Impact of Initial Stressor(s) on Cascading Failures in Power Grids

Rezoan A. Shuvro , Pankaz Das , Zhuoyao Wang , Mahshid Rahnamay-Naeini[y], and Majeed M. Hayat [z]

Fig. 1: Gaussian, circular and linear attacks mapped into a 2-D topological space. Failures in the power grid depends on the intensity of the stressor(s). Initial transmission line failures in the power grid calculated after an attack is simulated [1].

failures in the power grid based on interdependent system environment. A data-driven model for simulating the evolution of transmission line failure in power grids is proposed in [17]. Although failures in the communication layer and human operator responses are crucial in cascading failure analysis, we ignored their effects in this paper to simplify our analysis. Bernstein *et. al.* analyzed the power grid vulnerability due to geographically correlated failures in [3]. Impacts of operating characteristics on the sensitivity of the power grids to cascading failures are studied in [18]. In [19], the authors studied the impact of topology in power grids. In [1], the authors analyze the impact of various initial failures on physical infrastructures (e.g., communication networks).

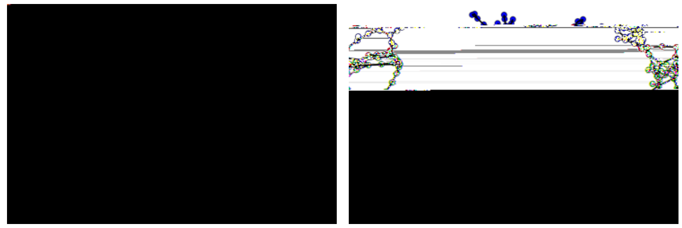
In recent years, researchers contributed significantly to model the cascading failures in power grid. To the best of our knowledge, most of the works done on the probabilistic modeling of cascading failures consider arbitrary initial failures and then focus on modeling the propagation of failures. However, fewer efforts are made to observe the impact of various initial conditions that lead to cascading failures, which is the crucial contribution of this paper. We map the intensity of stressor(s) events with failures in the power grid. No notable extensive analysis has been done to show the correlation between the status of power-grid parameters during an initial stressor(s) event and failures in the power grid that leads to cascading failures. Our work can map the correlation between an initial stressor event and cascading failures in the power grid; thus, this work can investigate cascading failure behavior of the power grid more realistically compared to other works.

III. Modeling the Initial Failures Due to the Stressor(s) and Impact of Stressor(s) on Cascading Failures in Power Grid

In this section, we map the initial transmission line failures in the power grid with stressor intensities.

A. Modeling the initial failures due to stressor(s)

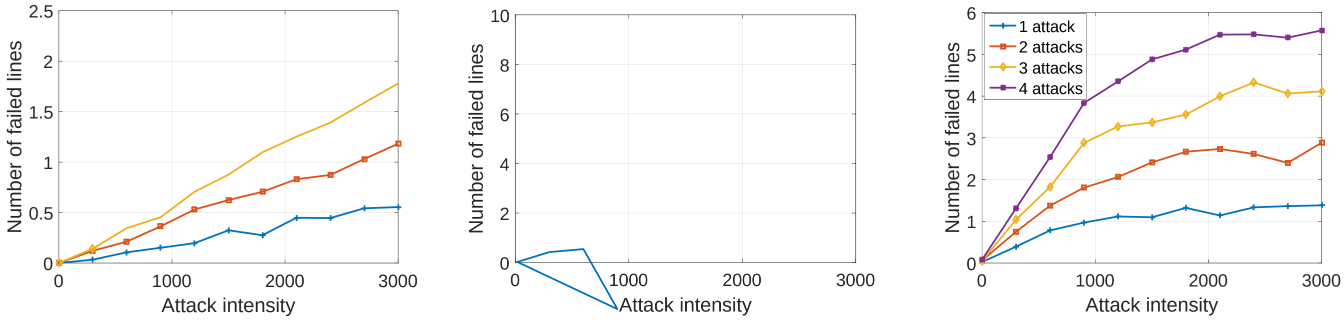
Multiple stressor(s) can occur in one geographical location, or they can spread over different geographical areas. These stressor(s) events can range from natural disasters (e.g., tornado, cyclone, earthquake) to intentional human-made attacks (e.g., use of weapons of mass destruction (WMDs), High



