A Bundle Method for On-Line Transient Security Constrained Dispatch

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Optimization and Dynamics

- In operations, or planning, *both* optimization and dynamics features are needed simultaneously.
- In most (all?) operations and literature, these are treated separately.
- When transient stability fails (on N-x) a constraint is added in operations, but distance to optimality unclear.
- One would hope that the future would have coupled optimization and dynamics.
- We investigate the complexity or consequences of doing that.

Dynamic Security

- Transient
  - (for example) Generator frequency excursion following a disturbance
  - Lost of synchronicity will yield additional disturbances
- Stability
  - Ability withstand large disturbances
  - Requires involved numerical simulations in order to be assessed
  - Combinatorial nature of contingency scenarios
  - Typically assessed offline under current practices, used to set op
  - Growing need for online assessment and control

How to couple dynamics and optimization

- Ideally, the optimization should have algebraic access to the dynamics.
- That is quite a ways away.
- We propose a loose connection between optimization and dynamic simulation based on first-order oracle functions.
- This assumes only that the dynamics has been instrumented with adjoint differentiation.
- Otherwise, the tools can be distinct.

Dynamics

Transients are model as DAEs:

$$\dot{x}(t) = F(x(t), y(t), p)$$
$$0 = G(x(t), y(t), p)$$

Dynamic stability is modeled as

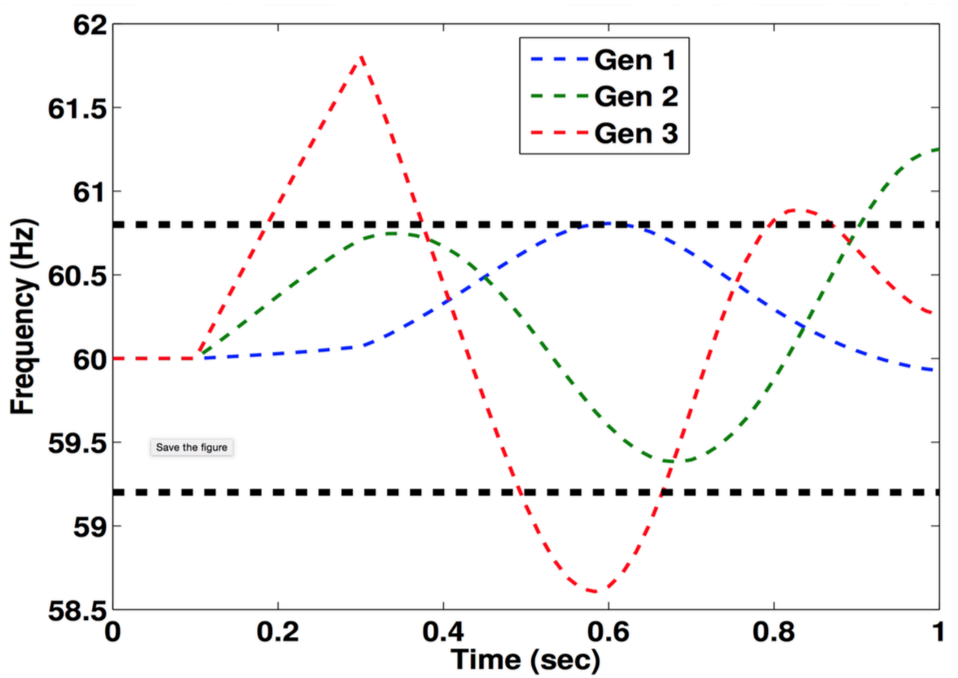
$$H(x(t), y(t), p) \leq \delta_H, \quad 0 \leq t \leq T$$

which can be explicitly expressed as functions of the initial conditions :

$$\tilde{H}(t, x_0, p) = H(\phi_t(x_0), q(\phi_t(x_0)), p) \leq \delta_H, \quad 0 \leq t \leq T$$

… this is semi-infinite optimization

Illustration (9 bus example)



- Fault at t=0.1, cleared at t=0.3
- Not dynamically secure: Gen 2 and Gen 3 exceed their operational limits

Finite dimensional stability measure

Requirement for a finite dimensional stability metric compatible with the optimization, such as

