Role of Power System Relays in a Large Scale Physical Attack

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***Abstract*—In this paper we analyze the response of the electric power grid to a hypothetical nuclear attack inside a major city in the US. We assume that the protective devices of the power system located within a given distance of the attack will be affected by the resulting radiation and hence will not work. A probabilistic examination of the resulting power surges indicates that, if left unchecked, the surges can propagate to large distances. However, by protecting the protection system suitably, the effects can be minimized considerably.**

***Index Terms*—Electromagnetic pulse (EMP), Improvised nuclear device (IND), Power system, Protection devices, Relays.**

I. Introduction

The electric power system is one of the most critical infrastructures of modern cities. It plays a crucial role in supporting rescue and recovery operations in the event of large-scale disasters inside the city. We analyze the protection afforded by the power system's protective relays in a National Planning Scenario (NPS1) described by Bos et al. [1]. In this scenario, a hypothetical improvised nuclear device explodes inside Washington DC

Cascading failures in power systems have been studied previously in the literature [2]-[5]. The difference between this scenario and the ones studied previously is that this attack is directed towards the human populace of the city and is meant to cause immense physical damage to the city's built infrastructure. Under such circumstances, the role of the electric power grid becomes very critical because most of the other infrastructures depend on it for their successful operation. Hence, the resiliency of the power grid under such conditions must be high.

The effects of such wide-spread failures on the infrastructures, as well as on the population, depend significantly on individual behavior. An example of this is that although people would be advised to shelter-in-place [6], many people would not comply, preferring to search for their family members and friends. They would try to use their phones and/or other means of communication. Since operating the cellular towers, for instance, would require power supply, it is important to understand where the electric grid *would* and *would not* be able to provide the desired support.

In our previous research on the NPS1 topic, we developed a *model* that draws out the connections between spatial variations in population behaviors and the resulting outcomes [7]. The importance of the communication network in altering the behavior of the population was highlighted in [8]. An assessment of the cost of damage to the major components of the power infrastructure in the aftermath of such an attack was made in [9]. The importance of performing a transient stability analysis in comparison to a steady-state analysis was stressed in [10]. In this paper, by comparing our results with those obtained in [10], we show how the behavior of the power system's protection devices can alter the final outcome.

The rest of the paper is structured as follows. Section II gives an overview of the scenario that was simulated in this study. Our probabilistic analysis of the power surges that spread from the affected area into the rest of the electric grid is explained in Section III. The results of this analysis are described in Section IV and the conclusion is provided in Section V.

II. Overview of Attack Scenario

The Washington DC power grid is located in the East-Central region of the Eastern Interconnection (EI) [11]. The model of the power system used in our study had 54,740 buses, 51,780 transmission lines, 6,290 generators and 32,780 loads. Power to the city is provided by two utilities. The city has a generation capacity of approximately 700 MW while the total load of the city and its immediate vicinity is around 2800 MW. Therefore, the city imports 2100 MW from the generating substations that are located near it. Fig. 1 shows the influx of power into the city before the initiating event occurs. It is important to highlight here that Washington DC is only used as an example of a modern city. The analysis done here is general and can be applied to any modern city that has similar characteristics (small in-house generation, more power supplied from outside, multiple sources for sending power into the city, etc.).

The initiating event is a hypothetical ground burst of a 10KT improvised nuclear device (IND) on a weekday morning in downtown Washington DC. The IND blast causes complete destruction within a 0.6 mile radius of the epicenter, and partial destruction up to a certain distance (see green line

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in Fig. 2) mainly due to the emitted electromagnetic pulse (EMP). The damage to the power system can be quantified in terms of physical destruction of lines, generators, substation equipments, and loads. The areas in Fig. 2 were identified by studying the typical physical impacts of an IND such as blast wave, radiation, and thermal effects, as well as geographical factors such as weather patterns and urban canyons.

