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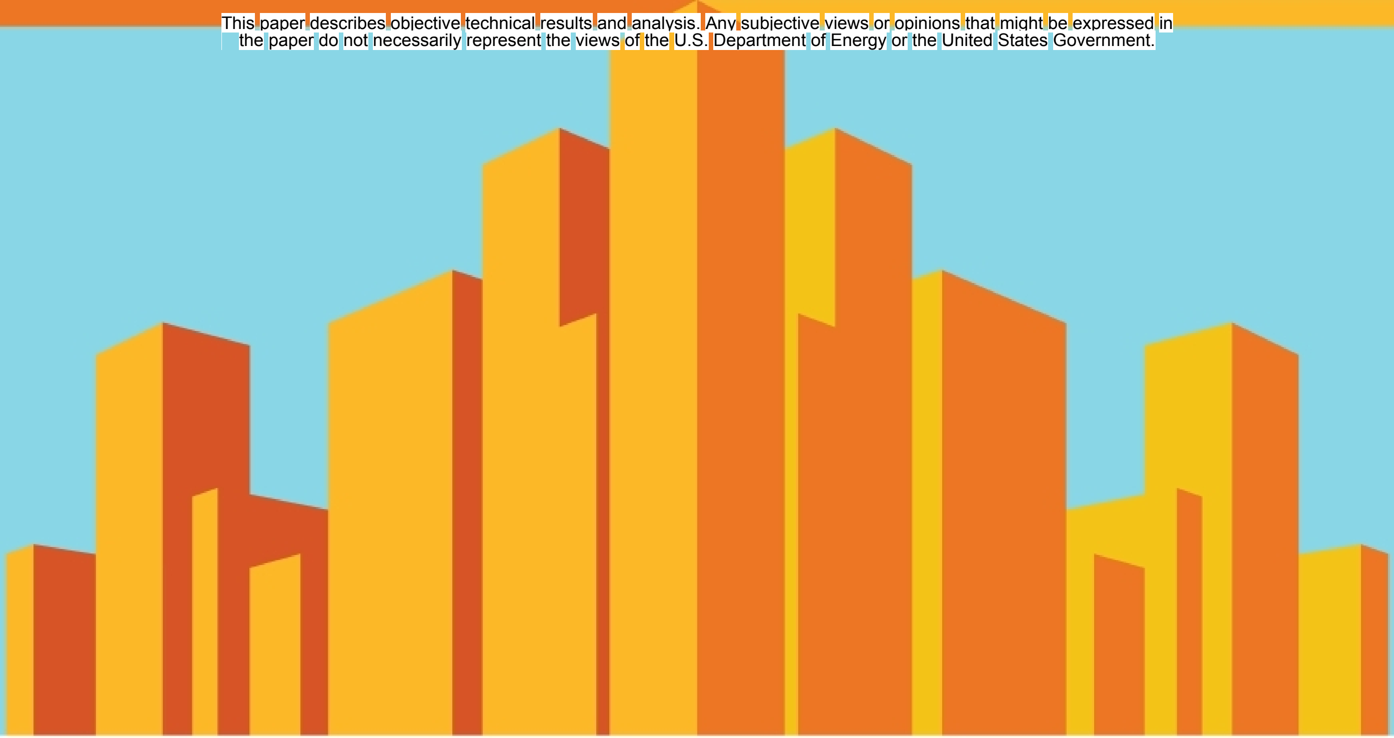

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2021 ANAHEIM, CALIFORNIA

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Resilience Optimization with Grid Dynamics

Presented by: Nathan Stewart

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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Problem

- Objective: Mitigation planning optimization for wide-area n-k emergencies where multiple contingencies occur across a wide area in quick succession
- Even with mitigations in place, major dynamics and protective tripping are likely to ensue, with major implications to system stability and operability
    - Particularly want to avoid cascading and large blackouts
- Current goals are to minimize cascading, widespread blackout & permanent damage to long-lead devices, and to improve restorability
- Decisions may include hardening, preventive & emergency control, strategic spare purchases and placement, etc.

