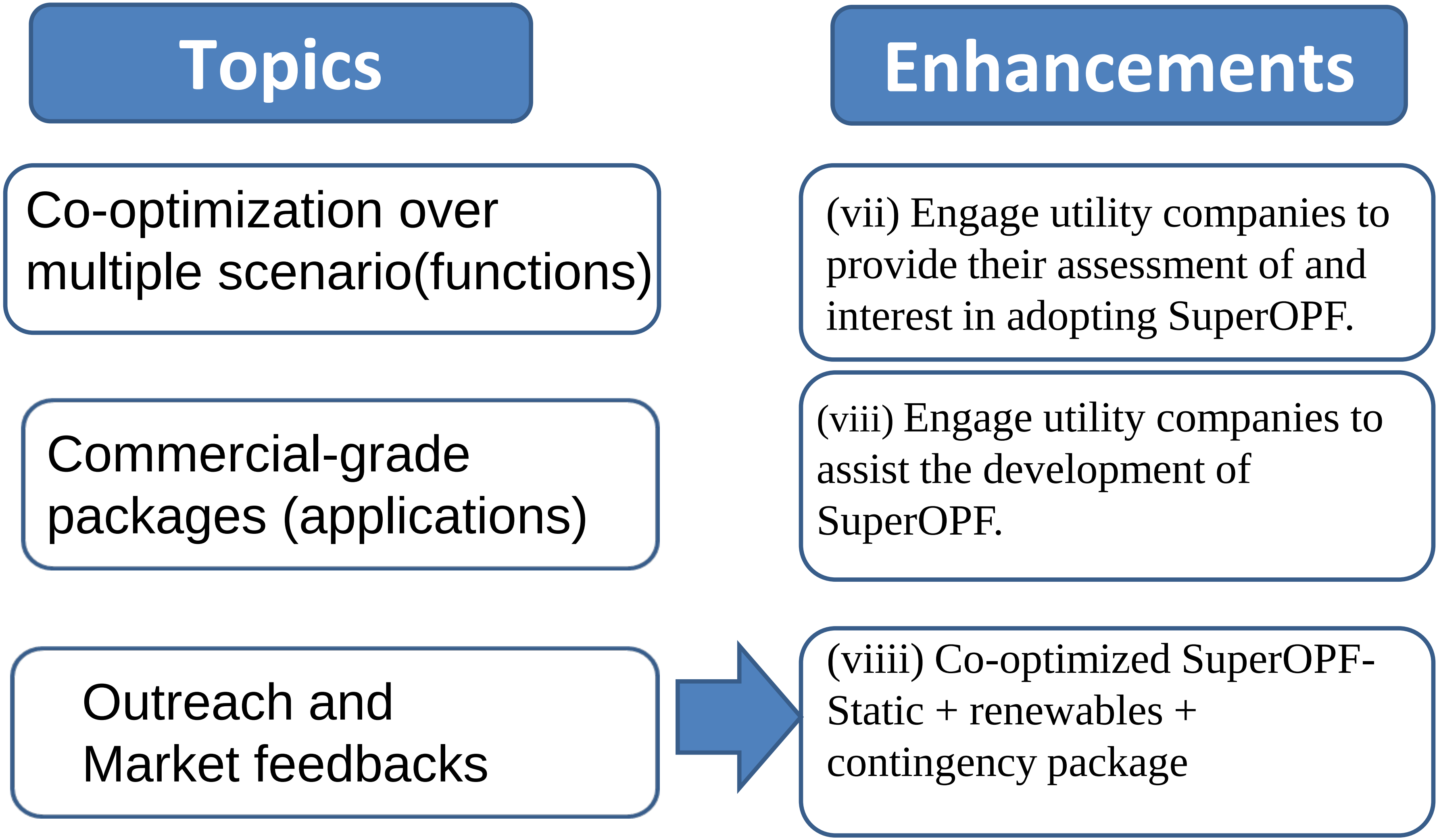
(ii) deal with thermal limits and voltage limits under AC power flow models of a large set of contingencies.

(iii) deal with uncertainties of wind generations and other renewables

This phase is focused on the following enhancements

Topicss	Enhancements
Co-optimization over multiple scenario(functions)	(iv) adjusting both real and reactive control variables, continuous as well as discrete, needed in (EMS)
Commercial-grade packages (applications)	(v) Co-optimized SuperOPF-Static-renewables package
Outreach and Market feedbacks	(vi) Co-optimized SuperOPF-Static-contingency package

This phase is focused on the following enhancements



Topics

Co-optimization over multiple scenario(functions)

Commercial-grade packages (applications)

Outreach and Market feedbacks

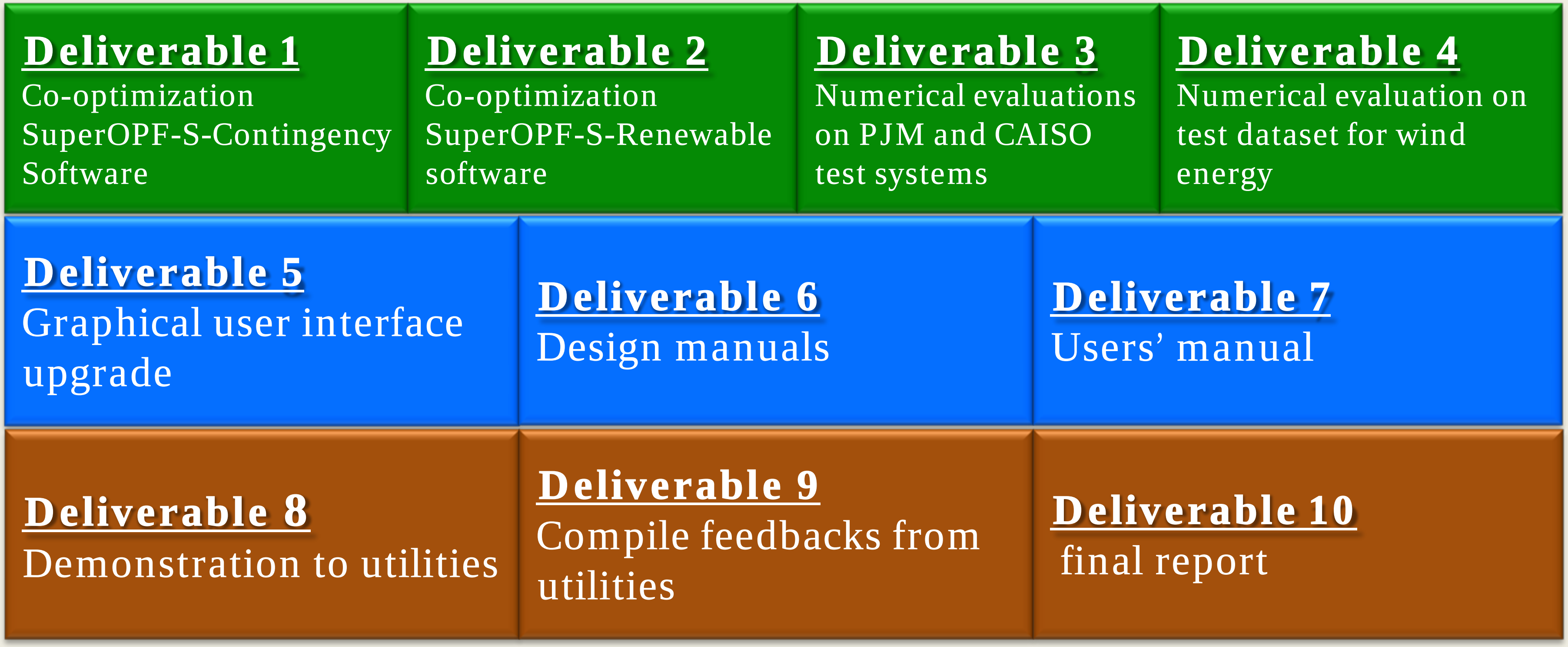
Enhancements

(vii) Engage utility companies to provide their assessment of and interest in adopting SuperOPF.

(viii) Engage utility companies to assist the development of SuperOPF.

(viiii) Co-optimized SuperOPF-Static + renewables + contingency package

Project Status



Deliverable 1
Co-optimization SuperOPF-S-Contingency Software

Deliverable 2
Co-optimization SuperOPF-S-Renewable software

Deliverable 3
Numerical evaluations on PJM and CAISO test systems

Deliverable 4
Numerical evaluation on test dataset for wind energy

Deliverable 5
Graphical user interface upgrade

Deliverable 6
Design manuals

Deliverable 7
Users' manual

Deliverable 8
Demonstration to utilities

Deliverable 9
Compile feedbacks from utilities

Deliverable 10
final report

🟩 Done	🟦 In progress	🟧 Scheduled

SuperOPF Co-optimization

- Objective: minimizing the expected cost across all the scenarios

$$\begin{aligned}
min \quad & f(x) = f_0(x_0) + \sum_{k=1}^{K} p_k[f_k(x_k) + c_k(x_k - x_0)] \\
s.t. \quad & h_0(x) = 0 \\
& g_0(x) \leq 0 \\
& \cdots\ \cdots \\
& h_K(x) = 0 \\
& g_K(x) \leq 0
\end{aligned}$$

$x = (x_0, x_1, \cdots, x_K)$: optimization variables

p_k: probability for k-th scenario

$x_i = (\Theta^k, V^k, T^k, S^k, B^k, P_G^k, Q_G^k)$: variables of the k-th scenario (0: base case)

$f_0(x_0)$: base case cost

$f_k(x_k)$: k-th base cost (reserves, load shedding, etc)

$c_k(x_k - x_0)$: cost of scenario-induced deviations (from base-case)

SuperOPF Co-optimization

Four types of scenarios

Type-1 scenario: Base case

$$
\begin{array}{llr}
\min & f(x) & \\
s.t. & P_i(x) + P_{Di} - P_{Gi} = 0 & 1 \le i \le n_B \\
 & Q_i(x) + Q_{Di} - Q_{Gi} = 0 & \\
 & S_k = \sqrt{P_{ij}^2(x) + Q_{ij}^2(x)} \le S_k^{max} & (i,j) \in L \\
 & x^{min} \le x \le x^{max} &
\end{array}
$$

n_B: the number of buses L: the set of branches

Type-2 scenario: Base case + contingency

$$
\begin{array}{llr}
\min & f(x) & \\
s.t. & P_i(x) + P_{Di} - P_{Gi} = 0 & 1 \le i \le n_B \\
 & Q_i(x) + Q_{Di} - Q_{Gi} = 0 & \\
 & S_k = \sqrt{P_{ij}^2(x) + Q_{ij}^2(x)} \le S_k^{max} & (i,j) \in \hat{L} \\
 & x^{min} \le x \le x^{max} &
\end{array}
$$

