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Investment Optimization to Improve Power System Resilience

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Project team

- Sandia National Laboratories
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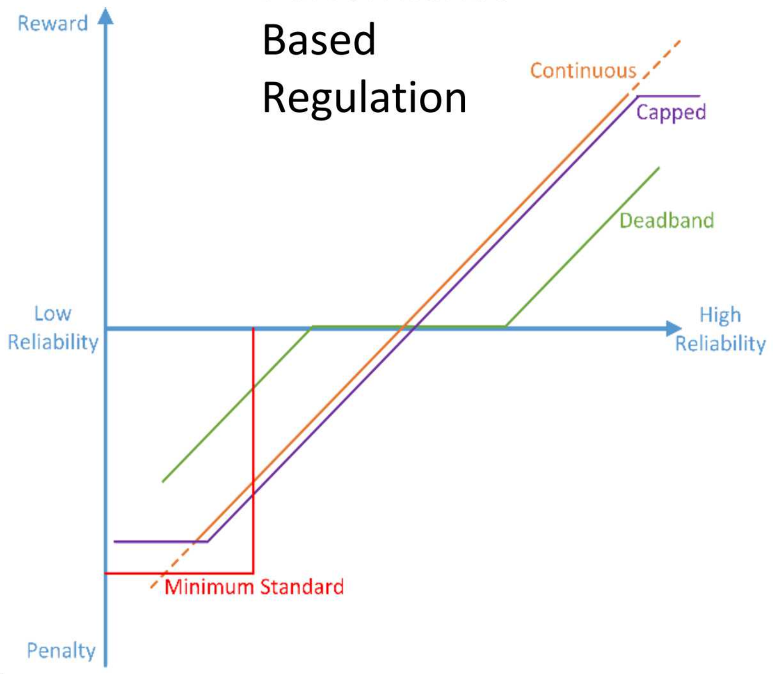
Power System Resilience

- Reliability – Low consequence high probability
  - Squirrels, birds, etc.
  - Traffic accidents
  - Trees/wind
  - Lightning
- Resilience - High consequence low probability events
  - Severe winter storms
  - Hurricanes
  - Tornados
  - Earthquakes
  - EMPs and GMDs
  - Fires
  - Physical attack

Utilities are incentivized to be reliable not resilient

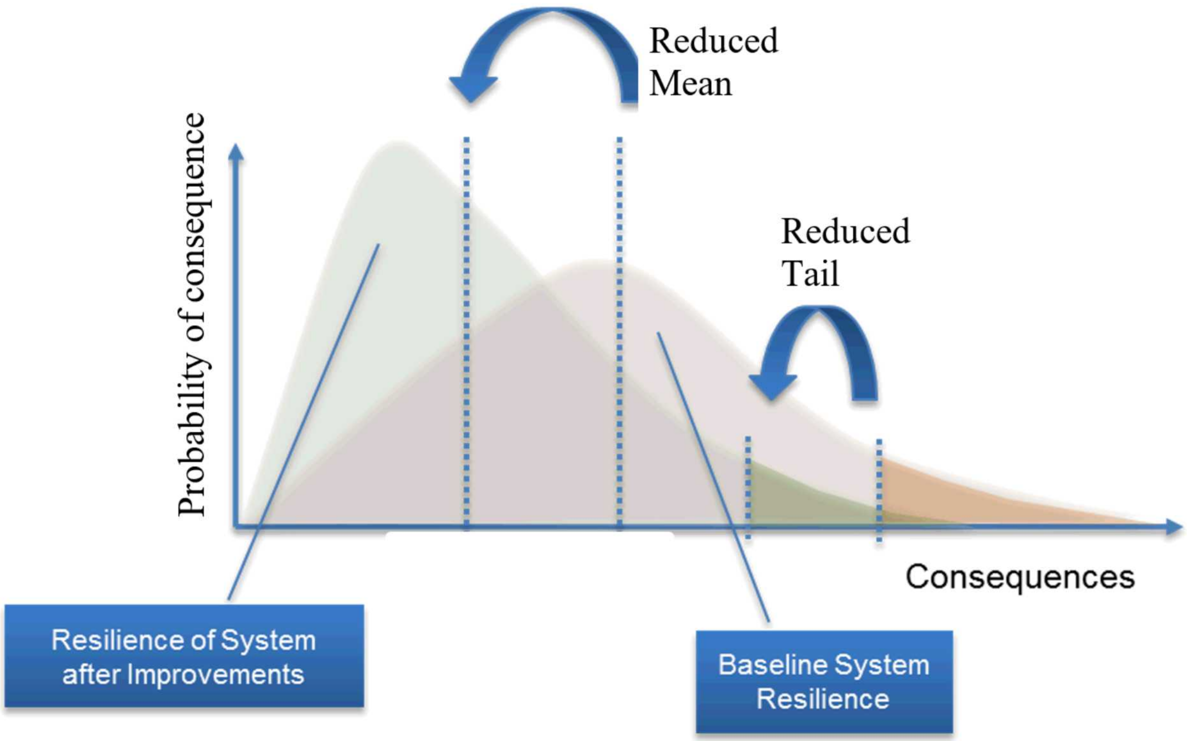
- Utilities are often incentivized to be more reliable (improve their SAIDI and SAIFI metrics)
- Some utilities have performance based regulation (PBR)
- Large scale events (severe winter storms, hurricanes, etc.) are removed from the SAIDI and SAIFI metrics
- Less incentive to invest in resiliency