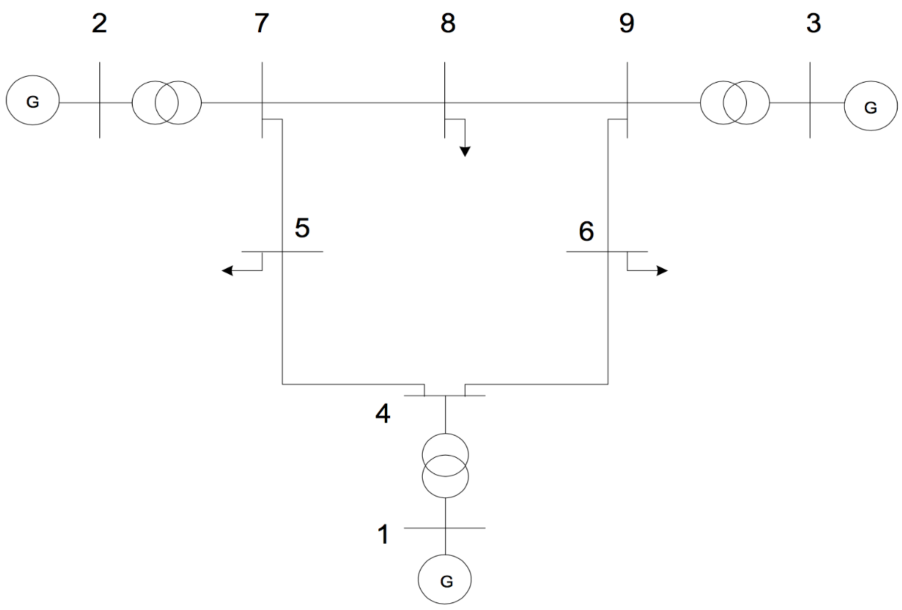
$$\tilde{c}_g^k(d) = \int_0^T [\max(0, \omega_g^k(t) - \omega^+, \omega^- - \omega_g^k(t))]^\eta \, dt \qquad g \in \mathcal{G}$$

and then (covering multiple contingencies):

$$c_g(d) = \sum_{k \in \mathcal{C}} \tilde{c}_g^k(d).$$

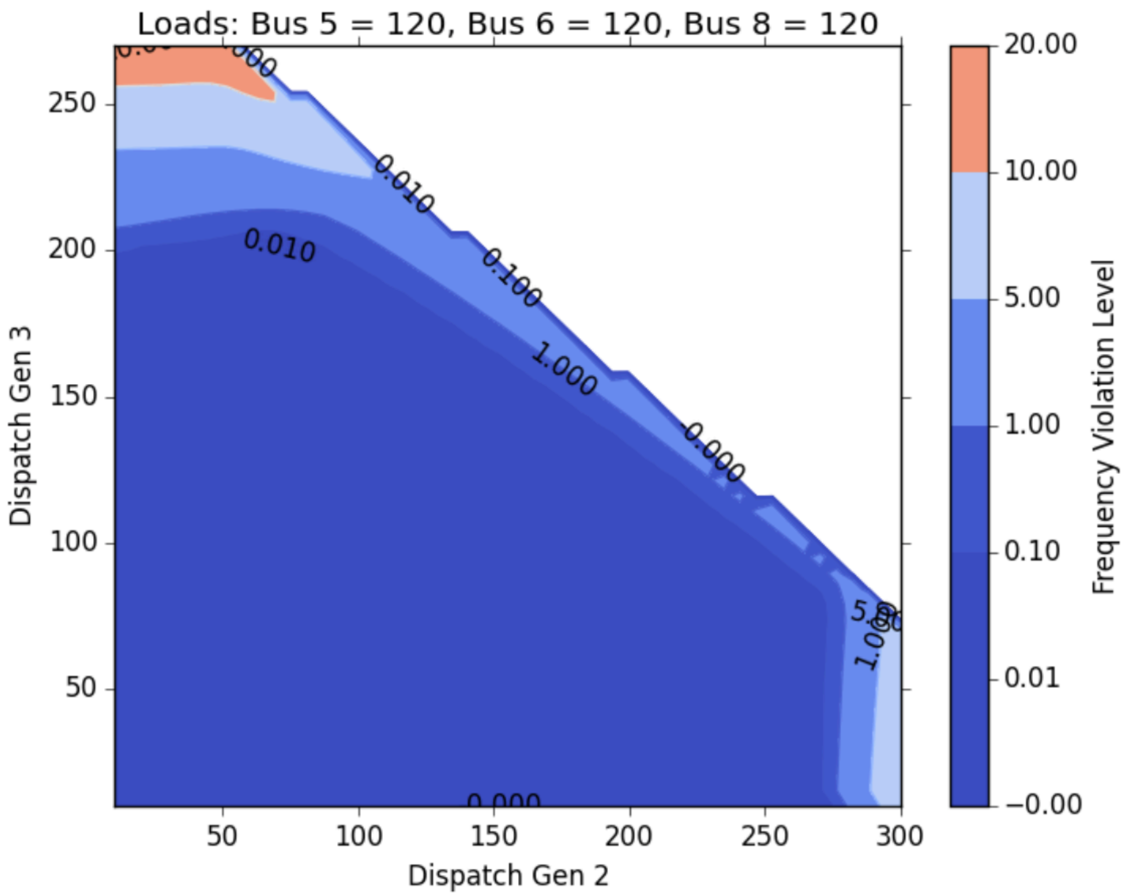
provides a measure of generator *g* frequency excursion beyond its operational limits.