$\hat{L}$: L excludes contingent branches

Type 3 scenario: Base case + renewable energy

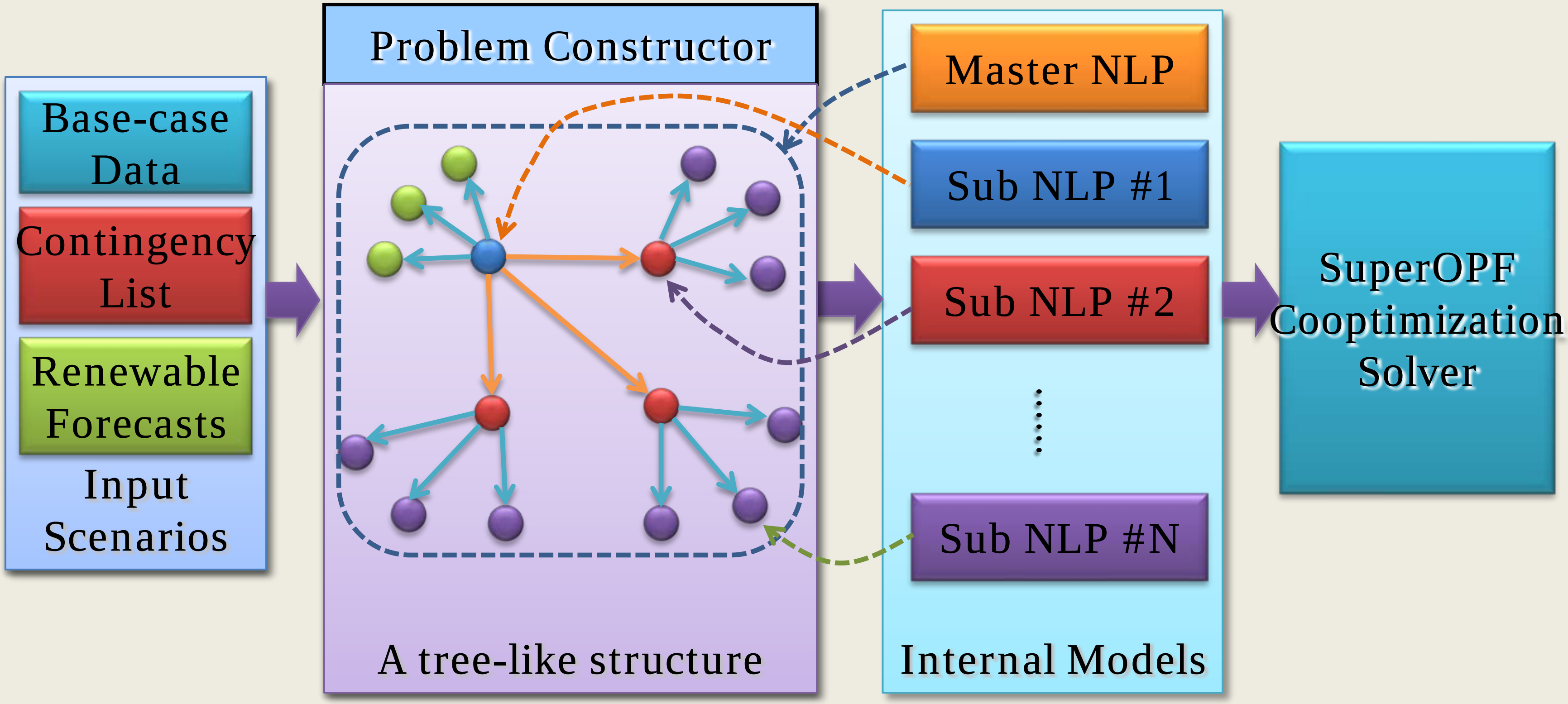
$$
\begin{array}{llr}
\min & f(x) & \\
s.t. & P_i(x) + \hat{P}_{Di} - P_{Gi} = 0 & 1 \le i \le n_B \\
 & Q_i(x) + \hat{Q}_{Di} - Q_{Gi} = 0 & \\
 & S_k = \sqrt{P_{ij}^2(x) + Q_{ij}^2(x)} \le S_k^{max} & (i,j) \in L \\
 & x^{min} \le x \le x^{max} &
\end{array}
$$

$\hat{P}_D, \hat{Q}_D$: equivalent loads with renewable energies

Type 4 scenario: Base case + renewable energy + contingency

$$
\begin{array}{llr}
\min & f(x) & \\
s.t. & P_i(x) + \hat{P}_{Di} - P_{Gi} = 0 & 1 \le i \le n_B \\
 & Q_i(x) + \hat{Q}_{Di} - Q_{Gi} = 0 & \\
 & S_k = \sqrt{P_{ij}^2(x) + Q_{ij}^2(x)} \le S_k^{max} & (i,j) \in \hat{L} \\
 & x^{min} \le x \le x^{max} &
\end{array}
$$

SuperOPF Co-optimization



Base-case Data

Contingency List

Renewable Forecasts

Input Scenarios

Problem Constructor

A tree-like structure

Master NLP

Sub NLP #1

Sub NLP #2

Sub NLP #N

Internal Models

SuperOPF Cooptimization Solver

● Base-case ● Contingent scenario ● Renewable scenario

● Contingent + renewable scenario

SuperOPF Co-optimization

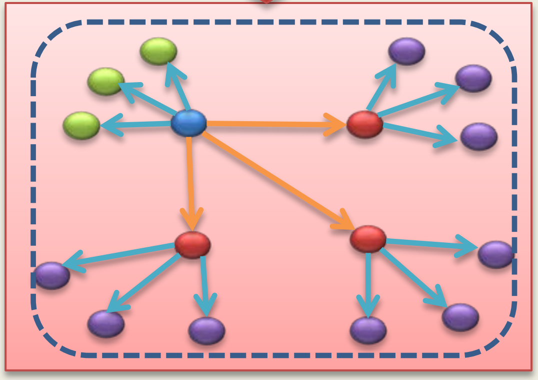
Base Case

$$\begin{aligned} \min \quad & f_0(P_0) \\ s.t \quad & h_0(x) = 0 \\ & g_0(x) \leq 0 \end{aligned}$$

Contingencies
+
Renewable Energy Forecasts

M: # of contingencies
N: # of renewable energy forecasts

Internal Combinatorial Scenarios
K=(M+1)*(N+1)

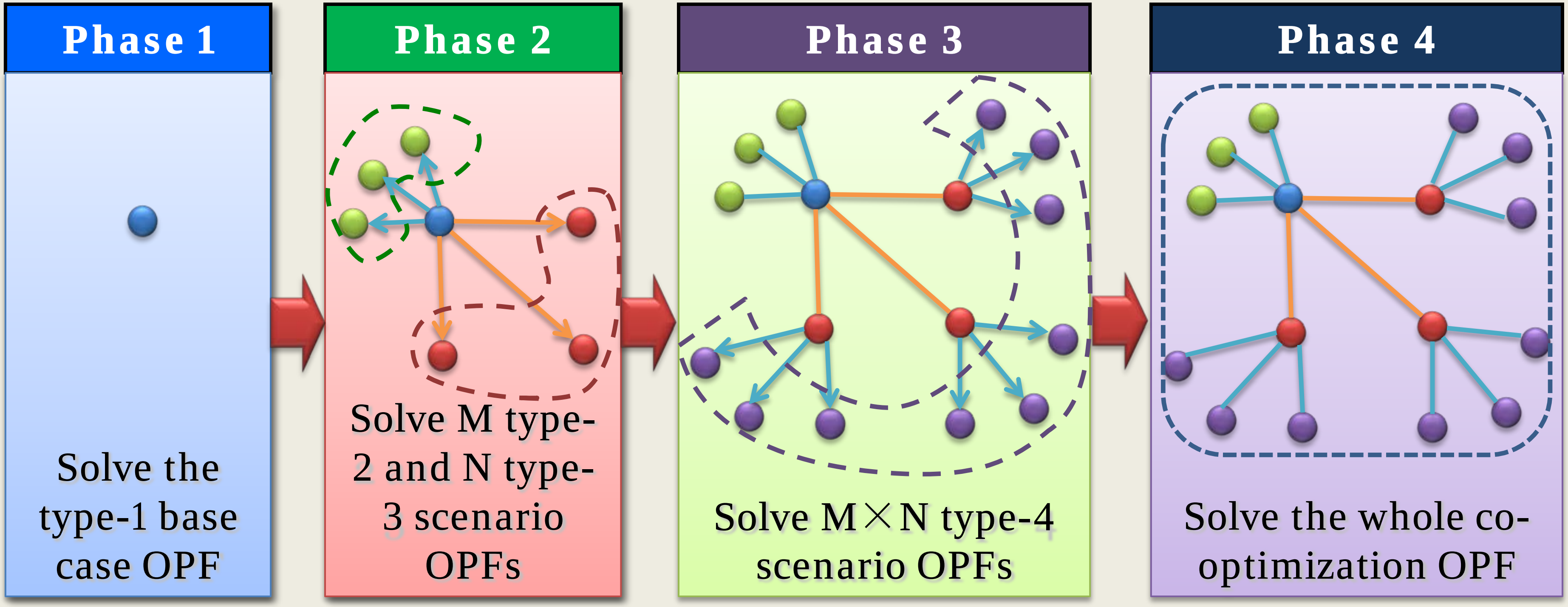


SuperOPF Co-optimization

$$\begin{aligned} \min \quad & f(x) = f_0(x_0) + \sum_{k=1}^{K} p_k[f_k(x_k) + c_k(x_k - x_0)] \\ s.t. \quad & h_0(x) = 0 \\ & g_0(x) \leq 0 \\ & \cdots \cdots \\ & h_K(x) = 0 \\ & g_K(x) \leq 0 \end{aligned}$$

Multi-phase Approach

- A multi-phase scheme is developed in which base case OPF solutions are used as initial points for solving scenario problems. A combination of all sub-problem solutions combined is used as the initial point to the entire co-optimization problem.



Phase 1

Solve the type-1 base case OPF

Phase 2

Solve M type-2 and N type-3 scenario OPFs

Phase 3

Solve M×N type-4 scenario OPFs

Phase 4

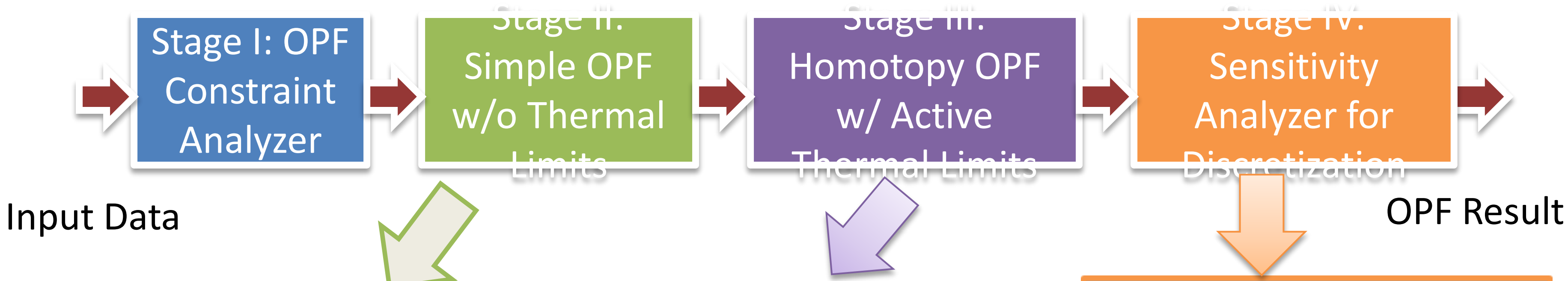
Solve the whole co-optimization OPF

🔵 Base-case scenario 🔴 Contingent scenario 🟢 Renewable scenario

🟣 Contingent + renewable scenario

Super-OPF (for operation)

Super-OPF Method



Stage I: OPF Constraint Analyzer

Stage II: Simple OPF w/o Thermal Limits

Stage III: Homotopy OPF w/ Active Thermal Limits

Stage IV: Sensitivity Analyzer for Discretization

Input Data

OPF Result

$$
\begin{aligned}
\min \quad & f(V,\theta,t,\phi,b,P^G,Q^G) \\
s.t. \quad & P_i(V,\theta,t,\phi,b) + P_i^L - P_i^G = 0,\ i = 1,\cdots,n_B \\
& Q_i(V,\theta,t,\phi,b) + Q_i^L - Q_i^G = 0,\ i = 1,\cdots,n_B \\
& \underline{V}_i \le V_i \le \overline{V}_i,\ i = 1,\cdots,n_B \\
& \underline{t}_i \le t_i \le \overline{t}_i,\ i = 1,\cdots,n_T \\
& \underline{\phi}_i \le \phi_i \le \overline{\phi}_i,\ i = 1,\cdots,n_P \\
& \underline{b}_i \le b_i \le \overline{b}_i,\ i = 1,\cdots,n_S \\
& \underline{P}_j^G \le P_j^G \le \overline{P}_j^G,\ j = 1,\cdots,n_G \\
& \underline{Q}_j^G \le Q_j^G \le \overline{Q}_j^G,\ j = 1,\cdots,n_G
\end{aligned}
$$

