TRANSMISSION NETWORK EXPANSION PLANNING UNDER DELIBERATE OUTAGES

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Outline

- Introduction
- Scenario generation procedure
- Formulation
- Case studies
- Conclusions & Further Research

Introduction

Why is the transmission network a potential target for destructive agents?

- Critical infrastructure for the society welfare
- It spreads over wide geographical areas
- Remotely operated
- Cascading effects of outages
- Operated close to static and dynamic limits $\Rightarrow$ higher level of vulnerability

Introduction

What can be done to mitigate the vulnerability?:

- Reinforcement of the network ⇒ Preventive actions
- Adequate and fast restoration of power supply after an attack ⇒ Corrective actions

Introduction

Classical transmission expansion planning

- Optimal timing, location and sizing of transmission facilities
- 1-year planning horizon ⇒ static
- Only economic issues (centralized/competitive frameworks)

Introduction

Transmission network expansion planning under deliberate outages

- Nonrandom uncertain events $\Rightarrow$ no statistics can be derived from historical data
- Uncertainty must be addressed $\Rightarrow$ scenarios
- Perceived likelihood of scenarios $\Rightarrow$ weights, $\pi(\omega)$

Scenario generation procedure

Scenario generation procedure

Uncertainty on destructive agent behaviour:

- Set of scenarios Ω characterizes the uncertainty
- Each scenario ω represents a credible attack plan resulting in a particular level of damage
- Level of damage measured in terms of the total load shed

