Evaluation of Electrical Grid Resilience based on ΦΛΕΠ Metrics and Integration of a Nuclear Power Plant

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Abstract - *This paper presents the study of electrical grid resilience based on ΦΛΕΠ metrics, and the impact of nuclear power plant as a base-load supply on the resilience of the electrical grid during extreme event such as high-speed winds or hurricanes. The case study is implemented on a IEEE 39-bus, 10 generators (New England) bus system using PowerWorld, and the data extraction and plotting was done using MATLAB. The wind speeds, fragility curves and time-to-restore (TTR) were randomly created based on the models in the literature, and the numbers were extracted from MATLAB calculation using randomly generated, but uniformly distributed wind speeds. The resilience metrics chosen are the ΦΛΕΠ metrics which help with demonstrating the operational and the infrastructural resilience of the grid, but quantifying the rates of service loss and restoration, duration of interruption and damage time of the transmission lines. Finally, the bus system was modified to be hardened using nuclear power plant, which serves the base loads of the grid, and the same failure scenario was applied, and the metrics calculated, and compared to the base case.*

Key Words: **Resilience, Fragility Curve, Time-to-Restore, Resilience Metrics.**

1.INTRODUCTION

The power grid is a one of the greatest human inventions of the 20th century responsible for the welfare and development of all the societies in the world. The Grid continues to grow larger and keeps adopting new generation technologies like Renewable Energy Sources (RES) like solar energy and wind energy, penetration of large generation plants like Nuclear Power Plants (NPP), and introduction of the Distributed Generation (DG) concepts, and recently integrating Machine Learning and AI to help support the safe and reliable operation of the grid [1]. However, with introduction of such power sources, some challenges might appear while operating them and ensuring the plants safety from outside threats, unplanned outages, and extreme events. One of the issues that face continuously growing and significantly important infrastructure such as the electrical grid is the grid's resilience against High Intensity Low Probability (HILP) such as earthquakes, tsunamis or even sabotages, that has been impacting the electrical grid recently [2]. As it is shown in Table -1, the power outages that faced the US national grid and the total number of customers who were impacted by those outages [3].

Table -1: Power Outages due to natural disasters in the US

Type	% of events	Mean size in MW	Mean size in customers
Earthquake	0.8	1,408	375,900
Tornado	2.8	367	115,439
Hurricane / Storms	4.2	1,309	782,695
Ice storm	5	1,152	343,448
Lightning	11.3	270	70,944
Wind/rain	14.8	793	185,199
Other cold weather	5.5	542	150,255
Fire	5.2	431	111,244
Other external cause	4.8	710	246,071

2.RESILIENCE

The National Infrastructure Advisory Council (NIAC) for example defines resiliency as the grid system's ability to anticipate, prepare, and adapt to changes in the system's conditions and can recover from events such as attacks or natural disasters. [4]. The UK Cabinet Office defines it as the ability of the grid and its different systems, networks, and assets to anticipate, absorb, adapt to rapid changes, and recover from them [5]. Despite having multiple definition, and lack of consensus on what is true resilient system, different regulating bodies and standards agree on the characteristics of a resilient system against High Impact Low Probability (HILP) events such as Resourcefulness, Robustness, Adaptability and Rapid Recovery as shown in Fig-1 , another entities might have enlisted other features such as Redundancy which means having a substitution of the impacted system, Capacity that allow the system to operate against expected and unexpected events, Flexibility allows the system to change depend on the conditions, and Tolerance to the extreme events that might reduce the functionality of the system [6].

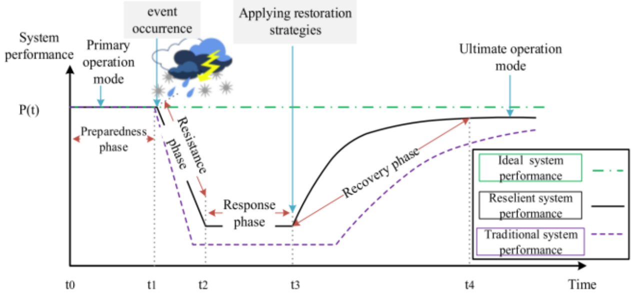


Fig -1: Performance of a system against a HILP event

2.1 NPP Impact on Grid Resilience

A nuclear power plant adds some positive attributes to the electrical grid, such as continuous supply of electricity to the base load, limited ability to flexibly follow load changes and grid dynamics, and the ability to be connected with other sources. On the other hand, NPP might have impact the grid negatively due to its operation restrictions and safety requirements in terms of supplying house load, having a strict and defensive protection scheme and overall impact to the grid stability if NPP is isolated from grid. So, to have a high resilience electric grid with the presence of nuclear power plants, it is important to have a resilient nuclear power plant (rNPP). A resilient nuclear power plant is new concept but is defined by latest literature as a nuclear power plant that has functionalities and design attributes that enables it to enhance the grid resilience and minimize the power interruption to customers during certain times, in other words, it has the ability to adapt to grid abnormalities, and improve the grid's ability to recover and restore electricity to consumers [7].

