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Stochastic Optimization of Power System Dynamics for Grid Resilience

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Agenda

- Background Information
- Key Variables and Parameters
- Model Components
- Single Scenario Deterministic Case
- Multi-scenario Case
- Conclusion
- Future Research

Dynamic Power Systems Modeling

- In major emergencies, dynamics is paramount for system stability
- Swing equation at generators: $\frac{2H}{\omega_0}\frac{d^2\delta}{dt^2} = P_m - P_e$
  - We use a slightly higher-fidelity flux-decay model commonly used in stability studies [1]
  - An additional term (turbine with no reheating) is used to model how mechanical torque responds to a change in setpoint
- Network power balance equations: $0 = V \odot (YV)^* - S_{net}$
- Load dynamics
  - Play an important role in stability studies [2, 3]
  - We use exponential recovery model to capture load responses to voltage fluctuations [4]
- Combined, these pose a system of differential algebraic equations (DAE)

Dynamic Optimization Literature

- Transient Stability Constrained
  - Optimal Power Flow (TSCOPF)
  - Emergency Control (TSEC)
- Minimize objective subject to DAE path constraints, over some contingency
  - TSCOPF: optimize initial conditions x_0 for *potential* contingencies
  - TSEC: optimize control inputs *u* for *realized* contingency
  - Economic (generation cost) objectives
  - Simple stability constraints limiting:
    - Power angles with respect to center of inertia (approximate treatment of transient stability)
    - Line currents
    - Voltages
  - Decision variables: Generator setpoints and load shed

$$\text{Min } h(x, y, u)$$ objective

subject to

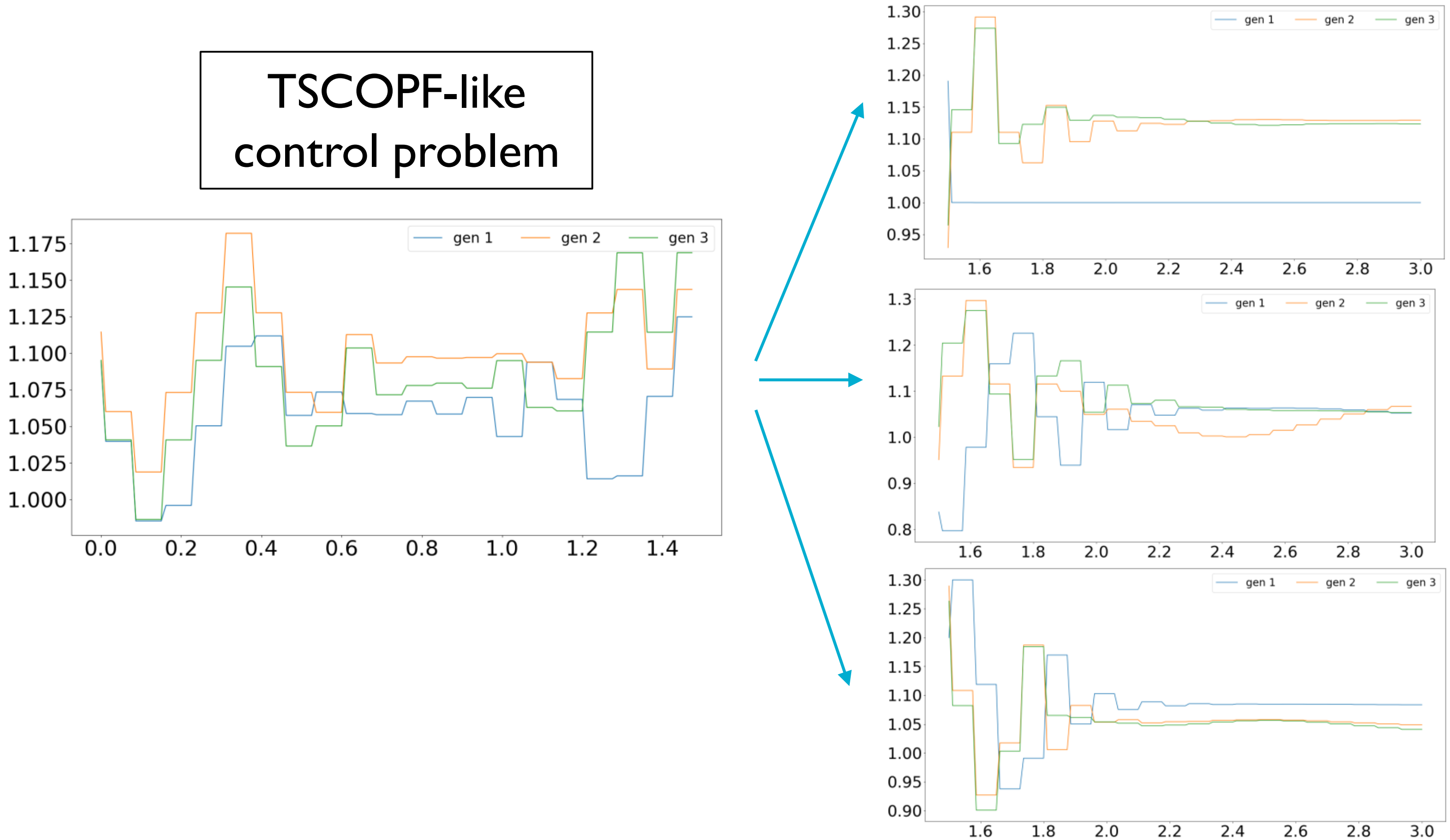
$$\frac{d}{dt}x = f(x, y, u)$$
$$0 = g(x, y, u)$$
DAE