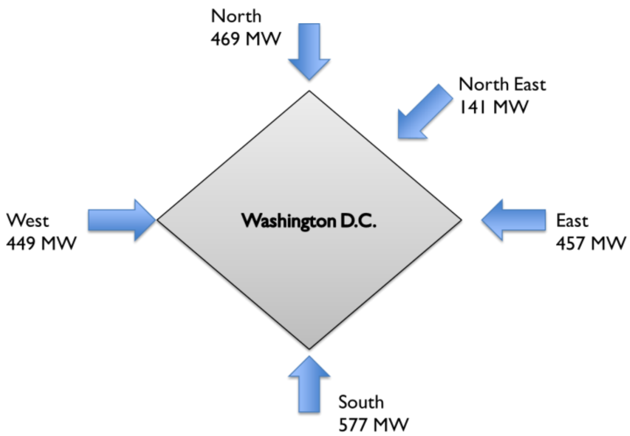

Fig. 1. Pre-blast power flow entering Washington DC

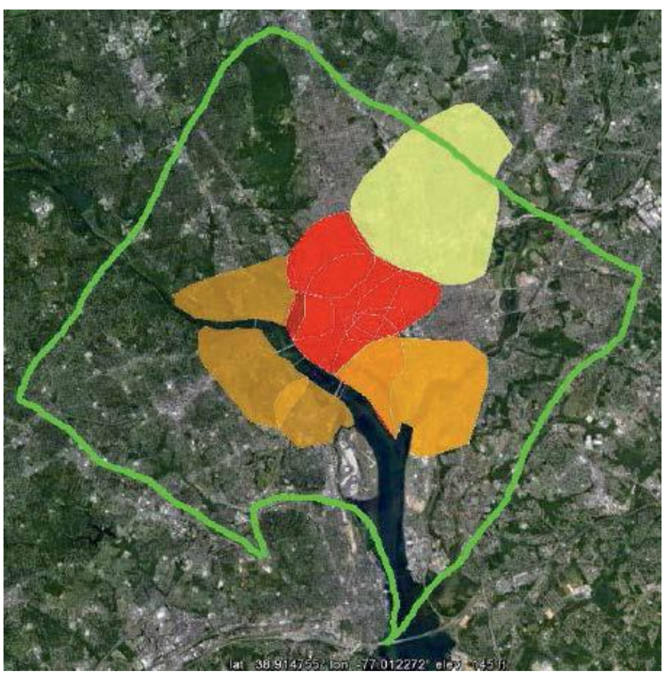

Fig. 2. Map of Washington DC (green contour) showing the likelihood of the damage due to the blast. The area in red depicts the damage zone where the probability of damage is 80-100%; the area in orange depicts the damage zone where the probability of damage is 40-80%; and the area in yellow depicts the damage zone where the probability of damage is 10-40%. The rest of the area inside the green boundary is assumed to have less than 10% damage probability. This figure was originally published in [9].

It is safe to assume that all six substations in the red area will be immediately completely destroyed by the blast. From a simulation perspective, this is equivalent to creating a three-phase bus-fault on all those buses. The corresponding loss in load is approximately 1400 MW. This scenario is identical to the one simulated in [10]. However, in [10] it was assumed that the protection devices are immune to the effects of the blast. Here we take into account likely damage to relays due to the associated EMP [12]. Under such circumstances, the faulty part of the system (six substations) will not immediately separate from the rest of the system and a scenario different from the one described in [10] will result.

In this study, we assume that relays located inside the green boundary of Fig. 2 are non-functional. The relays that lie outside the green boundary area are assumed to operate correctly and isolate the faulty part of the system from the healthy part. However, the relays outside the green contour are typically operated under a Zone 3 scheme. Zone 3 is the *remote* back-up protection scheme that clears the fault in case the primary protection scheme (Zone 1) and the *main* back-up protection scheme (Zone 2) fail to clear the fault. However, because of the nature of a Zone 3 operation, a larger area is affected [13]. For the case under study, the red, orange and part of the yellow areas go out-of-service, instead of just the red area. This results in a total loss of load of approximately 2400 MW. Moreover, there is a slight delay in the operation of Zone 3 (the industry accepted value is one second). During this delay, the fault continues to get fed from the rest of the system. Therefore, when the relays *do* operate, a significant redistribution of power occurs around them. For the given case, this can be thought of as a wave/power surge that originates from the green boundary of Fig. 2 and proceeds outwards into the rest of the grid. The next section analyzes the characteristics of these waves using probability theory.

III. Probabilistic Analysis of the Resulting Waves

The power surge that originates from the green boundary of Fig. 2 can be thought of as a wave that can *hit* the different components of the power grid located outside the boundary. The following are some of the propagation and stopping criteria that were identified for these waves. Apart from the initial impact of the blast, the factor that had the most effect on the propagation of the wave into the grid was the presence of massive generators. Since these machines have high inertias, they are slow to speed up, which allows them to pass the power surge along to other parts of the system. Moreover, these machines are typically firmly connected to the rest of the system. This means that even if a power surge comes along one of its branches, it has other branches through which it can let the power surge pass almost without inhibition.