IEEE 9-Bus System

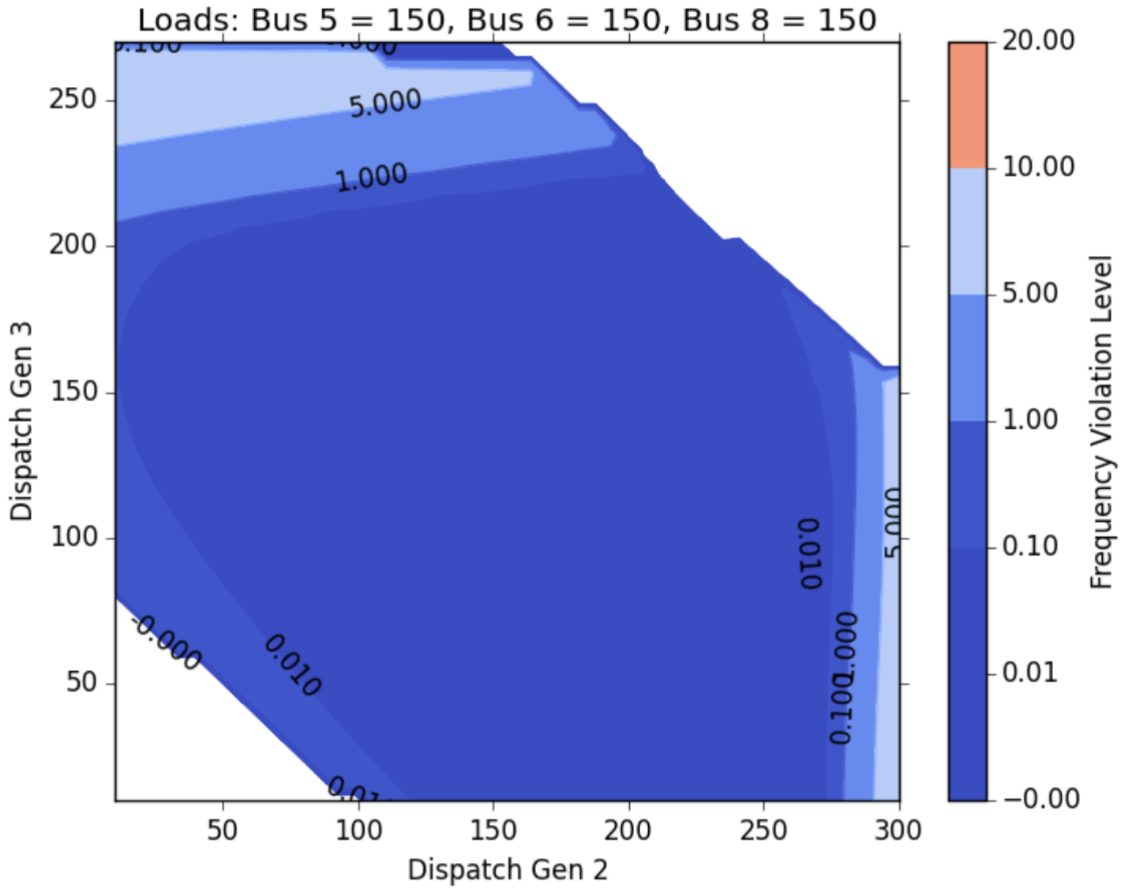


bus	d_g^{min}	d_g^{max}	mrg_g	inertia	damping
1	10	350	0.11	13.64	2.64
2	10	300	0.14	3.94	0.29
3	10	270	0.6	10.09	1.01

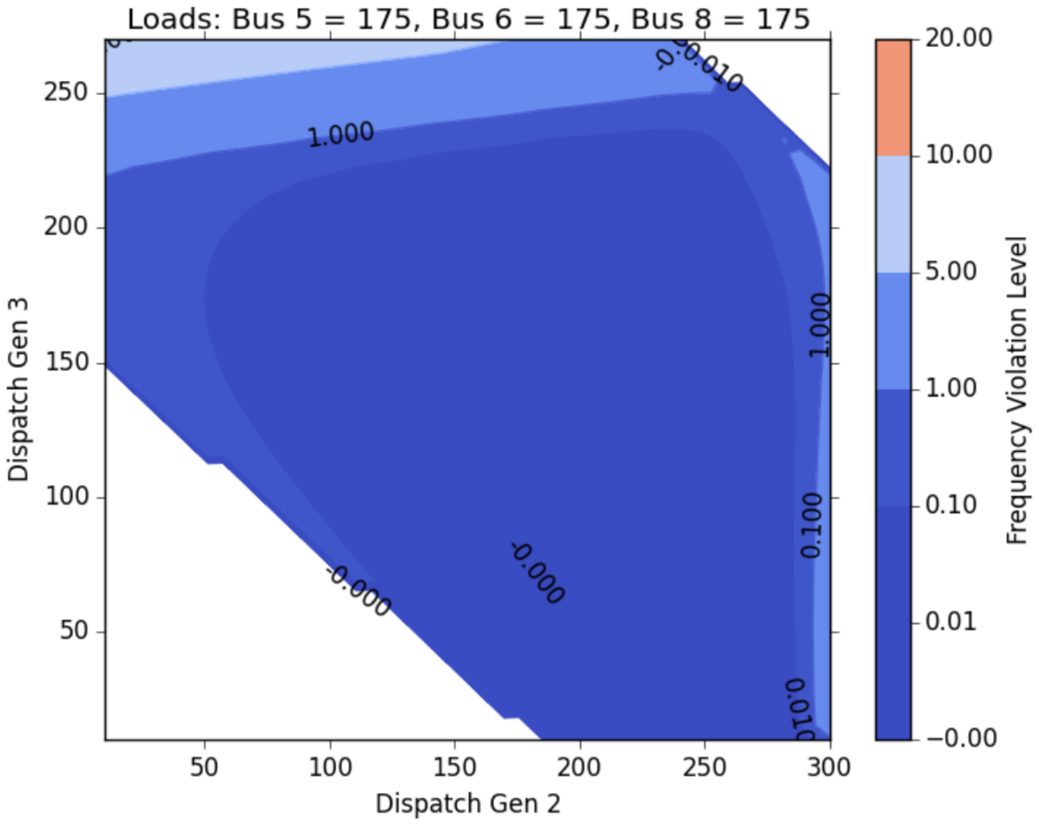
IEEE 9-Bus System Stability Region (Scenario 1)