One of the resilience challenges that are exacerbated by the nuclear power plant is the vulnerability against national disasters. Due to the nature of nuclear power that requires a final heat sink which is usually the sea or the ocean, the location of the nuclear power plant is prone to natural disasters like earthquakes, tsunamis, hurricanes, and tornadoes which tend to happen near coastal areas [8]. In Japan for example, the NPPs are designed to withstand and quickly react to earthquakes because they are in seismically active areas [9]. For example, in March 2011, the Great East Japan earthquake with magnitude of 9.0 hit the Honshu region, which caused eleven nuclear power plant to shut down immediately losing generation of about 4400MW from Fukushima Daini NPP, 2175MW from Onagawa NPP, and 4580MW from Tokai Daini NPP. Because of those loss of generation, 220000 households and business lost electric power which also impact the oil production in Japan oil refineries [10].

Another resilience issue that is unique to connecting nuclear power plants to the grid is the NPP inability to quickly recover from shutdown or ramp up to meeting demand when the system is restored. Due to its safety concerns, nuclear power plants must go through several stages of operation design and safety features checks and tests before power up. In addition to that, if the plant trips due to an event, a long checklist and tests need to be conducted to restore the plant to full operation, a process which can take sometimes hours and several days depending on the design, plant and fuel condition and operation mode of the reactor when it tripped [11]. In addition to that, if the plant was operational for a long period, and there was accumulation of Xenon in the reactor, restarting the reactor will take an additional time from 12 hours up to 72 hours depending on the stage of which the fuel is in [12]. The nature of nuclear power plants during shutdown status and startup are also unique, it can impact the resilience and the reliability of the grid. Unlike traditional power plants like gas or coal, when it is in shutdown mode, it is still requires electric power to provide cooling for the onsite stored fuel that is generating decay heat, in addition to providing cooling for the Spent Fuel Pool (SFP) and the reactor [13]. Because of that, during shutdown, the NPP is considered a high-priority critical load that must be constantly serviced by the grid. On the other hand, during startup, the NPP will require additional power from the grid to supply power to the plant's auxiliary power like the Reactor Cooling Pumps (RCP), generator excitation system, and the Circulating Water Pumps (CWP), which can be a total of about 30MW to 40MW of electric power that need to be supplied by the grid since the inhouse diesel generators and battery systems are not able to satisfy this load. As a result, during catastrophes and events impacting the grid, NPP will add additional burden to the grid to startup rather than support the restoration of the services and meeting the grid's demand [14].

NPP demonstrated its ability to endorse grid resilience during two events in the United States that showed the nuclear power's advantageous fuel security aspect. The first event was in February 2011 and impacted Texas and the New Mexico states in the United States. On February 1st, a major winter storm arrived at Texas states, causing a spike in demand for gas and electricity for heating purpose. By February 2nd, the impact of wind chill, the demand for gas and electric power continued to grow. What made it worse, power plants that use coal and natural gas as fuel had challenges running due to freezing issues in their process, which made those plant shut down, and make the problem worse. Another contributing factor was gas processing and transferring plants had blackouts and could not continue with their gas supply despite the high demand. More than 7000MW of generation capacity from gas, coal and even wind were lost in this event, causing blackout in about four million customers. The only power plant that was not impacted and continue to provide their full generation capacity were NPPs like Comanche Peak NPP and South Texas NPP because they did not require daily supply of fuel and most critical components were protected by the nuclear enclosure [15]. Other events that demonstrated the grid resiliency adding features of NPP with regard interdependencies and fuel security is the Polar Vortex event in January 2015, which caused a rapid increase in gas and electricity demand for home and commercial heating. The addition of high precipitation closed traffic and caused curtailment of the gas supplies to gas power generation plant. Despite this event being after the 2011 event, the magnitude of polar vortex extended beyond expect covering the entire US and focused on the east side of the continent. As shown in Figure 8, the third highest generation capacity were nuclear power plant, however, it was the least impacted generation plant compared the tripped gas and coal plants. A total of about 35,000MW of generation capacity were lost due to Polar Vortex [16]. fuel security of NPPs are know to be a significant advantage for nuclear power plants, especially during unusual environmental events, issues in logistics and fuel delivery or even the geopolitical issues that usually effect oil and gas [17].