The factors that aided most in stopping the wave were: (a) small/loosely connected machines; (b) low voltage buses; and (c) buses with high connectivity. Small machines typically have low inertias and therefore can speed up or slow down faster than the large machines. Hence, if the disturbance is within its capacity limits, a smaller machine will be able to absorb it and continue functioning. Similarly, if the machine is located at the radial end of a line, it may not be connected to any other portion of the system. In that case, it will have no choice but to absorb the power surge. In case the excess power is more than the absorption capacity of the machine, it will cause the machine to trip. This will then result in loss of generation, which will compensate for the loss of load that has occurred due to the attack. Many load buses have low voltage magnitudes in their normal state. When such buses receive excess power from a power surge their voltage magnitudes rise. However, since the voltage magnitude values of these buses were low to start with, they have a high buffer/capacity to absorb the power surge. Finally, buses with high connectivity have links to many other buses. Because of this they can redistribute the power surge to the downstream buses without letting them feel the full impact of the surge. As a rule of thumb, buses with more than 5 connections were found to be the ones that could do this effectively.

The probability of a line getting affected by the power surge is calculated as follows. It is initially assumed that the likelihood of a particular line failing is a function of only the power flowing in that line. This makes sense because the only factor that can affect the line is the power that is flowing through it. Now, if the maximum change in power flow occurring in the i^{th} line is given by (Δf_i) and if its pre-blast steady-state power flow is given by $\left(f_{steady_i}\right)$, then the probability of failure of that line (taking into account only the power flowing in the line) is given by (1).

$$p_{f_i} = \frac{\Delta f_i}{f_{steady_i}} \tag{1}$$

However, this is not the overall probability that the line fails, because it does not take into account what happens to "upstream" lines. The probability that a line overloads depends on whether upstream elements survive the surge. Mathematically, this implies that the probability the surge propagates to the second line in the sequence is given by (2).

$$P_{f_2} = \left(1 - p_{f_1}\right) p_{f_2} \tag{2}$$

Now, as the probabilities of the lines located downstream depend on the failure of upstream lines, the *overall* probability of the $(n+1)^{th}$ line failing is given by (3).

$$P_{f_{n+1}} = \left(\prod_{i=1}^{i=n} \left(1 - p_{f_i}\right)\right) \times p_{f_{n+1}} \tag{3}$$

The analysis is slightly different for generating units, because generators may trip if the power surge exceeds their limits. The probability that the surge affects lines that are beyond the generators must take into account the probability of the upstream generators tripping. Accordingly, the *overall* probability that the j^{th} line overloads where it is located beyond a generator having m units is given by (4).

$$P_{f_j} = \left(\prod_{i=1}^{i=m} \left(1 - p_{f_i}\right)\right) \times p_{f_j} \tag{4}$$

