U.S. DEPARTMENT OF ENERGY

Electricity Delivery & Energy Reliability

Advanced Grid Modeling 2014 Peer Review

Management & Optimization of VARs for Future Transmission Infrastructure with High Penetration of Renewable Generation (MOVARTI)

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Presentation Outline

- **Project Overview**
- **Technical Approaches and Accomplishments**
- **Conclusions and Future Works**

Challenges and Project Objective

- Challenges
  - The increasingly diversified generation sources, including renewables and gas turbines, are changing the power systems in both system topologies and operation strategies.
  - The flourish of renewables and the deactivation from fossil fuel synchronous generators may lead to higher pressure for optimization of various VAR sources, esp. dynamic ones.
  - The value of future reactive power resources are critical to utility planners.
- Objective
  - Develop an integrated VAR analysis and planning tool which can achieve the above motivations with different types of VAR sources.

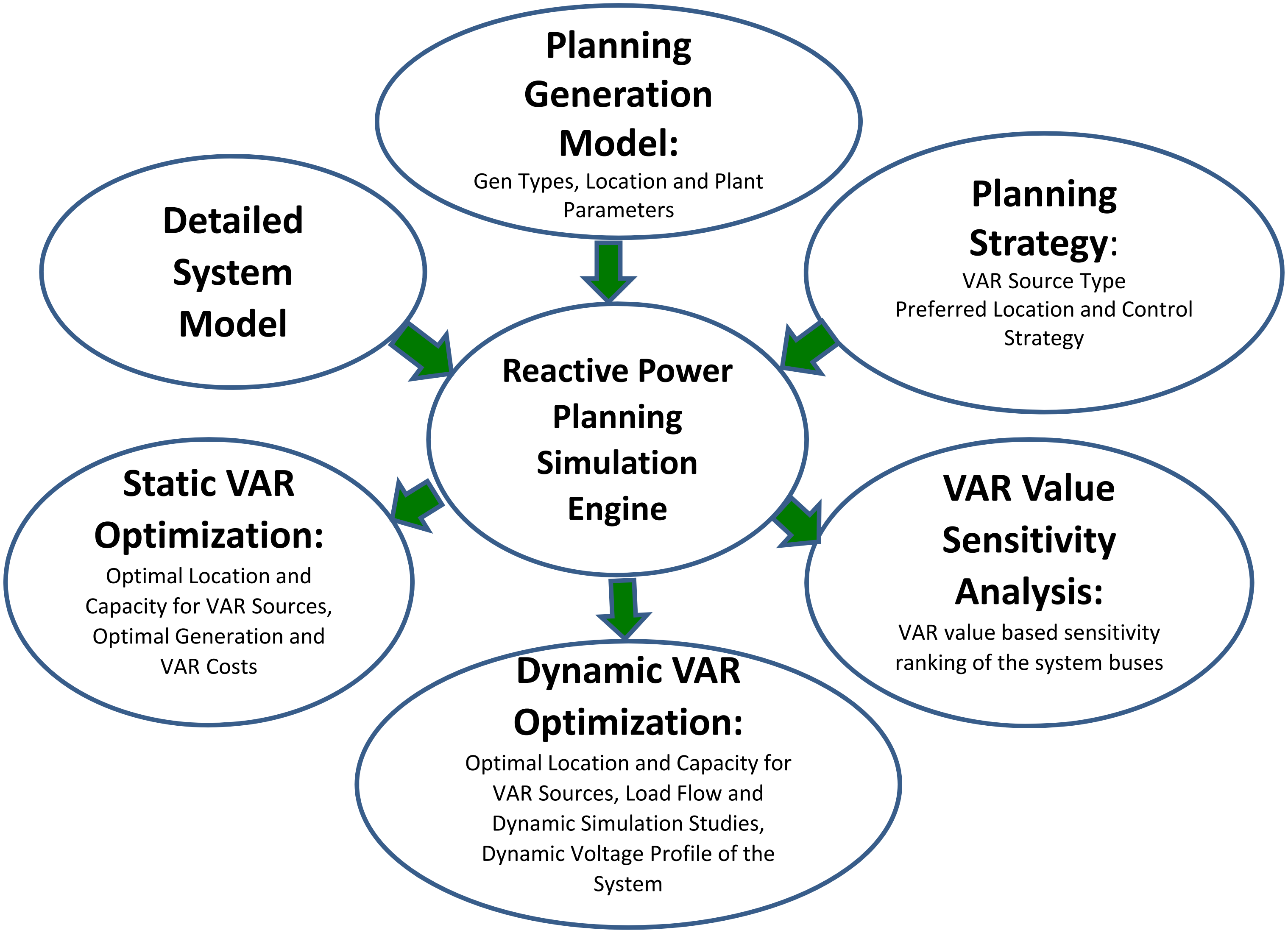
Significance and Impacts

- Generation uncertainty and new characteristics are addressed in the long-term VAR planning.
- VAR sources are differentiated as static VAR and dynamic VAR sources in the short-term VAR planning to further optimize the VAR planning and ensure dynamic voltage stability – a utility concern
- The benefit and value of VAR are evaluated and assessed to either determine feasibility of investment or value streams from VAR optimization – a utility benefit
- Framework of the future VAR planning and operation which could lead to the power system VAR planning and operation revolution.