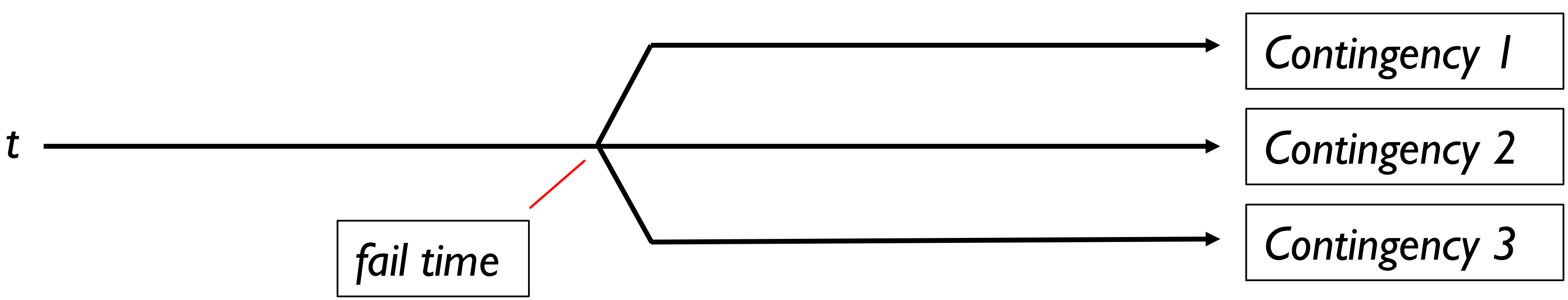
$$c(x, y, u) < 0$$ constraints

$$x(0) = x_0,$$
$$y(0) = y_0$$
initial conditions

Prepositioning and Recourse Control

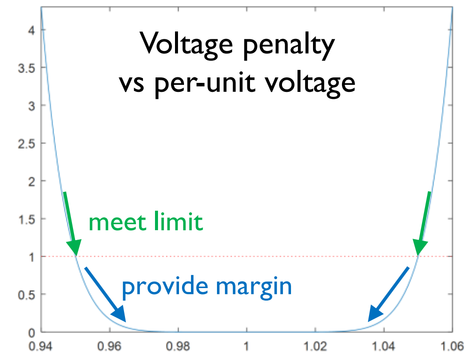
TSEC problems





System Stability Penalty Objectives

- In severe emergencies, bound constraints may be temporarily exceeded, and our goal is to position the system within bounds as quickly as possible
- Instead of treating limits as path constraints, we penalize approaching/ exceeding limits in the objective function
  - Example: Transient stability
    $$\overline{\delta}_i = \left|\delta_i - \frac{\sum_{k=1}^{ng} H_k \delta_k}{\sum_{k=1}^{ng} H_k}\right|$$
    (want <100 degrees)
- Minimizing over penalty functions
  - Nonlinear objective cost function for deviation from nominal



- Decision variables
  - Mechanical torque
  - Exciter voltage reference

DAE Variables

Variable	Index	Description
δ	g	Rotor angle
ω	g	Generator frequency
E_q'	g	q-axis transient voltage
E_{fd}	g	Field voltage
I_q	g	q-axis current
I_d	g	d-axis current
T_M	g	Shaft mechanical torque
V	b	Voltage
θ	b	Phase angle
P_L	l	Active load power draw
Q_L	l	Reactive load power draw
x_p	l	Load active power state variable
x_q	l	Load reactive power state variable

b, *g*, and *l* denote the indices of buses, generators, and loads respectively.