Key Research Challenge

Prior resilience optimization work does not address wide-area *n-k* events

- Typically assumes either minor or localized hazards
- Relies on non-dynamic impact models, which cannot detect loss of stability
- Relies upon tight bound constraints which are likely not feasible in these emergencies (e.g., protective tripping may be unavoidable)
  - Incapable of addressing hybrid/cascading behavior due to assuming away protective devices

We intend to incorporate both dynamic system physics *and* discrete protection in our optimization model

- for accuracy of impact modeling and
- to allow relaxing constraints that severely limit feasible space

Approach

Stochastic planning optimization

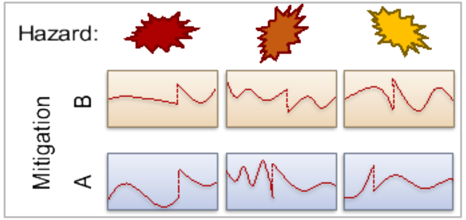
- choose from proposed hardening and mitigation measures and locations
- optimize dynamically-assessed resilience
- across a set of scenarios representing hazard uncertainty

Two optimization stages:

- mitigation decisions enacted across all hazard scenarios
- impacts (and emergency control) assessed for each hazard scenario, using dynamic system physics and discrete protective schemes

Our phased project plan:

1. build stochastic, continuous-dynamic optimization models
2. add appropriate discrete planning options to address hazard scenarios
3. add variables and constraints to represent discrete dynamics from protective devices, and address temporal discretization challenges



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

$$
\begin{aligned}
s.t.\quad & f(x) \le b & \\
& g_\psi(y_\psi) \le f_\psi & \forall \psi \in \Psi \\
& h(x) + k(y_\psi) \le g_\psi & \forall \psi \in \Psi
\end{aligned}
$$

We are here ▼ (Year 3)

Year 1	Year 2	Year 3
Optimal control	+ optimal planning	+ hybrid dynamics
stochastic NLP	+ discrete 1^{st} stage vars (MINLP)	+ switching vars in 2^{nd} stage (time-sensitive)

Dynamics 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

$$\min h(x, y, u)$$ objective

subject to

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

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

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

Dynamic Power Systems Modeling

In major emergencies, dynamics play important role in system stability

Generator dynamics (Sauer, Pai, Chow)

- Angular acceleration = mechanical power in, minus electrical power out
- We use the 4th order flux-decay model commonly used in stability studies
- An additional term (turbine with no reheating) models torque response delay

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt^2} = P_m - P_e$$

Network power balance

$$0 = Ve^{i\theta} \odot \left(YVe^{i\theta}\right)^* - S_{net}$$

Load dynamics

- Play an important role in stability studies*
- Exponential recovery model (Karlsson & Hill) captures load responses to voltage fluctuations

Combined, these pose a system of differential algebraic equations (DAE)

*R. Zhang, Y. Xu, W. Zhang, Z. Y. Dong, and Y. Zheng (2016), *Impact of dynamic models on transient stability-constrained optimal power flow*, 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), pp. 18–23

Decision Variables, Parameters, and DAE Variables

Set	Index Symbol	Description
$\mathcal{B}$	b	Buses
$\mathcal{G}$	g	Generators
$\mathcal{L}$	l	Loads
Ψ	ψ	Scenarios

Set	Index Symbol	Description
$\mathcal{G}_b$	b	Generators at bus b
$\mathcal{L}_b$	b	Loads at bus b

Variable	Index	Description
V_{ref}	g	Exciter reference voltage
P_{ref}	g	Generator mechanical torque power

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

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
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