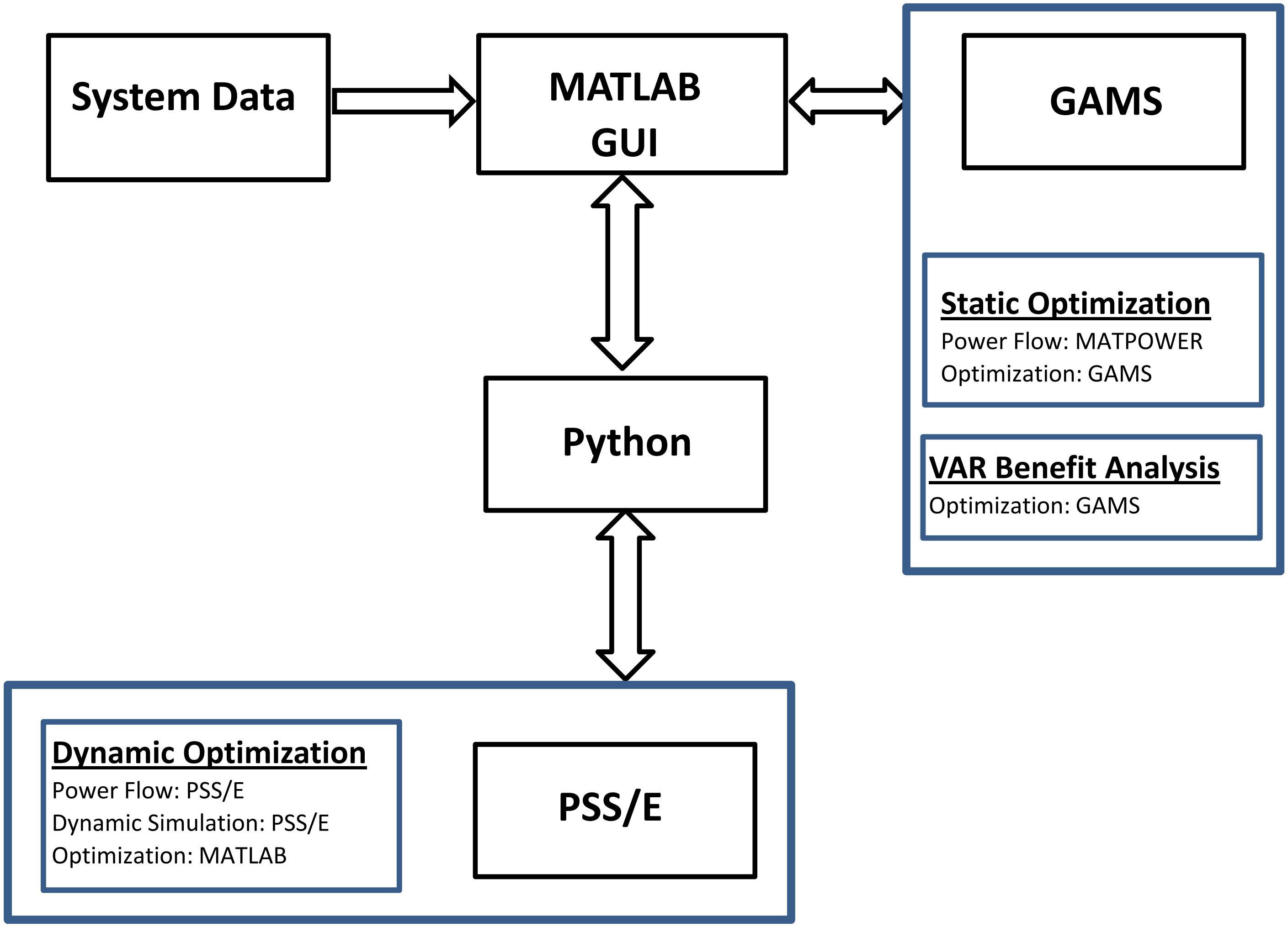
Presentation Outline

- **Project Overview**
- **Technical Approaches and Accomplishments**
  - **MOVARTI tool overview**
  - **VAR Value Assessment:** budget constrained VAR planning
  - **Long-term VAR planning:** considering static voltage constraints
  - **Short-term VAR planning:** considering post-contingency voltage dynamics
- **Conclusions and Future Works**

MOVARTI Tool Overview - Capability

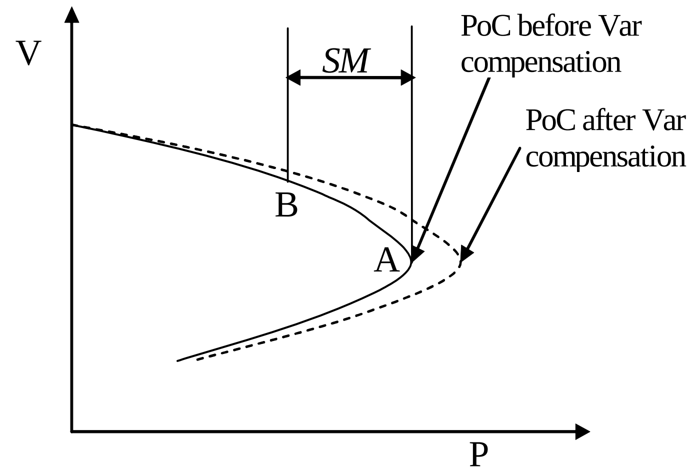


MOVARTI Tool Overview - Architecture

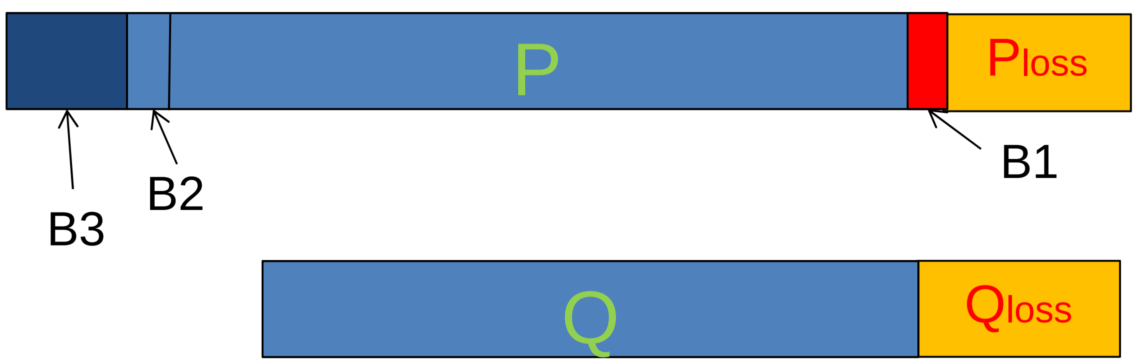


VAR Value Assessment

Without VAR compensation



With VAR compensation



VAR value streams:

B1: Benefit from reduced power losses

B2: Benefit from shifting reactive power flow to active power flow

B3: Benefit from increasing line transfer capability

Quantitative Assessment Model

- Base Case (z): Base system without VAR compensation (Qc=0).
- Perturbed Case (z'): Compensation is available at a given bus in the given amount for evaluation.
- VAR value (i.e., benefits from the OPF model) = z' – z, which is essentially a sensitivity study which can be used for budget-constrained planning.

Based on ACOPF model:

Min: $\sum f(P_{Gi})$ (Total production cost)

Subject to:

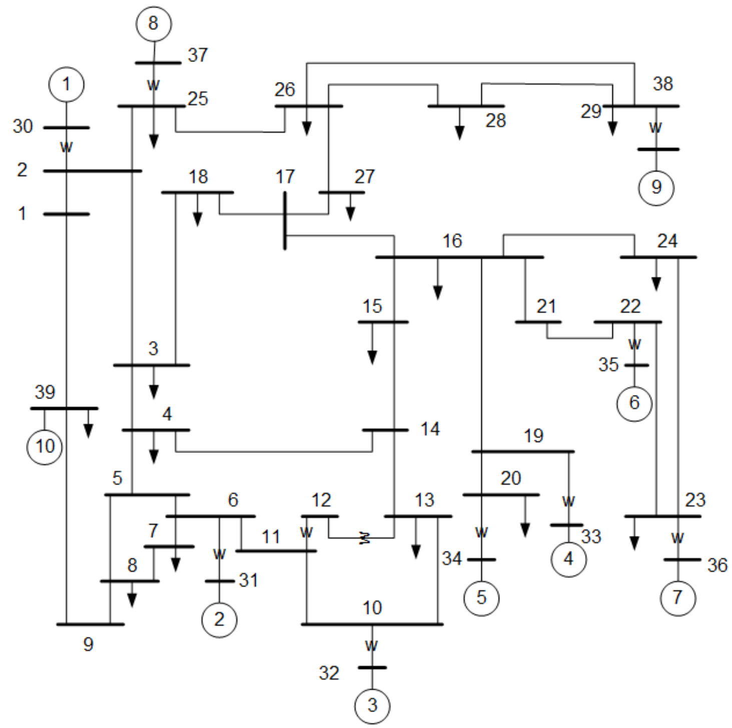
$P_{Gi} - P_{Li} - P(V,\theta) = 0$ $Q_{Gi} + Q_{ci} - Q_{Li} - Q(V,\theta) = 0$ (Nodal power balance)

$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max}$ $Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max}$ (Generation active and reactive limit)