Parameters

Parameter	Index	Description
$\mathcal{T}$		Time horizon
ω_s		Rated synchronous speed
M	g	Shaft inertial constant
D	g	Damping coefficient
K_A	g	Exciter amplifier gain
T_A	g	Exciter amplifier time constant
R_s	g	Scaled resistance after dq transformation
X_q	g	q-axis synchronous reactance
X_d	g	d-axis synchronous reactance
$X_d^{'}$	g	d-axis transient reactance
$T_{do}^{'}$	g	Transient time constant
T_{ch}	g	Mechanical torque damping const.
b_g	g	Bus connected to generator g

Parameter	Index	Description
Po_L	l	Initial active power
Qo_L	l	Initial reactive power
Tp_L	l	Active power time constant
Tq_L	l	Reactive power time constant
α_s	l	First active power exponent
α_t	l	Second active power exponent
β_s	l	First reactive power exponent
β_t	l	Second reactive power exponent
b_l	l	Bus connected to load l
Y	b,b	Admittance magnitude matrix
A	b,b	Admittance phase angle matrix
η_1		V objective scaling parameter
η_2		ω objective scaling parameter
γ_1		V objective shaping parameter
γ_2		ω objective shaping parameter

Stability Metrics Objective Functions

- Purpose of objective function is to maximize system stability margins
- Deviations between nominal voltage and frequency between each time step were used to achieve this

$$M_v(t_1, t_2) = \sum_{t \in \{\tau \in \mathcal{P} | t_1 \leq \tau < t_2\}} \sum_{b \in \mathcal{B}} \left(\frac{1 - V_{b,t}}{\eta_1} \right)^{\gamma_1}$$

$$M_\omega(t_1, t_2) = \sum_{t \in \{\tau \in \mathcal{P} | t_1 \leq \tau < t_2\}} \sum_{g \in \mathcal{G}} \left(\frac{\omega_{g,t} - \omega_s}{\omega_s \cdot \eta_2} \right)^{\gamma_2}$$

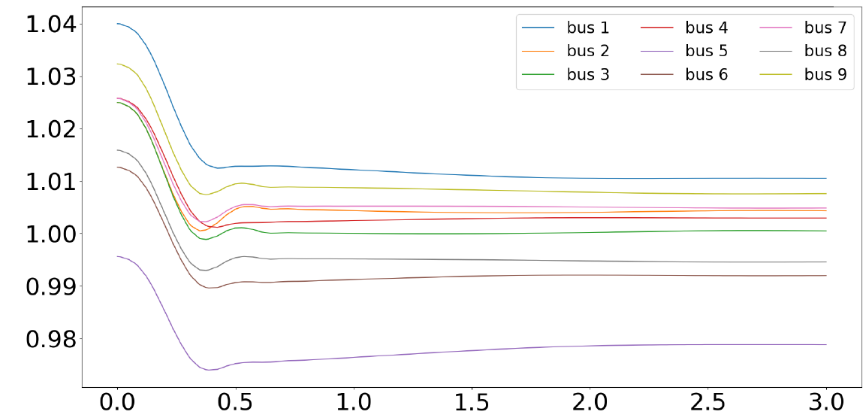
Note: gamma and eta are shaping parameters