Performance Based Regulation



Improve Power System Resilience

- The goals are to push the mean consequence and the tail of the consequence to the left.
- Reducing the tail, reduces the consequence from the large worst-case scenarios
- Resilience metrics used in this project are Loss of Load and Duration.



Project goals

- Determine optimal investment locations to improve power system resilience.
- Determine worst case buses, lines, generators which if taken out, would cause the greatest damage.
- Determine if a large impact can be achieved by hardening only a few particular components

Scenario development

- Create scenarios based on real threats which disable Buses, Generators, Lines (transformers represented as lines also), and Loads
- Informative scenarios are critical yet difficult to generate
- Need high quality data
- Synthetic scenarios are difficult to produce due to limited number of actual scenarios
- Data needed to create scenarios for each type of threat can vary
- Create scenarios based on probability density functions of failure rates from historical data

Optimization Model

Objective function to minimize weighted load shed:

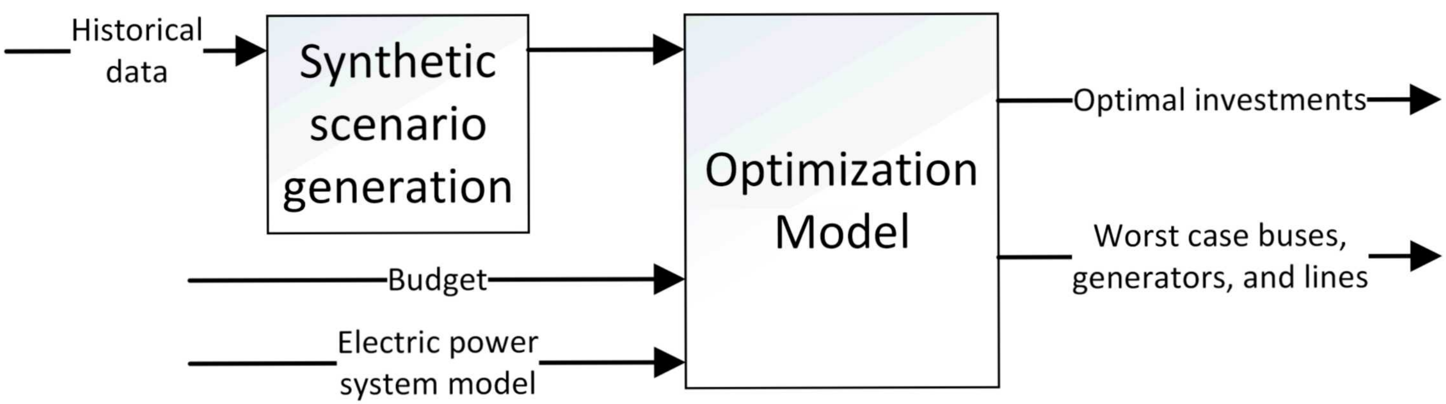
Minimize (without duration):