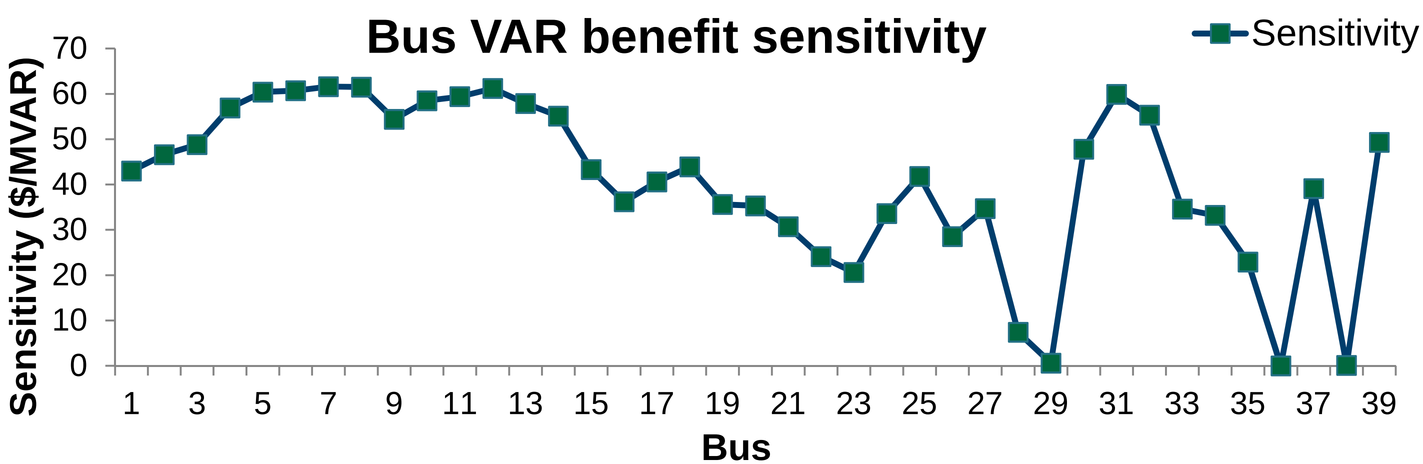
$V_i^{\min} \le V_i \le V_i^{\max}$ $Q_{ci}^{\min} \le Q_{ci} \le Q_{ci}^{\max}$ (Voltage limit and VAR capacity limit)

$|LF_l| \le LF_l^{\max}$ (Line capacity limit)

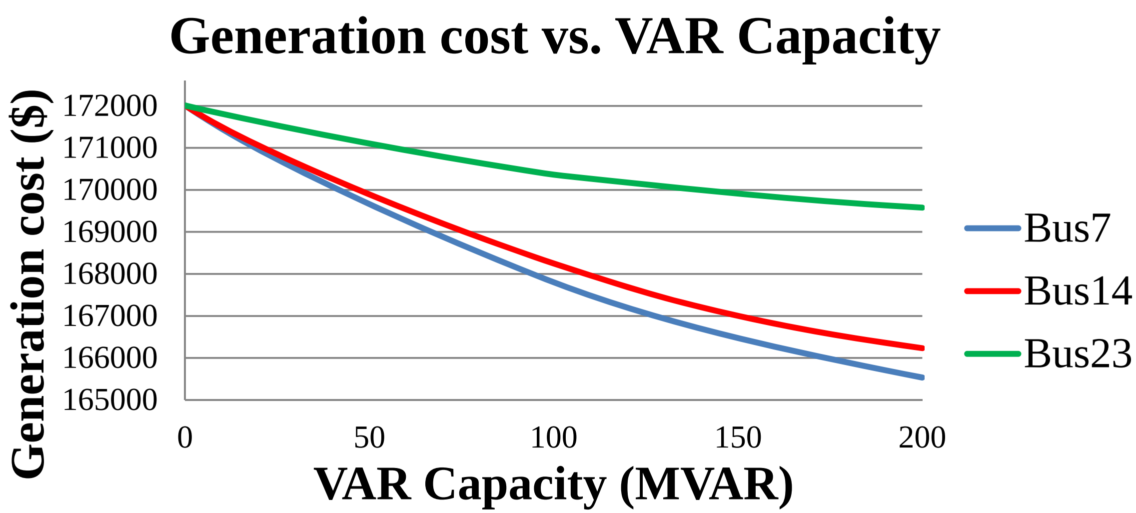
VAR Value Study with IEEE 39 Bus System (1)

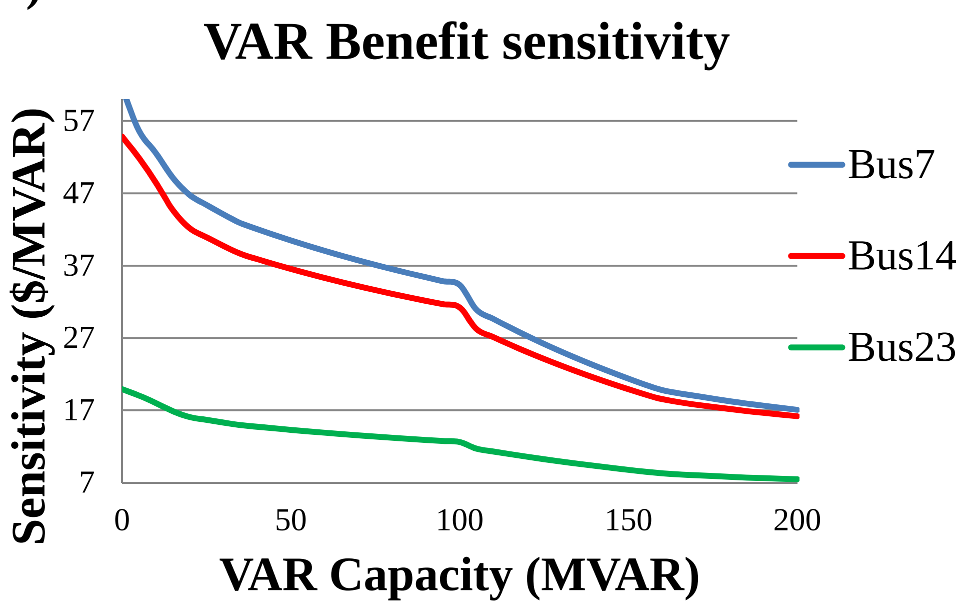


Rank	Benefit Sensitivity ($/MVAR)	Bus	Rank	Benefit Sensitivity ($/MVAR)	Bus
1	61.6	7	8	58.5	10
2	61.5	8	9	57.9	13
3	61.2	12	10	56.9	4
4	60.7	6	11	55.3	32
5	60.4	5	12	55.1	14
6	59.9	31	13	54.4	9
7	59.4	11	14	49.3	39



VAR Value Study with IEEE 39 Bus System (2)





Long-term VAR Planning: Considering Static Voltage Constraints

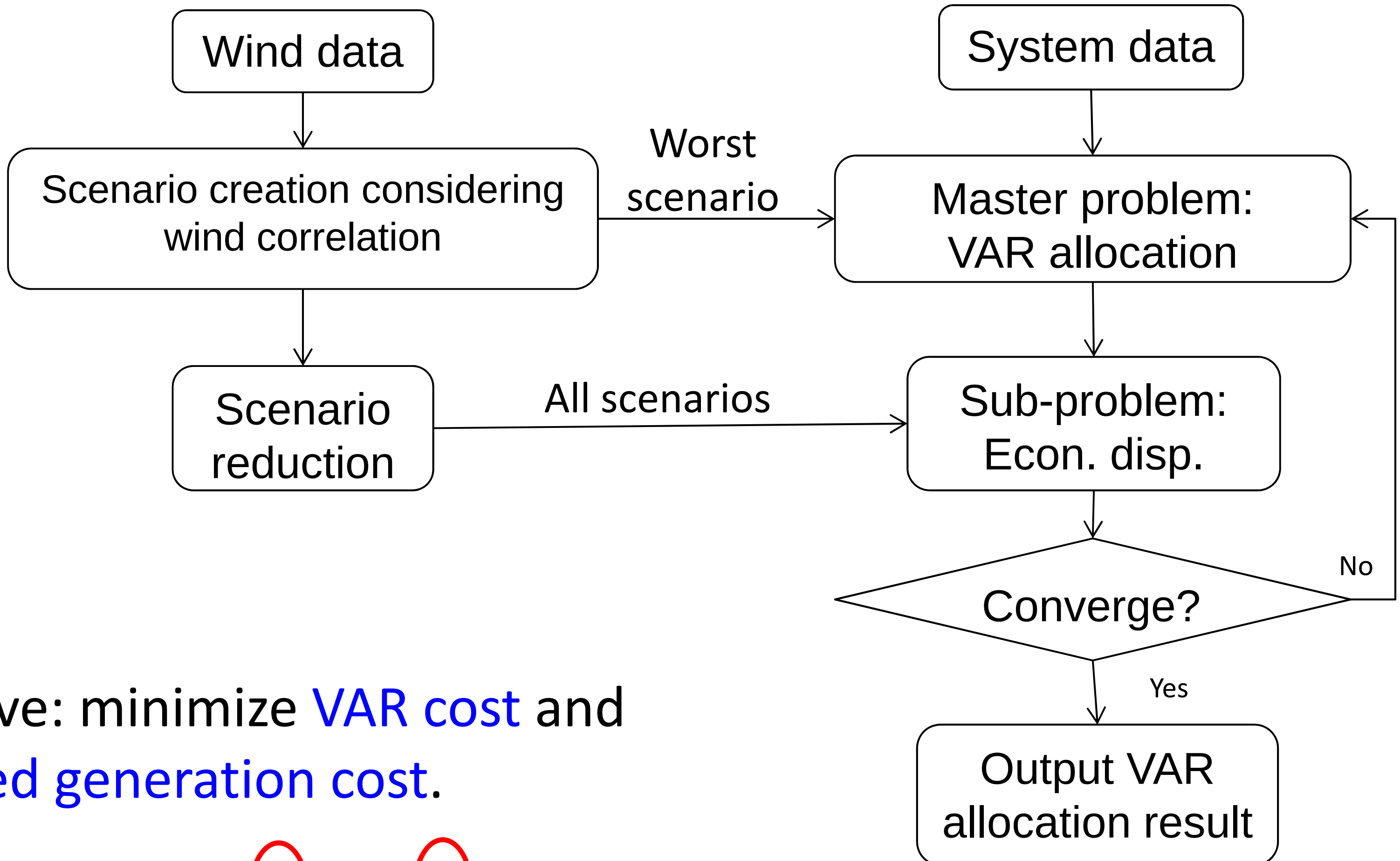
Considerations:

1. Different generation types including coal, gas, and renewables
2. Wind energy Weibull distribution
3. Correlation between multiple wind farms
4. Different VAR capabilities of wind farms
5. Static voltage constraints

Results:

To determine static VAR source size and location that minimizes the total cost

Bi-level Optimization Model



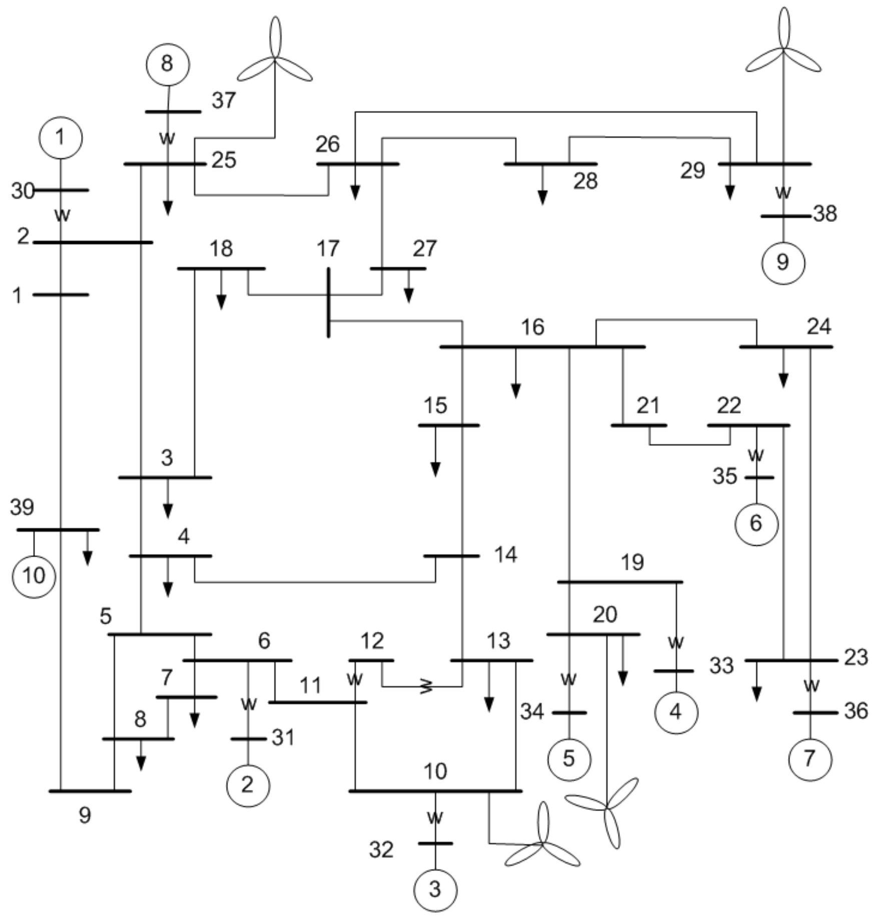
Objective: minimize VAR cost and expected generation cost.

$$\min \sum_{k \in N^Q} \left(c_1 + c_2 \cdot Q_{ck}^{*} \right) \cdot u_k + \sum_{t \in W^N} p_t \sum_{i \in N^G} f(P_{Gi,t})$$

Binary Variable

Probability Weights

Case Study with IEEE 39 Bus System (1)



Four wind farms connected at Bus 10, Bus 20, Bus 25 and Bus 29.

Wind farm data

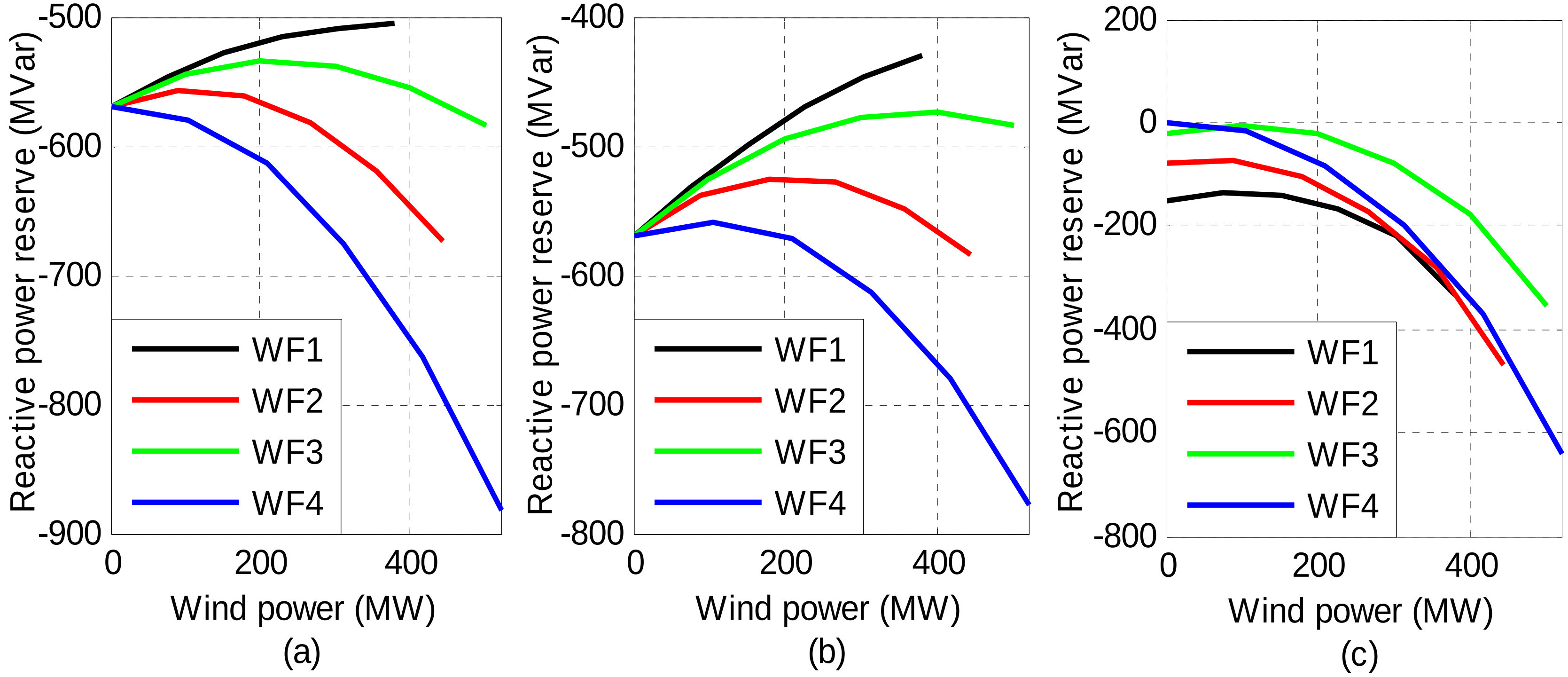
WF	Bus	Wind power (MW)	k	λ
1	10	380	8.13	1.99
2	20	445	8.24	2.3
3	25	500	7.52	2.11
4	29	520	9.24	2.41