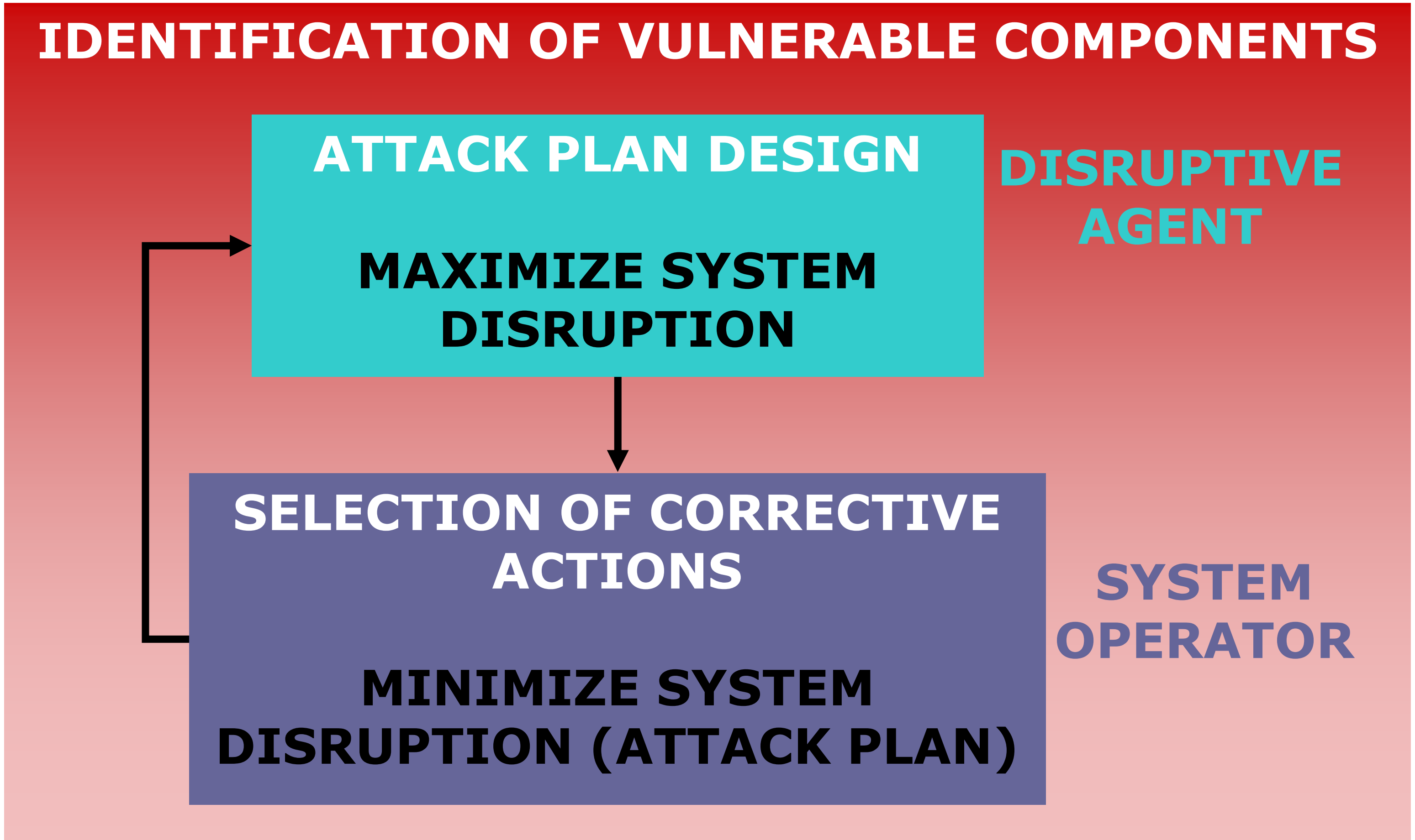
Scenario generation procedure

- Attack plans are selected as scenarios depending on the level of damage caused

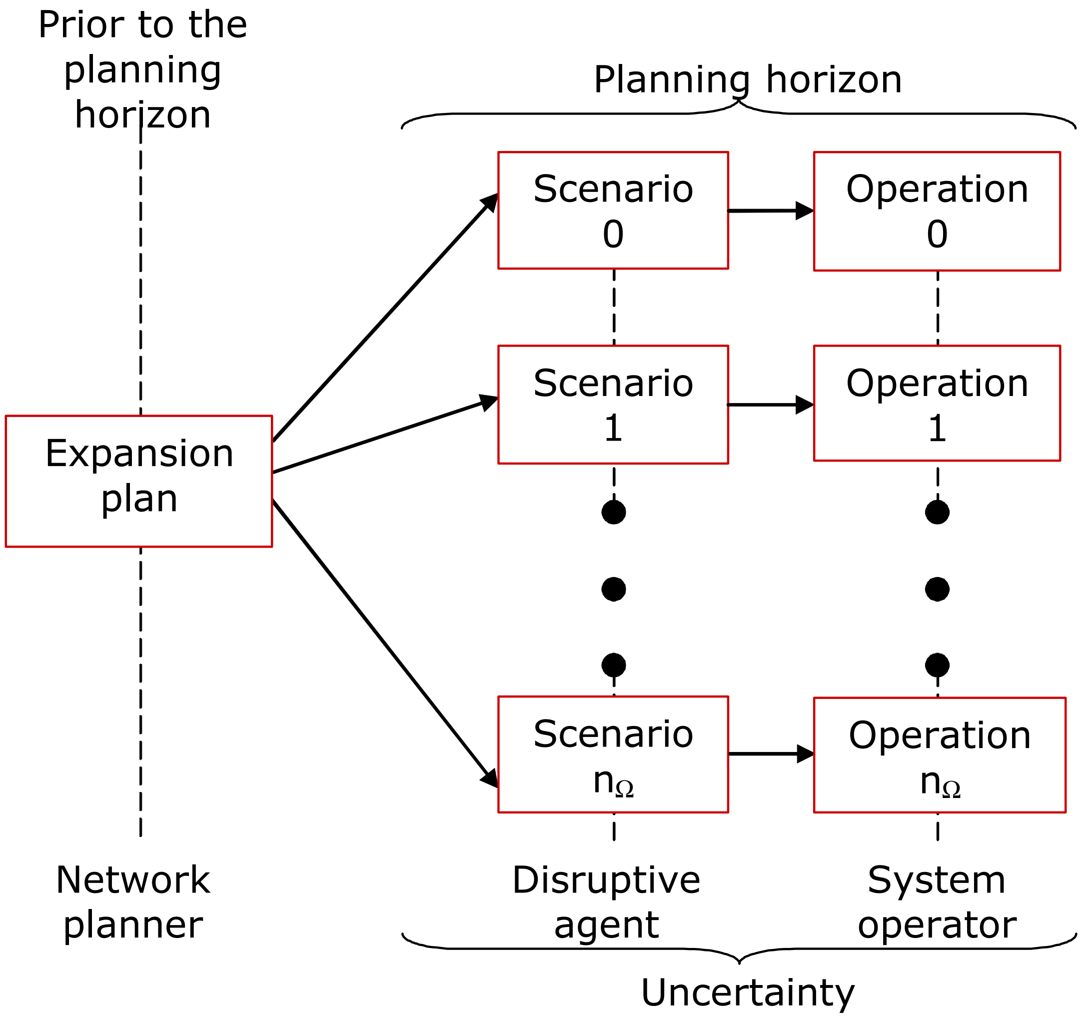
- Iterative procedure based on the solution of the so-called terrorist threat problem

Introduction

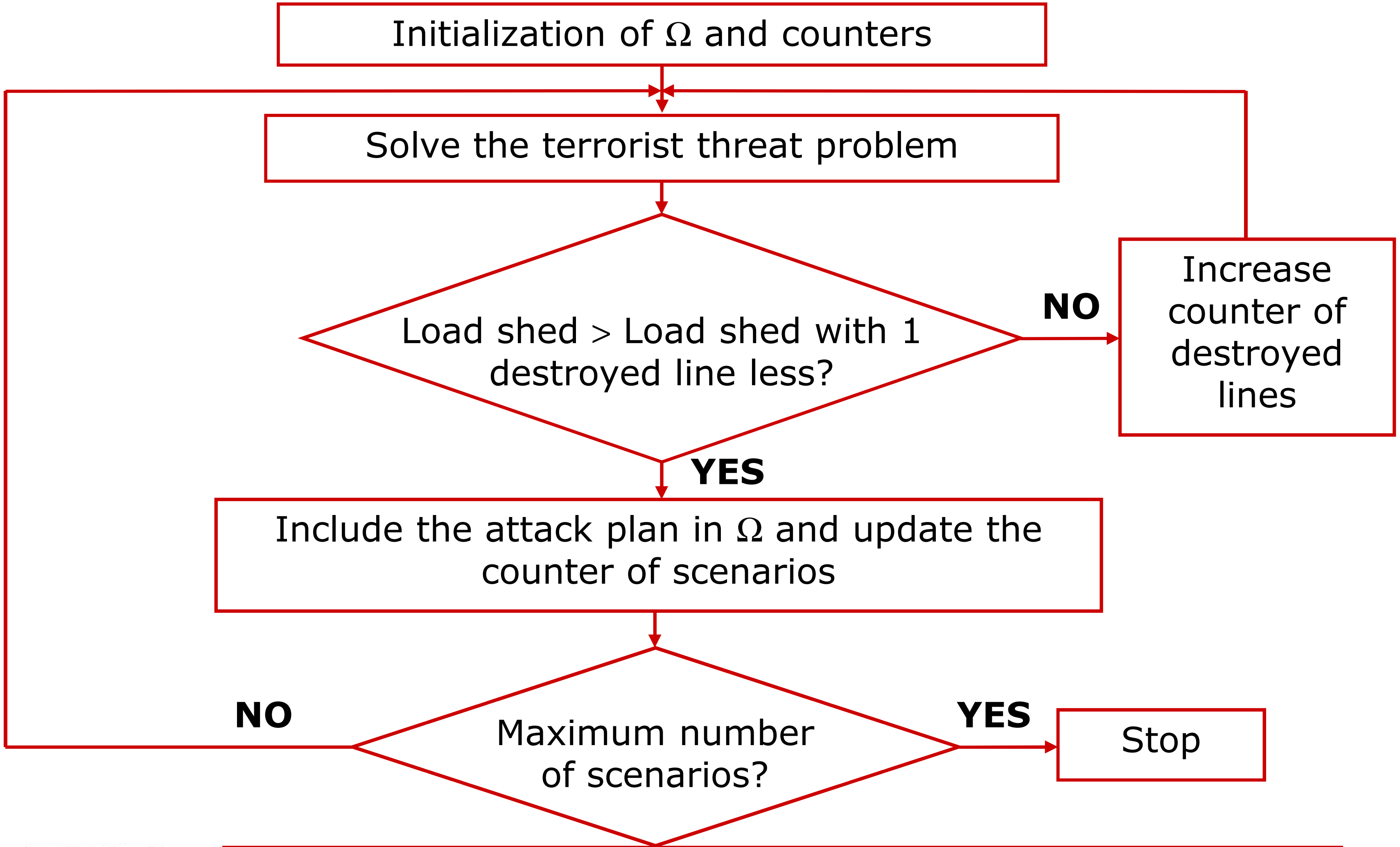
SYSTEM PLANNER: Terrorist Threat Problem



