SAND2022-14706C

IEEE PES Power & Energy Society® | IEEE

EESAT
Austin, TX. November 7-9, 2022

Optimal Mobile Energy Storage Pre-Placement for Black-Start Restoration

Joshua Yip[1], Manuel Garcia[2], Brian Pierre[2], Erhan Kutanoglu[3], and Surya Santoso[1]

[1]Electrical and Computer Engineering
University of Texas at Austin
Austin, TX

[2]Electric Power Systems Research
Sandia National Laboratories
Albuquerque, NM

[3]Operations Research and Industrial Engineering
University of Texas at Austin
Austin, TX

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Problem Statement

- Following blackout, bringing transmission system back into service requires black-start (BS) restoration

- Utility-scale mobile energy storage (MES) can supply cranking power in order to "black-start" generators

- Topic: optimal pre-blackout placement of MES to enhance BS restoration in view of islands isolated by component damage

Source: U.S. Department of Energy

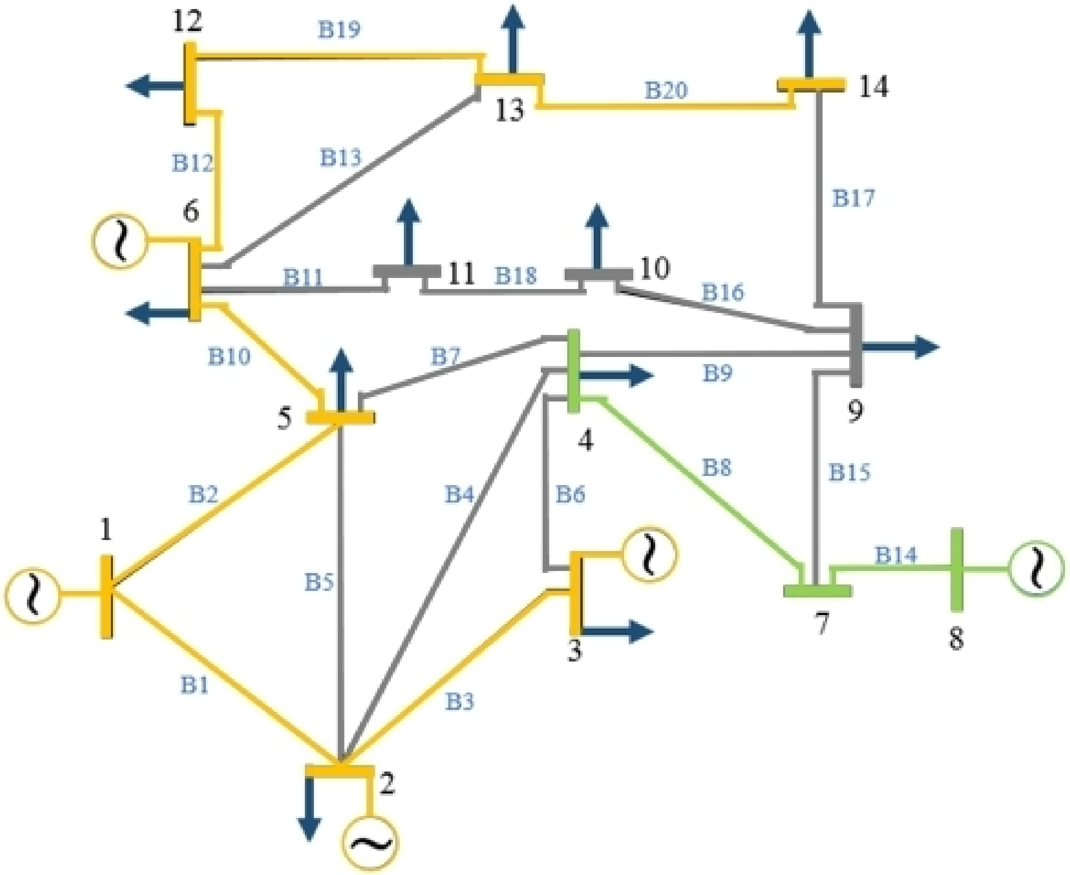
Source: Batteries and Energy Storage Technology Magazine

Description of Optimization Model

- Binary-valued uncertain parameters for outage of **branches**, generators, and buses

- Two-stage stochastic mixed-integer linear program (MILP):
  - First stage: pre-placement of mobile energy storage (MES) at buses
  - Second stage: steady-state DC power flow without further MES relocation

- McCormick relaxation obviates need for integer variables in second stage



Stochastic Programming Concepts

- Standard form of two-stage linear stochastic program:

$$z^* = \min \boldsymbol{c}^{\mathrm{T}}\boldsymbol{x} + \mathbb{E}[Z(\boldsymbol{x},\boldsymbol{\xi})] \quad \text{s.t. } \boldsymbol{x} \in \mathcal{X} \subseteq \mathbb{R}^{N_1}$$