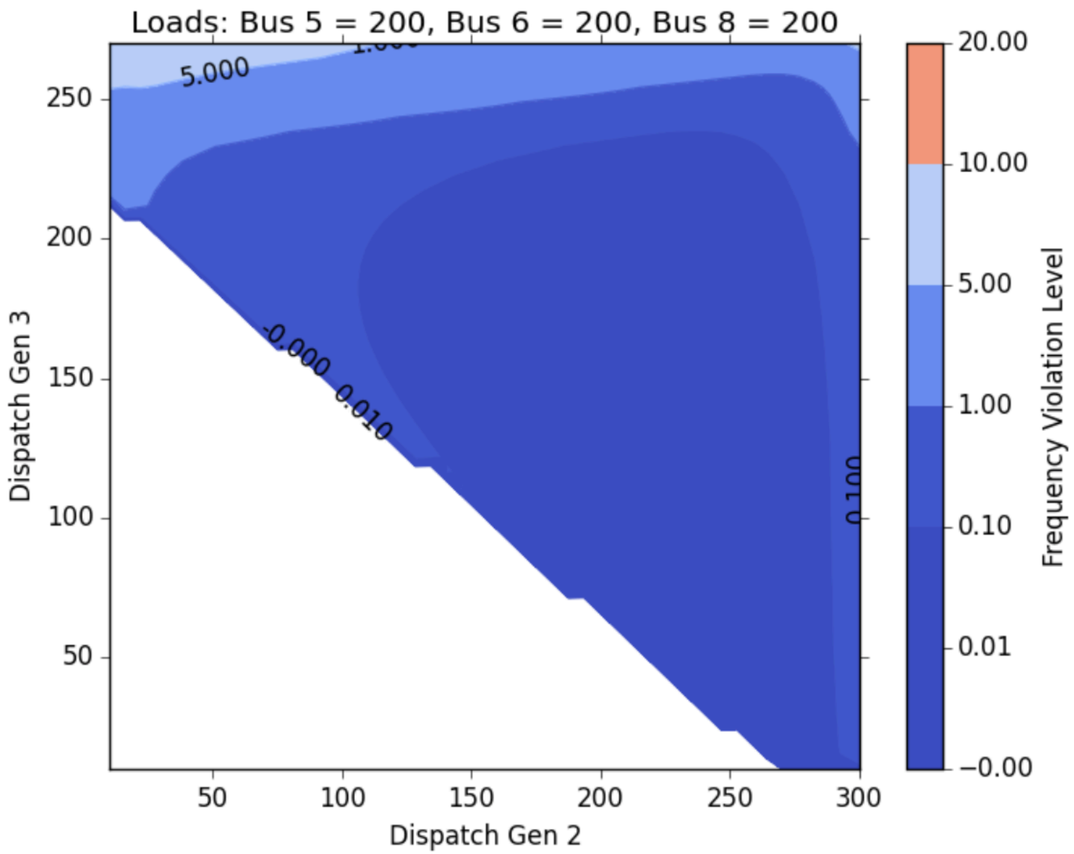
IEEE 9-Bus System Stability Region (Scenario 2)