Scenario generation procedure



Scenario generation procedure



Scenario generation procedure

Scenario weight assignment represents the tradeoff between:

- the level of damage
- the required effort to achieve it (number of destroyed lines)

$$\pi(\omega) = \frac{\dfrac{\textbf{load shed}(\omega)}{\textbf{\#destroyed lines}(\omega)}}{\displaystyle\sum_{\omega'=1}^{n_\Omega} \dfrac{\textbf{load shed}(\omega')}{\textbf{\#destroyed lines}(\omega')}} \quad ; \ \omega = 1, \ldots, n_\Omega$$

Formulation of the risk-neutral model

Formulation of the risk-neutral model

Decision variables common to all scenarios:

- Construction of prospective lines

Decision variables for each scenario, ω:

- Load shed
- Voltage angles
- Power generation dispatch

Formulation of the risk-neutral model

Minimize

$$\text{weight}(\omega)[\text{level}-\text{of}-\text{damage}]+\beta\,[\text{investment}-\text{costs}]$$

$$\sum_{\omega=1}^{n_\Omega} \pi(\omega)\left[\sum_{n\in N} \Delta P_n^D(\omega)\right] + \beta \sum_{\ell\in L^C} C_\ell^L s_\ell$$

β: tradeoff between vulnerability and economic issues

Formulation of the risk-neutral model

Subject to:

- Maximum budget $\sum_{\ell \in L^C} C_\ell^L s_\ell \leq C_T^L$

- Power balance

$$\sum_{g \in G_n} P_g^G(\omega) - \sum_{\ell | O(\ell)=n} P_\ell^L(\omega) + \sum_{\ell | R(\ell)=n} P_\ell^L(\omega) = P_n^D - \Delta P_n^D(\omega); \quad \omega = 0,\ldots,n_\Omega, \forall n \in N$$

- Line flows (original)

$$P_\ell^L(\omega) = \frac{1}{x_\ell}\left[\delta_{O(\ell)}(\omega) - \delta_{R(\ell)}(\omega)\right] v_\ell(\omega); \omega = 0,\ldots,n_\Omega, \forall \ell \in L^O$$

Formulation of the risk-neutral model

Subject to:

- Line flows (candidates), non-linearity

$$P_\ell^L(\omega) = \frac{1}{x_\ell}\left[\delta_{O(\ell)}(\omega) - \delta_{R(\ell)}(\omega)\right] s_\ell ; \omega = 0, \ldots, n_\Omega, \forall \ell \in L^C$$

- Line flow limits

$$-\overline{P}_\ell^L \leq P_\ell^L(\omega) \leq \overline{P}_\ell^L; \quad \omega = 0, \ldots, n_\Omega, \forall \ell \in \left\{L^O \cup L^C\right\}$$

- Generator limits

$$0 \leq P_g^G(\omega) \leq \overline{P}_g^G; \quad \omega = 0, \ldots, n_\Omega, \forall g \in G$$

Formulation of the risk-neutral model

Subject to:

- Nodal phase angle limits

$$\underline{\delta} \le \delta_n(\omega) \le \overline{\delta}; \quad \omega = 0,\ldots,n_\Omega, \forall n \in N$$

- Load shed limits

$$\Delta P_n^D(\omega) = 0; \quad \omega = 0, \forall n \in N$$

$$0 \le \Delta P_n^D(\omega) \le P_n^D; \quad \omega = 1,\ldots,n_\Omega, \forall n \in N$$

- Binary variables

$$s_\ell \in \{0,1\}; \quad \forall \ell \in L^C$$

Formulation of the risk-neutral model

MINLP formulation:

- Power flows through candidate lines (per scenario) <u>non-linearity</u>

$$P_{\ell}^{L}(\omega)=\frac{1}{x_{\ell}}\left[\delta_{O(\ell)}(\omega)-\delta_{R(\ell)}(\omega)\right]s_{\ell};\omega=0,\ldots,n_{\Omega},\forall\ell\in L^{C}$$

Equivalent MILP formulation!!

Formulation of the risk-neutral model

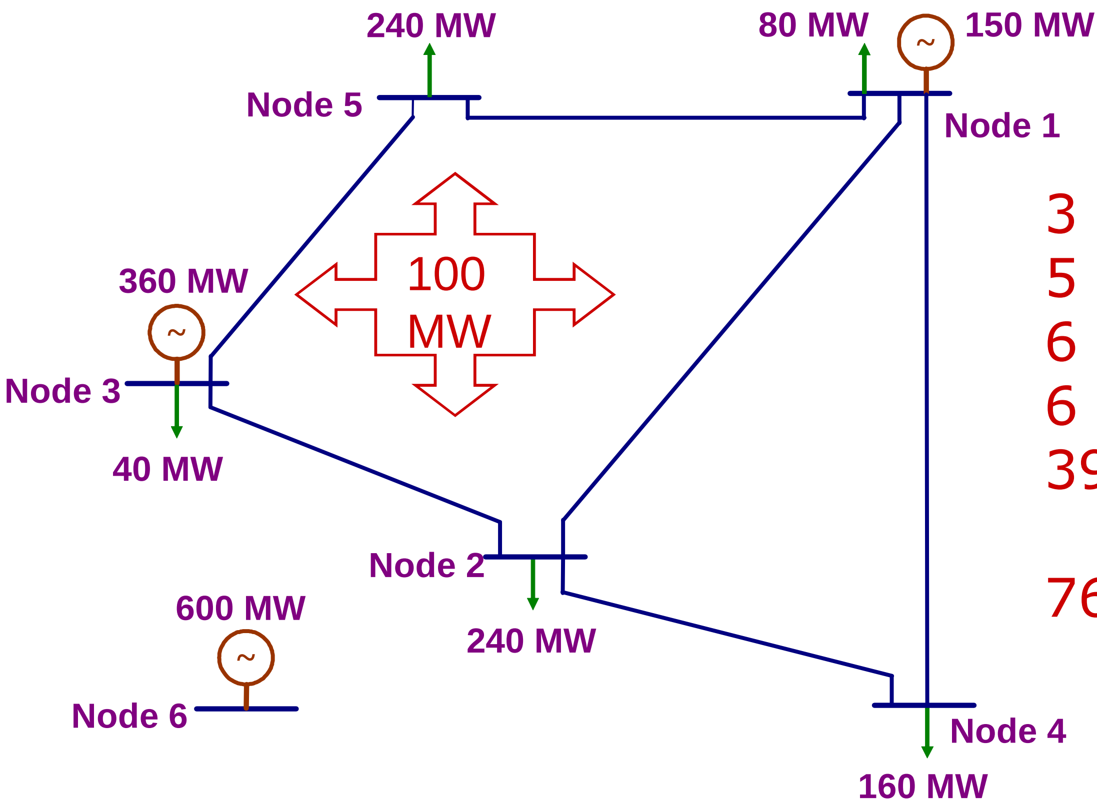
Advantages of the proposed formulation:

- Development of solutions based on mathematical programming $\Rightarrow$ Efficient and sound approaches
- Straightforward modification of network planner preferences

TRANSMISSION NETWORK EXPANSION PLANNING UNDER DELIBERATE OUTAGES

Case studies for the risk neutral approach

Garver's System



3 generators
5 loads
6 nodes
6 existing lines
39 candidate lines

760 MW system load

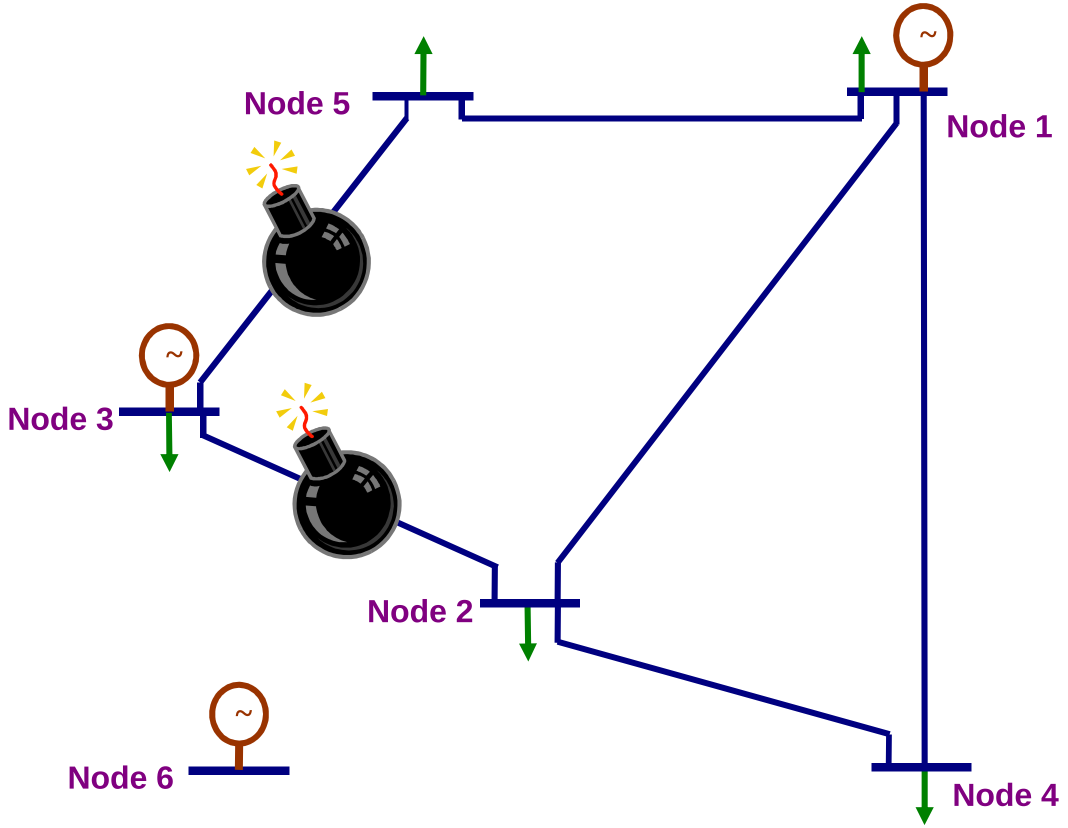
Garver's System

ω	Destroyed Lines	$\Delta D(\omega)$ (MW)	$\pi(\omega)$
1	2-3	470	0.3474
2	3-5	470	0.3474
3	2-3, 3-5	570	0.2106
4	1-2, 1-4, 1-5, 2-3, 3-5	640	0.0946

- Level of vulnerability:
  - Maximum: 115.1 MW (3 lines built, traditional)
  - Minimum: 0 MW (8+ lines built, traditional)