OPF without thermal constraints

$$
\begin{aligned}
\min \quad & f(V,\theta,t,\phi,b,P^G,Q^G;\lambda) \\
s.t. \quad & P_i(V,\theta,t,\phi,b) + P_i^L - P_i^G = 0,\ i = 1,\cdots,n_B \\
& Q_i(V,\theta,t,\phi,b) + Q_i^L - Q_i^G = 0,\ i = 1,\cdots,n_B \\
& S_{ij}(V,\theta,t,\phi,b) \le \overline{S}_{ij} + \lambda \tilde{S}_{ij},\ (i,j) \in \mathcal{L}_\alpha \\
& S_{ji}(V,\theta,t,\phi,b) \le \overline{S}_{ij} + \lambda \tilde{S}_{ij},\ (i,j) \in \mathcal{L}_\alpha \\
& \underline{V}_i \le V_i \le \overline{V}_i,\ i = 1,\cdots,n_B \\
& \underline{t}_i \le t_i \le \overline{t}_i,\ i = 1,\cdots,n_T \\
& \underline{\phi}_i \le \phi_i \le \overline{\phi}_i,\ i = 1,\cdots,n_P \\
& \underline{b}_i \le b_i \le \overline{b}_i,\ i = 1,\cdots,n_S \\
& \underline{P}_j^G \le P_j^G \le \overline{P}_j^G,\ j = 1,\cdots,n_G \\
& \underline{Q}_j^G \le Q_j^G \le \overline{Q}_j^G,\ j = 1,\cdots,n_G
\end{aligned}
$$

OPF with active thermal constraints

$$
\begin{aligned}
S_y^f &= \frac{\partial f}{\partial y} - \left(\frac{\partial g}{\partial y}\right)^T \left[\left(\frac{\partial g}{\partial x}\right)^T\right]^{-1} \frac{\partial f}{\partial x} \\
S_y^h &= \frac{\partial h}{\partial y} - \frac{\partial h}{\partial x} \left(\frac{\partial g}{\partial x}\right)^{-1} \frac{\partial g}{\partial y}
\end{aligned}
$$

$$
\begin{aligned}
\Delta f_i^+ &= S_{d_i}^f (d_i^{j_i+1} - d_i^{j_i}) \\
\Delta f_i^- &= S_{d_i}^f (d_i^{j_i-1} - d_i^{j_i}) \\
\Delta h_{k_i}^+ &= S_{d_i}^{h_k} (d_i^{j_i+1} - d_i^{j_i}),\ \forall k = 1,\cdots,n_h \\
\Delta f_{k_i}^- &= S_{d_i}^{h_k} (d_i^{j_i+1} - d_i^{j_i}),\ \forall k = 1,\cdots,n_h
\end{aligned}
$$

$$
\begin{aligned}
\eta_i^+ &= w_f \Delta f_i^+ + \textstyle\sum_{k=1}^{n_h} w_h \max[0, h_k(\hat{x},\hat{y}) + \Delta h_{k_i}^+] \\
\eta_i^- &= w_f \Delta f_i^- + \textstyle\sum_{k=1}^{n_h} w_h \max[0, h_k(\hat{x},\hat{y}) + \Delta h_{k_i}^-]
\end{aligned}
$$

$$
\begin{aligned}
& y_i^{j_i} \leftarrow y_i^{j_i+1} \text{ if: } \eta_i^+ \le \eta_i^- \text{ and } \eta_i^+ \le \eta_{th} \text{ or} \\
& y_i^{j_i} \leftarrow y_i^{j_i-1} \text{ if: } \eta_i^- < \eta_i^+ \text{ and } \eta_i^- \le \eta_{th}.
\end{aligned}
$$

Sensitivity based adjustment

Results: Efficiency and Robustness (Analytical Jacobian matrices)

Robustness of our method

Loading Condition	**One-Staged Scheme**	**Multi-Staged Scheme**
1	Succeeded	Succeeded
2	Succeeded	Succeeded
3	Succeeded	Succeeded
4	Succeeded	Succeeded
5	Failed	Succeeded
6	Failed	Succeeded
7	Failed	Succeeded
8	Failed	Succeeded
9	Failed	Succeeded
10	Failed	Succeeded

Supported Objective Functions

- System Real Power Loss

$$f(x) = \sum_{(i,j)\in L} g_{ij}(V_i^2 - 2V_iV_j\cos(\theta_i - \theta_j) + V_j^2)$$

- System Reactive Power Loss

$$f(x) = -\sum_{(i,j)\in L} b_{ij}(V_i^2 - 2V_iV_j\cos(\theta_i - \theta_j) + V_j^2)$$

- System Real Power Generation

$$f(x) = \sum_{i=1}^{n_G} P_{Gi}$$

- System Reactive Power Generation

$$f(x) = \sum_{i=1}^{n_G} Q_{Gi}$$

- System Generation Cost

$$f(x) = \sum_{i=1}^{n_G} C_i(P_{Gi})$$

Optimization Variables

- All or a subset of:
  - Voltage magnitudes and phase angles
  - Real and reactive power generations
  - Transformer tap ratios (continuous or discrete)
  - Phase shifters (continuous or discrete)
  - Switchable shunts (continuous or discrete)
  - Load shedding

Supported Constraint Functions

- Power flow equality constraints

$$P_{Gi} - P_{Di} - V_i \sum_{j \in \aleph_i} V_j \big(G_{ij} cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j)\big) = 0$$

$$i = 1, \cdots, n_B$$

$$Q_{Gi} - Q_{Di} - V_i \sum_{j \in \aleph_i} V_j \big(G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j)\big) = 0$$

- Thermal-limit constraints

$$|P_{ij}| = \left|V_i V_j \big(G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j)\big) - V_i^2 G_{ij}\right| \le \bar{P}_{ij}, (i,j) \in L$$

- Interface-flow limit constraints

$\underline{F_k} \le F_k = \sum_{i,j} d_{ij} P_{ij} \le \overline{F_k},\ (i,j) \in \beth_k$, where $d_{ij} = \pm 1$ is the flow direction.

- All variables' lower and upper bounds

$$\underline{x_i} \le x_i \le \overline{x_i}, i = 1, \cdots, n_x.$$

Supported Scenario Types

- Contingent scenarios
  - Disconnection of branches
  - Removal of generators
  - Removal of shunts
  - Removal of loads
- Renewable forecast scenarios
- Combination of contingent and renewable forecast scenarios

Numerical Simulations

- Two practical large-scale systems
    - CAISO 6534-bus system
    - PJM 13183-bus system

- Simulation environment:
    - 2.6GHz quad-core Intel i7-3720QM processor (Turbo boost to 3.6GHz), 16GB 1600MHz DDR3 RAM, Mac OSX 10.8.4, GCC 4.8.1

Numerical Simulations

- Simulated scenarios
  - Contingencies (N-1):
    - Removal of a single randomly selected branch from the network (ensuring without resulting islands or isolated buses)
  - Renewable energy forecasts:
    - Wind generators: random selection of 20% system generators;
    - Forecasts: random outputs varying uniformly in the range of ±25% of the initial outputs. Each set of forecasts assigned a probability in 1%~10%.

Co-optimization Results on CAISO System

Base Case

Contingencies
+
Renewable Energy Forecasts

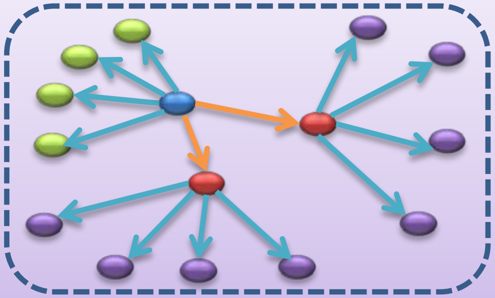
Internal Combinatorial Scenarios

SuperOPF Co-optimization

<u>CAISO System:</u>

Buses: 6534
Loads: 2901
Generators: 1903
Branches: 8295
Transformers: 294
Switchable shunts: 520

# of contingencies: 2
# of renewable forecasts: 4



# of internal scenarios: 15

Scale of the co-optimization problem:

- # of optimization variables: 226,215;
- # of constraints: 287,360 (equality: 181,260; inequality: 106,100);
- # of Hessian non-zeros: 3,190,566.

Co-optimization Results on CAISO System

Sub-problem	Scenario	*p*	F(x)	# of Iters	CPU Time (sec)	Sub-problem	Scenario	*p*	F(x)	# of Iters	CPU Time (sec)
	Initial PF		80.418985			9	Base case + Renewable 2 + Contingency 2	0.573%	21.076384	79	10.38
1	Base case		21.085284	80	10.48	10	Base case + Renewable 3	1.28%	21.089217	77	10.11
2	Base case + Contingency 1	10%	21.106819	79	10.52	11	Base case + Renewable 3 + Contingency 1	0.128%	21.110689	74	9.70
3	Base case + Contingency 2	10%	21.085464	78	10.32	12	Base case + Renewable 3 + Contingency 2	0.128%	21.089421	77	10.09
4	Base case + Renewable 1	3.04%	21.172620	79	10.46	13	Base case + Renewable 4	5.60%	21.218402	75	9.88
5	Base case + Renewable 1 + Contingency 1	0.304%	21.194469	80	10.43	14	Base case + Renewable 4 + Contingency 1	0.560%	21.240219	78	10.31
6	Base case + Renewable 1 + Contingency 2	0.304%	21.173087	80	10.58	15	Base case + Renewable 4 + Contingency 2	0.560%	21.218608	76	10.26
7	Base case + Renewable 2	5.73%	21. 076129	83	10.92	Cooptimization problem			21.129602	310	2281.02 (i.e. 38 min.
8	Base case + Renewable 2 + Contingency 1	0.573%	21. 097419	82	10.85						

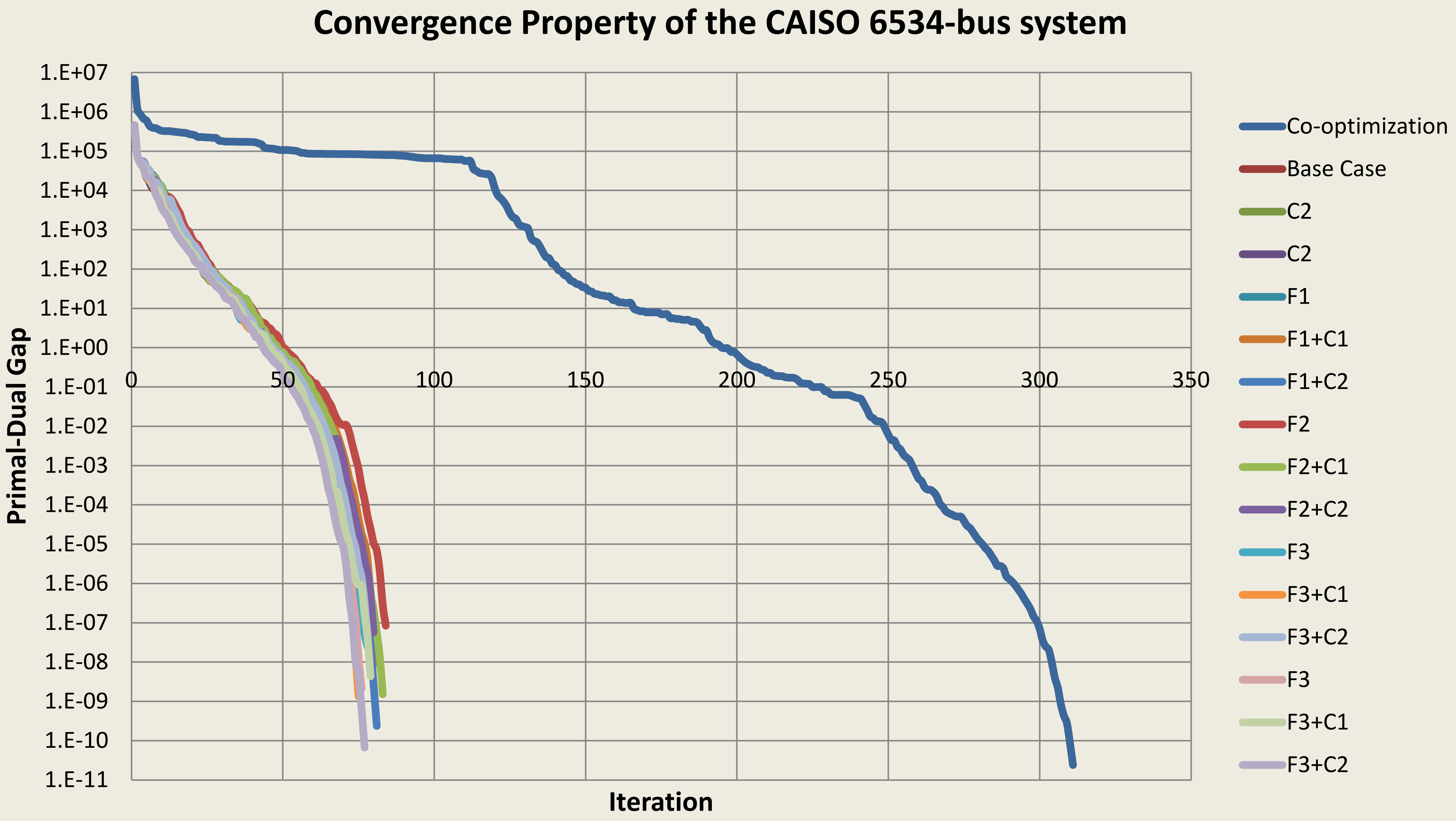
Complexity Analysis

- Rough calculation

15 X 15 = 225, 10 sec. X 225 = 2250 sec.

- Computation complexity increases quadratically with the number of senarios. Hence, the task of scenario reduction is important.