$$\sum_{b \in B} A_b \sum_{w \in \Omega} P_w p_b^w$$

Minimize (with duration):

$$\sum_{t \in T} t \sum_{b \in B} A_b \sum_{w \in \Omega} P_w p_{b,t}^w$$

*Duration is included in newest model



Sets, parameters, and variables

Sets

L	Transmission lines
G	Generators
B	Buses
Ω	Weather scenarios
Ω_l	Set of scenarios under which transmission line l
Ω_g	Set of scenarios under which generator g goes offline
Ω_b	Set of scearios under which bus b goes offline
G_b	Set of generators connected to bus b
L_b^{from}	Set of transmission lines leaving bus b
L_b^{to}	Set of tranmssion lines entering bus b
I	Set of investments for buses, generators, and transmission lines

Parameters

B_l^{from}	Bus from which transmission line l leaves
B_l^{to}	Bus transmission line l enters
S_l	Susceptance of tranmission line l
$\overline{P}_l$	Thermal limit of transmission line l
B_g	Bus containing generator g
RU_g	Ramp-up limit of generator g dispatch level
RD_g	Ramp-down limit of generator g dispatch level
SU_g	Start-up limit of generator g distpatch level
$\overline{P}_g$	Upper limit of generator g dispatch level
$\underline{P}_g$	Lower limit of generator g dispatch level
D_b	Demand at bus b
Y_l^o	On/off staus of line l during first stage
Y_g^o	On/off staus of generator g during first stage
Y_b^o	On/off staus of bus b during first stage
C_l	Cost of hardening transmission line l
C_g	Cost of hardening generator g
C_b	Cost of hardening bus b
P_w	Probability of scenario w occuring
T	Budget

Variables

p_l^0	Power flow through tansmission line l in first stage
p_l^w	Power flow through transmission line l in scenario w
p_g^0	Generator dispatch level for generator g in first stage
p_g^w	Generator dispatch level for generator g in scenario w
p_b^0	Load shed at bus b in first stage
p_b^w	Load shed at bus b in scenario w
θ_b^0	Phase angle for bus b in first stage
θ_b^w	Phase angle for bus b in scenation w
y_l^w	On/off status of line l during scenario w
y_g^w	On/off status of generator g during scenario w
y_b^w	On/off status of bus b during scenario w
i_l	Binary indicating whether or not transmission line l is hardened
i_g	Binary indicating whether or not generator g is hardened
i_b	Binary indicating whether or not bus b is hardened

Constraints

- Budget constraint
- Power flow constraints
- Generator limit constraints
- Line limit constraints (thermal and pseudo stability constraints)
- Ramp rate and start-up constraints
- Constraints to account for an investment in a line, but the line remains out due to outage of a bus.

Constraints

$$\sum_{b\in B} C_b i_b + \sum_{l\in L} C_l i_l + \sum_{g\in G} C_g i_g \le T \qquad (2)$$

$$\sum_{g\in G_b} p_g^0 + \sum_{l\in L_b^{to}} p_l^0 - \sum_{l\in L_b^{from}} p_l^0 = D_b - p_b^0 \quad \forall b \in B \qquad (3)$$

$$\sum_{g\in G_b} p_g^w + \sum_{l\in L_b^{to}} p_l^w - \sum_{l\in L_b^{from}} p_l^w = D_b - p_b^w \quad \forall b \in B, \forall w \in \Omega \qquad (4)$$

$$p_l^0 = Y_l^0 S_l \left(\theta^0_{B_l^{to}} - \theta^0_{B_l^{from}}\right) \quad \forall l \in L \qquad (5)$$

$$p_l^w = y_l^w S_l \left(\theta^w_{B_l^{to}} - \theta^w_{B_l^{from}}\right) \quad \forall l \in L, \forall w \in \Omega \qquad (6)$$

$$p_l^w \le p_g^0 + RU_g Y_g^0 + SU_g\left(y_g^w - Y_g^0\right) + \overline{P}_g\left(1 - y_g^w\right) \quad \forall g \in G, \forall w \in \Omega \qquad (7)$$