Failure Contingencies

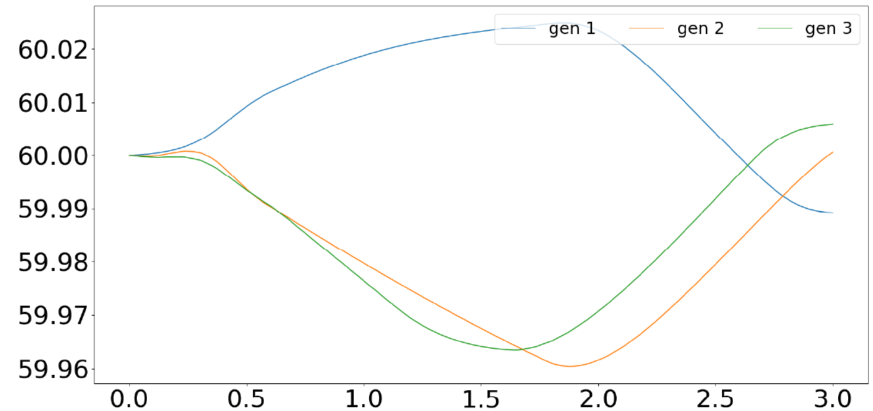
- Although failure contingencies could manifest in any number of ways, we focus on line, load, and generator trips
- Fail time can be any time t_{fail} in $[0, T]$
- Each of these trips can be modeled by fixing variables or deactivating constraints
- For our purposes, we only perform a maximum of one trip per failure contingency, but any number of trips could be triggered to model realistic failure phenomena