Co-optimization Results on CAISO System



Co-optimization Results on PJM System

Base Case → Contingencies + Renewable Energy Forecasts → Internal Combinatorial Scenarios → SuperOPF Co-optimization

PJM System:

Buses: 13183

Loads: 9691

Generators: 2304

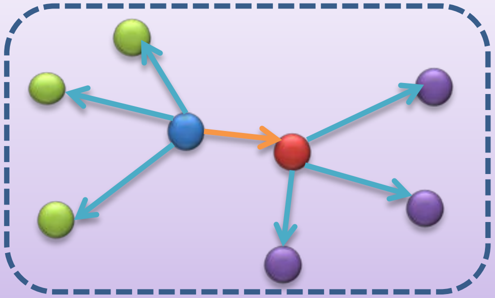
Branches: 18168

Transformers: 1410

Switched shunts: 1404

# of contingencies: 1

# of renewable forecasts: 3



# of internal scenarios: 8

Scale of the co-optimization problem:

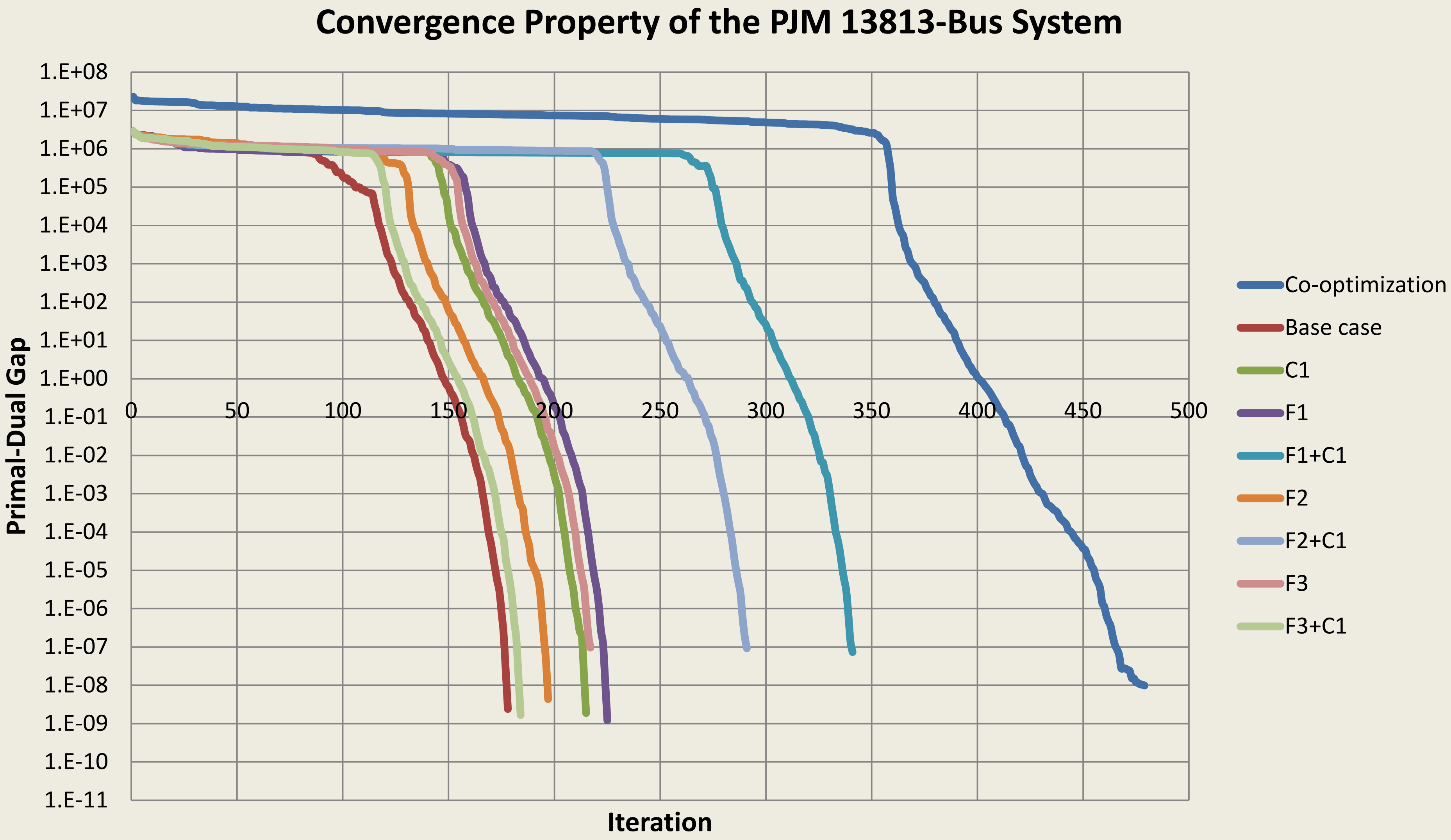
- # of optimization variables: 249,072;
- # of constraints: 309,016 (equality: 210,928; inequality: 98,088);
- # of Hessian non-zeros: 3,826,508.

Co-optimization Results on PJM System

Sub-problem	Scenario	*p*	F(x)	# of Iters	CPU Time (sec)	Sub-problem	Scenario	*p*	F(x)	# of Iters	CPU Time (sec)
	Initial PF		167.06924			5	Base case + Renewable 2	9.92%	67.875872	196	71.14
1	Base Case		67.959196	177	64.26	6	Base case + Renewable 2 + Contingency 1	0.992%	67.875573	290	106.07
2	Base case + Contingency 1	10%	67.958466	214	77.74	7	Base case + Renewable 3	9.01%	67.905719	216	78.71
3	Base case + Renewable 1	3.24%	68.053362	224	83.08	8	Base case + Renewable 3 + Contingency 1	0.901%	67.905028	183	66.54
4	Base case + Renewable 1 + Contingency 1	0.324%	68.052682	340	123.31	Cooptimization problem (using the 4-phase scheme)			67.972861	478	5582.25 (or 93 min.

1-shot scheme: cannot converge after 1000 iterations (about 5 hours)!

Co-optimization Results on PJM System



Observations

- SuperOPF solver can successfully solve multi-scenario co-optimization problems on large scale power systems.

- Complexity of the co-optimization problem grows considerably as the number of scenarios increases.

- Decomposition like methods and parallel implementation are needed to efficiently solving huge co-optimization problems of practical power system models.

- Scenario reduction schemes are needed for SuperOPF in solving large-size problems.

Proposed Requirements for Scenario Reduction Schemes

(reliability measure) identify all representative scenarios that properly maintain important information of stochastic variables.

(efficiency measure) the retain important information with the least number of scenarios.

(*speed and robust measure*) It should be fast and robust to operating conditions

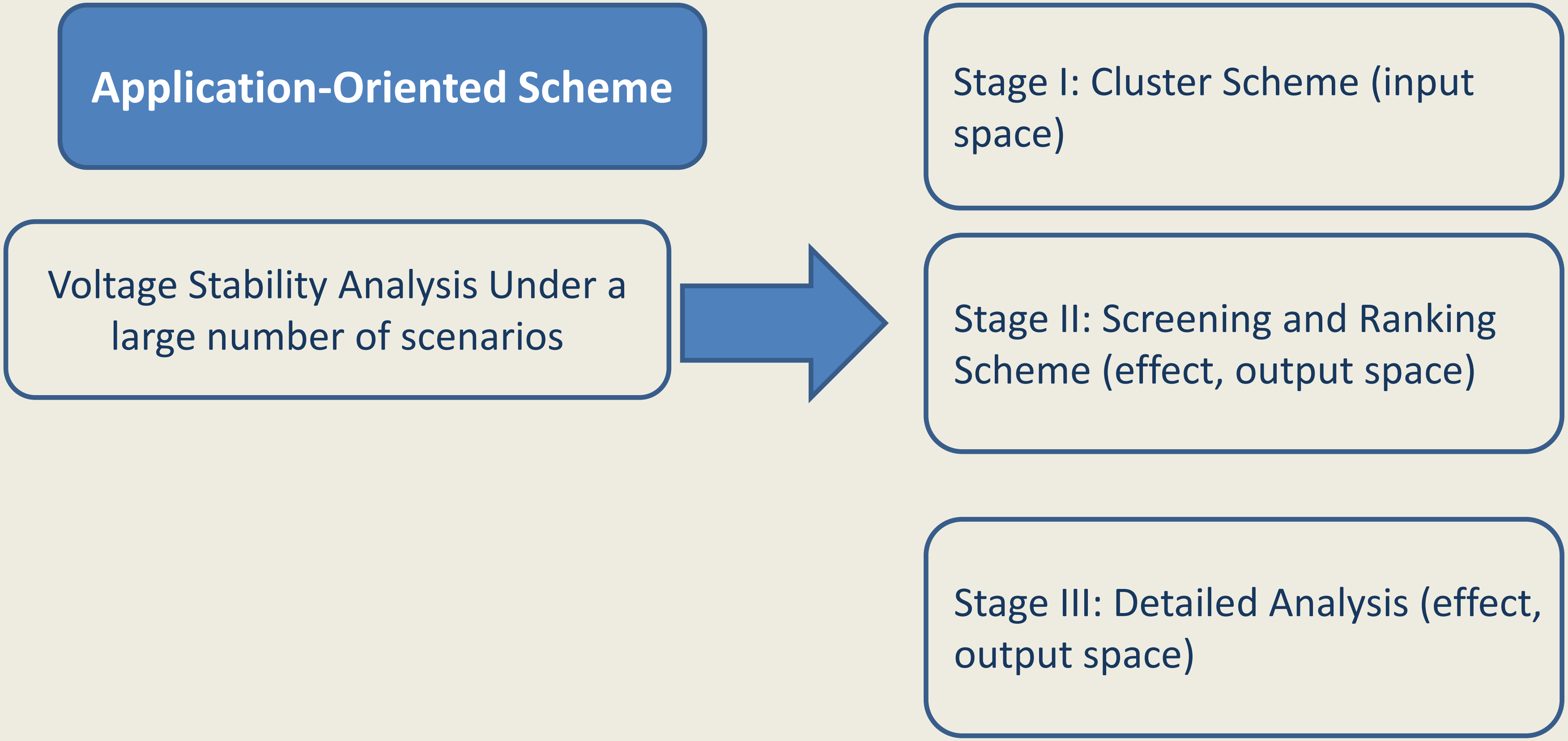
Scenario Reduction Techniques

- Forward selection and backward reduction are the most used scenario reduction technique.
- These methods all focus on :

“distance” between the selected scenario set and the original scenario set. They are problem-independent.