- Second-stage problem (with affine dependence on $\boldsymbol{\xi}$):

$$Z(\boldsymbol{x},\boldsymbol{\xi}) = \min \boldsymbol{q}(\boldsymbol{\xi})^{\mathrm{T}}\boldsymbol{y} \quad \text{s.t. } \boldsymbol{y} \in \mathbb{R}_+^{N_2},\ \mathbf{T}(\boldsymbol{\xi})\boldsymbol{x} + \mathbf{W}(\boldsymbol{\xi})\boldsymbol{y} = \boldsymbol{h}(\boldsymbol{\xi})$$

- Sample average approximation (SAA):

$$\min_{\boldsymbol{x}\in\mathcal{X}} \boldsymbol{c}^{\mathrm{T}}\boldsymbol{x} + \frac{1}{N}\sum_{n=1}^{N} Z(\boldsymbol{x},\boldsymbol{\xi}^n)$$

- Wait-and-see problem:

$$WS = \mathbb{E}[\min_{\boldsymbol{x}\in\mathcal{X}} \boldsymbol{c}^{\mathrm{T}}\boldsymbol{x} + Z(\boldsymbol{x},\boldsymbol{\xi})]$$

Note that $WS \leq z^*$

- Expected value problem:

$$EV = \min_{\boldsymbol{x}\in\mathcal{X}} \boldsymbol{c}^{\mathrm{T}}\boldsymbol{x} + Z(\boldsymbol{x},\boldsymbol{\mu})$$

Note that $EV \leq z^*$ if $\boldsymbol{q}, \mathbf{W}$ constant in $\boldsymbol{\xi}$
Moreover, $EV \leq WS$ if $\mathcal{X}$ continuous and $\mathbf{T}$ also constant in $\boldsymbol{\xi}$

- Expected cost of expected value solution:

$$EEV = \boldsymbol{c}^{\mathrm{T}}\boldsymbol{x}_{\mathrm{EV}} + \mathbb{E}[Z(\boldsymbol{x}_{\mathrm{EV}},\boldsymbol{\xi})]$$

Discretized Expected Value

- Wait-and-see problem:

$$WS = \mathbb{E}[\min_{\boldsymbol{x}\in\mathcal{X}} \boldsymbol{c}^{\mathrm{T}}\boldsymbol{x} + Z(\boldsymbol{x},\boldsymbol{\xi})]$$

Note that $WS \leq z^*$

- Expected value problem:

$$EV = \min_{\boldsymbol{x}\in\mathcal{X}} \boldsymbol{c}^{\mathrm{T}}\boldsymbol{x} + Z(\boldsymbol{x},\boldsymbol{\mu})$$

Note that $EV \leq z^*$ if $\boldsymbol{q}, \mathbf{W}$ constant in $\boldsymbol{\xi}$
Moreover, $EV \leq WS$ if $\mathcal{X}$ continuous and $\mathbf{T}$ also constant in $\boldsymbol{\xi}$

- Expected cost of expected value solution:

$$EEV = \boldsymbol{c}^{\mathrm{T}}\boldsymbol{x}_{\mathrm{EV}} + \mathbb{E}[Z(\boldsymbol{x}_{\mathrm{EV}},\boldsymbol{\xi})]$$

- Conditions for discretized expected value concept:
  - All second-stage variables $\boldsymbol{y}$ continuous,
  - Parameter vector $\boldsymbol{q}$ and matrices $\mathbf{T}, \mathbf{W}$ constant in $\boldsymbol{\xi}$,
  - Random parameter vector $\boldsymbol{\xi}$ with nonnegative, integer-valued (e.g., binary-valued) support Ξ, where nonzero component values represent adverse conditions (e.g., damages)

- MILP search problem for finding $\boldsymbol{\xi}_{\mathrm{DEV}}$:

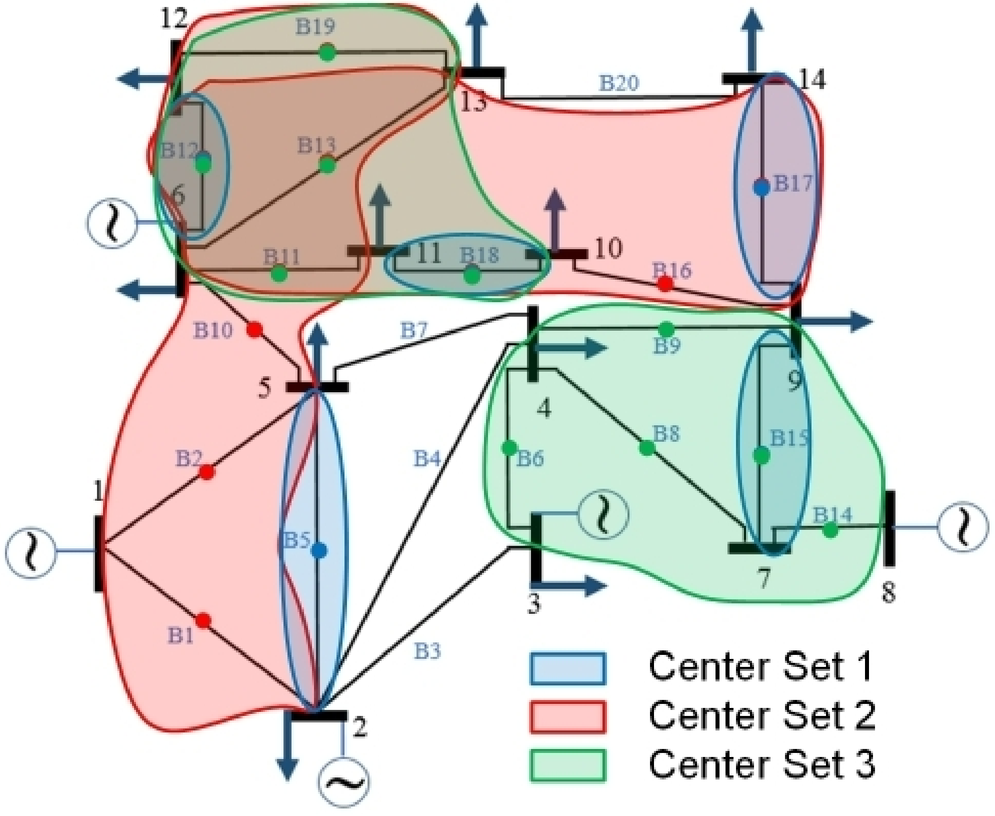
$$\begin{aligned} &\min \|\boldsymbol{\xi} - \boldsymbol{\mu}\|_1 \\ &\text{s.t. } \boldsymbol{x} \in \mathcal{X}, \boldsymbol{y} \in \mathbb{R}_+^{N_2}, \boldsymbol{\xi} \in \Xi \subseteq \mathbb{Z}_+^K \\ &\qquad \boldsymbol{c}^{\mathrm{T}}\boldsymbol{x} + \boldsymbol{q}^{\mathrm{T}}\boldsymbol{y} \leq WS \\ &\qquad \mathbf{1}^{\mathrm{T}}\boldsymbol{\xi} \geq \mathbf{1}^{\mathrm{T}}\boldsymbol{\mu} \\ &\qquad \mathbf{T}\boldsymbol{x} + \mathbf{W}\boldsymbol{y} = \boldsymbol{h}(\boldsymbol{\xi}) \end{aligned}$$

- Discretized expected value problem:

$$DEV = \min_{\boldsymbol{x}\in\mathcal{X}} \boldsymbol{c}^{\mathrm{T}}\boldsymbol{x} + Z(\boldsymbol{x},\boldsymbol{\xi}_{\mathrm{DEV}})$$

Note that $DEV \leq WS \leq z^*$, and $\boldsymbol{\xi}_{\mathrm{DEV}}$ contains at least as many damages as in realization on average

Branch Outage Distributions

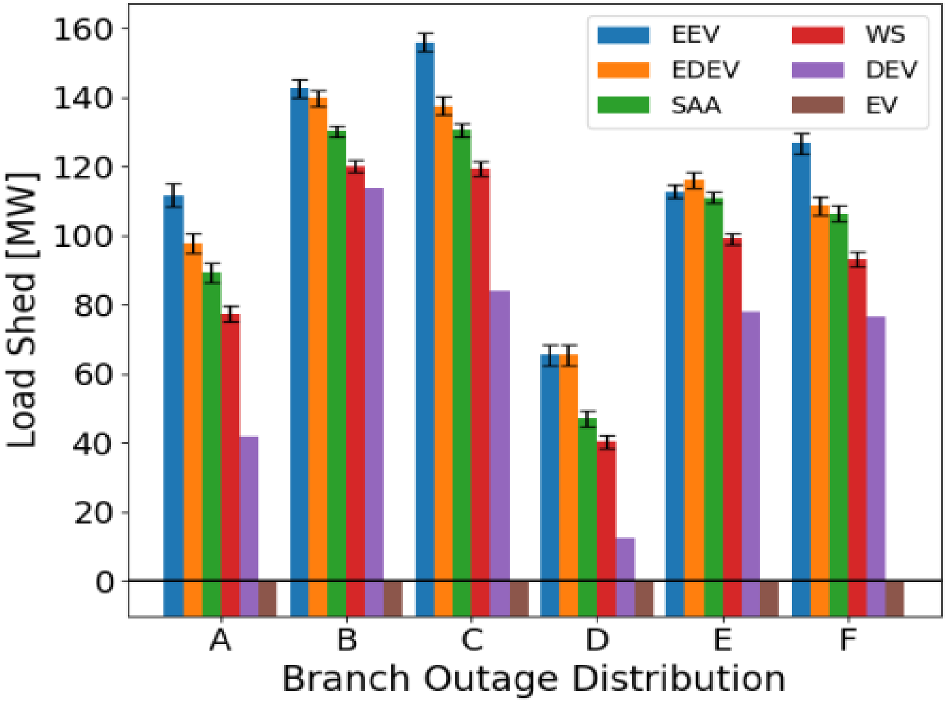


- Branch outage distributions each defined by:
  - Set of centers for outages
  - Outage conditional probability decay rate γ