$$p_g^0 \le \overline{P}_g y_g^w \quad \forall g \in G, \forall w \in \Omega \qquad (8)$$

$$p_g^0 - p_g^w \le RD_g y_g^w + \overline{P}_g\left(1 - Y_g^0\right) \quad \forall g \in G, \forall w \in \Omega \qquad (9)$$

$$-\frac{\pi}{3} \le \theta^0_{B_l^{to}} - \theta^0_{B_l^{from}} \le \frac{\pi}{3} \quad \forall l \in L \qquad (10)$$

$$-\frac{\pi}{3} \le \theta^w_{B_l^{to}} - \theta^w_{B_l^{from}} \le \frac{\pi}{3} \quad \forall l \in L, \forall w \in \Omega \qquad (11)$$

$$-\overline{P}_l Y_l^0 \le p_l^0 \le \overline{P}_l Y_l^0 \quad \forall l \in L \qquad (12)$$

$$-\overline{P}_l y_l^w \le p_l^w \le \overline{P}_l y_l^w \quad \forall l \in L, \forall w \in \Omega \qquad (13)$$

$$\underline{P}_g Y_g^0 \le p_g^0 \le \overline{P}_g Y_g^0 \quad \forall g \in G \qquad (14)$$

$$\underline{P}_g y_g^w \le p_g^w \le \overline{P}_g y_g^w \quad \forall g \in G, \forall w \in \Omega \qquad (15)$$

$$0 \le p_b^0 \le D_b \quad \forall b \in B \qquad (16)$$

$$0 \le p_b^w \le D_b \quad \forall b \in B, \forall w \in \Omega \qquad (17)$$

$$y_l^w \le i_l \quad \forall l \in L, \forall w \in \Omega_l \qquad (18)$$

$$y_l^w \le i_{B_l^{from}} \quad \forall l \in L, \forall w \in \Omega_l \qquad (19)$$

$$y_l^w \le i_{B_l^{to}} \quad \forall l \in L, \forall w \in \Omega_l \qquad (20)$$

$$y_g^w \le i_g \quad \forall g \in G, \forall w \in \Omega_g \qquad (21)$$

$$y_g^w \le i_{B_g} \quad \forall g \in G, \forall w \in \Omega_g \qquad (22)$$

$$y_b^w \le i_b \quad \forall b \in B, \forall w \in \Omega_b \qquad (23)$$

$$y_l^w \le y^w_{B_l^{from}} \quad \forall l \in L, \forall w \in \Omega_l \qquad (24)$$

$$y_l^w \le y^w_{B_l^{to}} \quad \forall l \in L, \forall w \in \Omega_l \qquad (25)$$

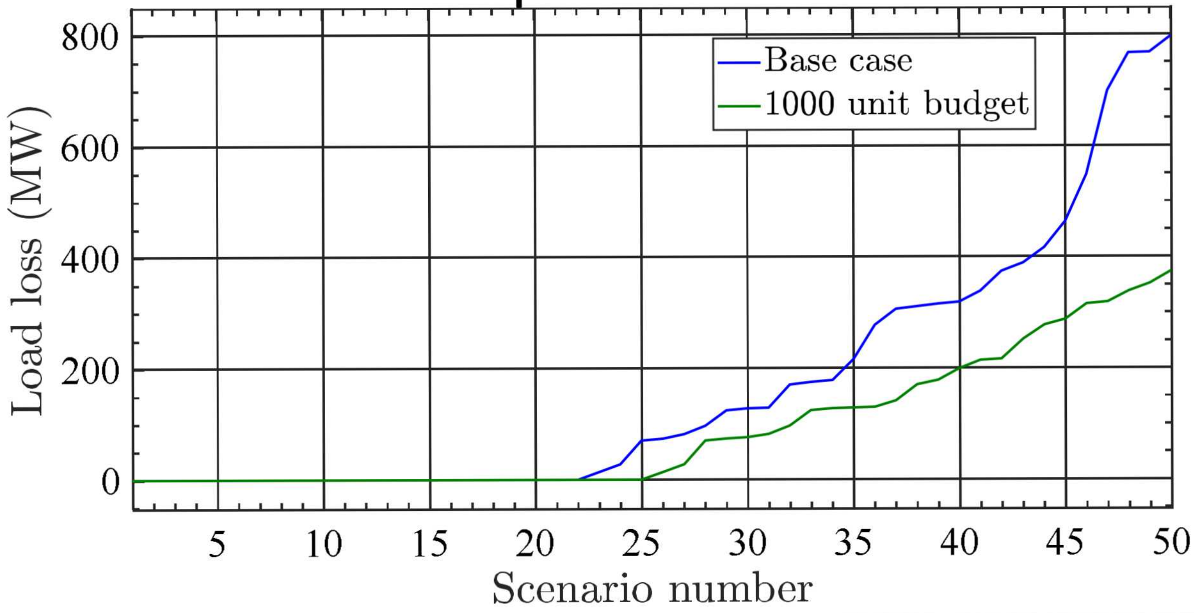
$$y_l^w \le y^w_{B_g} \quad \forall g \in G, \forall w \in \Omega_g \qquad (26)$$