Our Proposed Scenario Reduction Scheme for Voltage Stability

- Problem-dependent



Application-Oriented Scheme

Voltage Stability Analysis Under a large number of scenarios

Stage I: Cluster Scheme (input space)

Stage II: Screening and Ranking Scheme (effect, output space)

Stage III: Detailed Analysis (effect, output space)

Voltage Stability Analysis Under Uncertainty (Cluster + Screening + ranking + detailed analysis)

In comparison with Monte Carlo method (Scenario : 5000)

IEEE 118-bus Test System	
(Renewables at 1, 7, 40, 78, 117)	Weibull distribution

Reduction Ratio	Accuracy(%)	Missing Scenarios
99.08%	100%	0

Scenarios	5000
Stage I & II	Reduce to 46 scenarios
Stage III	Reduce to 17 scenarios

Voltage Stability Analysis Under Uncertainty (Cluster + Screening + ranking + detailed analysis)

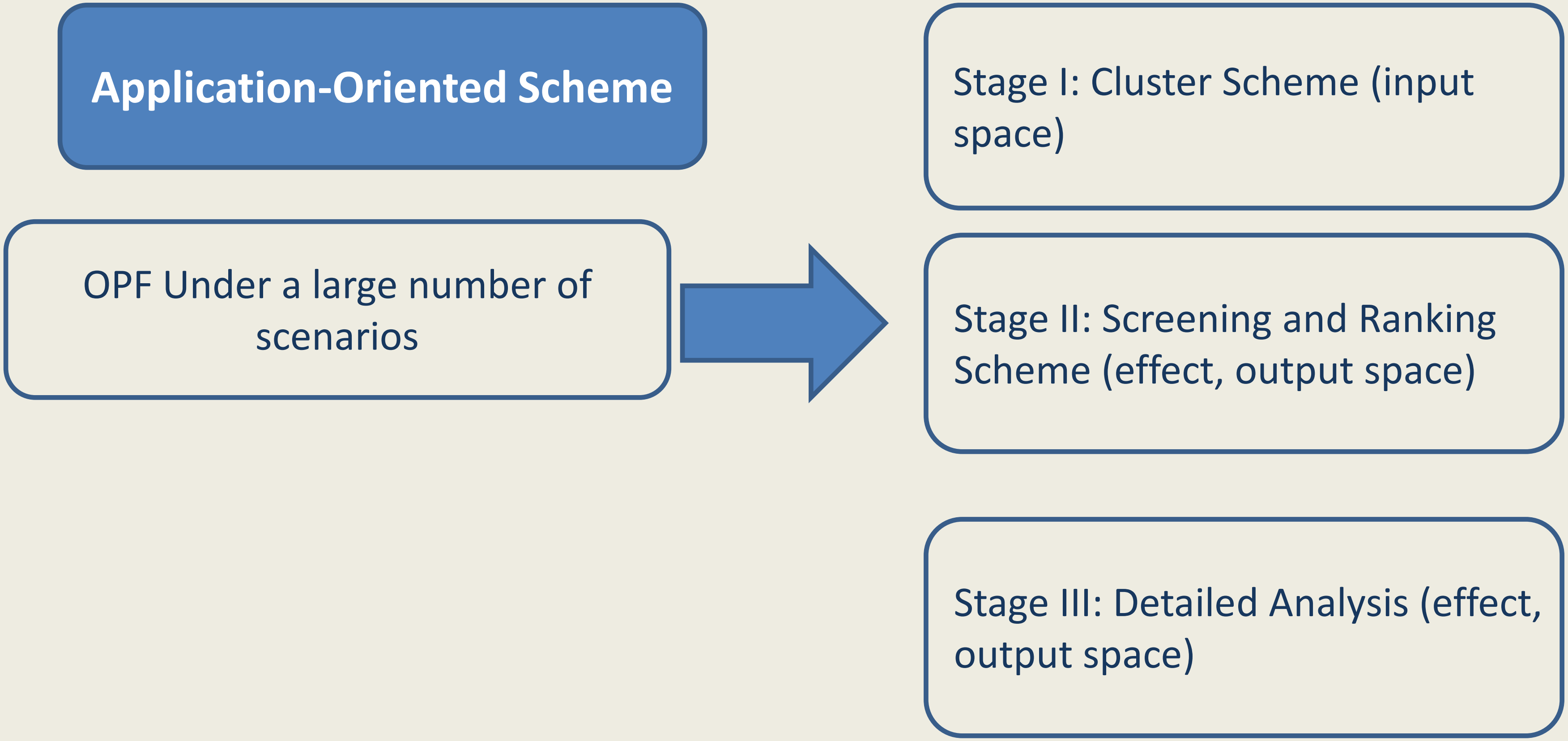
Poland 3120-bus	
(23, 68, 69, 70, 261, 263, 1393, 1395, 1398, 3100, 3101, and 3102)	Weibull distribution

Reduction Ratio	Accuracy(%)	Critical Missing Scenarios
98.52%	100%	0

Scenarios	5000
Stage I & II	Reduce to 74 scenarios
Stage III	Reduce to 29 scenarios

Scenario Reduction Scheme for OPF (Challenging)

- Problem-dependent



Application-Oriented Scheme

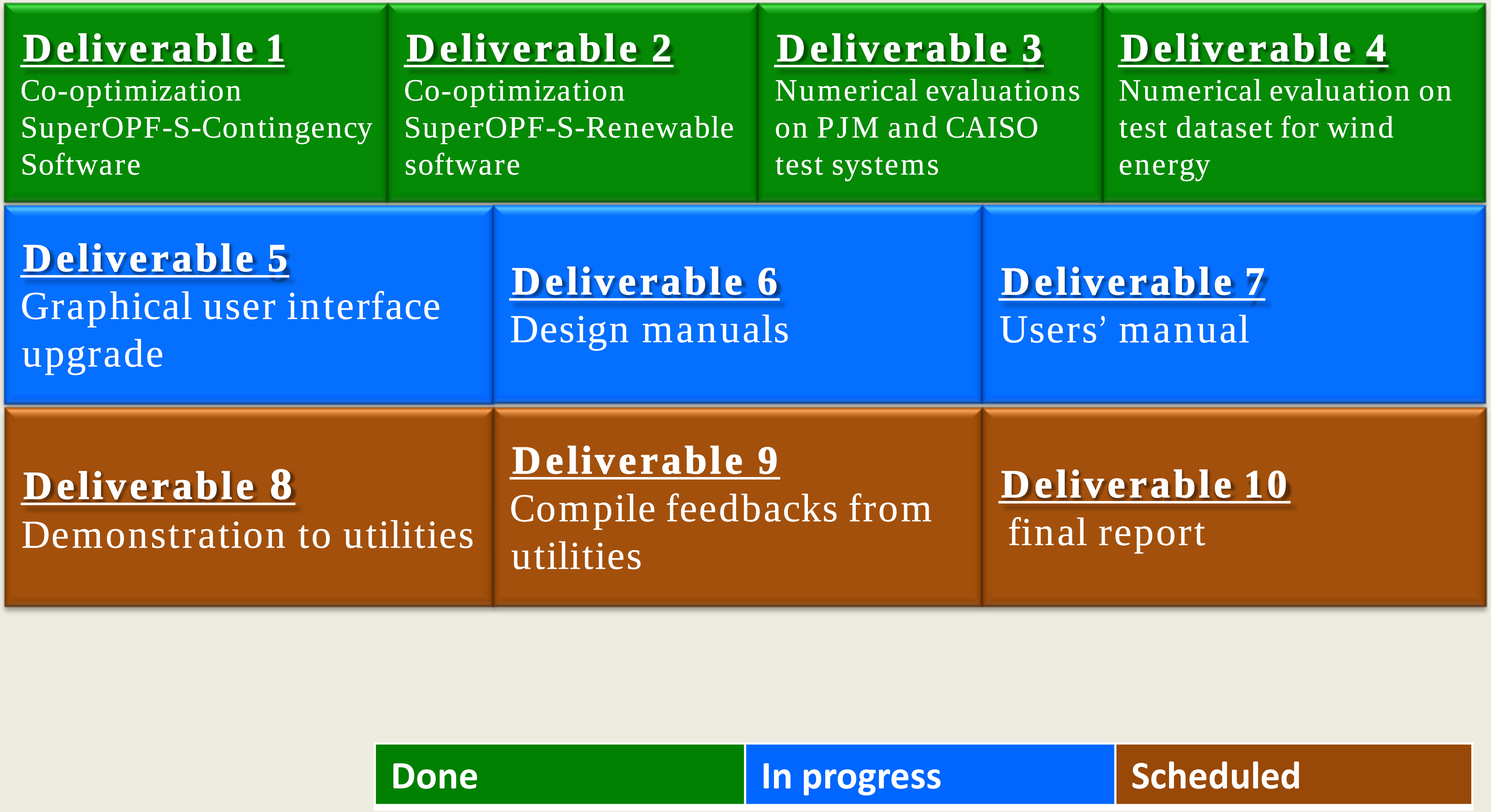
OPF Under a large number of scenarios

Stage I: Cluster Scheme (input space)

Stage II: Screening and Ranking Scheme (effect, output space)

Stage III: Detailed Analysis (effect, output space)

Project Status



Deliverable 1
Co-optimization SuperOPF-S-Contingency Software

Deliverable 2
Co-optimization SuperOPF-S-Renewable software

Deliverable 3
Numerical evaluations on PJM and CAISO test systems

Deliverable 4
Numerical evaluation on test dataset for wind energy

Deliverable 5
Graphical user interface upgrade

Deliverable 6
Design manuals

Deliverable 7
Users' manual

Deliverable 8
Demonstration to utilities

Deliverable 9
Compile feedbacks from utilities

Deliverable 10
final report

Done
In progress
Scheduled

Task13: Engage utility companies

Subtasks:

- Identify participating companies (CAISO, TVA, PJM and NYPA, and others)
- Identify the point person for each participating company
- Identify other persons in the participating company with interest in the topic
- Develop a questionnaire to highlight issues to survey at meetings or in response to materials sent out to participating company contacts. For each company:
    - Presentation/Demonstration/Discussion with company
    - Document meeting activities and feedback
    - Follow up session (web meeting) with program evaluators, to gather their comments and direction

Trust-Tech-Guided Branch and Bound Method for Nonlinear Integer Programming

Prof. Hsiao-Dong Chiang

School of Electrical and Computer Engineering

Cornell University, Ithaca, NY, USA

State of the Art : Nonlinear Optimization

- Global search;
- Good at locating promising regions;
- Easy to implement;
- Stochastic in nature;
- Cannot zoom in promising regions;
- Usually slow, not suitable for large scale problems.

- Deterministic;
- Fast convergence using 1st and 2nd order derivative information;
- Can be trapped in a local optimal solution;
- Can have numerical divergence issue.

Meta-Heuristic

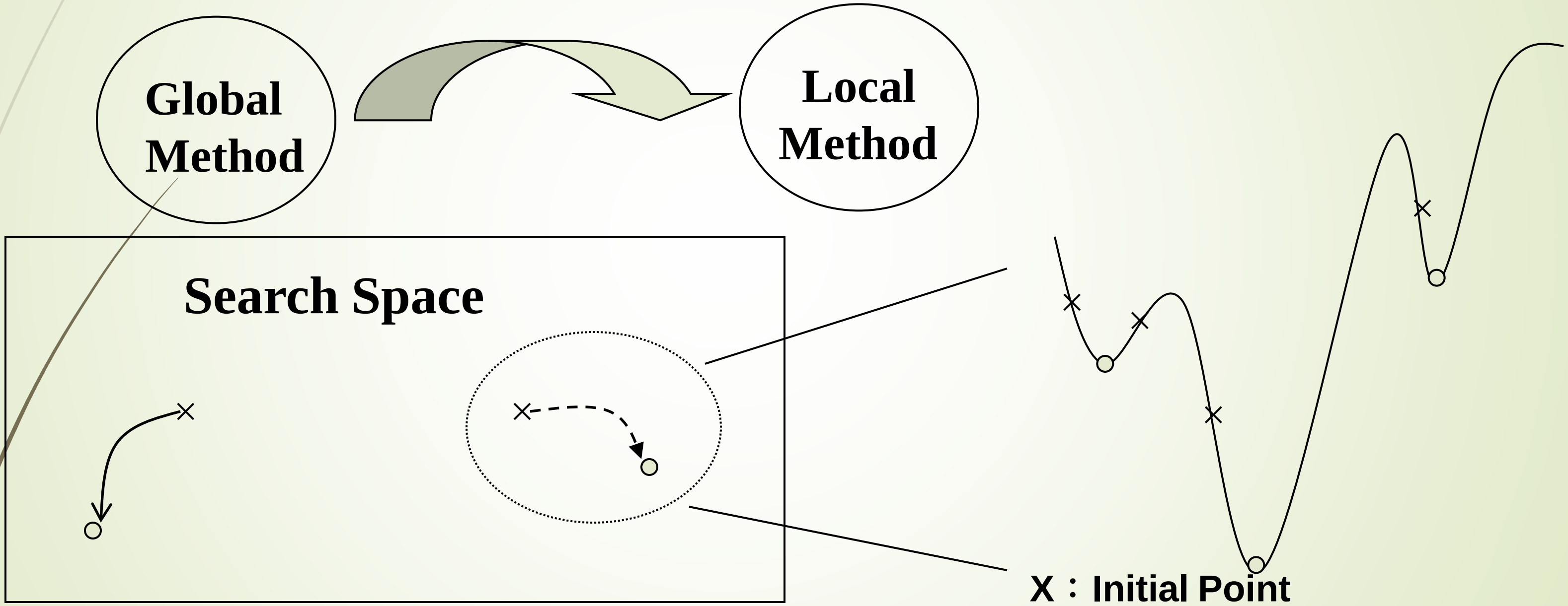
- Simulated annealing (SA);
- Genetic algorithms (GA); Evolutionary programming (EP);
- Swarm intelligence (SI): particle swarm optimization (PSO), ant colony optimization (ACO), etc.