1) From distribution's set of centers, randomly select one center to occur
2) Given selected center, consider all branches in center disabled, and then for each branch not in center:
   a) Consider $\gamma^{(\delta/\Delta)}$ conditional probability that non-center branch disabled, where δ gives distance on one-line diagram of branch's midpoint to nearest midpoint of any branch in selected center
   b) With conditional probability from a), randomly decide whether branch disabled

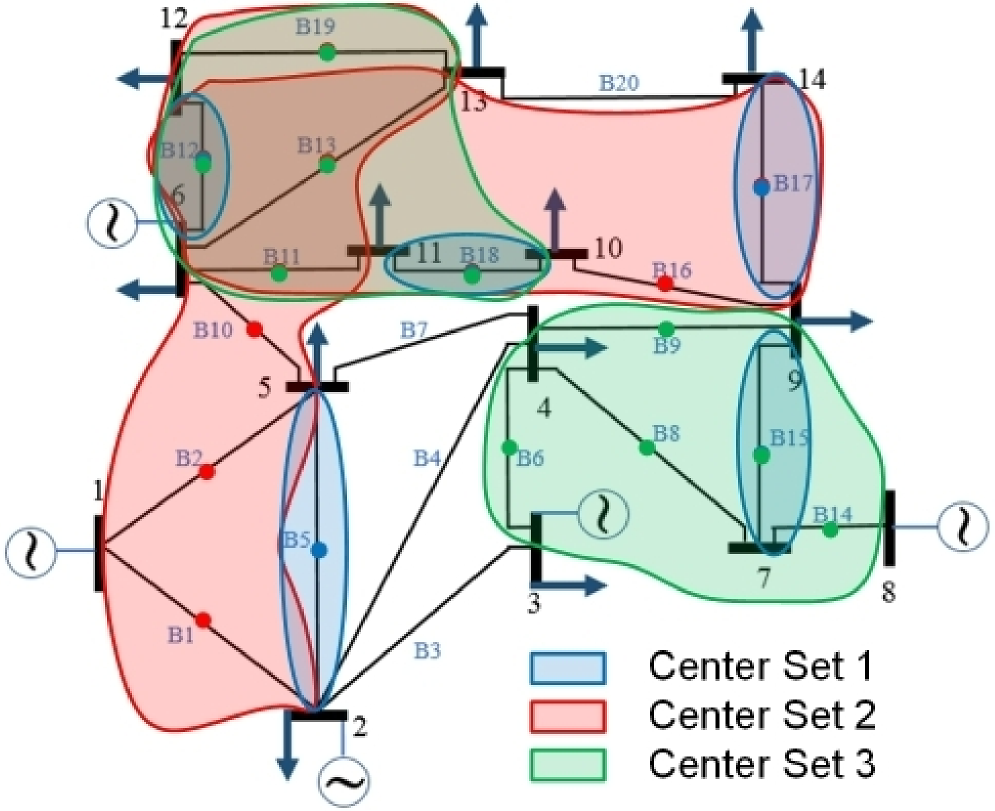
Outline of Experiments

- Procedure:
  - Training and validation samples, each 2000 scenarios
  - Solve SAA for training sample, then assess first-stage decisions with validation sample
  - Solve approximation of wait-and-see problem with validation sample
  - Solve expected value problem, then assess $\boldsymbol{x}_{\mathrm{EV}}$
  - Solve search problem for $\boldsymbol{\xi}_{\mathrm{DEV}}$, then solve discretized expected value problem, then assess $\boldsymbol{x}_{\mathrm{DEV}}$