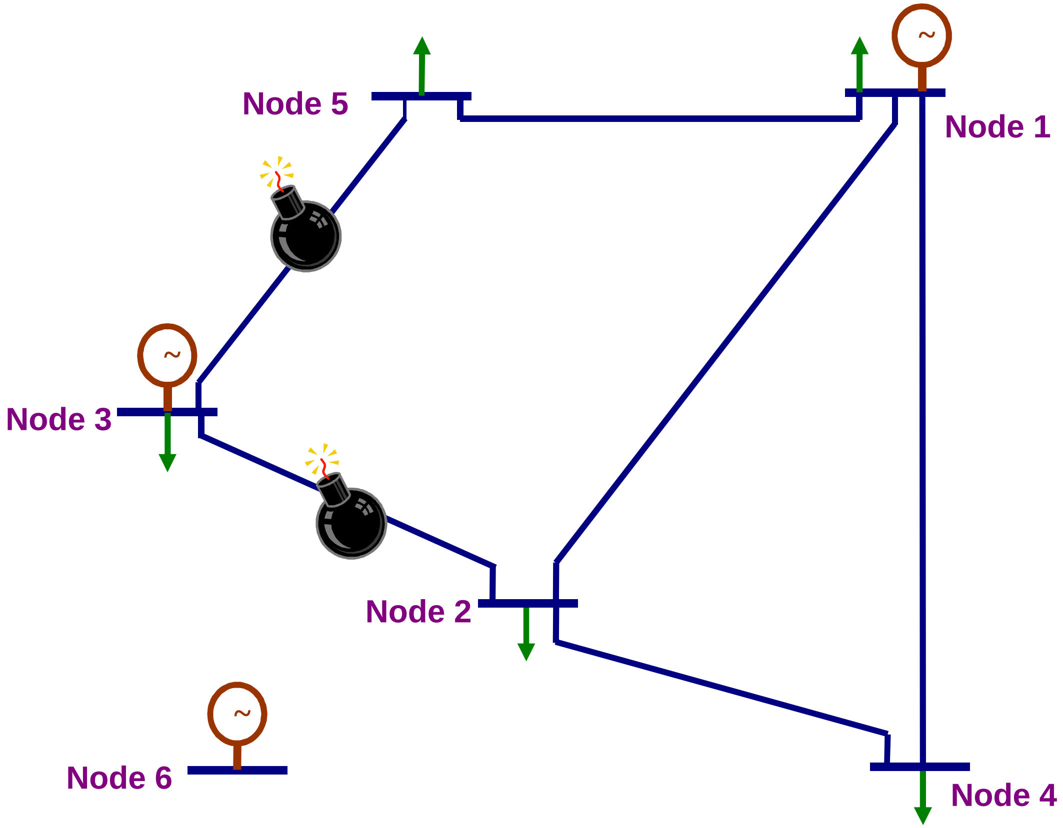
Garver's System

2 scenarios, 1 line destroyed ⇒ load shed: 470 MW
weight: 0.3474



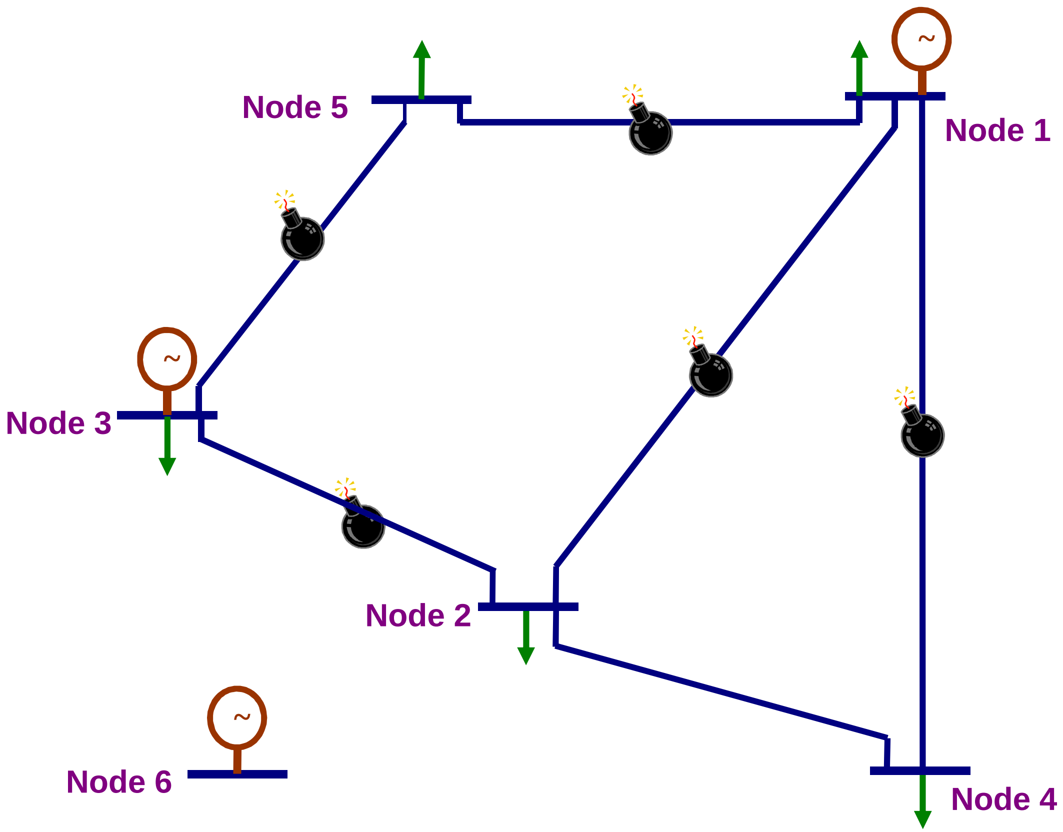
Garver's System

1 scenario, 2 lines destroyed ⇒ load shed: 570 MW
weight: 0.2106



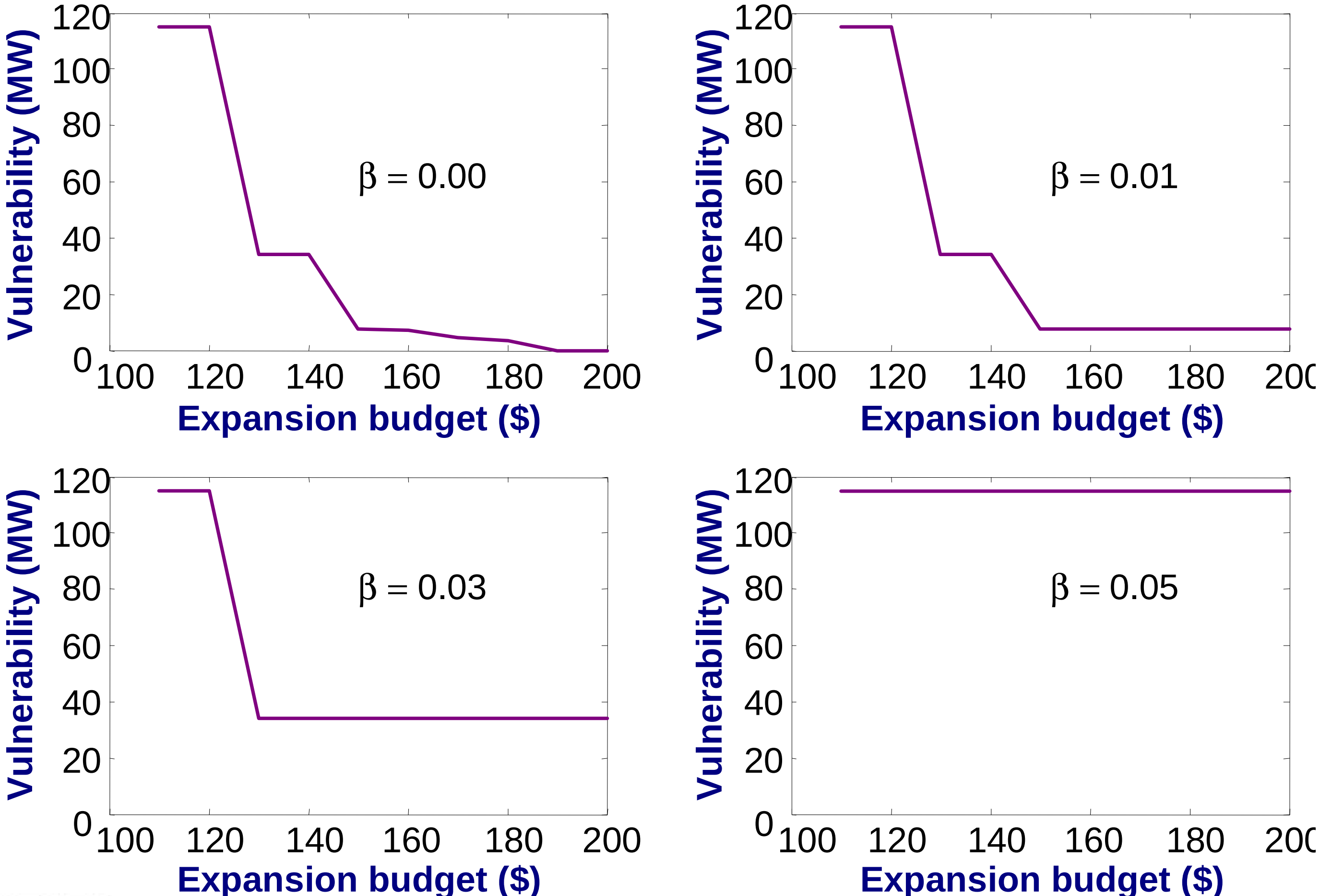