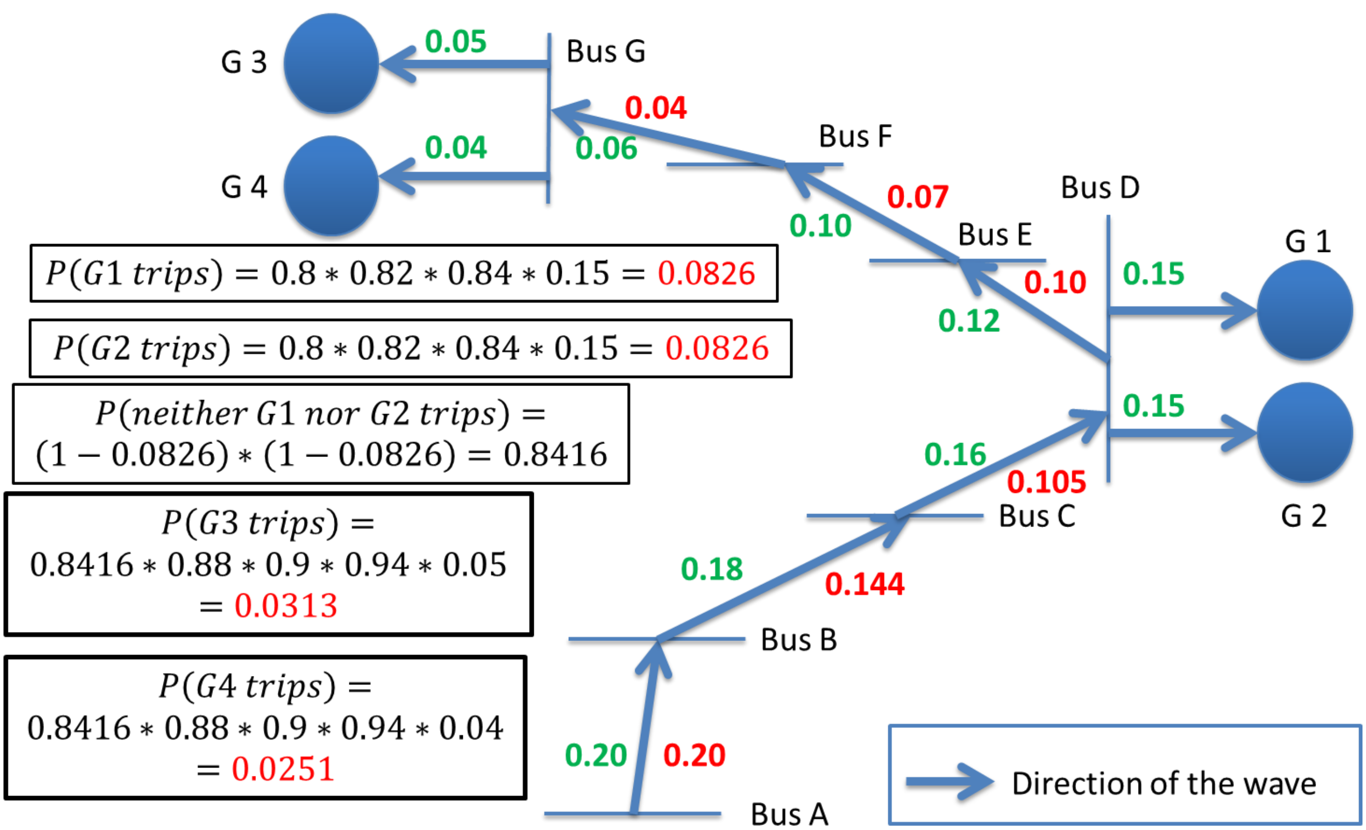

Fig. 3. Example depicting the failure probability calculations. The numbers in green denote individual failure probabilities while the ones in red denote overall failure probabilities. The arrows indicate the direction of the power surge.

An example describing the calculation on the basis of the probabilistic theory outlined above is provided in Fig. 3. In the figure, bus A is the first bus that faces the power surge. The arrow shows the direction of the power surge. The values in green denote the individual failure probabilities of the lines computed using (1), whereas the values in red denote the overall failure probability computed using (3) for lines or (4) for generators. Buses D and G are generator buses with each of them having two generating units G_1 and G_2 and G_3 and G_4 connected to them, respectively. From the figure it becomes clear that although the individual line failure probabilities depend on the line itself, the overall failure probability of a line depends on the lines that come before it. The results of the probabilistic analysis for Washington DC are described in the next section.

IV. Results

In our simulations, the blast occurs at $t = 1$ second while the system is in steady-state between $t = 0$ and $t = 1$. The Zone 3 operation was assumed to occur after a delay of 1 second (industry standard), i.e. at $t = 2$. Since a large number of lines were found to have changes in their flows after the attack, only the lines which had *significant* changes were selected for this analysis. A significant change was quantified as a flow change of more than 100 MVA from its steady-state value during the length of the simulation. The simulation was run for a total of 10 seconds in PSS/E using the Python programming language.

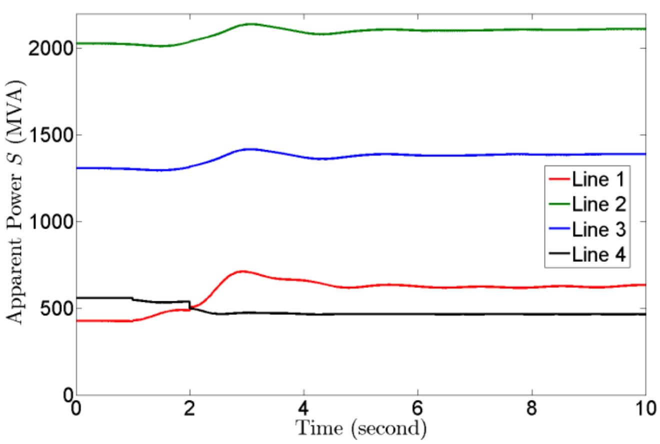

Fig. 4. Examples of the power flow redistribution in four lines before and after the blast. Line 4 is closest to the green boundary of Washington DC, while Line 1 is located a few lines away from Line 4. Line 3 and Line 2 are located far away from the green boundary.