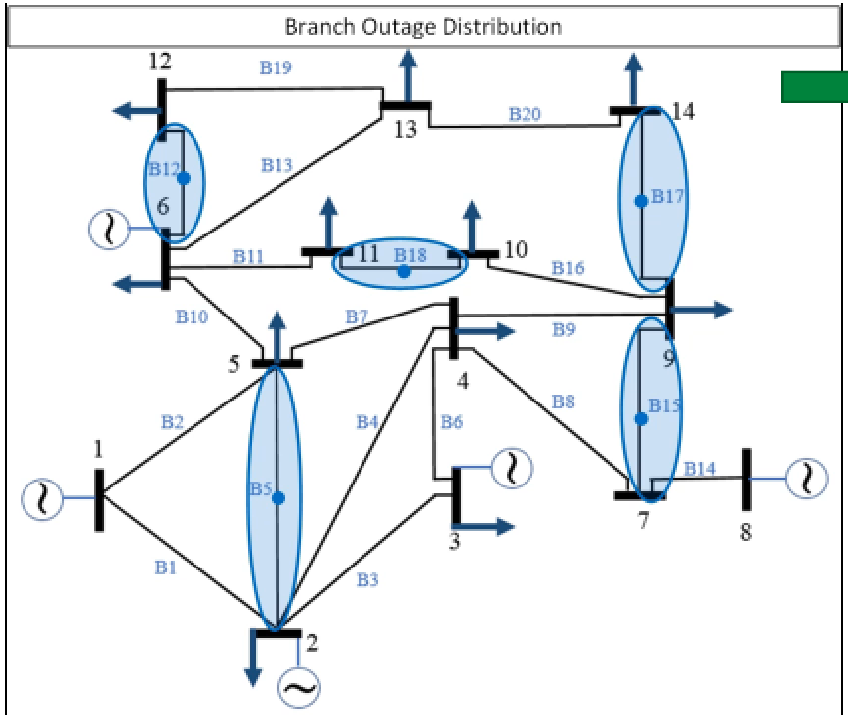
- Quantitative results:
  - Inequalities held empirically (e.g., $z^* \geq WS$)
  - Generally observed that $DEV > EV$ and that $EDEV < EEV$

Qualitative Results Summary

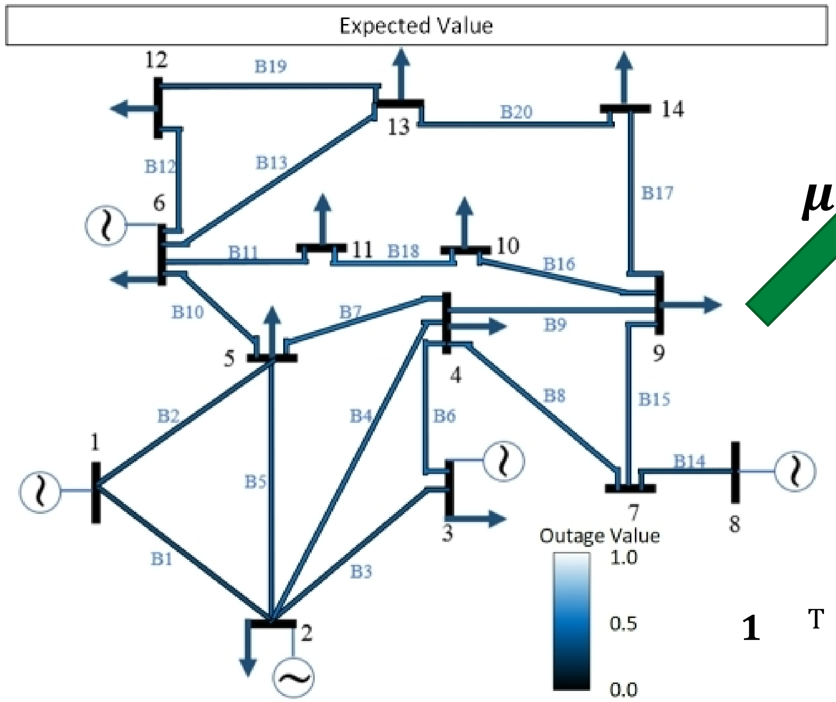


Branch Outage Distr.	MES Bus			Discretized Expected Value		
	SAA	EV	DEV	Dist.	Excess Dist.	Disabled Branches
A	6	None	8	9.25	0.04	4,5,6,7,9,11,13,15,16,17,18
B	3	6	8	5.49	0.05	1,2,4,5,6,7,8,9,10,11,12,13,16,17,18,19,20
C	3	None	6	6.63	0.48	2,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20
D	6	None	None	8.84	1.29	6,7,8,11,15,16,17,18
E	3	8	6	5.91	0.00	1,2,5,7,9,10,11,12,13,16,17,18,19
F	3	None	6	7.28	0.19	6,7,8,9,10,11,12,13,14,15,16,18,19