Model Dynamics

Generator model:

$$\frac{d\delta_g}{dt} = \omega_g - \omega_s$$

$$\frac{d\omega_g}{dt} = \frac{T_{M_g}}{M_g} - E'_{q_g}\frac{I_{q_g}}{M_g} - I_{d_g} I_{q_g}\frac{X_{q_g} - X'_{d_g}}{M_g} - D_g \frac{\omega_g - \omega_s}{M_g}$$

$$\frac{dE'_{q_g}}{dt} = -\frac{E_{q_g}}{T'_{do_g}} - X_{d_g} - I_{d_g}\frac{X'_{d_g}}{T'_{do_g}} + \frac{E_{fd_g}}{T'_{do_g}}$$

$$\frac{dE_{fd_g}}{dt} = -\frac{E_{fd_g}}{T_{A_g}} + (V_{ref_g} - V_{b_g})\frac{K_{A_g}}{T_{A_g}}$$

$\forall g \in \mathcal{G}$

Governor model:

$$\frac{dT_{M_g}}{dt} = \frac{P_{ref_g} - T_{M_g}}{T_{ch_g}}$$

$\forall g \in \mathcal{G}$

Stator equations:

$$V_{b_g}\sin(\delta_g - \theta_{b_g}) + R_{s_g} I_{d_g} - X_{q_g} I_{q_g} = 0$$

$$E'_{q_g} - V_{b_g}\cos(\delta_g - \theta_{b_g}) - R_{s_g} I_{q_g} - X'_{q_g} I_{d_g} = 0$$

$\forall g \in \mathcal{G}$

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Model Dynamics (cont.)

Balance equations:

$$-\sum_{i\in\mathcal{B}}(V_iV_bY_{i,b}\cos(\theta_i-\theta_b-A_{i,b}))$$

$$-\sum_{l\in\mathcal{L}_b}(P_{L_l})+\sum_{g\in\mathcal{G}_b}(I_{d_g}V_b\sin(\delta_g-\theta_b)$$

$$+I_{q_g}V_b\cos(\delta_g-\theta_b))=0$$

$$-\sum_{i\in\mathcal{B}}(V_iV_bY_{i,k}\sin(\theta_i-\theta_b-A_{i,b}))$$

$$-\sum_{l\in\mathcal{L}_b}(Q_{L_l})+\sum_{g\in\mathcal{G}_b}(I_{d_g}V_g\cos(\delta_g-\theta_b)$$

$$+I_{q_g}V_b\sin(\delta_g-\theta_b))=0$$

$\forall b\in\mathcal{B}$

Exponential recovery load model:

$$\frac{dx_{p_l}}{dt}=\frac{x_{p_l}}{Tp_{L_l}}+Po_{L_l}V_{b_l}^{\alpha_{s_l}}-Po_{L_l}V_{b_l}^{\alpha_{t_l}}$$

$$\frac{dx_{q_l}}{dt}=\frac{x_{q_l}}{Tq_{L_l}}+Qo_{L_l}V_{b_l}^{\beta_{s_l}}-Qo_{L_l}V_{b_l}^{\beta_{t_l}}$$

$$P_{L_l}=\frac{x_{p_l}}{Tp_{L_l}}+Po_{L_l}V_{b_l}^{\alpha_{t_l}}$$

$$Q_{L_l}=\frac{x_{q_l}}{Tq_{L_l}}+Qo_{L_l}V_{b_l}^{\beta_{t_l}}$$

$\forall l\in\mathcal{L}$

Generator Ramp Rate:

$$\left|\frac{dV_{ref_g}}{dt}\right|\leq k$$

$$\left|\frac{dP_{ref_g}}{dt}\right|\leq k$$

Time Discretization

- To approximate differential equations in [0,T] time horizon, time is partitioned into finite points:

$$\{0, t_2, \ldots, t_f, \ldots, t_{n-1}, T\}$$

- Discretized points are then used to discretize differential equations
  - Forward finite difference
  - Collocation

$$\frac{dx}{dt} \approx \frac{x_{t_k} - x_{t_{k-1}}}{t_k - t_{k-1}}$$

Stability Metrics

- In severe emergencies, bound constraints may be temporarily exceeded, and our goal is to position the system within bounds as quickly as possible