No-Failure Deterministic Case

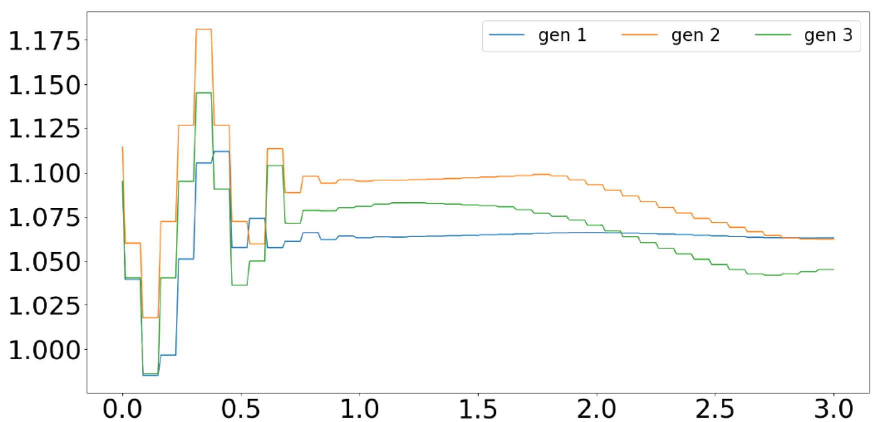
Note:
η = 1
γ = 2
T = 3



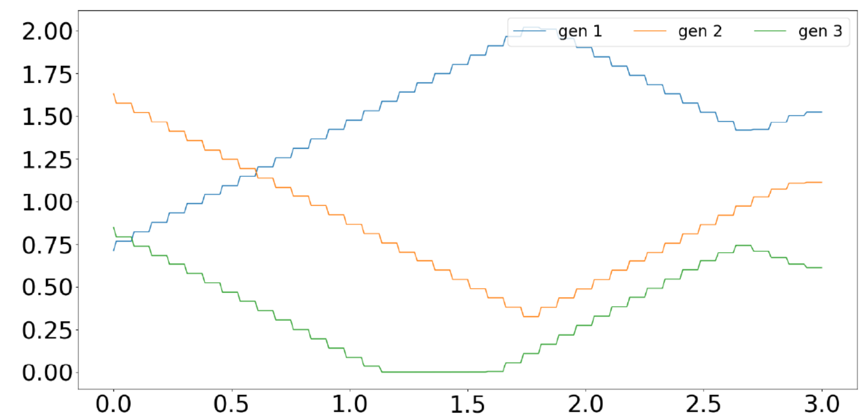
Voltage



Frequency

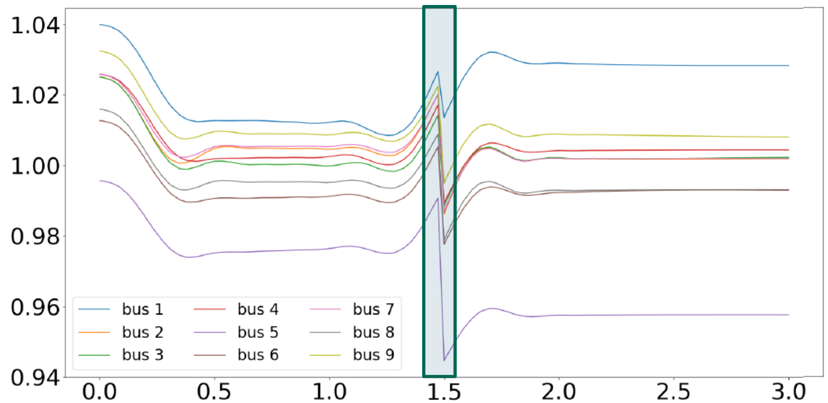


V_{ref}

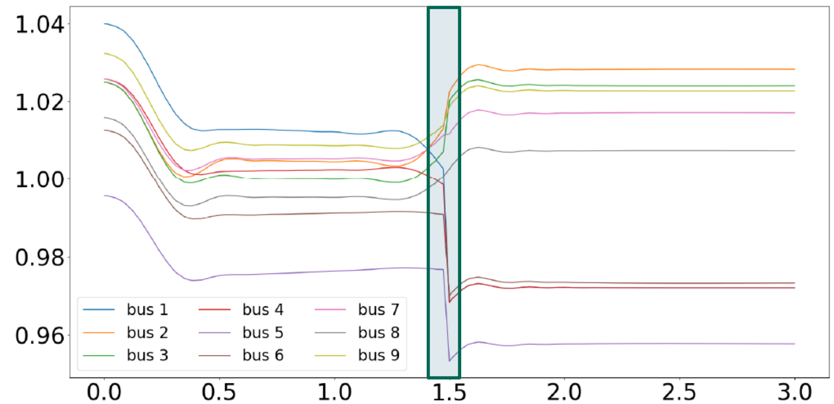


P_{ref}

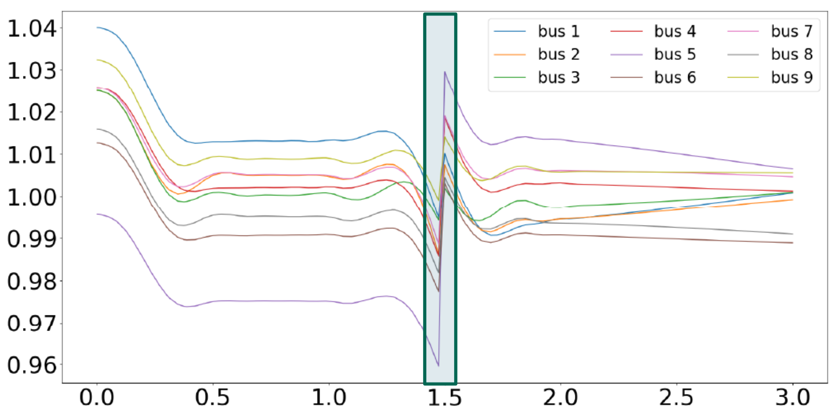
Voltage of Deterministic Failure Contingencies



Line Trip from Buses 5 - 7



Gen Trip at Gen 1



Load Trip at Bus 5

Significant differences in system dynamics for each failure contingency.

Fail time at t = 1.5

Stochastic Model

- A stochastic programming model with two-stage recourse is structured as follows:

$$\min_{x,y_\psi} c(x) + E[d(y_\psi)]$$

$$s.t.$$

$$f(x) \leq b$$

$$g_\psi(y_\psi) \leq f_\psi \qquad \forall \psi \in \Psi$$

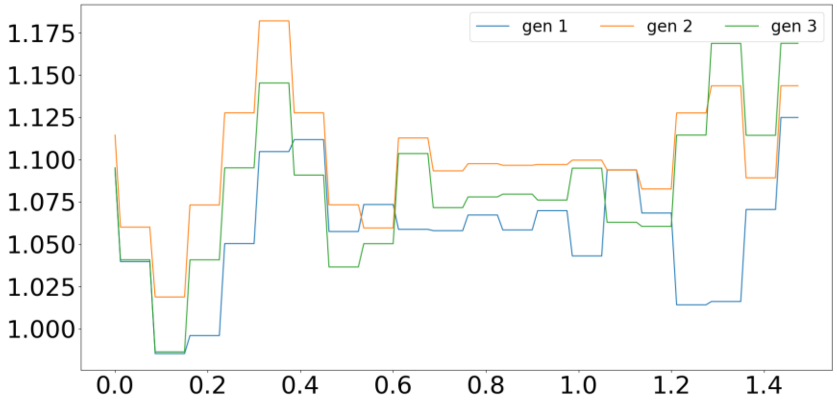
$$h(x) + k(y_\psi) \leq g_\psi \qquad \forall \psi \in \Psi$$