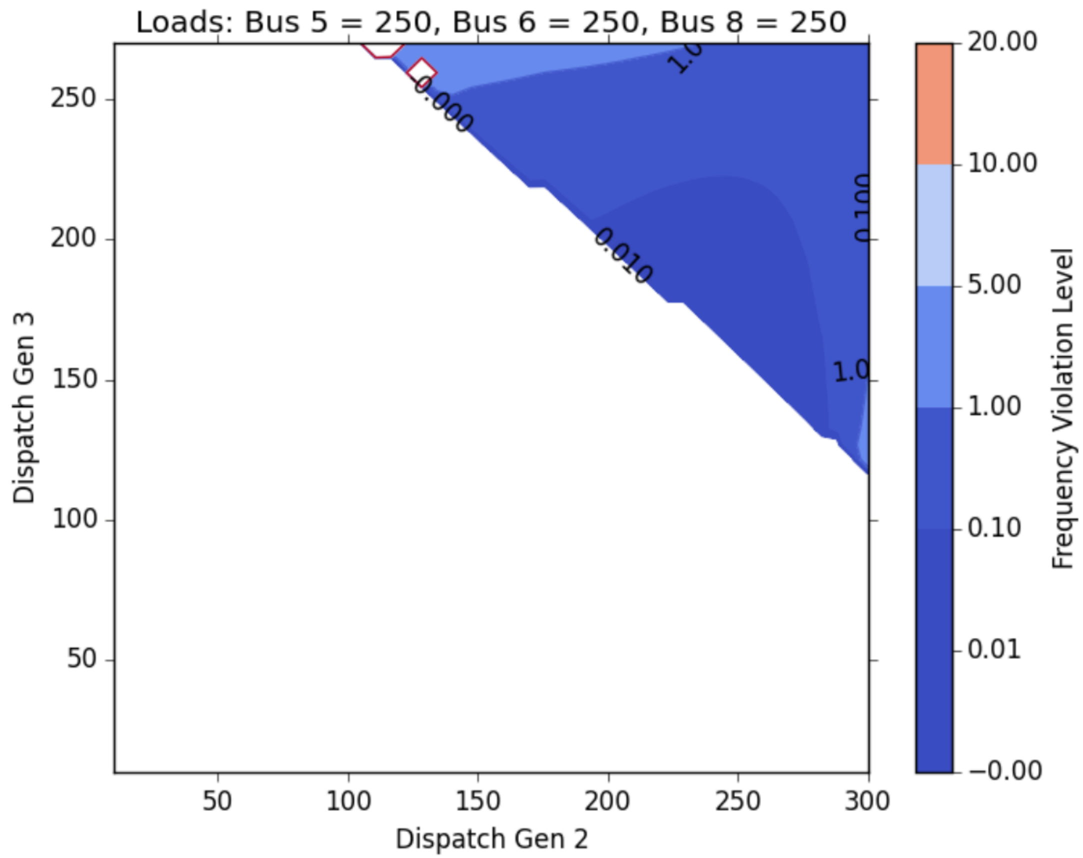
IEEE 9-Bus System Stability Region (Scenario 3)



IEEE 9-Bus System Stability Region (Scenario 4)



IEEE 9-Bus System Stability Region (Scenario 5)



- … it is convex! So first-order methods OK!
- Naturally we do not know if this holds in general, but results promising.

Transient Stability Constrained Economic Dispatch (simplified)

$$\min_{d \in D(\overline{u})} \quad f(d)$$

$$\text{s.t.} \quad c_g(d) \le \delta_c \qquad g \in \mathcal{G}$$

where $d \in D(\overline{u}) \Leftrightarrow$

Balance: $\displaystyle\sum_{g \in \mathcal{G}(b)} d_g + \sum_{\ell \in \mathcal{L}^-(b)} h_\ell - \sum_{\ell \in \mathcal{L}^+(b)} h_\ell = \text{dem}_b \qquad b \in \mathcal{B}$

Capacity: $d_g^{\text{min}} \overline{u}_g \le d_g \le d_g^{\text{max}} \overline{u}_g \qquad g \in \mathcal{G}$

$h_\ell^{\text{min}} \le h_\ell \le h_\ell^{\text{max}} \qquad \ell \in \mathcal{L}$

Reserve: $\displaystyle\sum_{i \in \mathcal{G}} d_g \ge R$

and $f(d) = \sum_{g \in \mathcal{G}} \text{mrg}_g \, d_g$.

Optimization Setting

- DC based steady state feasibility
  - Polyhedral constraints
  - Pre-contingency/post-contingency states
- Transient stability
  - Non-linear, non-convex (maybe), high-dimensional
  - Expensive but parallelizable
  - Provided via first-order oracle
  - Reliable mostly at the fringe
- Algorithm
  - Allow for infeasible iterate
  - Feasible set may be empty

Level-Bundle Method Overview I

- Gathers information from pervious oracle evaluations in a so-called *Bundle*
- Sequentially improves upon bounds (upper and lower) on the objective
- Solves quadratic sub-problems where current iterates are projected on prospective level sets
- Provides an outer-linear approximation of the nonlinear constraints
- Arbitrage between optimality and feasibility on the basis of an *improvement function* (no penalty)

Level-Bundle Method Overview II

- Initiated at the optimum of the security constrained economic dispatch (SCED)
- Optimization (CPLEX through Julia; model is in Julia) and simulation (PETSc) alternate at each iteration
- Gradients are computed through adjoint computation in PETSc
- Stability cuts are added to the formulation as frequency violations are encountered
- The (likely) unstable SCED optimum is gradually driven back to stability

Bundle Approach Pros/cons

- Pros
  - Provides an outer approximation of the feasible set (stability region) as a bi-product
  - Based on improvement functions and do not require a penalty
  - Readily handles polyhedral constraints
  - Straightforward implementation
- Cons
  - Handling non convexity is non trivial
  - Tend to produce infeasible iterates until convergence
  - Quadratic subproblem to solve at each iteration