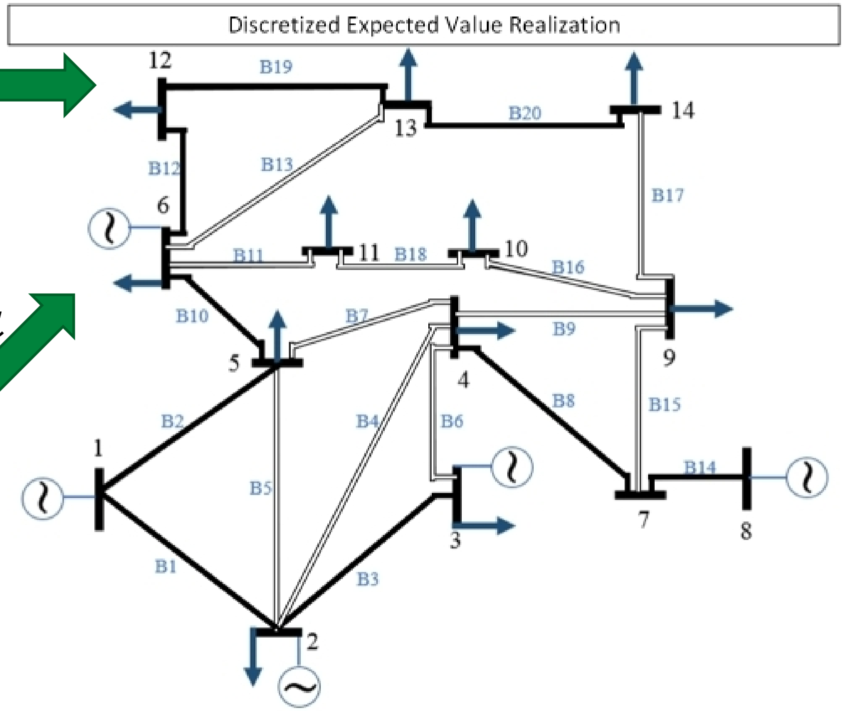
Distribution A: Center Set 1, $\gamma = 1/3$



WS



μ

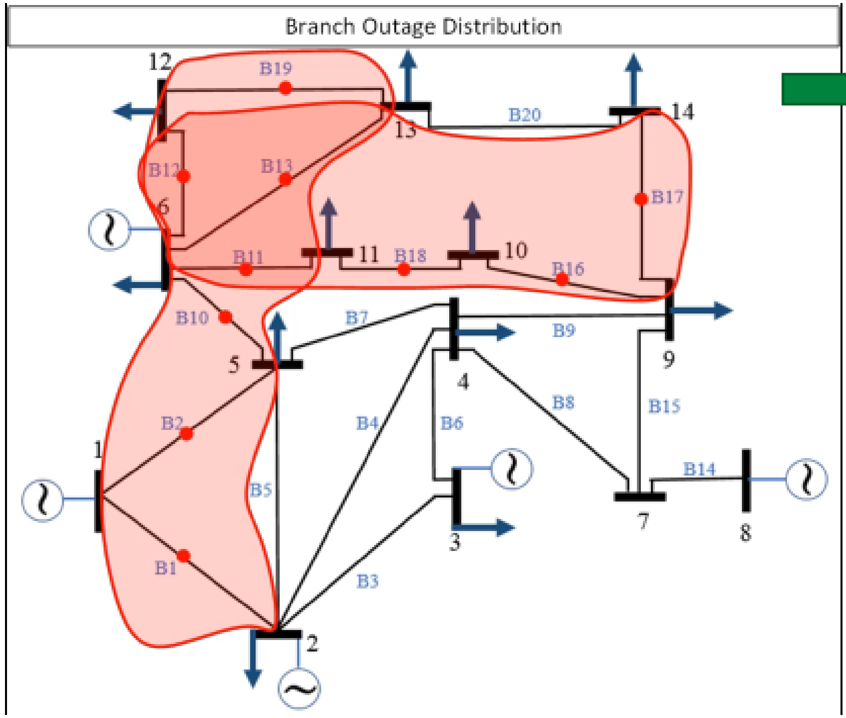


95% CI for WS: [74.96, 79.80]

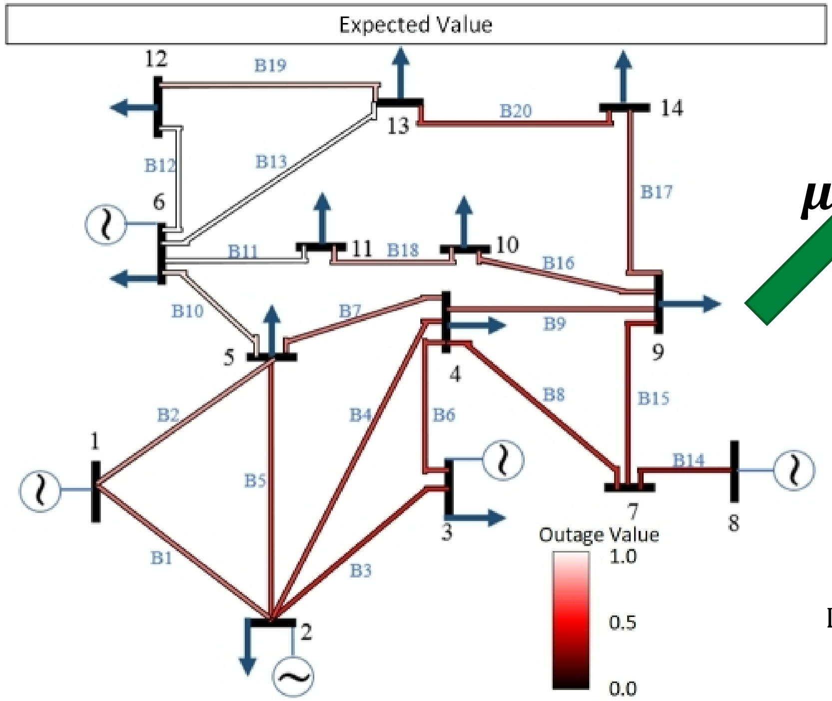
$\mathbf{1}^{\mathrm{T}} \boldsymbol{\xi}_{\mathrm{DEV}} = EV\mathbf{1} = 42.00$