$$\Omega = \begin{bmatrix} 1 & 0.81 & 0.54 & 0.43 \\ 0.81 & 1 & 0.58 & 0.41 \\ 0.54 & 0.58 & 1 & 0.93 \\ 0.43 & 0.41 & 0.93 & 1 \end{bmatrix}$$

Correlation Matrix

Case Study with IEEE 39 Bus System (2)

Select the worst scenarios in which the system has the least reactive power reserve.



Case a: unity power factor | Case b: pf = 0.98 | Case c: D curve operation

Case Study with IEEE 39 Bus System (3)

VAR allocation results under different optimization objectives

	Objective: VAR Cost				Objective: Total Cost			
	VAR Size (Bus)	Fuel cost ($/hr)	VAR cost ($/hr)	Total cost ($/hr)	VAR Size (Bus)	Fuel cost ($/hr)	VAR cost ($/hr)	Total cost ($/hr)
Case a (pf=1)	29.4 (5), 171.5 (7), 200 (8)	143,532	691.3	144,223	200 (5), 114.2 (7), 118.2 (18)	143,454	738.6	144,193
Case b (pf=0.98)	29.4 (5), 171.5 (8), 200 (8)	143,524	691.3	144,215	152 (7), 186.2 (11), 91.9 (17)	143,435	734.0	144,169
Case c (D curve)	95.3 (7)	143,512	173	143,685	95.6 (7)	143,512	173.4	143,685

When the correlation among wind farms is considered, the worst scenarios for Case a and Case b are the same. Therefore, VAR allocation results for these two cases are the same if only VAR cost is the objective.

It is recommended to use total cost as the objective if possible, since this may lead to different and better results from the overall system perspective.

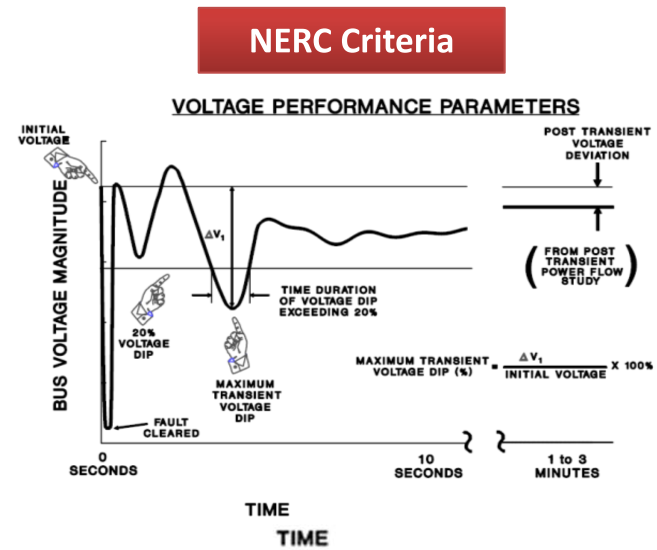
Dynamic VAR Planning: considering post-contingency voltage dynamics

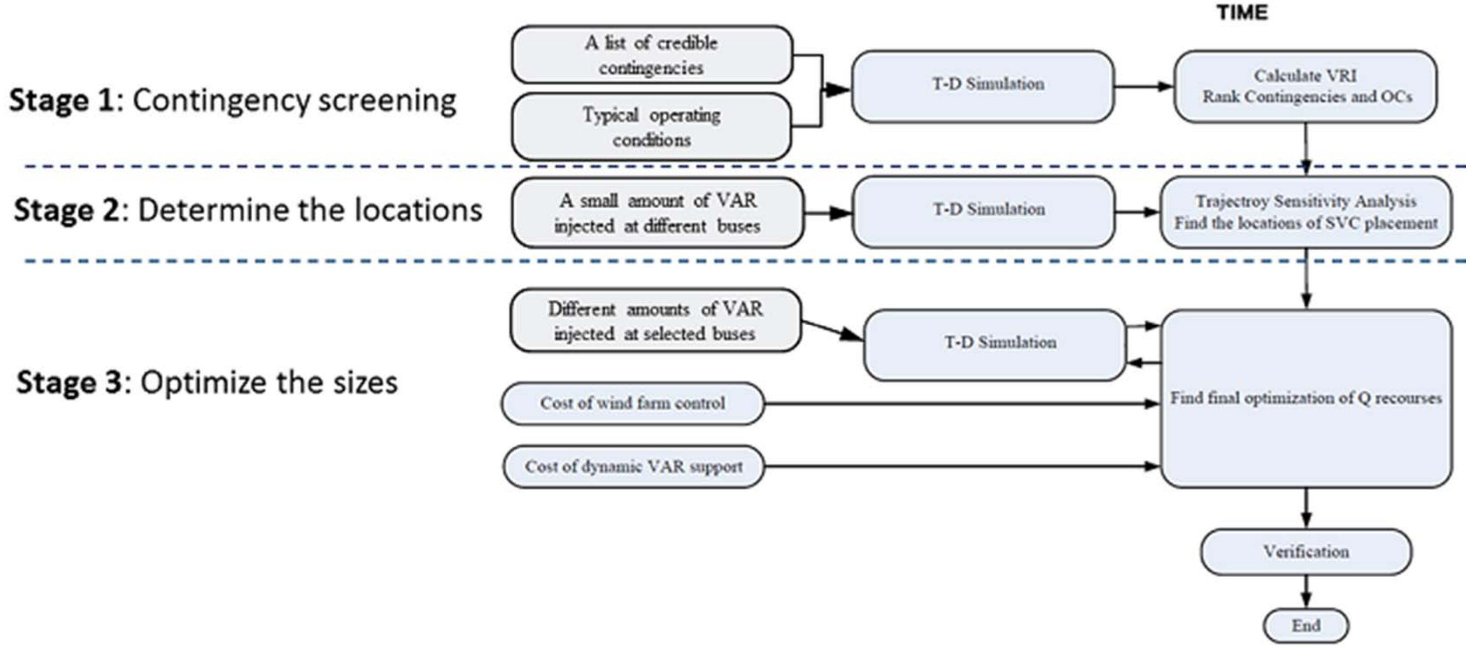
Approaches:

1. Use the static VAR optimization results as the reference.
2. Consider NERC criteria on post-fault voltage recovery performance.
3. Solve an nonlinear optimization problem to minimize the cost while meeting dynamic voltage requirements.