Stability region outer-linear approximation

The algorithm sequentially constructs

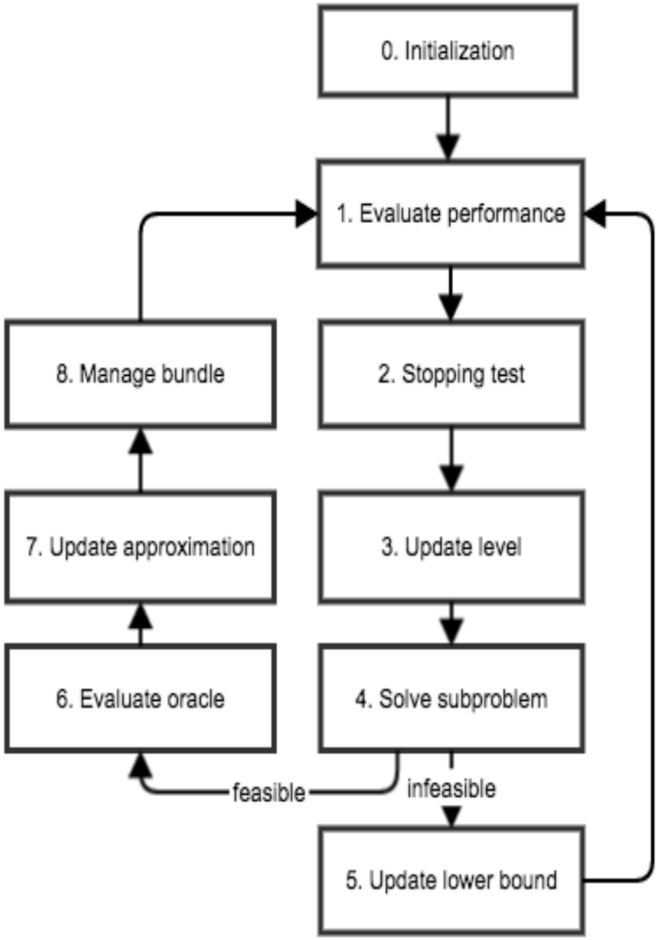
$$\check{c}_g^k(d) = \max_{j \in J_k} c_g^j + s_g^j \cdot (d - d^j) \leq 0 \quad g \in \mathcal{G}^k,$$

where $g \in \mathcal{G}^k \Leftrightarrow c_g^k \geq \delta_c$ and

$$c_g^j = c_g(d^j) \qquad g \in \mathcal{G}$$
$$s_g^j = \nabla_d c_g(d^j) \quad g \in \mathcal{G}$$
$$f^j = f(d^j)$$

with $\{d^j, f^j, c^j, s^j : j \in J_k\}$, the bundle of information gathered at previous iterates.

Level-Bundle Method Workflow



Level-bundle method: steps 1-4

- Step 1: Performance evaluation

$$v^k = \min_{j \in J^k} \{\max\{f^j - f^k_{\text{low}}, \max_g c^j_g\}\}$$

- Step 2: Stopping criteria

$$v^k \leq \delta_v$$

- Step 3: Level update

$$f^k_{\text{lev}} = f^k_{\text{low}} + \gamma\, v^k$$

Level-bundle method: steps 4-5

- Step 4: Proximal sub-problem

$$\begin{aligned} \min_d \;& \|d - \hat{d}^k\|^2 \\ \text{s.t.}\;& d \in D(u) \\ & f(d) \le f^k_{\text{lev}} \\ & \check{c}^k_g(d) \le 0, \quad g \in \mathcal{G}^k \end{aligned}$$

- Step 5: Lower bound update

$$f^k_{\text{low}} = f^k_{\text{lev}}$$

IEEE 9-Bus System Frequency Violations (SCED optimum)

Total load 300 MWh

branch	gen 1	gen 2	gen 3
6-9		0.072	19.794
7-8			10.248
8-9	0.024		29.399

Total load 375 MWh

branch	gen 1	gen 2	gen 3
4-6			0.118
6-9		0.025	15.887
7-8			7.335
8-9			24.954

IEEE 9-Bus Solution (TSCED optimum)