$\mathbf{1}^{\mathrm{T}} \boldsymbol{\mu} = 9\ 90\ EV = 0.00$

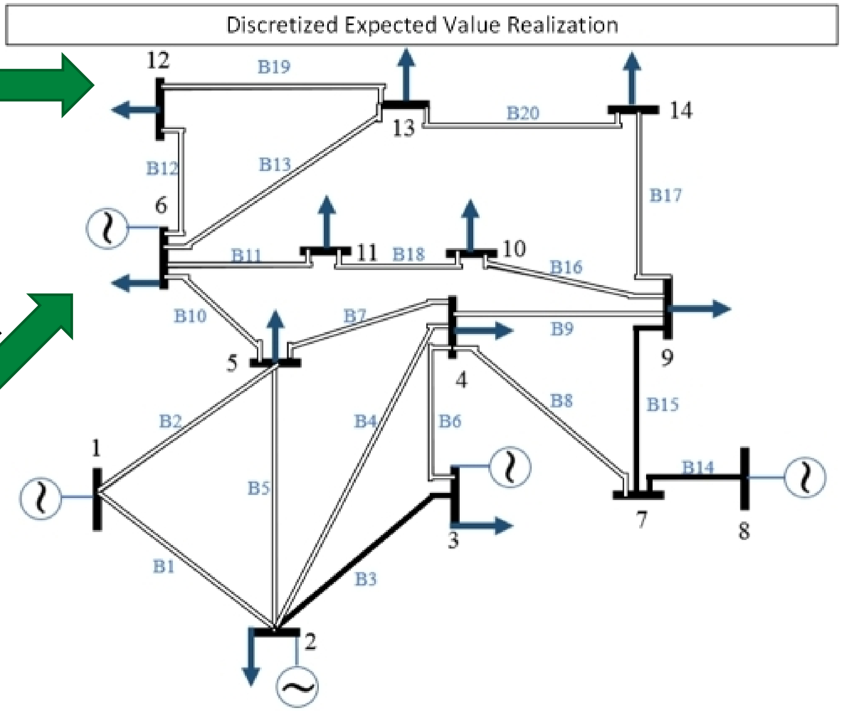
Distribution B: Center Set 2, $\gamma = 1/3$



95% CI for WS: [118.37, 121.96]