Results:

Locations and sizes of dynamic VAR sources





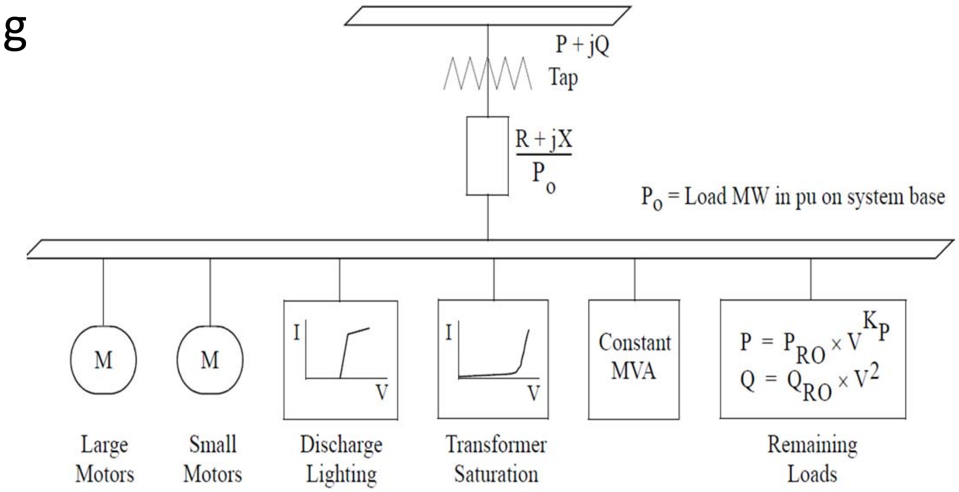
Stage 1: Contingency Ranking

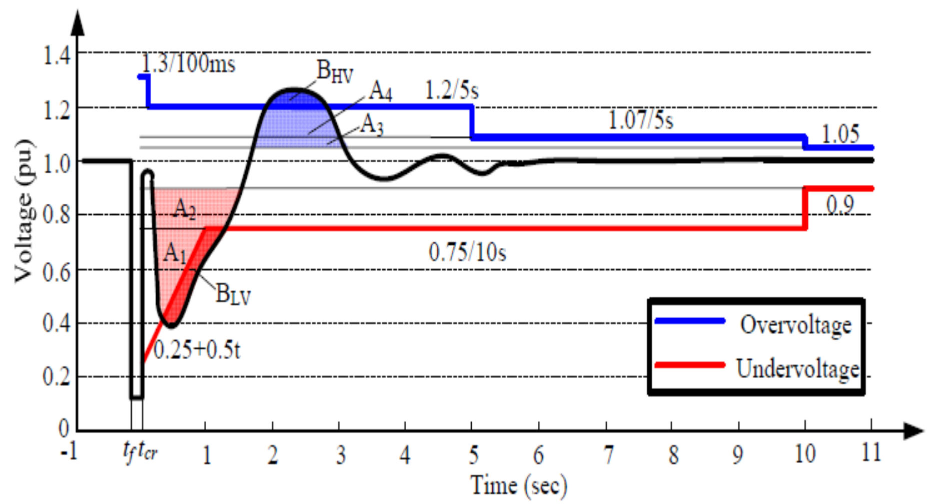
- Use a composite load model including motor loads
- Find the most severe N-1 or N-2 by a Voltage Recovery Index:

$$VRI_k = \frac{1}{N_{OC}} \sum_{n=1}^{N_{OC}} \left[\sum_{m=1}^{N_{Bus}} V_{dev,n,m} \right]$$

$$V_{dev,n,m} = \sum_i C_i \int_{t_{cr}}^{t_s} A_i dt + \sum_j D_j \int_{t_{cr}}^{t_s} B_j dt$$

(Voltage deviation for contingency *k* at bus *m* under condition *n*)





Stage 2: Placement of Dynamic VAR Sources

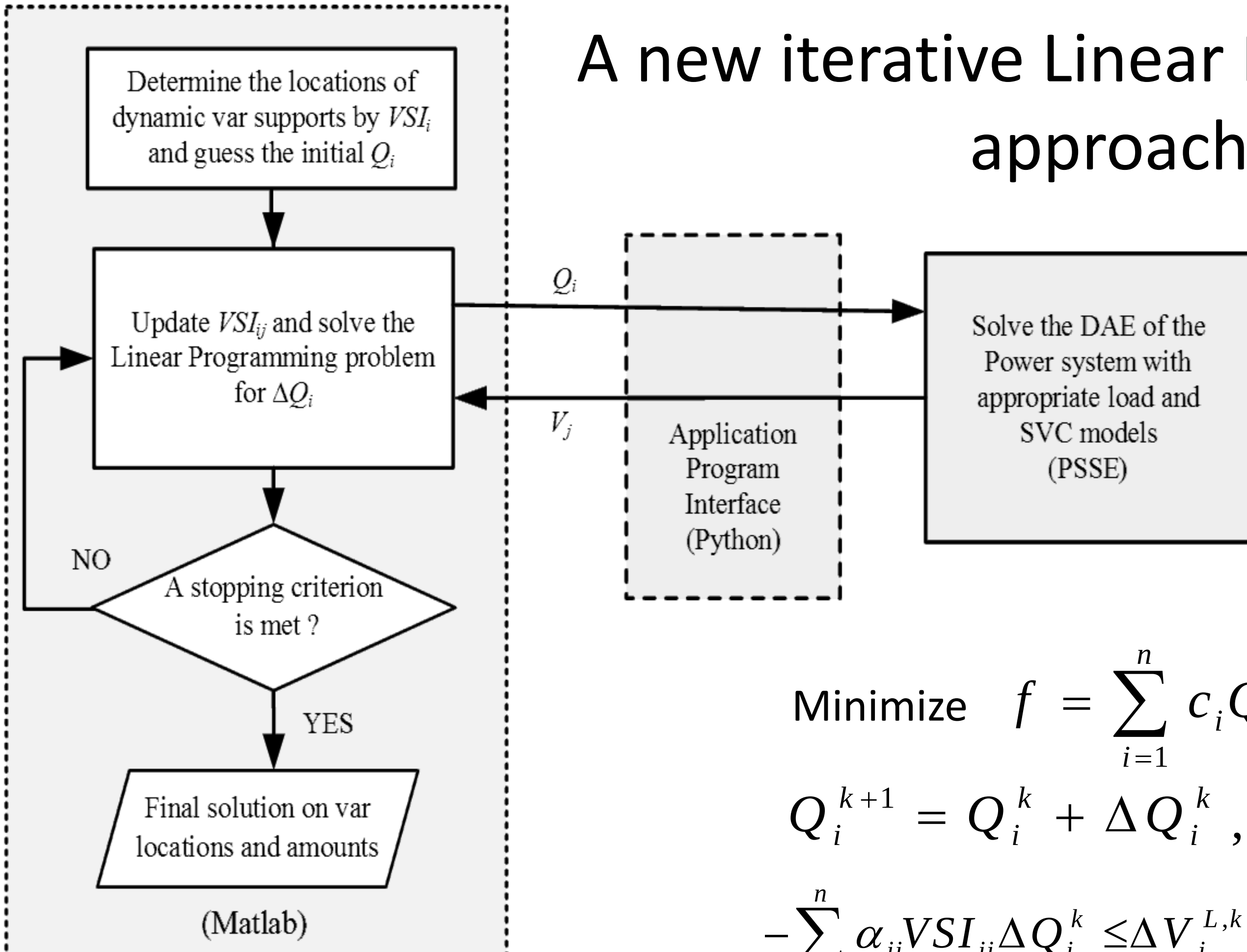
1. Evaluate a Voltage Sensitivity Index (VSI) for bus j or the overall system by simulated post-contingency voltage trajectories with a small q_i injected at bus *i*