Local Methods

- Trust-region methods (TR);
- Augmented Lagrangian methods;
- Sequential quadratic programming (SQP);
- Active set algorithms;
- Interior point methods (IPM);
- Combinations of above algorithms.

TRUST-TECH

- TRUST-TECH—A Commander for the existing optimization methods：



X ：Initial Point

● ：Local Optimal Solution

X： Initial Point

●： Local Optimal Solution

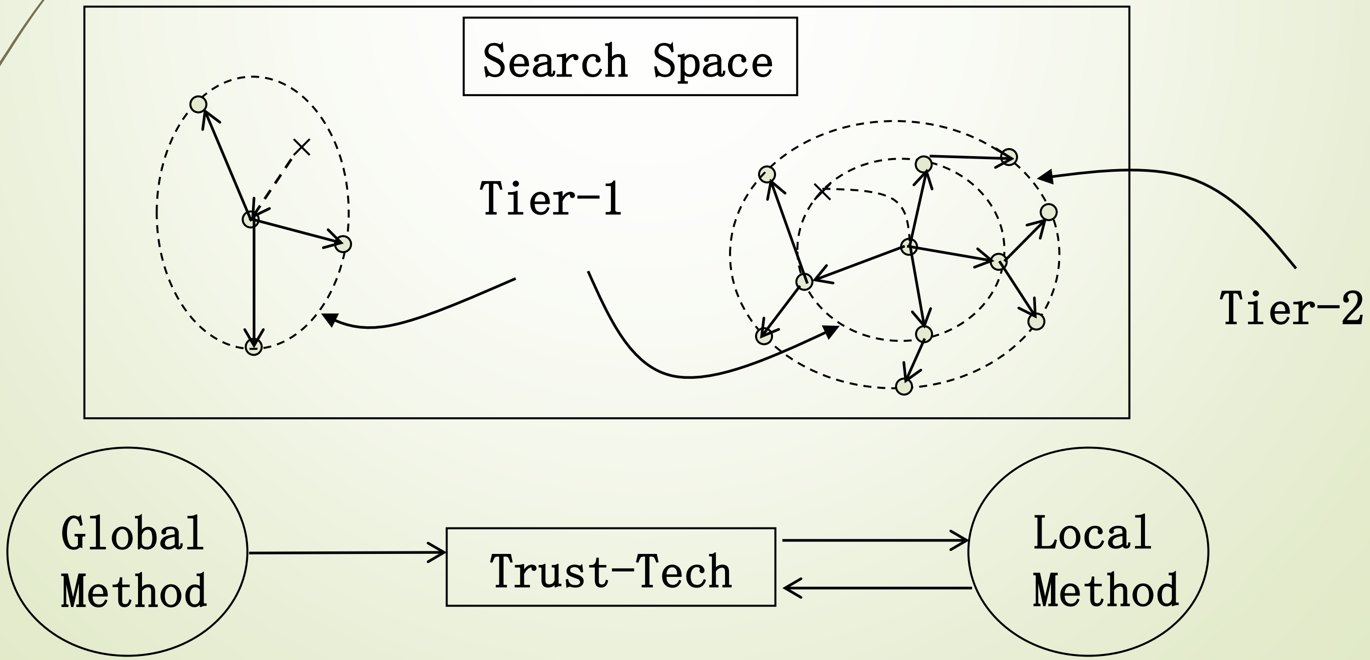
Issue ：

(i) Initial Condition

(ii) Convergence Region of Local Method

TRUST-TECH

- **TRUST-TECH Methodology**
  - It has a systematic and deterministic process to find multiple local optimal solutions; i.e. in a tier-by-tier manner with tier-1 local optimal solutions and then higher-tier local optimal solutions, etc.



TRUST-TECH (a commander)

- The methodology Trust-Tech, which stands for Transformation Under Stability-reTaining Equilibria Characterization, is dynamical method for obtaining a set of or all local optimal solutions of general optimization problems in a tier-by-tier manner.

Trust-Tech Methodology

A framework to realize effective cooperation between local and global methods.

- Systematic and deterministic, tier-by-tier search;
- Zoom in promising regions for good local optimal solutions, possibly the global one;
- Scalable for large scale problems.

- Ensure convergence;
- Better diagnosis of divergence;
- Can obtain a set of local optimal solutions, possibly the global one.

Meta-Heuristic

Local Methods

Projects of TRUST-TECH

- Test Results:

Benchmark Circuits	Number of Cells	Number of Cutsets obtained from the FM Method	Trust-Tech Method	
			Number of Cutsets	Improvement
S1423	831	17	15	13%
S38584	22451	199	54	268%
S38417	25589	405	120	238%
S13207	9445	91	78	17%
S15850	11071	144	79	82%
S35932	19880	120	100	20%
C7552	2247	23	21	9.5%
S9234	6098	56	51	9.8%
S5378	3225	98	76	29%

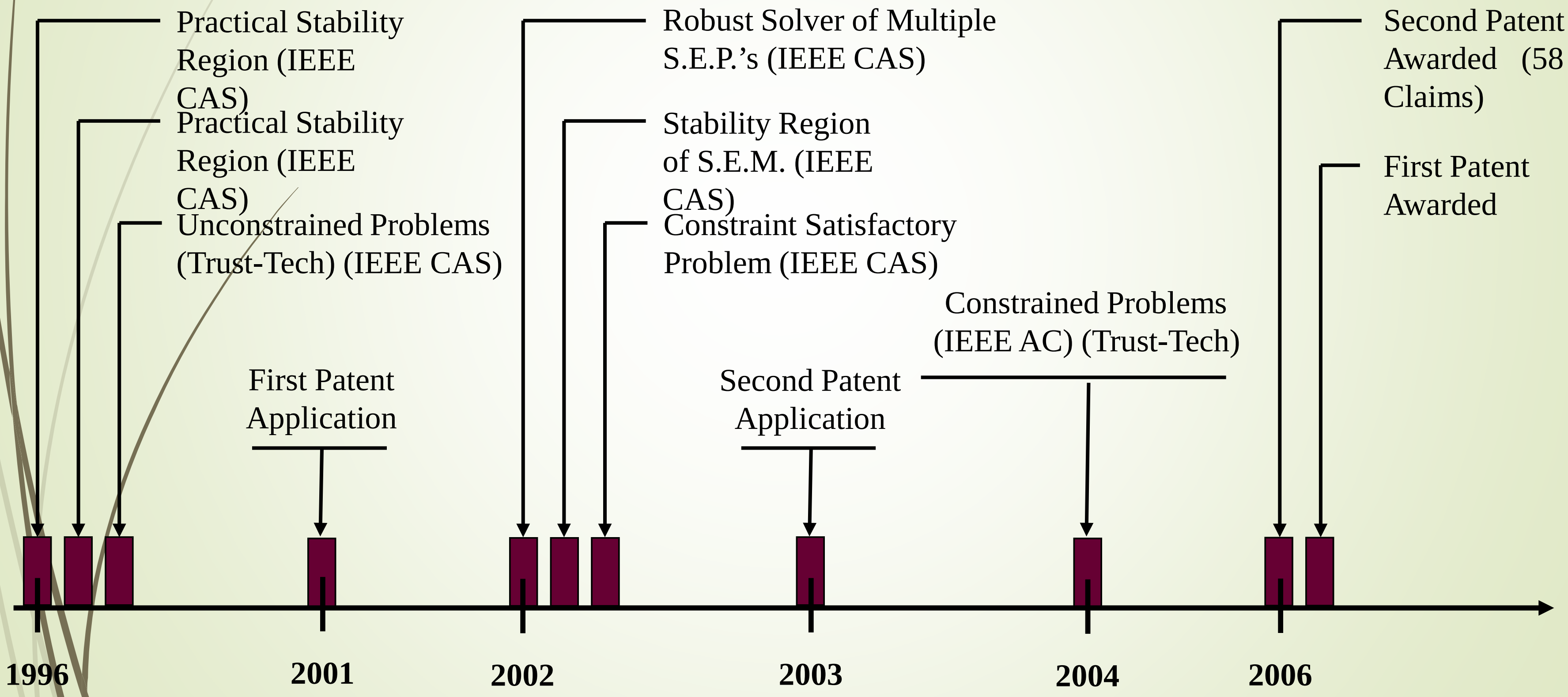
Projects of TRUST-TECH I

	Train XP = Trust-Tech			Test XP = Trust-Tech		
	Best BP	BP+XP	Improvement(%)	Best BP	BP+XP	Improvement(%)
Cancer	2.21	1.74	27.01	3.95	2.63	50.19
Image	9.37	8.04	16.54	11.08	9.74	13.76
Ionosphere	2.35	0.57	312.28	10.25	7.96	28.77
Iris	1.25	1.00	25.00	3.33	2.67	24.72
Diabetes	22.04	20.69	6.52	23.83	20.58	15.79
Sonar	1.56	0.72	116.67	19.17	12.98	47.69
Wine	4.56	3.58	27.37	14.94	6.73	121.99

Development of TRUST-TECH I

	Train XP = Trust-Tech			Test XP = Trust-Tech		
	Best GA	GA+XP	Improvement(%)	Best GA	GA+XP	Improvement(%)
Cancer	2.69	1.87	43.85	3.79	2.77	36.82
Image	13.08	10.09	29.63	14.72	12.81	14.91
Ionosphere	3.27	1.07	205.61	10.83	8.26	31.11
Iris	1.58	1.25	26.40	2.67	2.67	0.00
Diabetes	31.95	28.55	11.91	33.59	31.24	7.52
Sonar	9.55	0.36	2552.78	23.6	16.31	44.70
Wine	12.68	3.44	268.60	16.99	6.18	174.92

Introduction of TRUST-TECH



Practical Stability Region (IEEE CAS)

Practical Stability Region (IEEE CAS)

Unconstrained Problems (Trust-Tech) (IEEE CAS)

First Patent Application

Robust Solver of Multiple S.E.P.'s (IEEE CAS)

Stability Region of S.E.M. (IEEE CAS)

Constraint Satisfactory Problem (IEEE CAS)

Second Patent Application

Constrained Problems (IEEE AC) (Trust-Tech)

Second Patent Awarded (58 Claims)

First Patent Awarded

Introduction of TRUST-TECH

- Papers: Application
  - Bin Wang, **Hsiao-Dong Chiang**. ELITE: Ensemble of Optimal, Input-Pruned Neural Networks Using TRUST-TECH. *IEEE Transactions on Neural Networks*, 22(1): 96-109, 2011.
  - **Hsiao-Dong Chiang**, Bin Wang, Quan-Yuan Jiang. Applications of Trust-Tech Methodology in Optimal Power Flow of Power Systems. *Optimal Operations of Energy Systems*, Springer, International series in operations research and Management Science, 2009.
  - **Hsiao-Dong Chiang**, J-H Chen and C. Reddy. Trust-Tech-based Global Optimal Methodology for Nonlinear programming. *Recent advances in Global Optimization Methodology*, The Fields Institute Communication series, American Mathematical Society, 2009.

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- Paper-Theory and Application
  - Hsiao-Dong Chiang, Jaewook Lee. A Dynamical Trajectory-based Hybrid Method for Computing High-quality Optimal Solutions: Method and Theory (A Chapter of the IEEE Press Book). Modern Heuristic Optimization Techniques: Theory and application to Power Systems, IEEE Press Book, 2007.
  - Jaewook Lee, **Hsiao-Dong Chiang**. A Dynamical Trajectory-based Methodology for Systematically Computing Multiple Optimal Solutions of General Nonlinear Programming Problems. *IEEE Transactions on Automatic Control*, 49(6): 888-899, 2004

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- Paper-Theory and Application
  - **Hsiao-Dong Chiang**, Chia-Chi Chu. A Systematic Search Method for Obtaining Multiple Local Optimal Solutions of Nonlinear Programming Problems. *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, 43(2): 99-109, 1996.
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  - Jaewook Lee, **Hsiao-Dong Chiang**, Singular Fixed-Point Homotopy Method to Locate the Closest Unstable Equilibrium Point for Transient Stability Region Estimate. IEEE Transactions on Circuits Systems II: Express Briefs, 51(4): 185-189, 2004.