Unique scenario

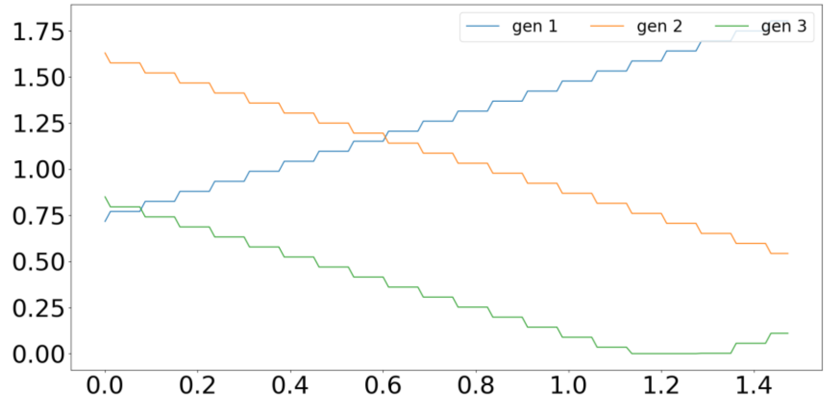
- First constraints are first-stage and only involve first-stage variables x
- Second-stage constraints contain second-stage variables y and possibly first-stage variables x
- Objective minimizes sum of $c(x)$ and expected value of $d(y)$ over the scenarios

Multi-scenario Case

- Consider now four possible scenarios – the no-failure case, line trip, load trip, and generator trip, each with probability of occurring of 0.25
- Below is prepositioning of V_{ref} and P_{ref} to minimize total deviation across all scenarios