$$VSI_{ij} = \max\left[V_j^{new,t} - V_j^{old,t}, t = 1 \sim T\right] / q_i$$

$$VSI_i = \frac{1}{N}\sum_{j=1}^{N} VSI_{ij}$$

2. Select a number (depending on budget) of the buses with the highest VSIs to place SVCs

Stage 3: Optimization of the Sizes of Dynamic VAR Sources



A new iterative Linear Programming approach

Minimize $f = \sum_{i=1}^{n} c_i Q_i^{k+1}$

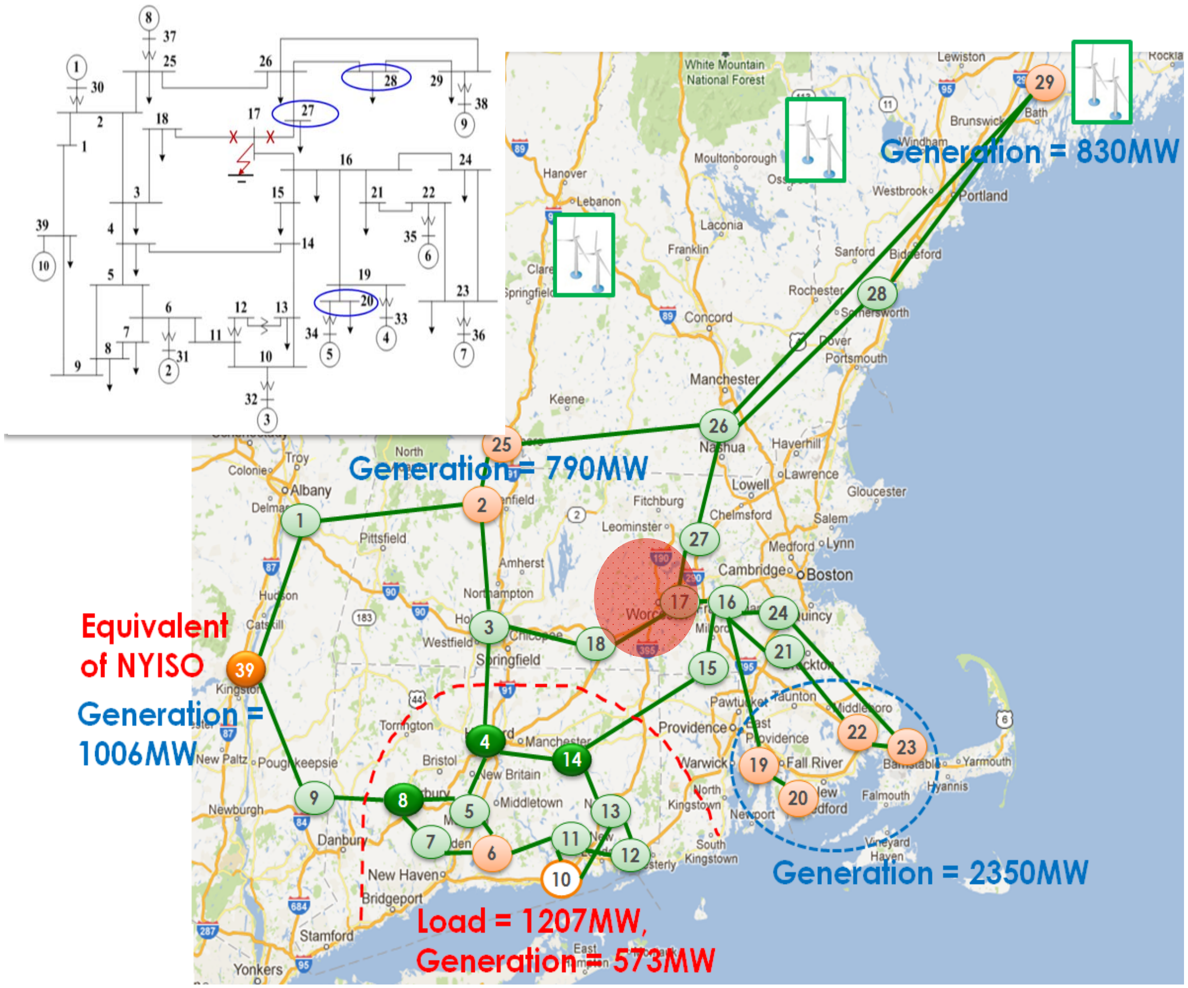
$$Q_i^{k+1} = Q_i^k + \Delta Q_i^k \;, \forall\, i = 1 \sim n$$

$$-\sum_{i=1}^{n} \alpha_{ij} VSI_{ij} \Delta Q_i^k \le \Delta V_j^{L,k} \;, \forall\, j = 1 \sim N$$

$$\sum_{i=1}^{n} \beta_{ij} VSI_{ij} \Delta Q_i^k \le \Delta V_j^{U,k} \;, \forall j = 1 \sim N$$

Case study with IEEE 39 Bus System

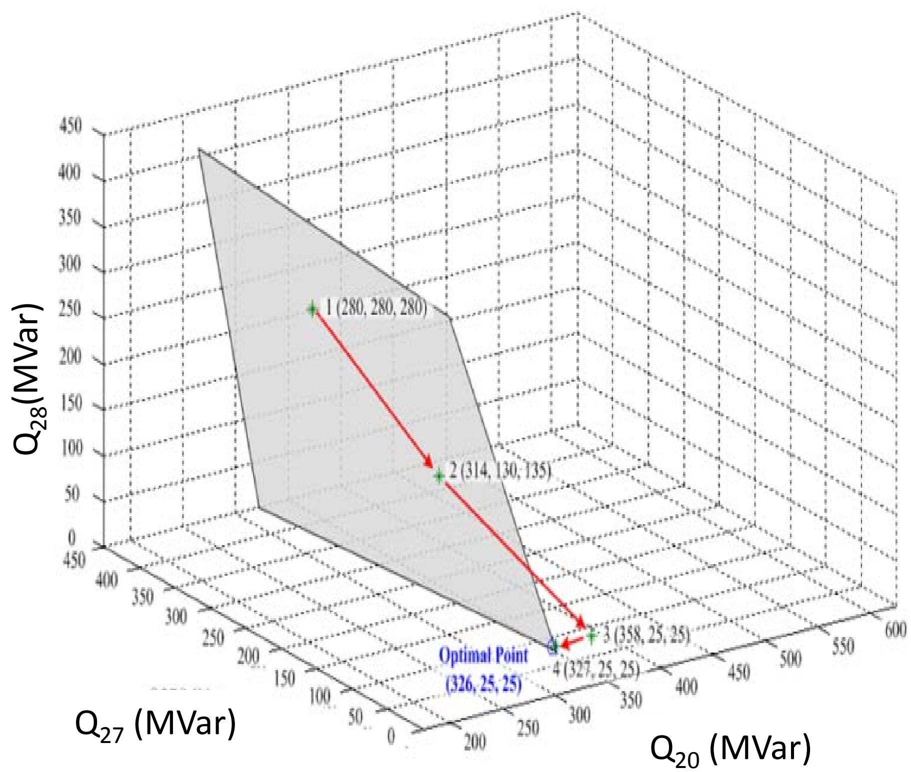
- Consider a severe N-2 contingency: a 3-phase fault on bus 17 cleared by opening lines 17-18 and 17-27 after 5 cycles
- Choose buses 28, 27 and 20 (top-3 VSI values) to install SVCs, and then optimize the sizes



