Wartime Powerflow Simulation Saves Potential Load Shed in Ukraine

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Executive Summary

This simulation is a rough estimate of the kind of calculations that would actually need to be done to protect Ukraines energy infrastructure during wartime. Given this simulation has plenty of limitations and is not indicative of real world events, the goal of this simulation is to have as little Ukrainian load shed as possible given a Russian attack on energy infrastructure. The attacker in this simulation can attack one to six times. We are allowed to place a number of defenses equal to four times the number of attacks. In this paper, we will explain multiple methods we used to strategically place those defenses and reduce load shed as well as explain why reducing load shed is a priority for the Ukrainian people in the first place.

Our first method uses the apparent power of each line to quantify its importance. It then uses an attack simulation to find the lines most likely to be targeted, and places a defense on the one with the most apparent power flowing on it. Given four Russian attacks, this method was able to reduce load shed from 28.82% with no defenses to 11.44% with sixteen defenses.

Our second method, The probabilistic contingency method, takes a more complicated approach. This method runs an attack simulation and analyzes the attacks N-3 and N-4 contingency scenarios. Looking at these two contingencies helps compensate for the possibility that an attack fails. If a line is a part of both the N-3 and N-4 contingency, it is given a defense. Simulation and addition of defenses is repeated until all defenses are placed. Given four Russian attacks, this method was able to reduce load shed from 28.82% with no defenses to 11.28% with sixteen defenses.

Ukrainian Energy Crisis

Ukraine has been at war with the Russian Federation since 2014 following Russia's annexation of the Ukrainian owned peninsula Crimea. In the years leading up to recent events, there have been numerous naval incidents, cyber attacks, and high political tensions between the two countries. However in 2021 Russia began building a large military force on the Ukrainian border. This force would eventually lead to a full scale invasion of Ukraine in February 2022. The resulting all out war has caused tens of thousands of deaths and has no end in sight. [1]

On October 10th 2022, Russia aimed its air strikes at civilian infrastructure, mainly the power grid, and they have not stopped yet. Instead of targeting military and government buildings as they have in the past, Russia now has its sights on Ukrainian power generation, power transmission, substations, and heating plants. These attacks have led to hundreds of civilian deaths, and left millions more without power and heat.[2]

At times, more than half of Ukraines power generation has been offline, and they are relying more and more on energy from neighboring countries. [3] Russia knows just how important energy is for the people of Ukraine, and not just the Ukrainian military, and their attacks on the energy infrastructure puts massive pressure on Ukraine as a whole. The worst part is that the approaching winter will kill thousands of civilians if they go without power. Even The World Health Organization’s Europe director stated that due to a lack in health care, water, and energy, this winter “will be about survival”.[3] This December, the average temperature in Ukraine is expected to be 25 degrees Fahrenheit, with January expected to be around 30 degrees Fahrenheit. [4]

This is why the energy grid is a top priority for Ukraine. They need to work as hard and as smart as they can to conserve as much of their infrastructure as possible and reduce the total load shed. Most likely, the Ukrainian energy experts would use a simulation much like this one to figure out which components of their grid are the most important. With their limited resources, they need to be as efficient as possible to save the most lives. Their simulations, while much more realistic than ours, are the first steps to solving this problem.

Summary of Defense Models

Apparent Power Method

This method was predicated on the assumption that the lines carrying the most apparent power were the most important to defend. To quantify the power on each line, the apparent power was calculated for power injection to a bus, and from a bus. Then, the greater of the two apparent powers was used to define the power on each line.

Next, an attack simulation is evaluated for each defense there is to place. On the first iteration, there are zero defenses present, and an attack simulation is ran to see which lines the Russian attack is most apt to hit. Out of those lines, the line with the highest apparent power is given a defense.

Then, the next attack simulation is ran with the single defense that was last placed. Out of the lines that russian attack is most apt to hit, the one with the greatest apparent power is given a defense. This loop continues for an amount of iterations equal to four times the number of allowed attacks, with a defense being placed on each iteration.