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

- Instead of treating limits as path constraints, we penalize approaching/ exceeding limits in the objective function

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

Disjunctive Constraints

- To model disjunctions between baseline dynamics and trips, we introduce binary protection variable *R*
    - Indexed by component *y* (load, generator, line)
    - Cost of protection depends on component
- Dynamics of the system for post-failure time horizon will be one of two disjuncts

$$D_y = R_y$$

$$\sum_{y \in Y} c(R_y)$$

$$\left[\begin{array}{l} P_{L_l} = \frac{x_{p_l}}{Tp_{L_l}} + Po_{L_l} V_{b_l}^{\alpha_{t_l}} \\ Q_{L_l} = \frac{x_{q_l}}{Tq_{L_l}} + Qo_{L_l} V_{b_l}^{\beta_{t_l}} \\ \frac{dx_{p_l}}{dt} = \frac{x_{p_l}}{Tp_{L_l}} + Po_{L_l} V_{b_l}^{\alpha_{s_l}} - Po_{L_l} V_{b_l}^{\alpha_{t_l}} \\ \frac{dx_{q_l}}{dt} = \frac{x_{q_l}}{Tq_{L_l}} + Qo_{L_l} V_{b_l}^{\beta_{s_l}} - Qo_{L_l} V_{b_l}^{\beta_{t_l}} \end{array}\right] \vee \left[\begin{array}{l} P_{L_l} = 0 \\ Q_{L_l} = 0 \\ x_{p_l} = 0 \\ x_{q_l} = 0 \end{array}\right]$$

Component Failure Disjunctions

Load Trip Disjunct

$$\begin{bmatrix} P_{L_l} = \frac{x_{p_l}}{Tp_{L_l}} + Po_{L_l} V_{b_l}^{\alpha_{t_l}} \\ Q_{L_l} = \frac{x_{q_l}}{Tq_{L_l}} + Qo_{L_l} V_{b_l}^{\beta_{t_l}} \\ \frac{dx_{p_l}}{dt} = \frac{x_{p_l}}{Tp_{L_l}} + Po_{L_l} V_{b_l}^{\alpha_{s_l}} - Po_{L_l} V_{b_l}^{\alpha_{t_l}} \\ \frac{dx_{q_l}}{dt} = \frac{x_{q_l}}{Tq_{L_l}} + Qo_{L_l} V_{b_l}^{\beta_{s_l}} - Qo_{L_l} V_{b_l}^{\beta_{t_l}} \end{bmatrix} \vee \begin{bmatrix} P_{L_l} = 0 \\ Q_{L_l} = 0 \\ x_{p_l} = 0 \\ x_{q_l} = 0 \end{bmatrix}$$

Generator Trip Disjunct

$$\begin{bmatrix} V_{b_g} \sin(\delta_g - \theta_{b_g}) + R_{s_g} I_{d_g} - X_{q_g} I_{q_g} = 0 \\ E'_{q_g} - V_{b_g} \cos(\delta_g - \theta_{b_g}) - R_{s_g} I_{q_g} - X'_{q_g} I_{d_g} = 0 \end{bmatrix} \vee \begin{bmatrix} I_{q_g} = 0 \\ I_{d_g} = 0 \end{bmatrix}$$

