Emergency Asset Positioning for Resilient Transmission Grid Operation

IEEE PES General Meeting, Orlando, Florida, July 17, 2023

NREL/PO-2C00-86874

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Introduction

In this paper we study a problem of hurricane emergency preparedness via placement of emergency storage assets prior to its strike. We present a two-stage stochastic model for choosing locations and quantities of emergency storage to help support the power grid through a hurricane event. The expectation of losses in our two-stage model is estimated using the sample average approximation. We construct damage scenarios for sample average approximation using WIND Toolkit meteorological data and fragility curves of various electric grid components. We demonstrate the efficacy of our two-stage planning model by simulating operations during Hurricane Dolly on the 2000-bus transmission test system. Our model, coupled with our scenario selection strategy, is effective at mitigating loss of load when compared to a model without emergency storage assets placed prior to an extreme event.

Problem formulation

A two-stage stochastic program can be defined as follows:

$$\min_{\boldsymbol{x}} \; f(\boldsymbol{x}) + \mathbb{E}_{\boldsymbol{\gamma}}\left[L(\boldsymbol{x}, \boldsymbol{\gamma})\right] \quad \text{s.t.} \quad \boldsymbol{g}(\boldsymbol{x}) \leq \boldsymbol{0} \qquad (1)$$

where

$$L(\boldsymbol{x}, \boldsymbol{\gamma}) = \min_{\boldsymbol{y}} \; l(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{\gamma}) \quad \text{s.t.} \quad \boldsymbol{g}_{\boldsymbol{\gamma}}(\boldsymbol{x}, \boldsymbol{y}) \leq \boldsymbol{0}. \qquad (2)$$

First stage of our model is given by:

$$\min_{\boldsymbol{S}} \; \sum_{i \in \phi} C_i S_i + \mathbb{E}_{\boldsymbol{\gamma}}\left[L(\boldsymbol{S}, \boldsymbol{\gamma})\right] \qquad (3)$$

$$\text{s. t.} \quad S_i^{min} \leq S_i \leq S_i^{max} \quad \forall\, i \in \phi, \qquad (4)$$

Second stage of our model is given by:

$$L(\boldsymbol{S}, \boldsymbol{\gamma}) = \qquad (5)$$

$$\min_{\boldsymbol{x}, \boldsymbol{y}^{\pm}, \boldsymbol{\omega}, \boldsymbol{s}} \; \sum_{g \in G, t \in T} c_g x_g^t + \sum_{w \in W, t \in T} c_w \omega_w^t + \sum_{i \in \phi, t \in T} \left(c_i^{+} y_i^{t,+} + c_i^{-} y_i^{t,-}\right)$$

such that

$$x_g^{min} \leq x_g^t \leq x_g^{max} \quad \forall\, g \in G, t \in T \qquad (6)$$

$$R_g^{down} \leq x_g^t - x_g^{t-1} \leq R_g^{up} \quad \forall\, g \in G, t \in T \qquad (7)$$

$$0 \leq s_i^t \leq S_i \quad \forall\, i \in \phi, t \in T \qquad (8)$$

$$s_i^t = s_i^{t-1} - \frac{\Delta p_i^t}{\eta_i} \quad \forall\, i \in \phi, t \in T \qquad (9)$$

$$0 \leq p_i^t \leq p_i^{max} \quad \forall\, i \in \phi, t \in T \qquad (10)$$

$$0 \leq y_i^{t,\pm} \quad \forall\, i \in \phi, t \in T \qquad (11)$$

$$0 \leq \omega_w^t \leq \gamma_w^t \omega_w^{t,fcst} \quad \forall\, w \in W, t \in T \qquad (12)$$

$$p_i^t + \sum_{w \in W_i} \omega_w^t + \sum_{g \in G_i} x_g^t + \sum_{e \in \mathcal{E}_{in}(i)} f_e^t - \sum_{e \in \mathcal{E}_{out}(i)} f_e^t = \gamma_i^t d_i^t + y_i^{t,+} - y_i^{t,-} \quad \forall\, i \in \phi, t \in T \qquad (13)$$

$$\gamma_e^t \underline{F}_e \leq f_e^t \leq \gamma_e^t \overline{F}_e \quad \forall e \in \mathcal{E} \qquad (14)$$

$$\gamma_e^t \left(B_e\left(\theta_i^t - \theta_j^t\right) - f_e^t\right) = 0 \quad \forall e \in \mathcal{E}, t \in T. \qquad (15)$$

Scenario: Hurricane Dolly

Our working example includes the path of the Hurricane Dolly (Fig 1-2) over a week in July of 2008 and synthetic ACTIVSg 2000-bus grid [1]. Using NREL's WIND Toolkit data [2] and fragility curve methodology [3,4] we generate damage scenarios to transmission lines (Fig 3), substations (Fig 4), and wind plants (Fig 5). Most of the damages occur within the first 8 hours of hurricane landing.