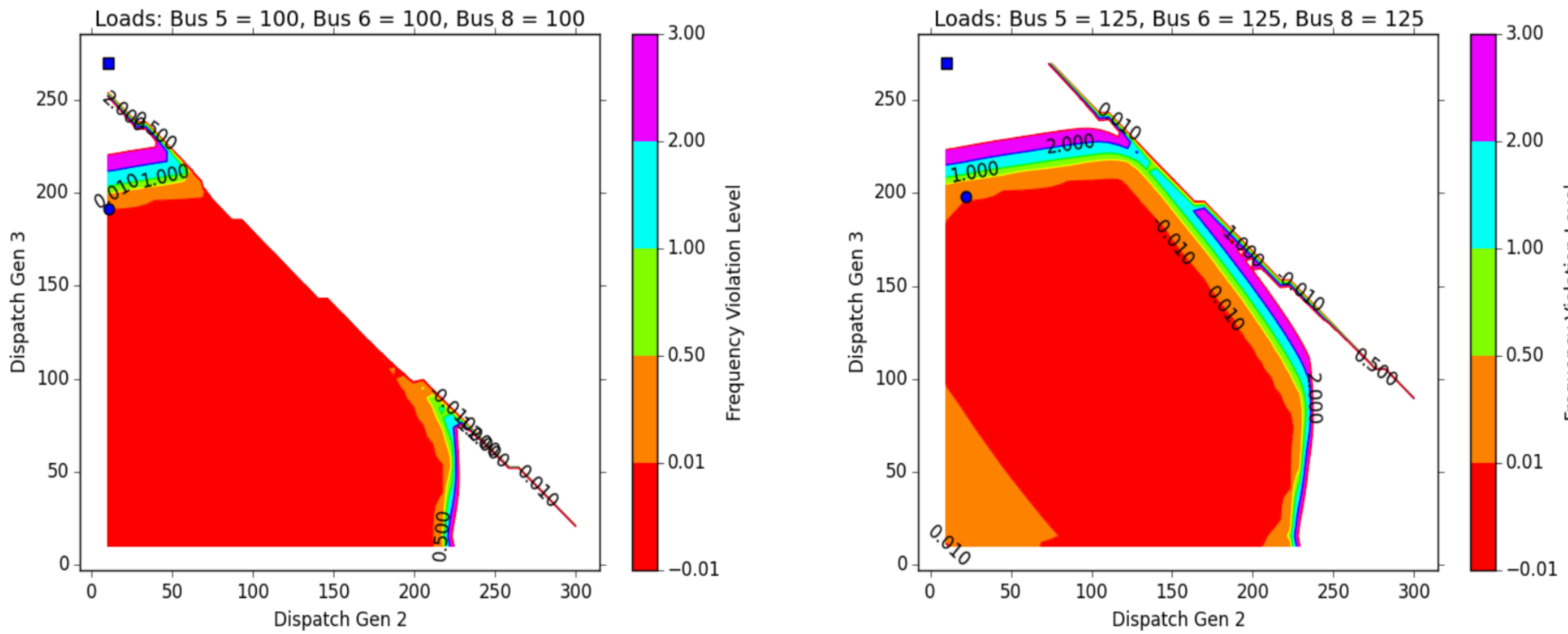
Total load 300 MWh

model	gen 1	gen 2	gen 3	mrg cost	freq violation
SCED	20.000	10.000	270.000	19.800	59.440
TSCED	98.464	10.175	191.361	23.737	0.010

Total load 375 MWh

model	gen 1	gen 2	gen 3	mrg cost	freq violation
SCED	95.000	10.000	270.000	28.050	47.874
TSCED	154.169	22.645	198.186	32.030	0.010

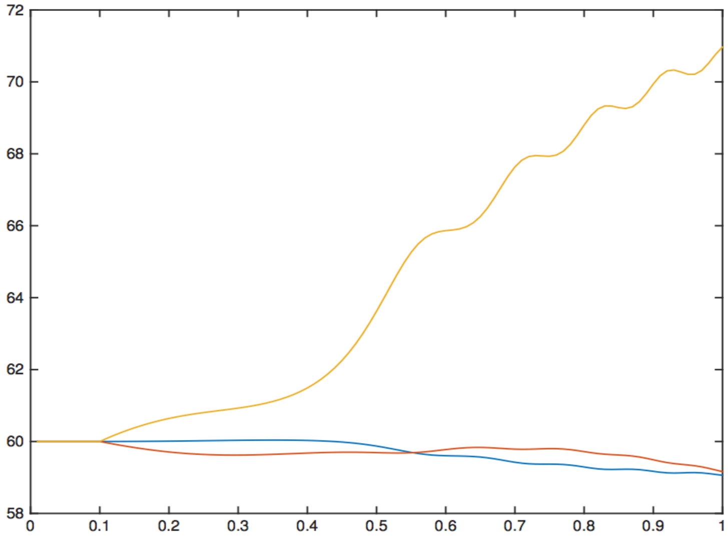
IEEE 9-Bus Solutions Comparison

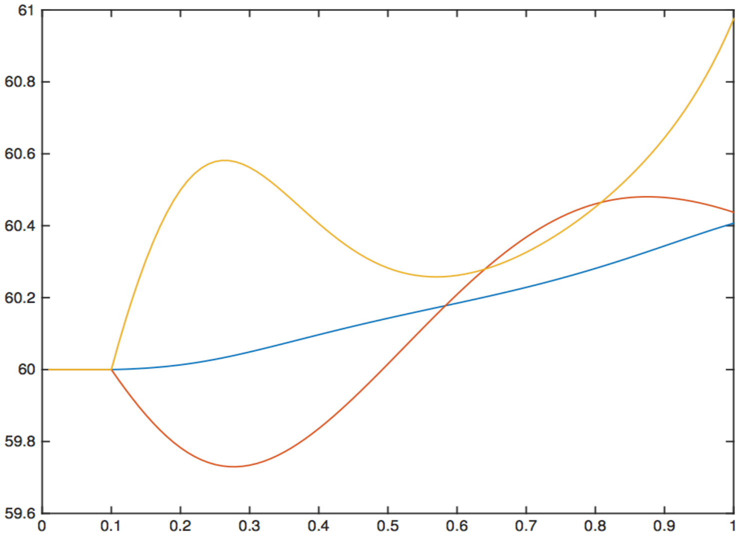


- Blue square – SCED optimum
- Blue circle – TSCED optimum
- Stability region – Red area