$$\forall g \in \mathcal{G}$$

Line Trip Disjunct

$$\begin{bmatrix} P_{ij} = \frac{1}{\tau_{ij}}(V_i^2 \frac{G_{ij}}{\tau_{ij}} - V_i V_j G_{ij} cos(\theta_i - \theta_j) - V_i V_j B_{ij} sin(\theta_i - \theta_j)) \\ P_{ji} = V_j^2 G_{ij} - \frac{1}{\tau_{ij}}(V_i V_j G_{ij} cos(\theta_i - \theta_j) + V_i V_j B_{ij} sin(\theta_i - \theta_j)) \\ Q_{ij} = \frac{1}{\tau_{ij}}(-V_i^2 \frac{B_{ij} - \frac{Bs_{ij}}{2}}{\tau_{ij}} + V_i V_j B_{ij} cos(\theta_i - \theta_j) - V_i V_j G_{ij} sin(\theta_i - \theta_j) \\ Q_{ji} = -V_j^2 (B_{ij} - \frac{Bs_{ij}}{2}) + \frac{1}{\tau_{ij}}(V_i V_j B_{ij} cos(\theta_i - \theta_j) + V_i V_j G_{ij} sin(\theta_i - \theta_j)) \end{bmatrix} \vee \begin{bmatrix} P_{ij} = 0 \\ P_{ji} = 0 \\ Q_{ij} = 0 \\ Q_{ji} = 0 \end{bmatrix}$$

Objective

- Objective value could be either:
  - Minimizing cost of protection subject to stability metric criteria
  - Minimizing total cost and stability deviation

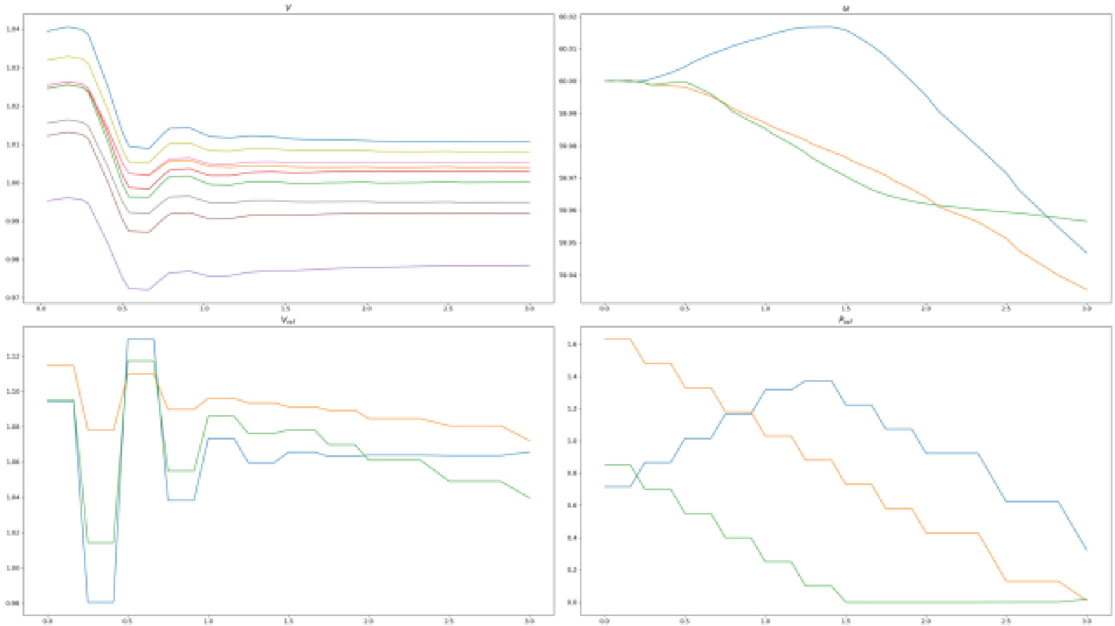
$$\min_{V_{ref}, P_{ref}} M_v(0,T) + M_\omega(0,T) + \sum_{y \in Y} c(R_y)$$