(a) IEEE 118-bus topology (b) IEEE 300-bus topology

Fig. 2: IEEE 118-bus and 300-bus topology

altitude electromagnetic pulses (HEMPs), cyber-attack in the communication layer of the power grid. These events can lead to initial disturbances in the power grid which may include the transmission line failures, generator loss or failures in the communication system. These initial failures can act as a trigger for initiating cascading failures in the power grid. In this paper, we have used spatially-homogeneous stressor(s) centers, which enables us to model multiple stressor(s) events at the same time. The spread of these stressor(s) can vary depending on the intensity of the stressor(s). We use Gaussian, circular and linear degradation functions, which can reasonably characterize various real-world stressor(s) [1]. The intensity of the Gaussian stressor degrades according to the Gaussian function as the spatial distance from the location of occurrence increases. The intensity of the function has the peak at the mean of the degradation function. Two parameters entirely describe a circular degradation function: radius of the circle (r) and the intensity of the stressor at the center (I). The main difference between a Gaussian and a circular stressor is in their degradation function. For a Gaussian stressor, the intensity of the stressor asonably



(a) For Gaussian stressor(s)

(b) For circular stressor(s)

(c) For linear stressor(s)

Fig. 3: Average number of failed transmission lines in IEEE 118-bus topology due to to Gaussian, circular and linear stressor(s) with various intensities.

be infinity large, i.e., the distance between two adjacent points can be close to zero) and measure the stressor intensity at those points after the occurrence of a stressor event. We then take the maximum intensity calculated in those N points. We assume that if the maximum intensity at any point over the line crosses a certain threshold, then the line will fail. Here, we assume N to be sufficiently large. An alternative approach of calculating the maximum stressor intensity on a transmission line can be to calculate the minimum distance between the transmission line and the stressor center. Since the stressor intensity degrades over distance, it is intuitive that minimum distance from the stressor center would result in maximum intensity; with the peak intensity being at the center of the stressor(s). Hence, the maximum stressor intensity on a transmission line would be inversely proportional to the minimum distance between the transmission line and the stressor center. For a single stressor event occurred in a geographical location, we define the failure probability of a transmission line as:

$$p((B_i, B_j)|W = w) = \min\left(\max_{k \in 1,\ldots,N} I_w(x_k, y_k), 1\right), \quad (1)$$

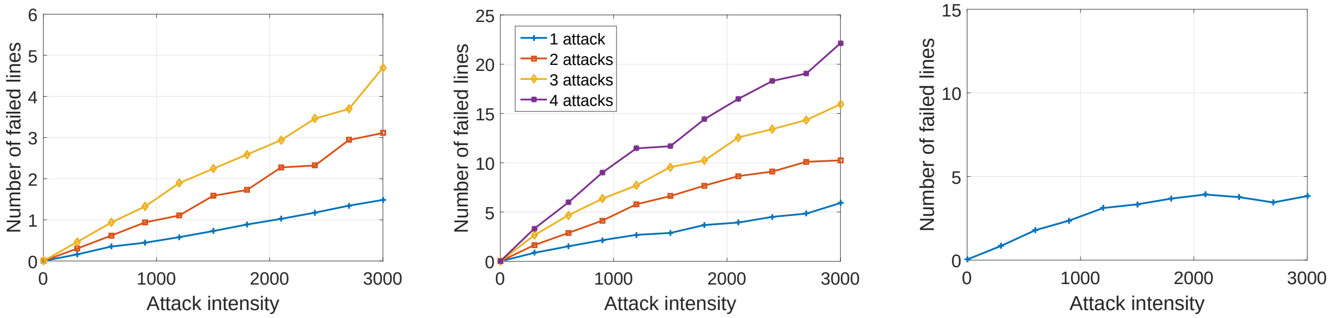
where $p((B_i, B_j)|W = w)$ denotes the failure probability of a transmission line of the power grid, (B_i, B_j) is the transmission line from B_ith bus to B_jth bus, and (x_k, y_k) is the location of the kth point on (B_i, B_j). For multiple stressor events occurring at the same time, the total stressor intensity at (x_k, y_k) is

$$p((B_i, B_j)|W = (w_1, \ldots, w_L)) = \min\left(\sum_{i=1}^{L} \max_{k \in 1,\ldots,N} I_{w_i}(x_k, y_k)), 1\right), \quad (2)$$

where L denotes the number of stressors.