Garver's System

1 scenario, 5 lines destroyed ⇒ load shed: 640 MW
weight: 0.0946



Garver's System

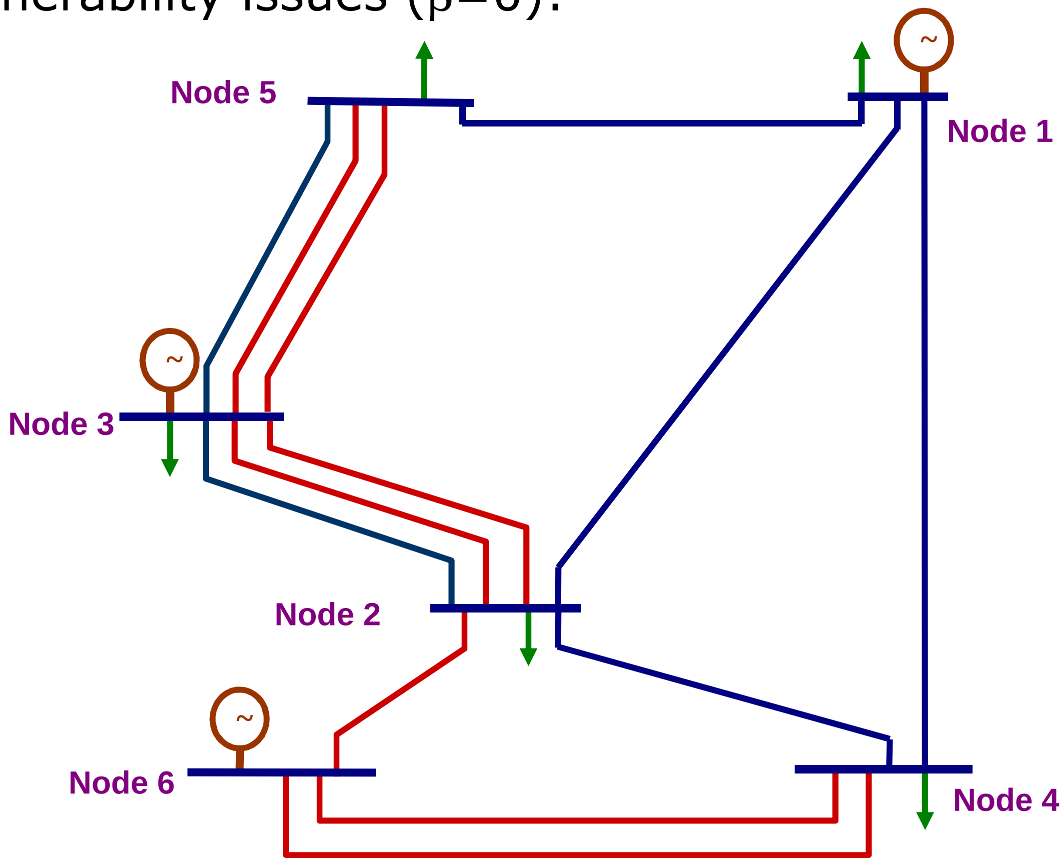
Risk neutral model



Garver's System

Risk neutral model

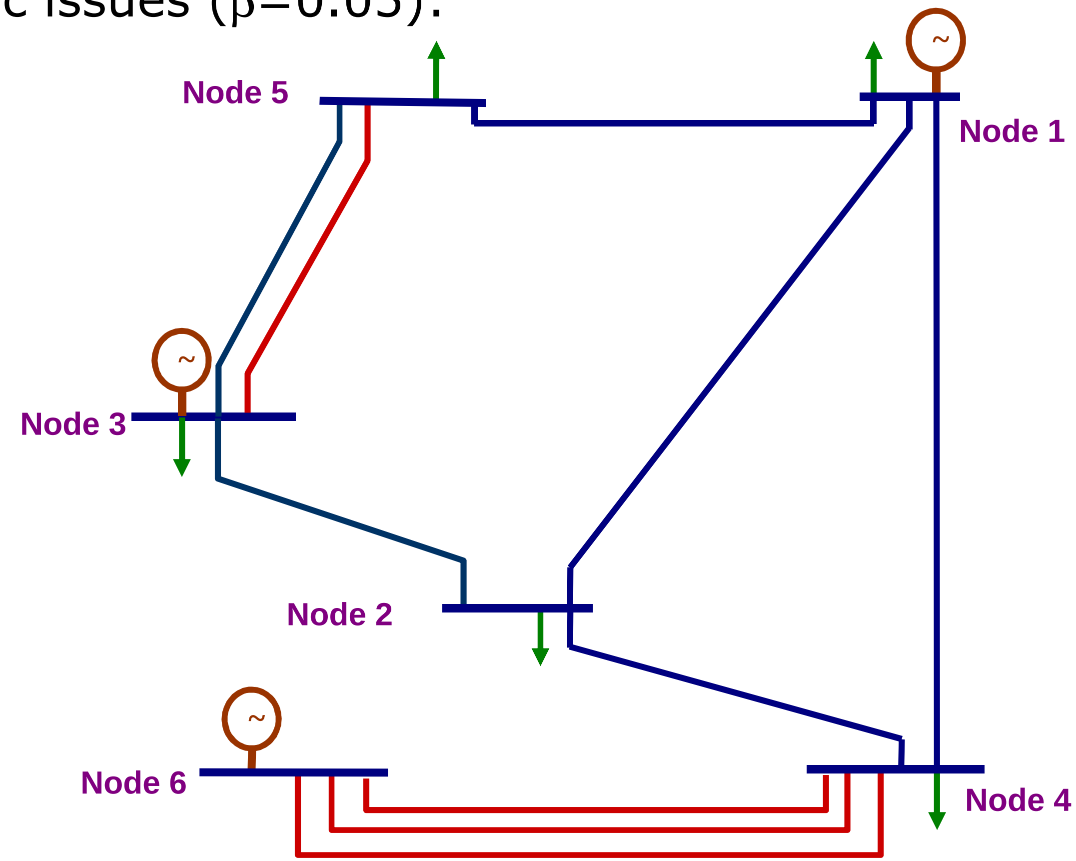
Only vulnerability issues (β=0):