Example – Baseline Dynamics, No Tripping

- WECC 9-bus system

- No trips are being incurred, just the initial conditions of the system

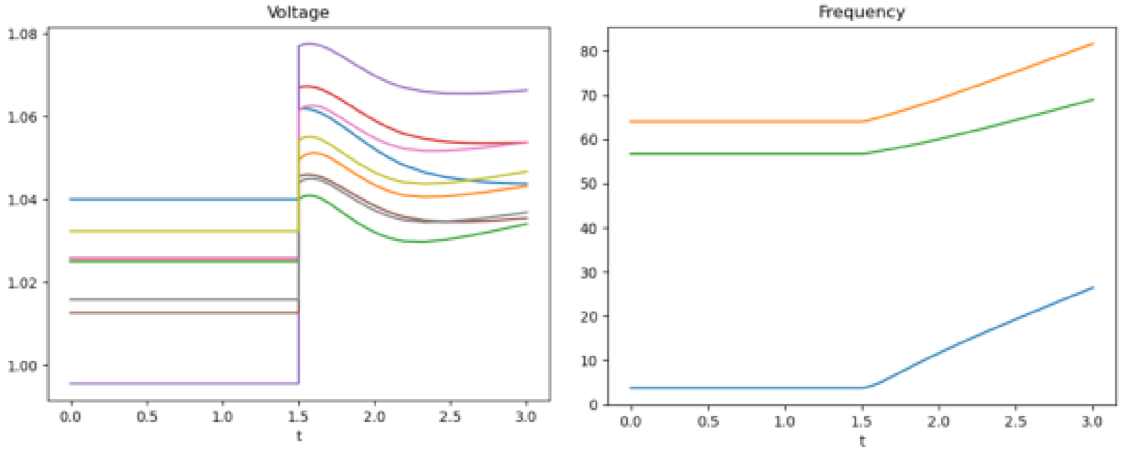
- Controls still occur to maximize stability over the time horizon



Example – Tripping, No Controls

- Three components tripped at time $t = 1.5$
    - Load trip (5)
    - Gen trip (2)
    - Line trip (2, 7)

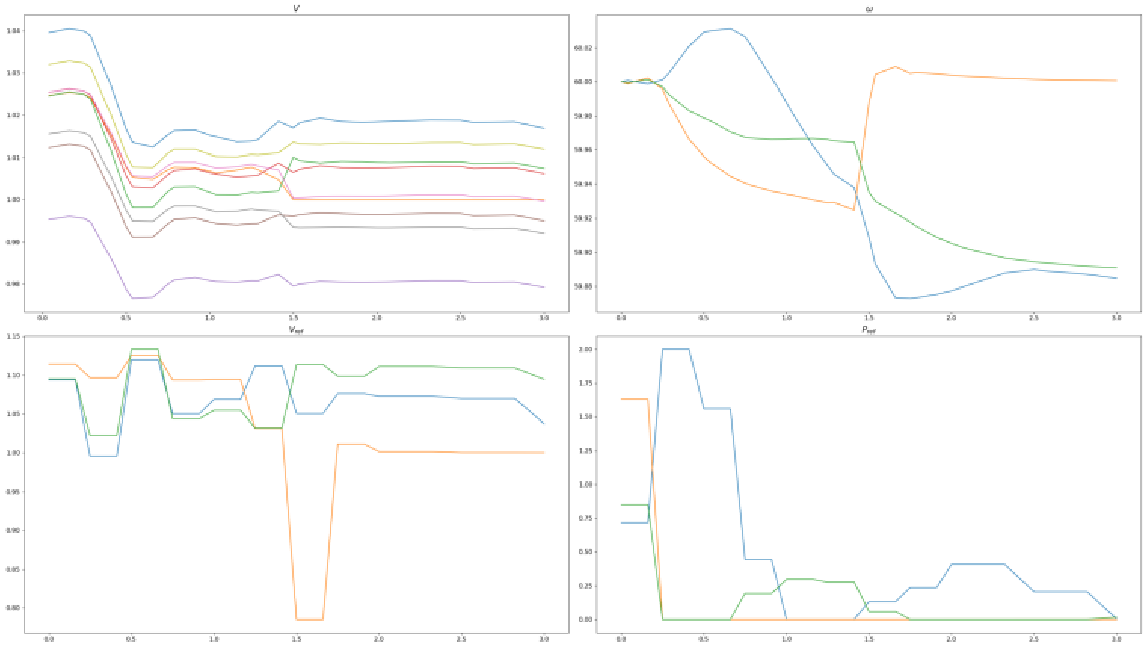
- Predisposed to overvoltage even before trip, overvoltage possible post trip