Test system

- IEEE RTS 96 test system
- Winter storm scenarios developed based on historical data
- 50 scenarios utilized in example
- Cost to protect a: line=10, generator=50, bus=100

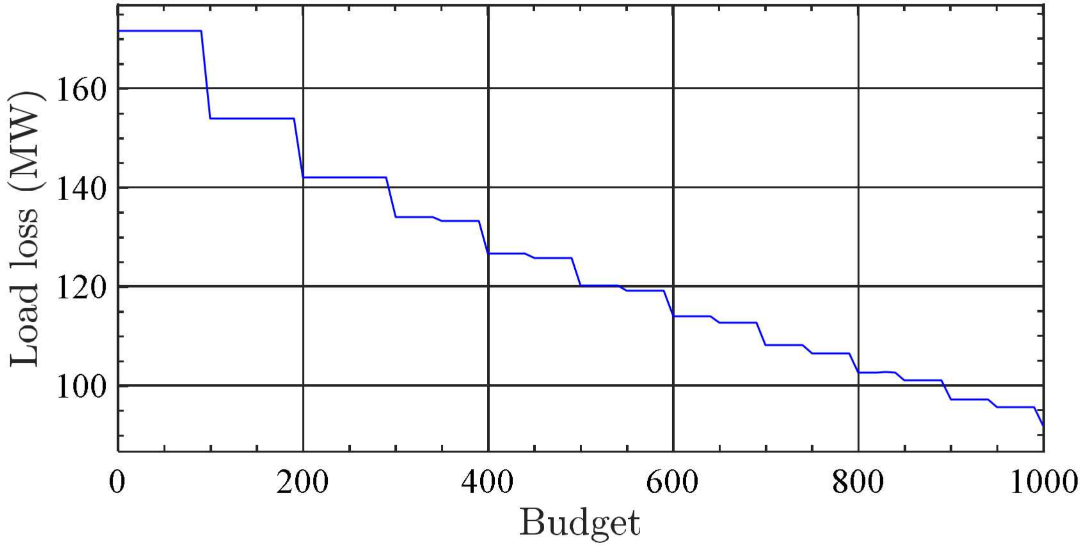
Results

- No investment vs. 1000 unit investment
- Impact to all 50 scenarios.
- Notice 22 scenarios have no outage occur during the storm
- Notice the tail of the curve has the greatest improvement, i.e. the worst scenarios are improved the most.



Results

- The optimal buses, lines, transformers, and generators are determined to reduce the objective function
- Increasing the budget as expect gives better results.



Conclusions

- Presented a optimization model to determine the optimal investments to improve power system resilience
- Accurate scenario generation is a key to valuable results
- The optimal investments can be determined through this formulation
- The worst case buses, lines, and generators can be determined through this formulation

Future work

- Include duration in this model (but requires accurate scenario generation), duration*MW lost is the objective function
- Instead of a scenario where a group of components fail at t=0, they now fail at a specific time and recover and another specific time
- Develop a co-optimization approach to determine the optimal investments to improve power system reliability and resiliency.
- Determine the trade-offs between reliability investments and resiliency investments

Thank you!

Questions?

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