We calculate the total number of failed transmission lines in the power grid due to the occurrence of the stressor(s) using the measured individual transmission line probability. Similarly, we can calculate the bus (node) failure probability due to multiple stressor events using the following equation

$$p((B_i)|W = (w_1, \ldots, w_L)) =$$
$$\min\left(\sum_{i=1} I_{w_i}(x_k, y\right.$$
line due



(a) For Gaussian stressor(s) (b) For circular stressor(s) (c) For linear stressor(s)

Fig. 4: Average number of failed transmission lines in IEEE 300-bus topology due to to Gaussian, circular and linear stressor(s) with various intensities.

system. From Fig. 3 and Fig. 4, it is visible that with same stressor intensity, circular stressor creates the worst impact on the both the IEEE 118-bus and IEEE 300-bus topology. On the contrary, Gaussian stressor has the least impact since Gaussian stressor(s) intensities decay at a faster rate ($e^{\;d^2}$)compared to a circular stressor(s) which degrades with $1{=}d^2$ where $d < r$.

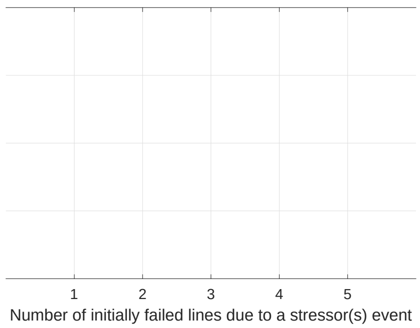


Fig. 5: Number of failed transmission lines when one stressor location with multiple failures (blue) and considering randomly distributed failed transmission lines (green) where a stressor event contribute one transmission- line failure (we pick the line with maximum intensity to fail).

Fig. 6: Number of cascading failure event in power grid with different number of attack points and number of transmission line failures.

failure in power grid.

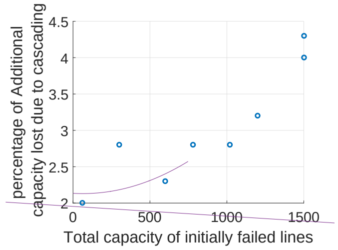
Figure 6 shows the simulation result for attacks with multiple transmission line failures. We can see that for the same number of transmission line failures, if we increase the number of attack points, power grid becomes more cascade-prone than the previous case. Here, in Fig. 6, we use linear curve fitting (blue, red, green, and orange lines represent various stressor(s)) to show the impact of inhibition clearly.

IV. Impact of Initial Failures Due to a Dtressor Event in Cascading Failures

We now apply our initial failure model in MATPOWER OPF simulator to calculate the impact of stressor(s) events on cascading failures in power grid. Simulations using the other IEEE topologies follow the same pattern.

A. Impact of number of failed transmission lines and capacity of the failed transmission lines

We define percentage of additional transmission lines lost due to the cascading failures as $_M=(M \quad M_{initial})$, where $_M$ = additional transmission lines lost due to cascading; M = total transmission lines of the power grid; $M_{initial}$ = number of transmission lines failed due to initial event. Similarly, percentage of additional capacity lost due to the cascading failures as $_C=(C_{total} \quad C_{initial})$, where $_C$ = additional capacity lost due to the cascading; C_{total} = total capacity of the power grid; $C_{initial}$ = total capacity of the initially failed lines. Figure 7 represents the impact of various initially failed transmission lines of fixed total capacity and the total capacity of the failed transmission line during an initial event using OPF simulations. In Fig. 7(a), we keep the total capacity of the failed lines as constant and then increase the number of failed transmission lines. We take randomly distributed line failures for 1000 samples in each case. These initial line failures are generated using random stressor events over the IEEE 118-bus topology. Our simulation results suggest that, if the total capacity of the failed lines is fixed, increase in the number of line failures makes the power grid more cascade-prone. In



(a) varying number of initially failed lines (b) varying total capacity of the initially failed lines

Fig. 7: Relationship between number of initially failed transmission line due to a stressor event with percentage of additionally failed lines due to cascading when the total capacity of the failed transmission lines are fixed, and the total capacity of the initially failed transmission lines with additional capacity lost due to cascading when the number of the failed transmission lines are fixed.

300-bus topology. Our simulations suggest that the number of initially failed transmission lines are linearly proportional with attack intensity. We observe that cascading failures in