Example – Tripping 3 Components

- Three components tripped at time *t* = 1.5
    - Load trip (5)
    - Gen trip (2)
    - Line trip (2, 7)

- At the given cost curves, the model chose to protect only load 5



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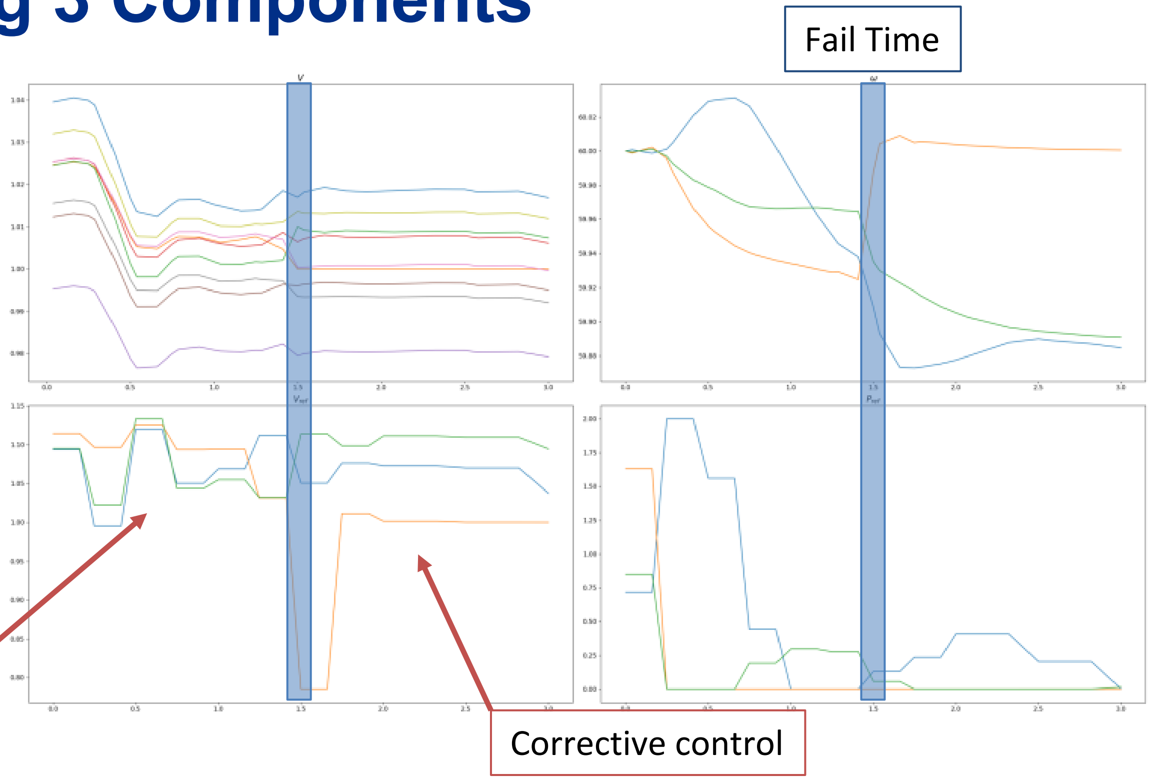

Conclusion

- Leveraging disjunctive programming, widespread outage performance can be improved
    - Both preventative and corrective controls
    - Hardening decisions to protect components that are costly to fail

Future Research

- Introduce stochastic failure scheme with discrete hardening decisions
- Adding behavior of discrete protective devices
- Scale to larger power systems such as the RTS-96 system
- Incorporate more complex failure contingencies