IEEE 9-Bus: ODEs solutions (300MWh)

Solution trajectories at the SCED optimum (left) and the TSCED optimum (right) in the 300MWh case:





Illustrates the inherent difficulty in defining a finite dimensional stability criteria.

IEEE 118-Bus System: Result Summary

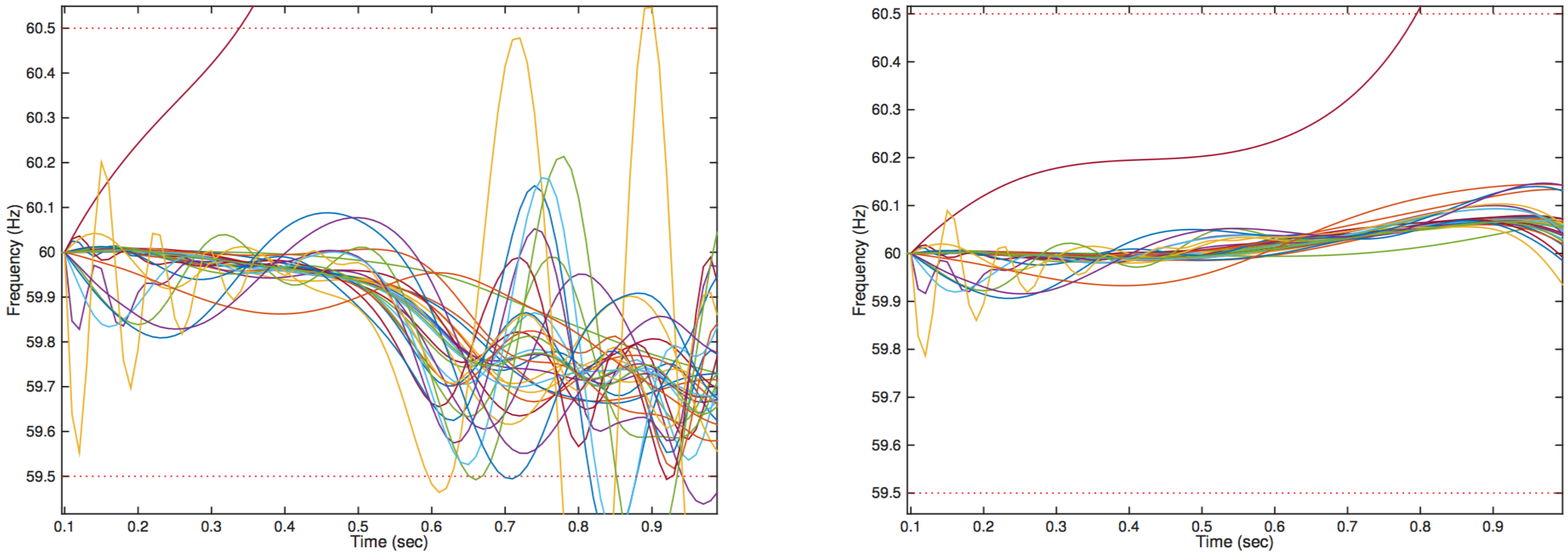
reserve (%)	f^{SCED}	freq	m	k	f^{TSCED}	CPU (sec)
7	49751.77	0.491	3	248	77363.06	958
10	49751.77	0.491	3	9	72842.32	119
20	50653.84	0.520	0	130	60952.85	785
30	51613.28	0.496	0	268	61876.86	645
40	56275.20	0.165	0	129	61617.88	680

branch	gen	freq violation (7% reserve)
8-5	4	0.4914
23-24	10	0.1634
38-37	16	0.1518
30-38	16	0.1352
65-68	29	0.3505
17-113	53	0.3229

branch	gen	freq violation (20 % reserve)
8-5	4	0.1312
23-24	10	0.1387
65-68	29	0.5196

IEEE 118-Bus System

Solution trajectories at the SCED optimum (left) and the TSCED optimum (right) in the 10% reserve case:



While the model behavior is consistent (as to the effect of reserve on the system stability), either the assessment period is too short or the stability criteria needs to be revised.

Summary

- We investigated an oracle-based approach for integrating optimization and dynamics.
- We used it for transient security constrained problems such as TSCED, but SOLs may be similar.
- We showed that we can compute to reasonable accuracy dynamically constrained dispatches for problems where SCED solutions are infeasible for transients.
- The approach allows a relatively unintrusive approach to dynamics, requiring only adjoints.
- Implemented in open-source tools.
- Future: larger problems, better models.