Fig. 4 shows the power surge occurring in four out of the 196 lines that were found to have significant changes in power flows. Here, the term *line* denotes transmission lines as well as transformers. Line 4 is located very close to the green boundary and Line 1 is located a few lines away from Line 4. From the figure it becomes clear that the surges in power occur between $2 < t < 3$ for Line 4, while the surge occurs almost at $t = 3$ for Line 1. This shows the effect of proximity on the propagation of the power surge. From the plots it also becomes clear that the power surge causes sharp transitions in the lines that are close by in comparison to the ones that are far away. As an example of this, Line 3 and Line 2 do not experience sharp power flow change during the length of the simulation because they are located far away from the green boundary of Fig. 2.

All the 196 lines that were identified with significant changes in power flows could be grouped under three waves that appear from the damaged area and propagate into the EI. The description of the waves is provided below.

Wave 1 had its origin in the Southwest region of Washington DC and continued in that direction into the neighboring utility. There were 14 generators that were affected by this wave. The peaks of the overall failure probabilities of this power redistribution wave on 13 of the affected generators were in the range of 1-4% with one generator getting affected by 5.6%. The generators closer to the source (epicenter of the attack) were found to have higher probabilities.

Wave 2 had two starting buses indicating that power redistribution from two independent *sources/paths* affect the downstream buses. Although originating from the Southeast region of Washington DC, this wave proceeded to affect the buses which lay in the North. This shows that for a general city and power system, it is the electrical connections that define the affected regions and not geographical proximity. Although 8 generators were affected by the power redistribution occurring due to this wave, the peaks of the overall failure probabilities for all of them were below 1%

Wave 3 was the largest of the three waves originating from the Northwest region of Washington DC and spreading into multiple utilities across different states. It had three originating sources. There were 35 generators that were affected by this wave. Overall failure probability peaks of thirteen generators were found to be less than 1%; seventeen generators had peaks that lay in the range of 1-4%, while five generators had peak probabilities that lay between 6% and 9%.

The two inferences drawn from this analysis are: (1) Electrical connectivity (and not geographical proximity) defines the flow of surge; (2) Safety of the protection devices (relays) is critical in protecting the power system. This is because if the relays work perfectly and isolate the minimum number of buses that will separate the faulty part from the healthy part of the system, then the scenario will become identical to the one considered in [10] where there were no surges/waves created.

V. Conclusion and Future Work

In this paper, we studied the dynamical response of the electric power grid to a large disaster inside a major city. We take into consideration the fact that the protection devices in a certain area may be damaged. Consequently, the disturbance in the power flow is made to trigger the relays to operate under Zone 3 and isolate a large area from the rest of the power grid. From our simulations, we observed that in the city of Washington DC, the power surge occurs as three waves that emanate out into the rest of the grid. Although this surge causes a major redistribution of power flows in the neighboring lines, there is no cascading failure leading to a large-scale blackout. To quantify the effect of the power surge, we introduced a probabilistic model to evaluate the vulnerability of the generators that are located in the paths of the three waves. We identified some of the generators that are located close to the boundary of the city and are more vulnerable than others. In addition, we found that transmission lines located close to the boundary experience sharp power flow transitions due to the blast and due to the operation of Zone 3, while transmission lines located far away from the boundary experience a smoother change in their power flows with fewer oscillations.

In our future work, we will extend the current deterministic relay-failure model to a stochastic one by assuming imperfect operations of the protective relays that follow a given probability of malfunction. The power flow of the transmission lines that experience the power surge may increase and become close to the thermal limit of the transmission line causing the relay to trip the line even if the surge is not harmful. This will also be incorporated in future analyses. Finally, we will simulate the same scenario in different metropolitan areas to study the vulnerability of the power grid to such an attack and to understand the difference in outcomes.

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