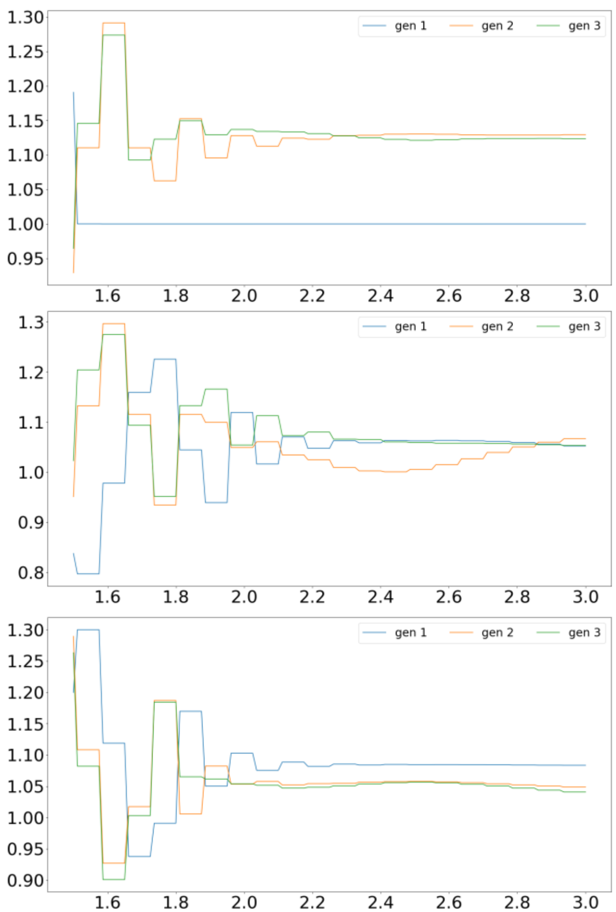


V_{ref}



P_{ref}

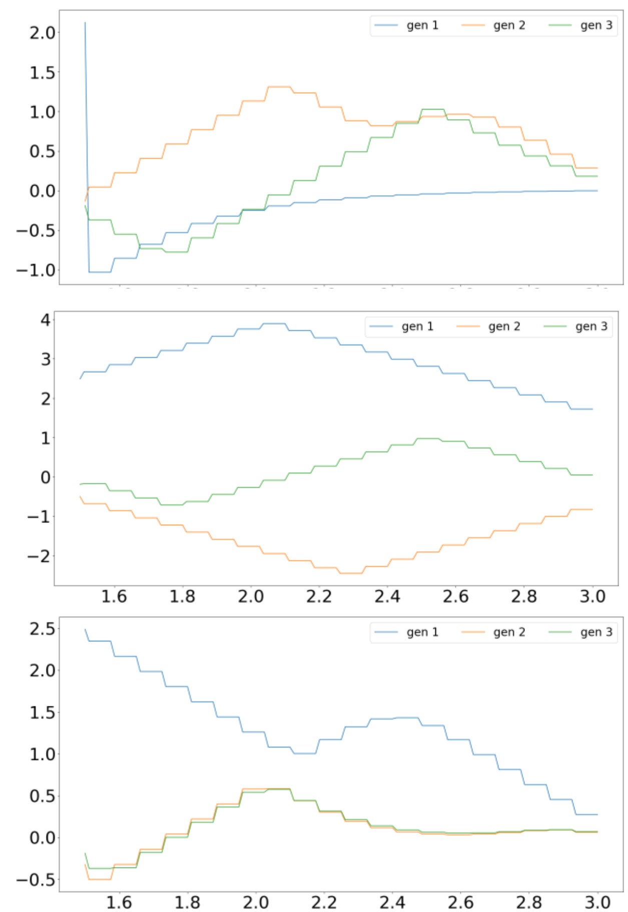
Multi-scenario Case Recourse Action



Gen Trip

Load Trip

Line Trip

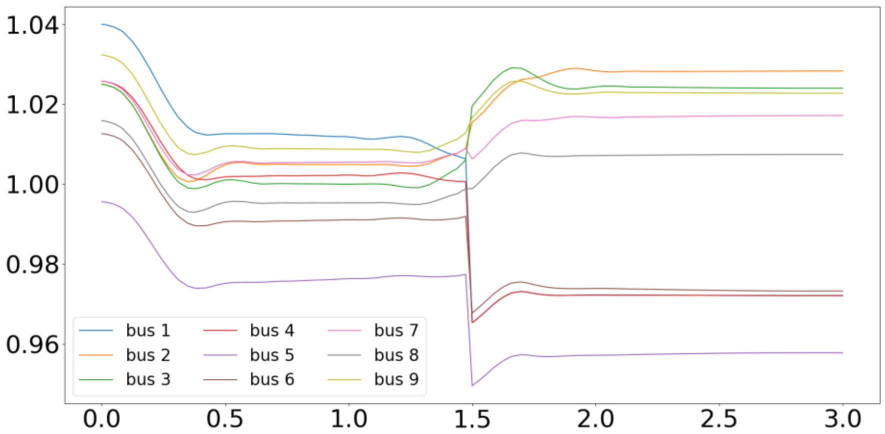


V_{ref}

P_{ref}

Impact of Optimal Prepositioning and Recourse Control

Gen Trip



- Despite sudden loss of 24% total generation, voltages are kept centered around 1.0 p.u.
- Coupling first and second-stage controls is particularly effective, yielding:
  - 65% reduction in objective value compared to pre-positioning alone
  - 61% reduction compared to recourse control alone

Conclusion

- Both preparation (first stage) and emergency control (second stage) are used to improve system resiliency to severe emergencies
- Coupling these decisions together in the same framework should allow better solutions across a wide set of contingencies
- System dynamics are critical to assessing grid stability in such emergencies

Future Research

- Add more robust objective functions such as economic generation cost, transient stability, and line transmission power limits
- Add more controls, such as load shedding
- Scale to larger power systems such as the RTS-96 system
- Incorporate more multi-layered failure contingencies

Bibliography

[1] P. W. Sauer, M. A. Pai, and J. H. Chow, *Power system dynamics and stability: with synchrophasor measurement and power system toolbox*. John Wiley & Sons, 2017.

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[3] M. Paramasivam, A. Salloum, V. Ajjarapu, V. Vittal, N. B. Bhatt, and S. Liu, "Dynamic optimization based reactive power planning to mitigate slow voltage recovery and short term voltage instability," *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 3865–3873, 2013.

[4] D. Karlsson and D. J. Hill, "Modelling and identification of nonlinear dynamic loads in power systems," *IEEE Transactions on Power Systems*, vol. 9, no. 1, pp. 157–166, 1994.