Garver's System

Risk neutral model

Economic issues (β=0.05):



Formulation of the risk-averse model

Formulation

Probabilistic choice vs risk analysis

Probabilistic choice:

$$\underset{j}{\mathrm{Min}} \sum_{\omega} \pi(\omega) \Delta D^{j}(\omega)$$

Risk analysis:

$$\underset{j}{\mathrm{Min}} \sum_{\omega} \pi(\omega) R_{j}(\omega)$$

where: $R_{j}(\omega) = \Delta D^{j}(\omega) - \Delta D^{min}(\omega)$

Formulation

Probabilistic choice vs risk analysis

$$\underset{j}{\mathrm{Min}} \sum_{\omega} \pi(\omega)\left[\Delta D^{j}(\omega) - \Delta D^{\min}(\omega)\right]$$

$$\underset{j}{\mathrm{Min}} \sum_{\omega} \left[\pi(\omega)\Delta D^{j}(\omega) - \pi(\omega)\Delta D^{\min}(\omega)\right]$$

$$\underset{j}{\mathrm{Min}} \sum_{\omega} \pi(\omega)\Delta D^{j}(\omega)$$

Formulation

Risk analysis

- Regret of expansion plan j and scenario ω is formulated as:

$$R_j(\omega) = \Delta D^j(\omega) - \Delta D^{min}(\omega) \;;\; \forall j \in J, \omega = 0, \ldots, n_\Omega$$

where: $$\Delta D^{min}(\omega) = \underset{j \in J}{Min}\left\{\Delta D^j(\omega)\right\} \;;\; \omega = 0, \ldots, n_\Omega$$

- Weighted regret of expansion plan j and attack plan ω is:

$$WR_j(\omega) = \pi(\omega) R_j(\omega) \;;\; \forall j \in J, \omega = 1, \ldots, n_\Omega$$

Formulation

Risk analysis

- Maximum weighted regret of expansion plan j is:

$$WR_j^{max} = \underset{\omega=0,\dots n_\Omega}{Max} \left\{ WR_j(\omega) \right\} \; ; \; \forall j \in J$$

- Minimax weighted regret criterion is formulated as:

$$WR^* = \underset{j \in J}{Min} \left\{ WR_j^{max} \right\}$$

Formulation of the risk-averse model

Decision variables common to all scenarios:

- Maximum weighted regret, WR^{max}
- Construction of prospective lines

Decision variables for each scenario, ω:

- Weighted regret, $WR(\omega)$
- Load shed
- Voltage angles
- Power generation dispatch

Formulation of the risk-averse model

Minimize

$$WR^{\max} + \beta \, [\text{investment costs}]$$

β: tradeoff between vulnerability and economic issues

Formulation of the risk-averse model

Subject to:

- Weighted regrets associated with each attack plan

$$WR(\omega) = \pi(\omega)\left[\sum_{n \in N} \Delta D(\omega) - \Delta D^{\min}(\omega)\right]; \quad \omega = 1, \ldots, n_\Omega$$

- Condition on the maximum weighted regret

$$WR^{\max} \geq WR(\omega); \quad \omega = 1, \ldots, n_\Omega$$

Formulation of the risk-averse model

Subject to:

- Maximum budget
- Nodal power balance (ω)
- Power flows through existing and candidate lines (ω)
- Limits on decision variables

Equivalent MILP formulation!

Formulation of the risk-averse model

Deterministic transmission expansion problem for scenario ω

$$\Delta D^{\min}(\omega) = \textit{Minimize} \sum_{n \in N} \Delta D_n(\omega)$$

Formulation of the risk-averse model

Subject to:

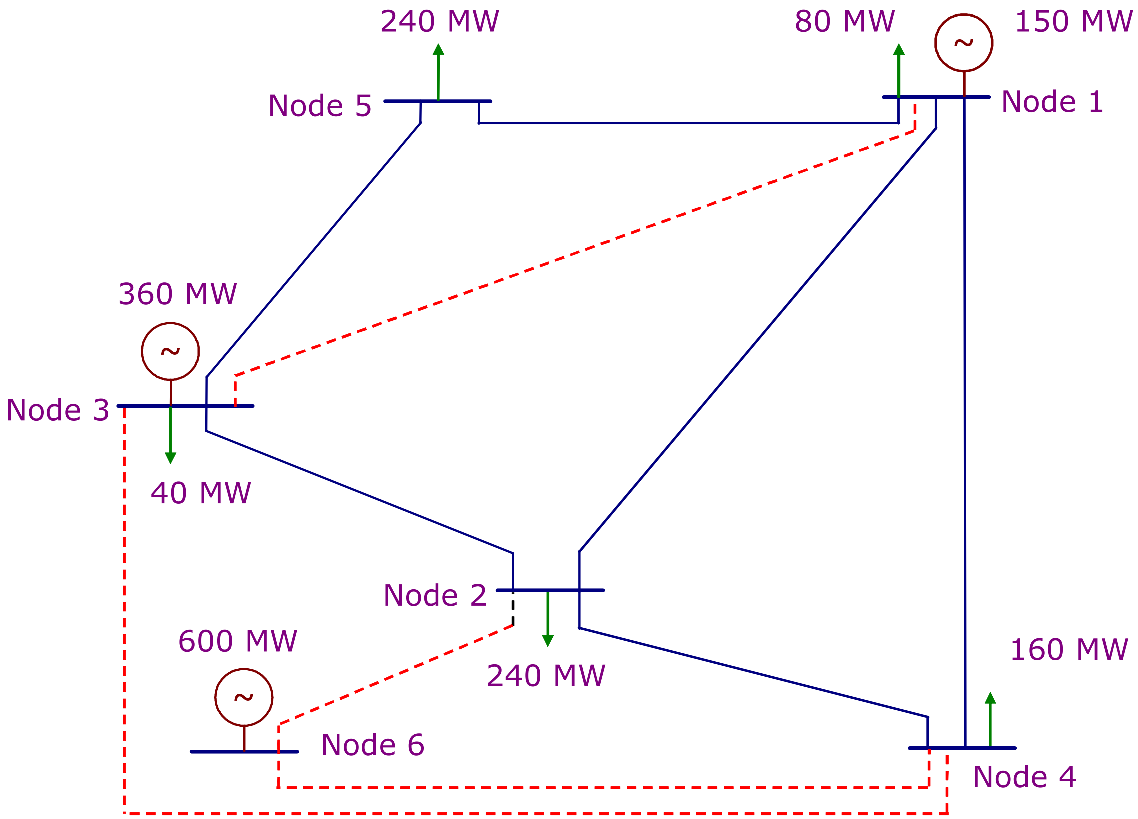
- Maximum budget
- Nodal power balance (ω)
- Power flows through existing and candidate lines (ω)
- Limits on decision variables