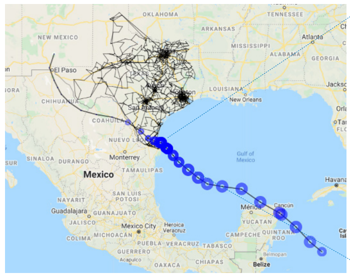

Figure 1: Path of the Hurricane Dolly (July 20 -27) and synthetic ACTIVSg 2000 bus transmission grid. Size of the blue circles corresponds to hurricane's radii and their color intensity correspond to maximum wind speed.

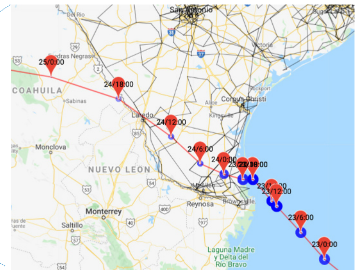

Figure 2: Landing and overland period: July 23, 00:00 – July 25, 00:00
Most damage occurs during 8-hour period: July 23, 18:00 – July 24, 02:00

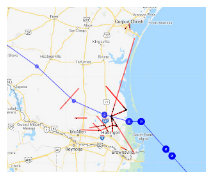

Figure 3: Realization when max number of branches were damaged. Damaged lines (red lines) and damaged poles (black dots)

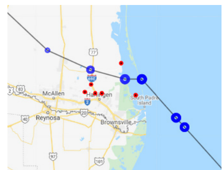

Figure 4: A realization when max number of substations (6) were damaged

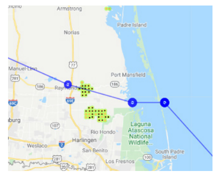

Figure 5: 3 wind plants (heat map) composed of individual wind sites (eight 2-MW turbines per site). Most wind sites had at least one damaged turbine (black dots).

Asset placement and operation

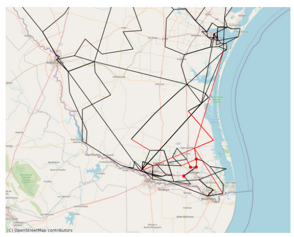

Figure 5: Battery placement decision under scenarios 6-10.

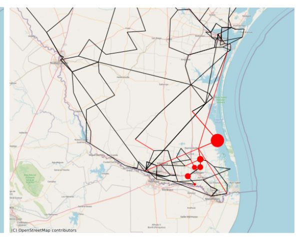

Figure 6: Battery placement decisions under scenarios 1-5

Using two different uncertainty sets results in different battery placement decisions. Damage scenarios 6-10 result in battery placement shown in Fig 5, while scenarios 1-5 result in placement decisions shown in Fig 6.

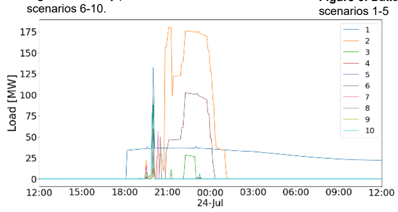

Figure 7: Loss of load without batteries in each of the 10 scenarios

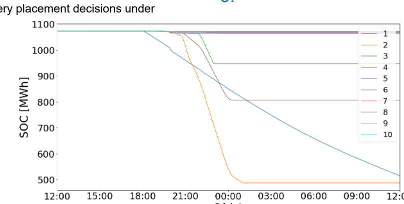

Figure 8: State of charge of large case emergency batteries in operation simulation under each of 10 scenarios.

Scen	Damaged branch #	Damaged substations	Islanded load buses	Loss of load		
				None	Small	Large
1	13	4089, 4111, 4186	4191	557	548	0
2	14	4111, 4186	4191, 4186	584	481	0
3	11	4191	None	30	5	0
4	10	4191	4191	1	0	0
5	12	4191	4191	3	0	0
6	14	4089, 4186, 4191	4191	252	158	0
7	14	4067, 4111, 4186, 4191	4191	7	0	0
8	11	4186, 4191	4191	6	0	0
9	12	4067, 4089, 4167, 4186, 4191	None	2	0	0
10	11	4191	None	9	0	0

Table 1: Summary of elements damaged and load lost in the simulations for each scenario. Branch column gives the total number of branches damaged, while substation and islanded bus columns show bus numbers (names) given in the network description.

In our experiments, we chose a planning horizon of 4 hours broken into 8 half-hour steps. This horizon is chosen to cover the time window of maximum damage caused by Dolly's landfall. Ten scenarios represent the uncertainty for the planning problem (Table 1). Loss of load without batteries is shown in Fig 7 and battery discharge is shown in Fig 8. Simulated transmission grid operations with planned storage show reduced amounts of load lost due to infrastructure damage caused by the hurricane.

Future work includes extending formulation to include other emergency assets, using larger uncertainty sets, and applying our method to other emergencies (e.g., flood or polar vortex).

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the Department of Energy's Exascale Computing Project and the Laboratory Directed Research and Development (LDRD) Program at NREL. A portion of this research was performed using computational resources sponsored by the Department of Energy's Office of Energy Efficiency and Renewable Energy and located at the National Renewable Energy Laboratory. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes. This research was supported by the Exascale Computing Project (17-SC-20-SC), a joint project of the U.S. Department of Energy's Office of Science and National Nuclear Security Administration, responsible for delivering a capable exascale ecosystem, including software, applications, and hardware technology, to support the nation's exascale computing imperative. NREL/PO-2C00-86874

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