After the final defense is placed, the last attack simulation is evaluated to calculate the expected load shed given the final placement of defenses. For this method, Ukraine experiences the following load shed:

Attacks	Expected Load Shed
1	3.262%
2	6.82%
3	9.17%
4	11.44%
5	12.32%

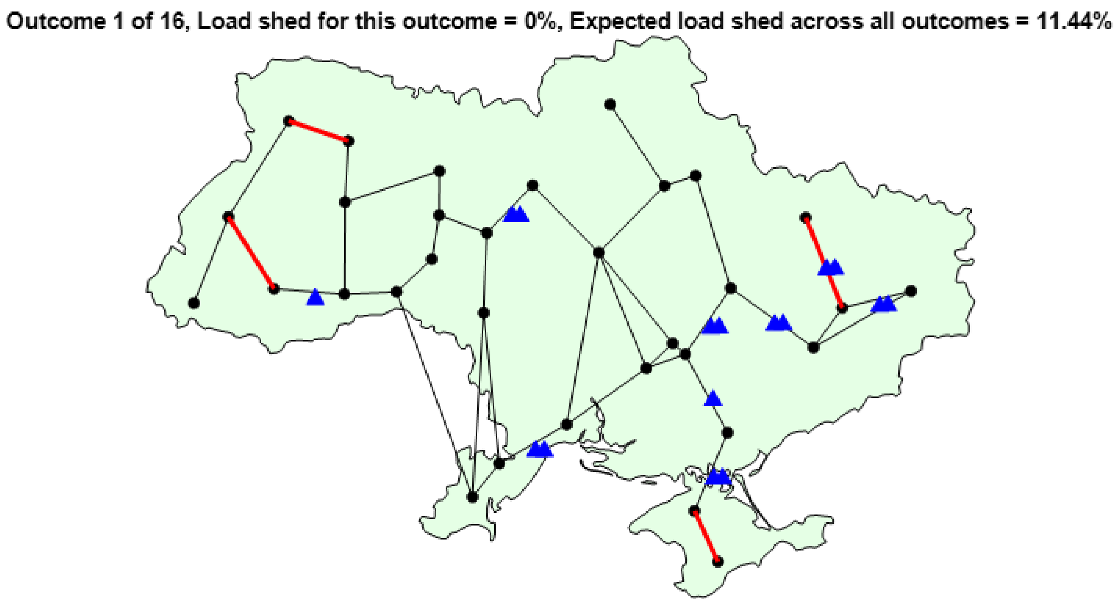

Figure 1. Defense locations for the apparent power method given four attacks.

Probabilistic Contingency Method (PC method)

The probabilistic contingency method takes a different approach. This method will be analyzed for maximal attackers (four) and lower amounts may be easily understood once this extreme is explained. This method takes advantage of considering the scenario in which one attacker fails in addition to the scenario in which all attackers succeed. This optimizes probabilistic outcomes by considering the two most probable scenarios.

To begin, the method leverages the attackers N-3 and N-4 contingency scenarios. This returns the three targeted lines from the N-3 scenario and the 4 targeted lines from the N-4 scenario. The algorithm then compares these two lists of locations and places a defender on each matching location. For example, if the N-3 targets included line 11 and the N-4 targets included line 11, then a defender would be placed on line 11. After this, the process is repeated considering the new defender's placement until all sixteen defenders are placed.

For three attackers, the algorithm swaps to calculating a N-3 and N-2 contingency to place the 12 defenders with the same idea of implementation. Because the scenario with three attackers entered an infinite loop due to the N-3 and N-2 attack locations having no match, the algorithm was modified to just place the defenders in the N-3 locations for each location when this error occurs.

Below in Figure 2 is the result of implementing this method on the Ukraine system. For this method, Ukraine experiences the following load shed:

Attacks	Expected Load Shed
1	3.262%
2	15.3%
3	10.37%
4	11.28%

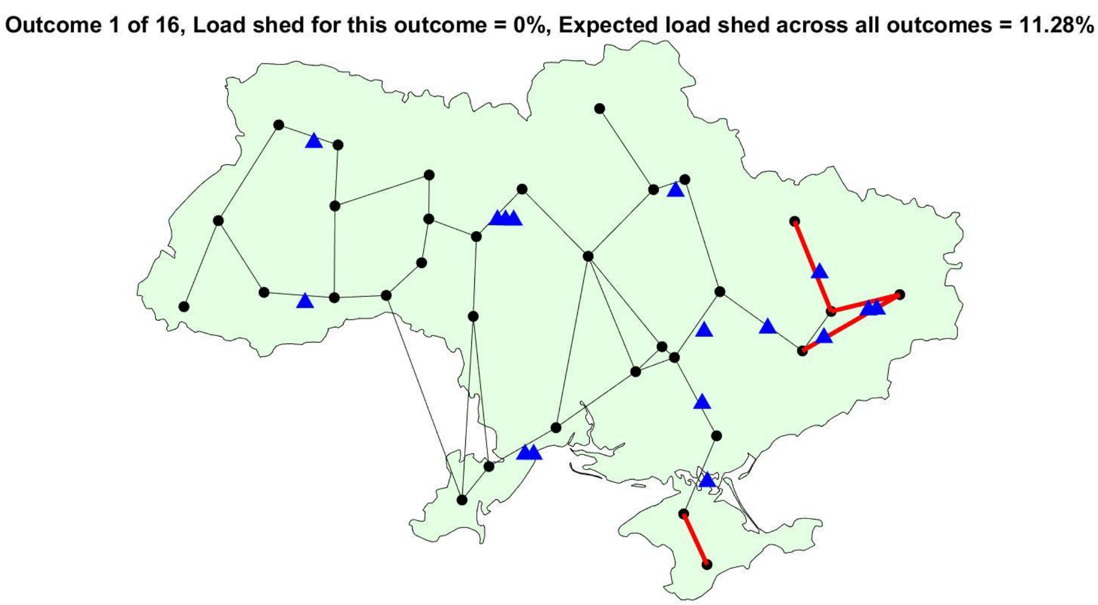

Figure 2. Defense locations for the PC method given four attacks.

Methodology Analysis

As the expected load shed values reveal, both methods are comparable in effectiveness. An alternative approach was simply interacting with the model manually and picking defense locations that seemed to defend generation, large loads, and limit isolation. This methodology proved effective, but had great variation in possible outcomes. With both the Apparent Power Method and the PC method, results proved robust.

For the PC method, we based the algorithm only on the N-3 and N-4 locations of attack. Using the N-2 method in conjunction with these results was considered, where each list of output locations would be compared and defend the common location that all returned. However, this was found to enter an infinite loop due to the three sets not having intersection for some scenarios. In fact, when three and two attackers are used, the algorithm also does not terminate, so some modifications were made to the original loop to reach a set of defenders. More work could be done to generalize the algorithm to work well for all values of attackers, but the current version is not as compatible yet.

The apparent power method is compatible with a wide range of attacks. The algorithm itself works well up to five attacks. Then the computing time becomes a major factor. Since this method runs an attack simulation for every single defense being placed, and since attack simulations take longer when considering more defenses, the algorithm takes longer and longer to place defenses. For example, four attacks takes the algorithm roughly thirty seconds to compute, five attacks can take a few minutes, and six attacks takes a few hours. Since Russia has actually performed over 100 attacks on the Ukrainian power grid since October 2022 [3], this method would take too long to compute with the current attack simulation script if it were used in a real world situation.

Simulation Limitations

Even though our defense models give great insight into possible solutions to protect Ukraine, we have to keep in mind all the limitations of our model. First and foremost, our model is not a fully accurate model of Ukraine's power grid. Their grid is not isolated; it has connections to Russia on the eastern border and other European countries on the western border. Since the beginning of the Russian-Ukrainian war, Russia has cut their power line connections to Ukraine. Adjustments in estimating reliability and efficiency through analyzing the lack of these connections would further improve the model's accuracy.

Due to the invasions, eastern cities have been evacuated, meaning the load demand in those areas has greatly changed both the defense and attack models. The defense model also lacks the prioritizations not related to power flow. For example, Ukraine would have to defend the capital, major hospitals, military bases, and important government buildings from losing power. Another issue with our defense model is that Russia would most likely not attack transmission lines, instead opting to attack power plants and substations. These act as important nodes in the grid and would take down every line attached to it if it were to be successfully attacked.

The attack model has limitations as well. Russia would have to be careful on attacking lines on the western border. Due to the interconnections to the other European countries, creating load shed to any of those countries would be seen as an act of war which Russia would want to avoid. Furthermore, the attack model does not take into consideration multiple attacks on one line. Russia could use a N-3 attack, but still use four attacks, putting two attacks on a line that might have defenses giving them a higher chance of success. Also, in actuality Russia could use the best N-4 attack but send the first attack and see if it is successful and if it is, will continue with lines of the same N-4 scenario. If the first attack failed, they could recalculate for the best N-3 scenario then send the next attacks. Finally, the simulation model could be improved by going into detail of the types of defense and attacks that would be used and the actual probabilities of success.

Conclusion

The Russo-Ukrainian War is a tragedy and should have been prevented. You can't change the past, all you can do is the best you can to improve the current situation and hope that it continues to improve in the future. When in war time it is common for the average person to believe that politicians, generals, soldiers, or engineers designing weapons are the most important factors in fighting a war. In actuality it is the moral of the everyday citizen that helps give the heart and patriotism needed to overcome your enemy. Keeping the "lights on" is a huge contributor to keeping this moral. One of the last groups of professionals you would expect, Power System Engineers, can be a crucial part to not only winning the war but saving lives. Even coming up with the defense models to solve our simple model of Ukraine, us undergrads could give insight to the Ukraine government as we got the expected load shed down to 11.28%. With a more complicated and accurate model of Ukraine's power grid and the brightest power flow optimization engineers we could help Ukraine keep the "lights on" and win the war.

References

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