Equivalent MILP formulation!

TRANSMISSION NETWORK EXPANSION PLANNING UNDER DELIBERATE OUTAGES

Case studies

Garver's System



3 generators
5 loads
6 nodes
6 existing lines
4 candidate lines

760 MW system load

Garver’s System

ω	Destroyed Lines	$\Delta D(\omega)$ (MW)	$\pi(\omega)$	$\Delta D^{min}(\omega)$ (MW)
1	**2-3**	**470**	**0.3474**	**205.7**
2	**3-5**	**470**	**0.3474**	**226.1**
3	**2-3, 3-5**	**570**	**0.2106**	**270.0**
4	**1-2, 1-4, 1-5, 2-3, 3-5**	**640**	**0.0946**	**370.6**

Garver's System

Risk-neutral model

Load shed (MW)

$150 budget

Expansion Plan	ω =1	ω = 2	ω = 3	ω = 4	WD
1 (-)	470.0	470.0	570.0	640.0	507.2
2 (4-6)	370.0	370.0	470.0	540.0	407.2
3 (3-4)	388.0	392.7	488.0	558.0	426.8
4 (3-4, 4-6)	288.0	323.7	388.0	458.0	337.5
5 (2-6)	370.0	370.0	470.0	540.0	407.2
6 (2-6, 4-6)	270.0	270.0	370.0	440.0	307.2
7 (2-6, 3-4)	288.0	291.0	388.0	458.0	326.2
8 (2-6, 3-4, 4-6)	220.1	236.1	292.9	370.6	255.2
9 (1-3)	397.6	403.7	470.0	640.0	437.9
10 (1-3, 4-6)	303.1	316.8	370.0	540.0	344.4
11 (1-3, 3-4)	328.4	340.5	388.0	558.0	366.9
12 (1-3, 3-4, 4-6)	240.8	283.4	288.0	458.0	286.1
13 (1-3, 2-6)	297.6	300.3	370.0	540.0	336.7
14 (1-3, 2-6, 4-6)	205.7	226.1	270.0	440.0	248.5
15 (1-3, 2-6, 3-4)	228.4	240.5	288.0	458.0	266.9
16 (1-3,2-6,3-4,4-6)	-	-	-	-	-

Garver's System

Risk-averse model

Weighted regret (MW)

$150 expansion budget

Expansion Plan	$\omega = 1$	$\omega = 2$	$\omega = 3$	$\omega = 4$	WR^{max}
1 (-)	91.8	84.7	63.2	25.5	91.8
2 (4-6)	57.1	50.0	42.1	16.0	57.1
3 (3-4)	63.3	57.9	46.0	17.7	63.3
4 (3-4, 4-6)	28.6	33.9	24.9	8.3	33.9
5 (2-6)	57.1	50.0	42.1	16.0	57.1
6 (2-6, 4-6)	22.4	15.2	21.1	6.6	22.4
7 (2-6, 3-4)	28.6	22.6	24.9	8.3	28.6
8 (2-6, 3-4, 4-6)	5.0	3.5	4.8	0.0	5.0
9 (1-3)	66.7	61.7	42.1	25.5	66.7
10 (1-3, 4-6)	33.9	31.5	21.1	16.0	33.9
11 (1-3, 3-4)	42.6	39.7	24.9	17.7	42.6
12 (1-3, 3-4, 4-6)	12.2	19.9	3.8	8.3	19.9
13 (1-3, 2-6)	31.9	25.8	21.1	16.0	31.9
14 (1-3, 2-6, 4-6)	0.0	0.0	0.0	6.6	6.6
15 (1-3, 2-6, 3-4)	7.9	5.0	3.8	8.3	8.3
16 (1-3,2-6,3-4,4-6)	-	-	-	-	-

Garver’s System

	Risk-neutral	Risk-averse	% Reduction
Risk [MW]	6.6	5.0	24.2
Weighted average system load shed [MW]	248.5	255.2	-2.7
Investment cost [$]	98	119	-17.6
Expansion plan	14	8	-

TRANSMISSION NETWORK EXPANSION PLANNING UNDER DELIBERATE OUTAGES

Conclusions & Further Research

Conclusions

Main contributions:

- Generation of a set of plausible scenarios based on a vulnerability analysis
- Risk-neutral model: expansion plan is optimal “on the weighted average” for all scenarios
- Risk-based model: the optimal expansion plan is the one that minimizes the maximum weighted regret for all scenarios

Conclusions

Main contributions:

- Risk aversion is modeled by the minimax weighted regret criterion
- Risk paradigm is an appropriate framework to model the impact of intentional outages
- Mixed-integer linear formulation
- Tool for the network planner to model the trade off between vulnerability and investment issues

Further Research

- More complex power flow models (AC vs. DC)
- Inclusion of unit decommitment and line switching
- Single-period (power disrupted) vs. multi-period (energy disrupted)
- Weight stability

Obrigada!

GSEE:
http://www.uclm.es/area/gsee