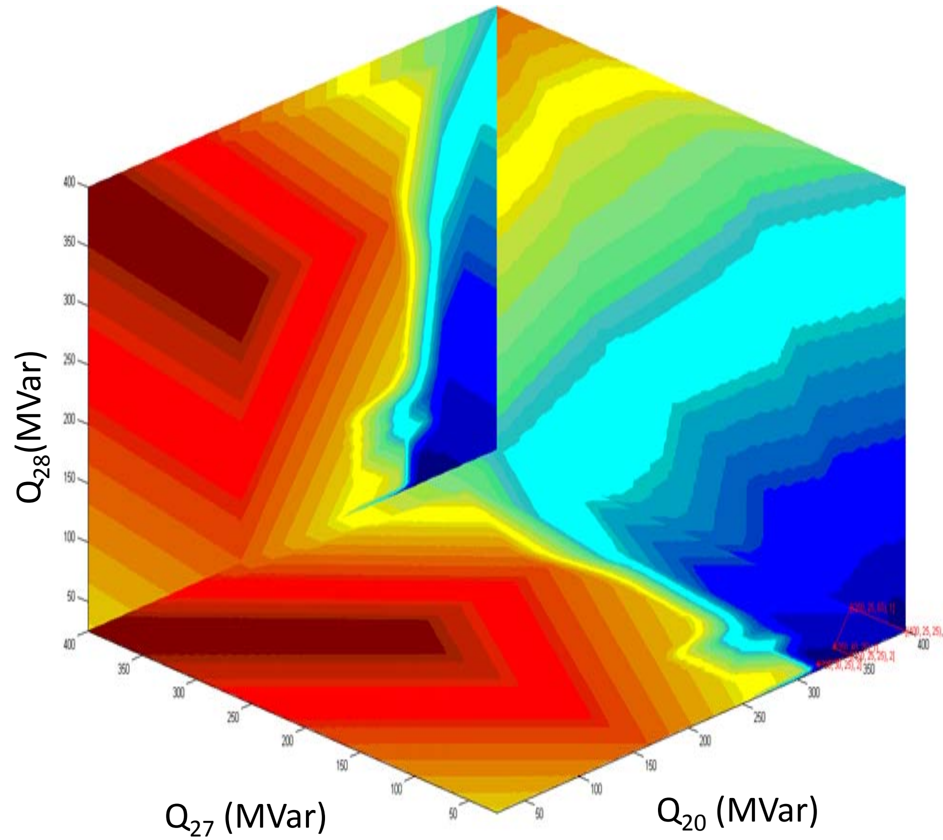
BUS NO.	VSI	Qj pu	Rank based VSI
28	0.0971	0.015	1
27	0.0297	0.0004	2
20	0.0236	0.5765	3
26	0.0229	0.075	4
21	0.0202	0.0889	5
24	0.0202	0.0005	6
16	0.0188	0.0337	8
23	0.0188	1.1345	7
15	0.0182	0.0001	9
18	0.0158	0.0023	10
25	0.0138	1.896	11
13	0.0136	0.4844	12
29	0.0135	0.3082	13
3	0.0133	0.2751	14
7	0.0122	0.1249	15
8	0.0118	0.07833	16

Optimizing the Sizes of Dynamic VARs

Optimal Solution: Q_{20}=326MVar, Q_{27}=25MVar and Q_{28}=25MVar

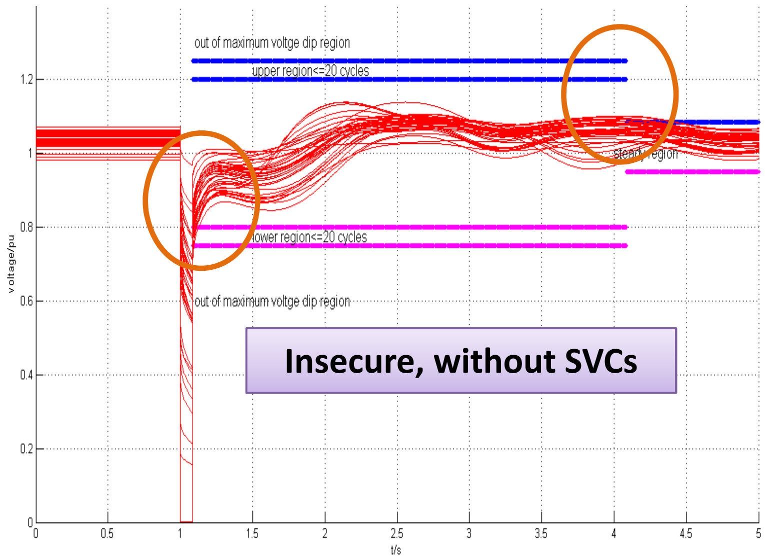


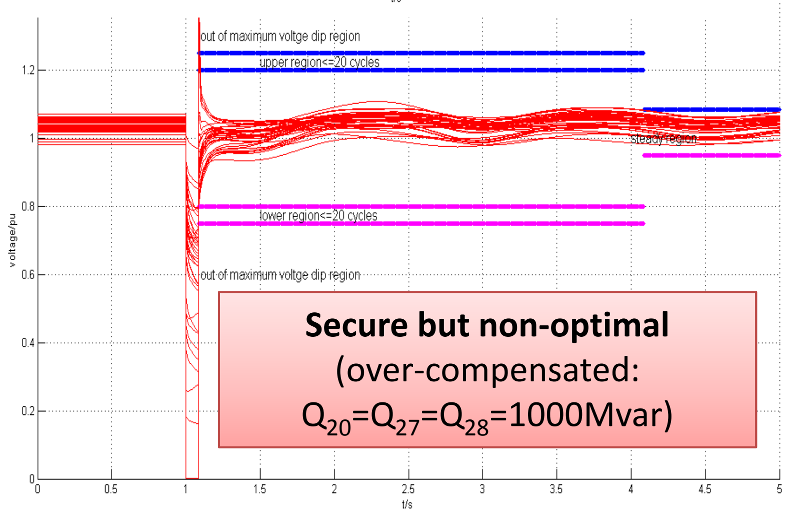
Searching by Linear Programming

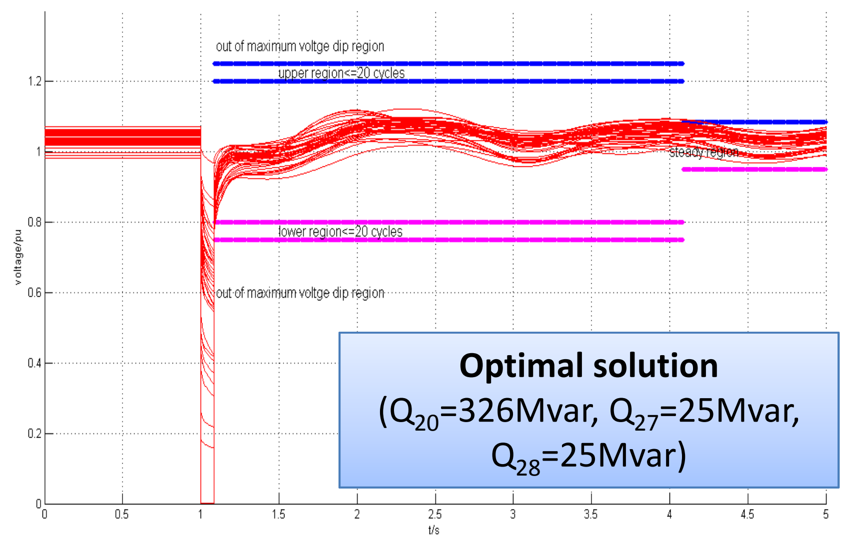


Speeding up searching using a contour map

Comparison of Trajectories







The optimized solution gives secure voltage response while minimizing the total cost.

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- **Conclusions and Future Works**

Conclusions

- An integrated VAR planning and analysis tool is developed.
  - Concept verification tool for utility users to test and verify the concepts developed in this project, under the paradigm of considering uncertainty and post-contingency voltage dynamics
  - Functions include VAR value assessment, long-term VAR planning considering static voltage constraints, and short-term VAR planning considering post-contingency voltage dynamics
  - Easy user interface with PSS/E and GAMS

Future Works

- FY 2015: Continue engagement of Dominion Virginia Power (DVP) and other companies to develop the MOVARTI tool to address utility challenges and needs:
  - Operational consideration of VAR sources
  - Uncertainty at the demand side
- FY 2015: Further development of the tool to integrate the static planning and dynamic planning, methodology validation using a real system.
- Out-year plan: Deployment as an open-source tool.

Acknowledgements

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Thank you!

Q & A?