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- Papers: Application
  - Chandan K. Reddy, **Hsiao-Dong Chiang**. A Stability Boundary based Method for Finding Saddle Points on Potential Energy Surface. *Journal of Computational Biology*, 13(3): 745-766, 2006.
  - Chandan K. Reddy, **Hsiao-Dong Chiang**, Bala Rajaratnam. TRUST-TECH-Based Expectation Maximization for Learning Finite Mixture Models. *IEEE Transactions on Pattern Analysis and Machine Intelligence,* 30(7): 1146-1157, 2008.
  - Chandan K. Reddy, Yao-Chung Weng, **Hsiao-Dong Chiang**. Refining Motifs by Improving Information Content Scores using Neighborhood Profile Search. *BMC Algorithms for Molecular Biology*, 1:23, 2006.

How Trust-Tech methodology guides branch and bound method

- Trust-Tech-enhanced Branch and Bound Method (Outside B&B/Solver)

- Trust-Tech-guided Branch and Bound Method (Inside B&B/Solver)

- Hybrid Approach

Benchmark Functions

- Rosenbrock’s function
-

$\hat{L}$: L excludes contingent branches

- Griewanks’s function

$$\begin{array}{lll} min & f(x) & \\ s.t. & P_i(x) + \hat{P}_{Di} - P_{Gi} = 0 & 1 \le i \le n_B \\ & Q_i(x) + \hat{Q}_{Di} - Q_{Gi} = 0 & \\ & S_k = \sqrt{P_{ij}^2(x) + Q_{ij}^2(x)} \le S_k^{max} & (i,j) \in L \\ & x^{min} \le x \le x^{max} & \end{array}$$

- Rastrigin’s function

$$f(x) = \sum_{i=1}^{n-1} \left\{ x_i^2 - 10\cos(2\pi x_i) + 10 \right\}$$

- Generalized Rosenbrock’s function
-

n_B: the number of buses L: the set of branches

- Test-Function for Baron

$$= f(g(x)); for x_i \in [-17,17] integer$$

- System Real Power Loss

$$f(x) = \sum_{(i,j)\in L} g_{ij}(V_i^2 - 2V_iV_j\cos(\theta_i - \theta_j) + V_j^2)$$

- System Reactive Power Loss

$$f(x) = -\sum_{(i,j)\in L} b_{ij}(V_i^2 - 2V_iV_j\cos(\theta_i - \theta_j) + V_j^2)$$

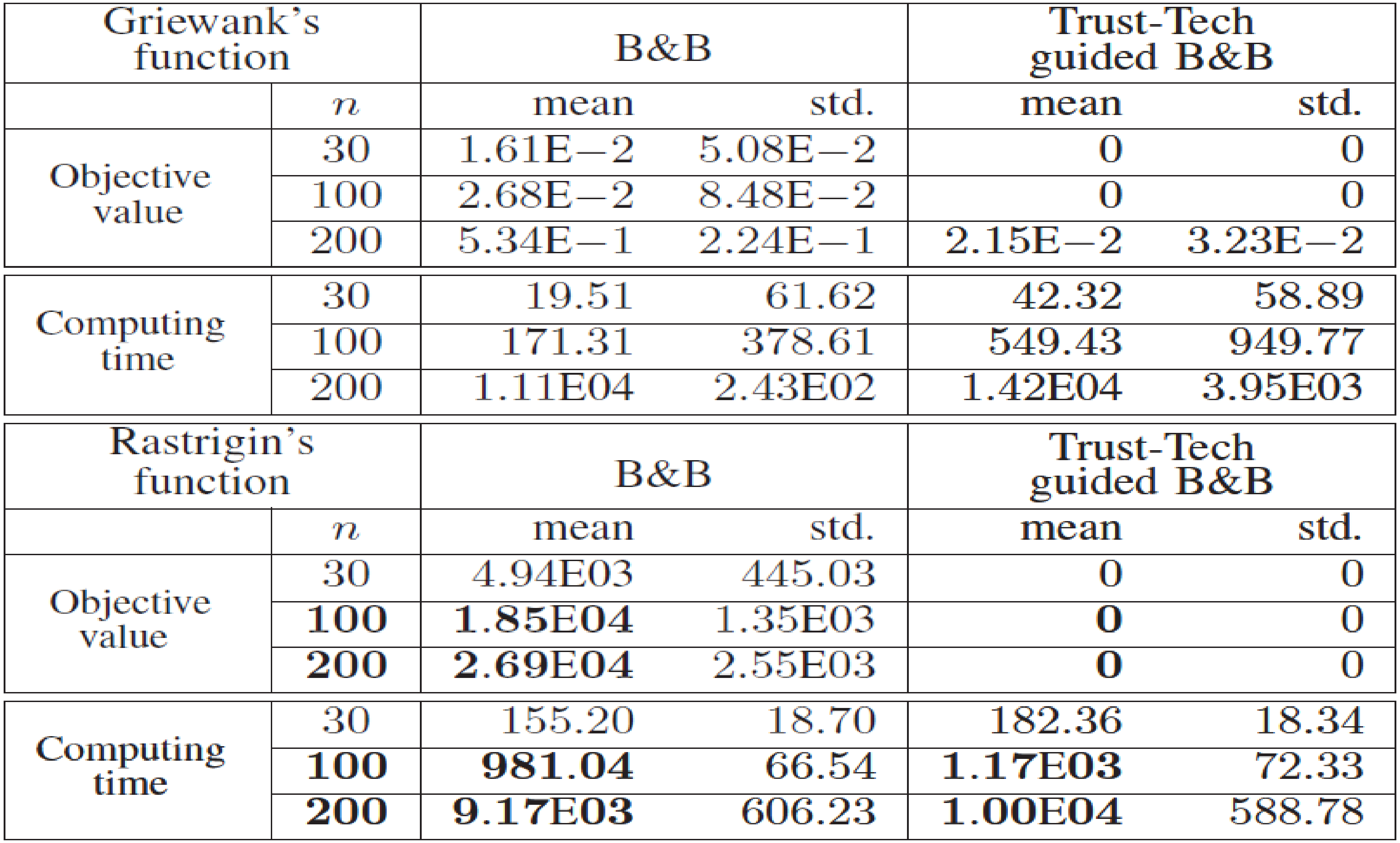
- System Real Power Generation

$$f(x) = \sum_{i=1}^{n_G} P_{Gi}$$

$\hat{P}_D, \hat{Q}_D$: equivalent loads with renewable energies

Examples and Simulation Results

(a) Branch-and-Bound (B&B) (b) Trust-Tech enhanced B&B

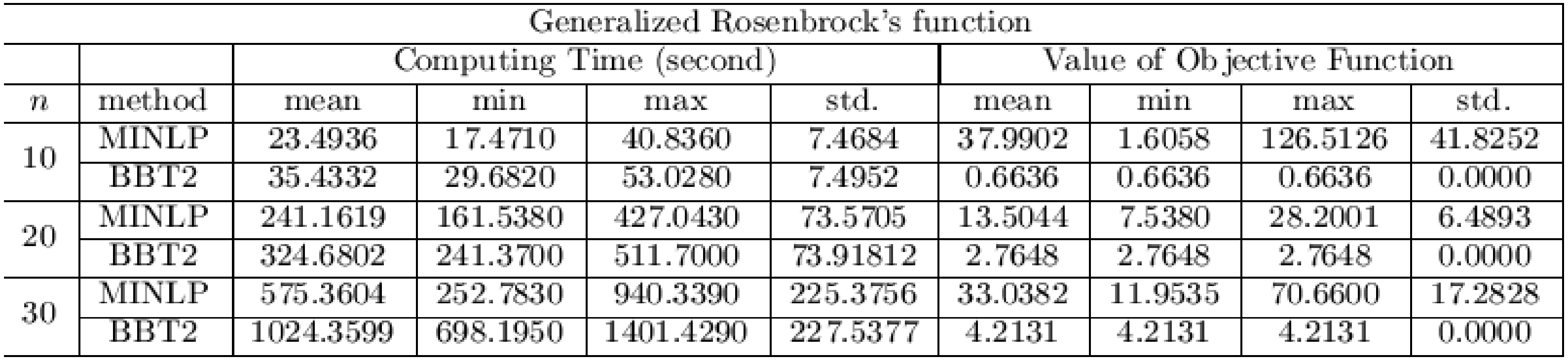


Griewank's function		B&B		Trust-Tech guided B&B	
	n	mean	std.	mean	std.
Objective value	30	1.61E−2	5.08E−2	0	0
	100	2.68E−2	8.48E−2	0	0
	200	5.34E−1	2.24E−1	2.15E−2	3.23E−2
Computing time	30	19.51	61.62	42.32	58.89
	100	171.31	378.61	549.43	949.77
	200	1.11E04	2.43E02	1.42E04	3.95E03

Rastrigin's function		B&B		Trust-Tech guided B&B	
	n	mean	std.	mean	std.
Objective value	30	4.94E03	445.03	0	0
	100	**1.85E04**	1.35E03	**0**	0
	200	**2.69E04**	2.55E03	**0**	0
Computing time	30	155.20	18.70	182.36	18.34
	100	**981.04**	66.54	**1.17E03**	72.33
	200	**9.17E03**	606.23	**1.00E04**	588.78

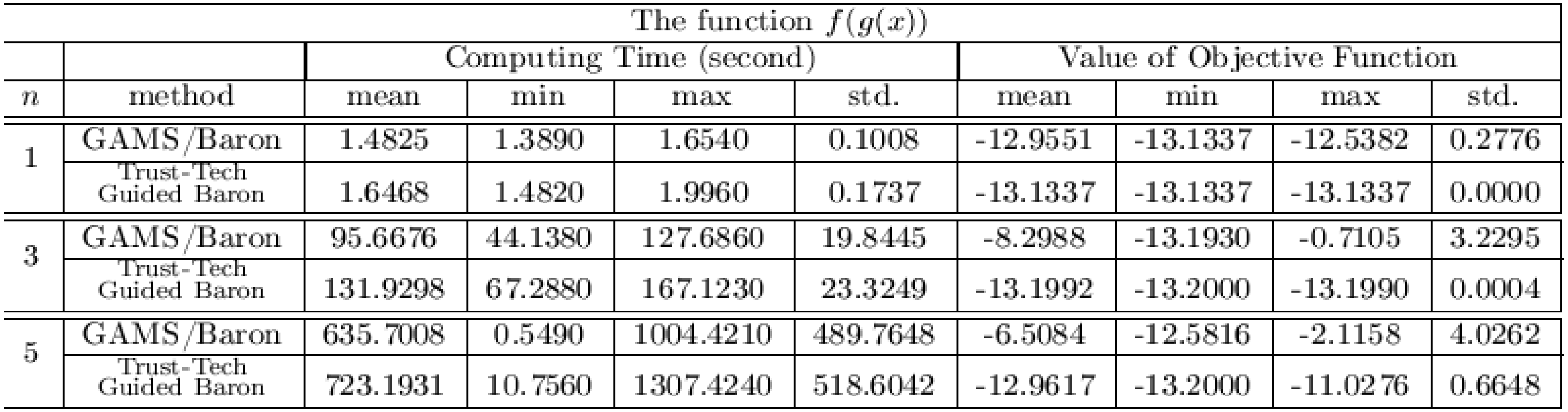
Examples and Simulation Results

- Outside: (b) Commercial solves:
  - GAMS/LINDO (MINLP)



Generalized Rosenbrock's function

		Computing Time (second)				Value of Objective Function			
n	method	mean	min	max	std.	mean	min	max	std.
10	MINLP	23.4936	17.4710	40.8360	7.4684	37.9902	1.6058	126.5126	41.8252
	BBT2	35.4332	29.6820	53.0280	7.4952	0.6636	0.6636	0.6636	0.0000
20	MINLP	241.1619	161.5380	427.0430	73.5705	13.5044	7.5380	28.2001	6.4893
	BBT2	324.6802	241.3700	511.7000	73.91812	2.7648	2.7648	2.7648	0.0000
30	MINLP	575.3604	252.7830	940.3390	225.3756	33.0382	11.9535	70.6600	17.2828
	BBT2	1024.3599	698.1950	1401.4290	227.5377	4.2131	4.2131	4.2131	0.0000