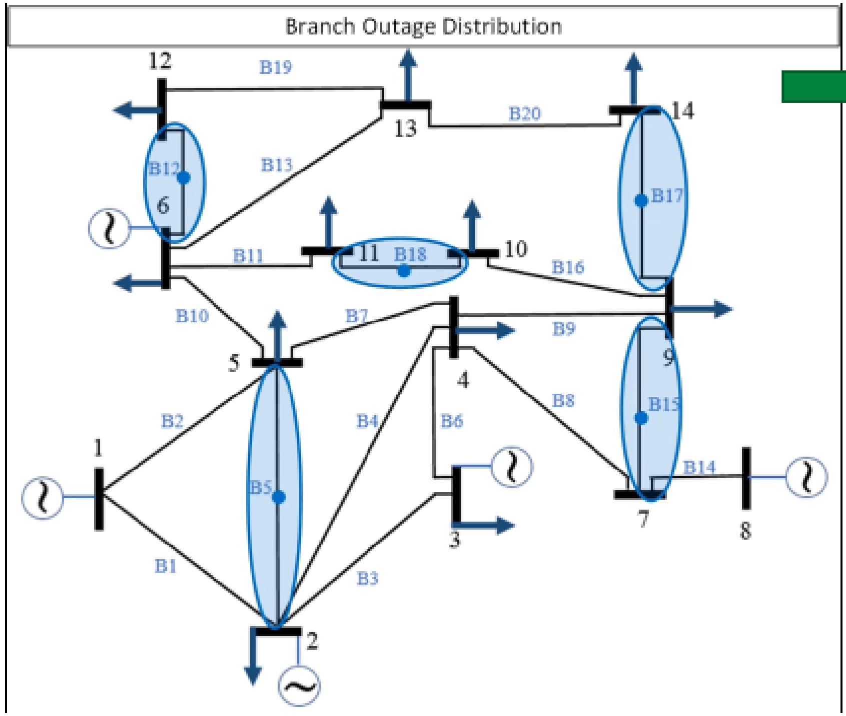


$\mathbf{1}^{\mathrm{T}} \boldsymbol{\mu} = \ldots = 0.00$



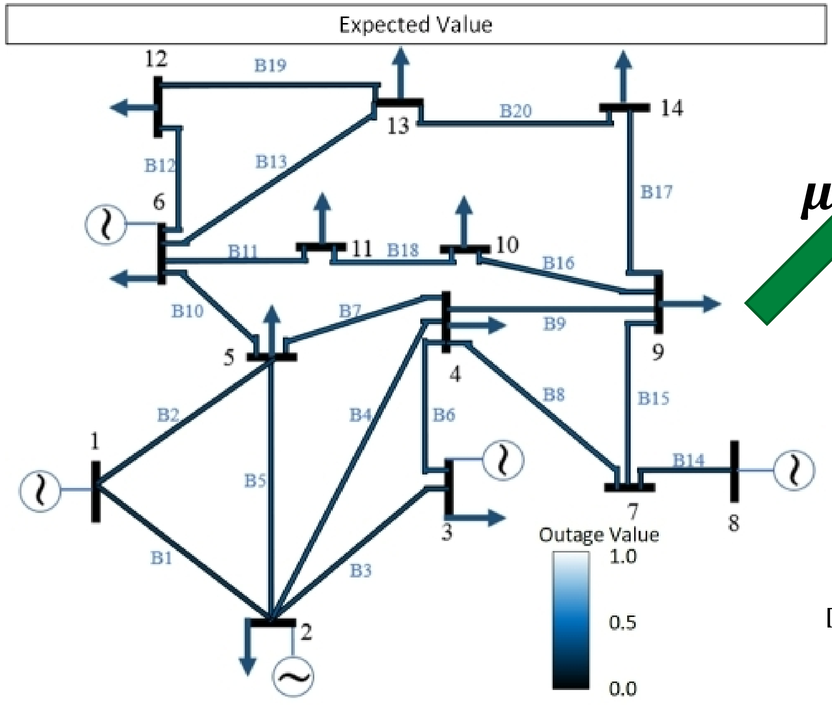
$\Gamma \quad \xi_{\mathrm{DEV}} \ldots = 113.60$

Distribution D: Center Set 1, $\gamma = 1/5$



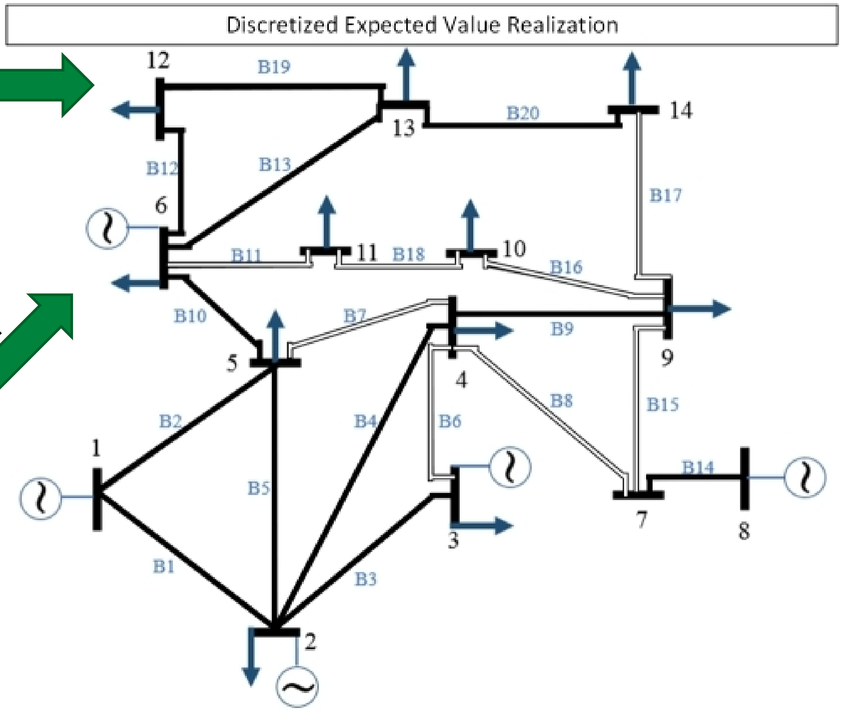
95% CI for WS: [38.45, 42.28]

WS



$\mathbf{1}^T \boldsymbol{\mu} = 7.53$ $EV = 0.00$

$\boldsymbol{\mu}$



$\Gamma(\xi_{\text{DEV}}) = 8$ $EV = 12.50$

Conclusion

- Developed stochastic MILP for pre-blackout placement of MES to assist BS restoration

- Observed that expected value problem may not work well for integer-valued uncertain parameters

- Devised concept of discretized expected value realization, which may lead to more effective first-stage decisions

Source: POWER Magazine

Thank you!

joshua.yip@utexas.edu