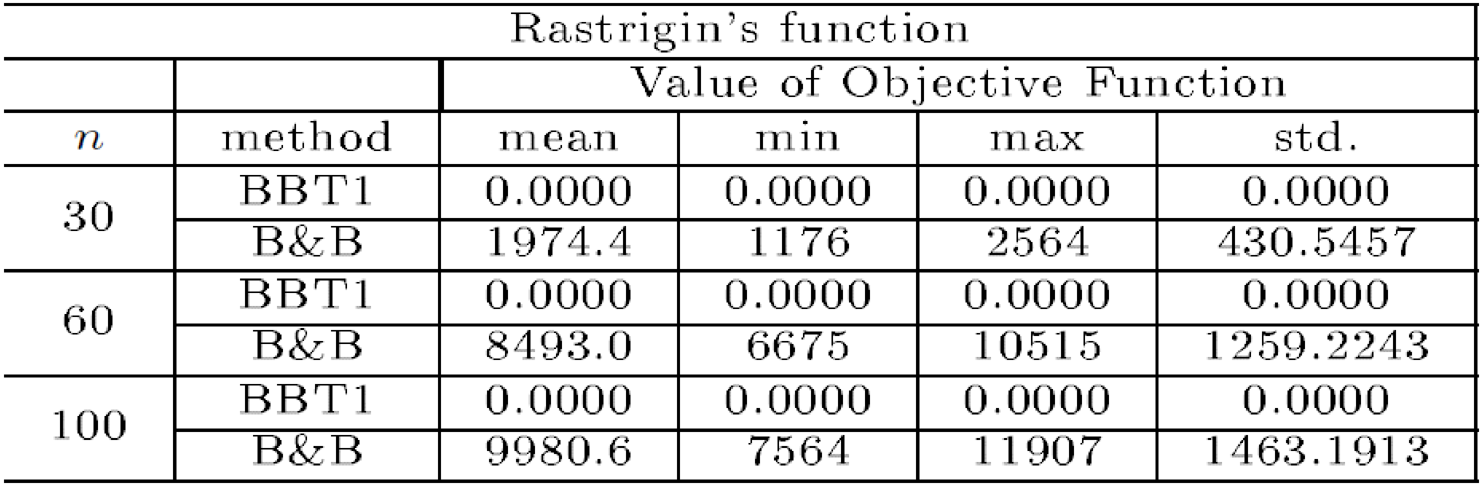


The function $f(g(x))$

		Computing Time (second)				Value of Objective Function			
n	method	mean	min	max	std.	mean	min	max	std.
1	GAMS/Baron	1.4825	1.3890	1.6540	0.1008	-12.9551	-13.1337	-12.5382	0.2776
	Trust-Tech Guided Baron	1.6468	1.4820	1.9960	0.1737	-13.1337	-13.1337	-13.1337	0.0000
3	GAMS/Baron	95.6676	44.1380	127.6860	19.8445	-8.2988	-13.1930	-0.7105	3.2295
	Trust-Tech Guided Baron	131.9298	67.2880	167.1230	23.3249	-13.1992	-13.2000	-13.1990	0.0004
5	GAMS/Baron	635.7008	0.5490	1004.4210	489.7648	-6.5084	-12.5816	-2.1158	4.0262
	Trust-Tech Guided Baron	723.1931	10.7560	1307.4240	518.6042	-12.9617	-13.2000	-11.0276	0.6648

Examples and Simulation Results

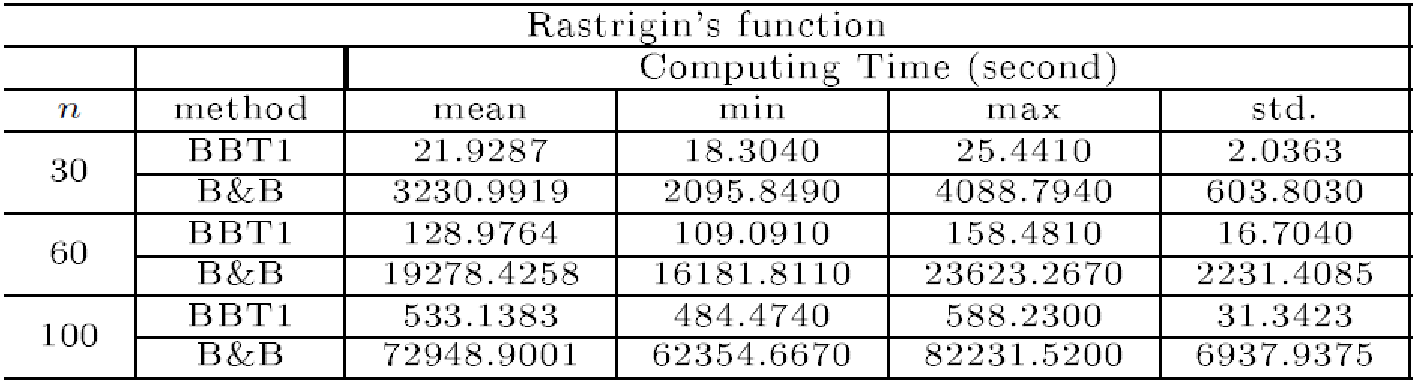
- Inside: (c) Branch-and-Bound (B&B)
- - improvement in solution quality and consistency



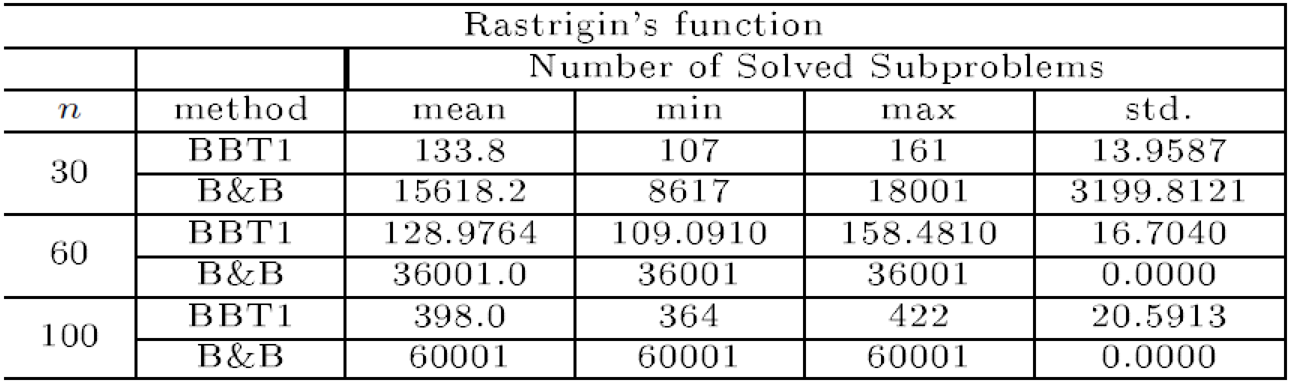
Rastrigin's function					
		Value of Objective Function			
n	method	mean	min	max	std.
30	BBT1	0.0000	0.0000	0.0000	0.0000
	B&B	1974.4	1176	2564	430.5457
60	BBT1	0.0000	0.0000	0.0000	0.0000
	B&B	8493.0	6675	10515	1259.2243
100	BBT1	0.0000	0.0000	0.0000	0.0000
	B&B	9980.6	7564	11907	1463.1913

Examples and Simulation Results

- Inside: (c) Branch-and-Bound (B&B)
- - reduction in computing time
-



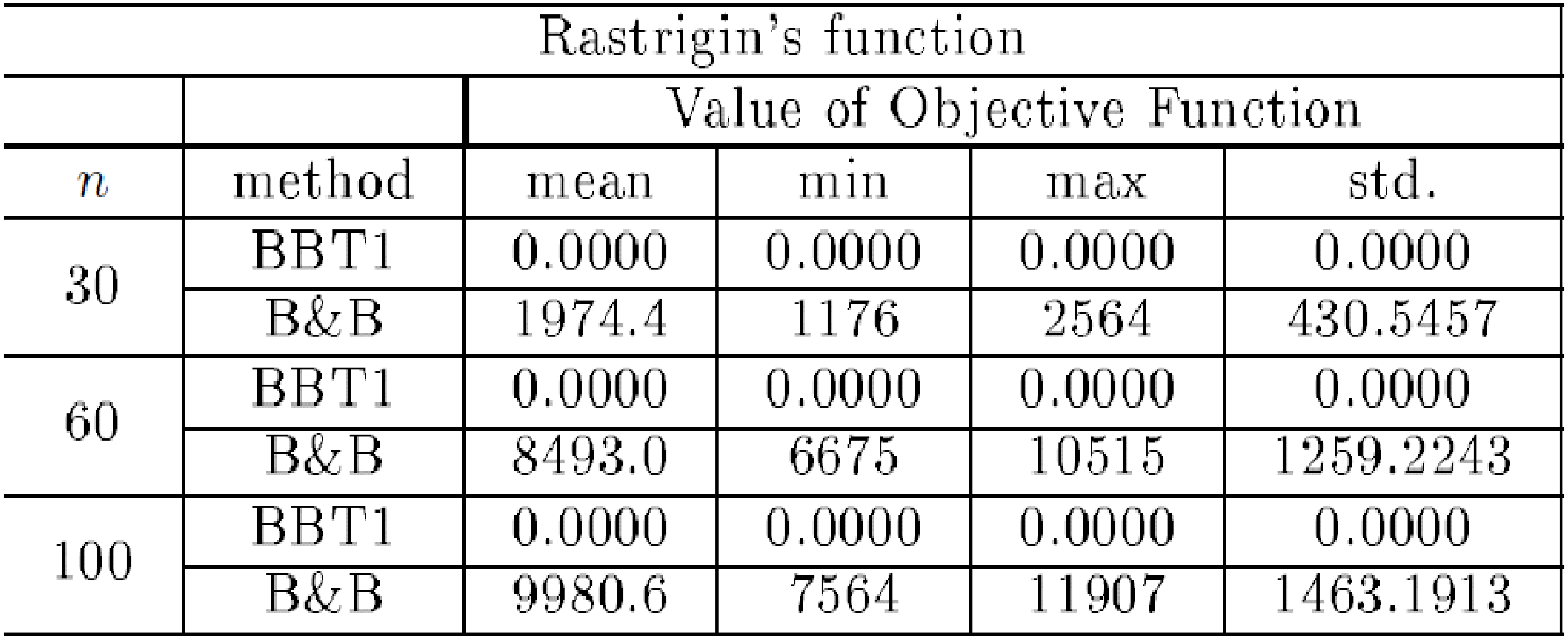
Rastrigin's function					
		Computing Time (second)			
n	method	mean	min	max	std.
30	BBT1	21.9287	18.3040	25.4410	2.0363
	B&B	3230.9919	2095.8490	4088.7940	603.8030
60	BBT1	128.9764	109.0910	158.4810	16.7040
	B&B	19278.4258	16181.8110	23623.2670	2231.4085
100	BBT1	533.1383	484.4740	588.2300	31.3423
	B&B	72948.9001	62354.6670	82231.5200	6937.9375



Rastrigin's function					
		Number of Solved Subproblems			
n	method	mean	min	max	std.
30	BBT1	133.8	107	161	13.9587
	B&B	15618.2	8617	18001	3199.8121
60	BBT1	128.9764	109.0910	158.4810	16.7040
	B&B	36001.0	36001	36001	0.0000
100	BBT1	398.0	364	422	20.5913
	B&B	60001	60001	60001	0.0000

Simulation Results

- Trust-Tech Guided Branch-and-Bound (BTT1) vs. Branch-and-Bound (B&B)
  - **Solution Quality and Consistency**



Rastrigin's function					
		Value of Objective Function			
n	method	mean	min	max	std.
30	BBT1	0.0000	0.0000	0.0000	0.0000
	B&B	1974.4	1176	2564	430.5457
60	BBT1	0.0000	0.0000	0.0000	0.0000
	B&B	8493.0	6675	10515	1259.2243
100	BBT1	0.0000	0.0000	0.0000	0.0000
	B&B	9980.6	7564	11907	1463.1913