2.2 Resilience Metrics

During High Impact, Low Probability (HILP) events, it is critical to monitor and track certain metrics that allow operators and decision makers to realize the current condition of the grid and take proper action and adopt enhancement techniques. And while there is no current consensus on resilience metrics, several metrics were adopted from other fields such as system engineering, reliability engineering and power system optimizations that can be seen in Fig-2 [18]. The performance-based metrics represent the direct outputs magnitudes of the power system that include power, voltage, and frequencies. The non-performance metrics related to factors that can impact the power system before, during and after the HILP event.

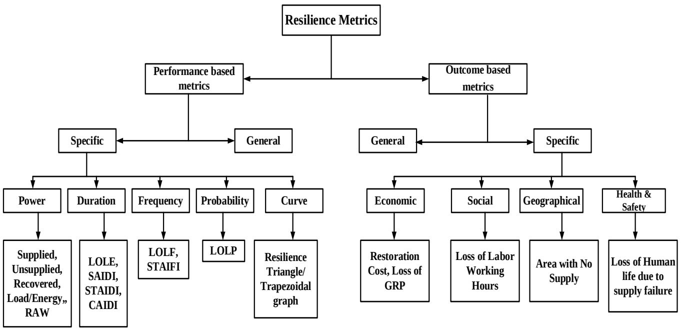


Fig -2: Power System Resiliency Metrics

One of the basic methods to illustrate the resilience of the grid is to graph one of the resilience metrics and quantify it as a function of time. Fig-3 shows a multi-phase resilience trapezoid consisting of three phases, phase I, disturbance in progress, phase II, post-disturbance degraded state of the system, and phase III, restoration state.

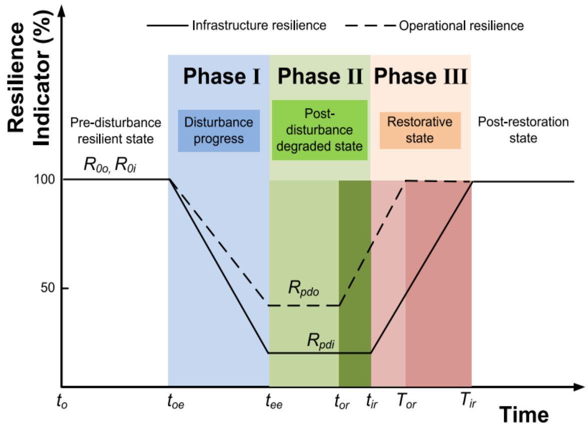


Fig -3: Multiphase Resilience Trapezoid

In Phase I, starting from toe when the HILP even impacts the electrical grid, and ends at tee when the event has ended. During Phase I, resilience is reduced until it reaches R_{pd}. This phase can last from minutes to days depend on the events that is happen such as a fast earthquake or long running hurricane or ice storm. At this point, the system undergoes Phase II, from t_{ee} to tor for the operation and t_{ir} for the infrastructure. At this stage, the system continues to degrade until restoration process occur. This stage may last up to weeks depends on the recovery plan and implementation capabilities. In Phase III, is the phase of the operational and infrastructure recovery from t_{ir} to T_{ir} or T_{or}. This phase can last from months to years, and focused on increasing system resilience, and prepare for the next HILP events. The resilience curve can be obtained from plotting real life data or simulated data for certain resilience indicators [19]. Typically, the resilience will be the area under the curve for such situation which is shown in equation (1)

$$R_1 = \int_t S(t)dt \qquad (1)$$

From Fig-3, more metrics can be obtained that can describe the events and the restoration of the service. Those metrics are identified as a function of time [79] [80]. The first metric in Phase I is Φ which describes how fast resilience has dropped, and measures MW/Hours lost during event in the operational side (2), and number of tripped lines/hours in the infrastructure side (3).

$$\Phi_o = \frac{R_{pdo} - R_{0o}}{t_{ee} - t_{oe}} \quad \text{(MW/Hours)} \qquad (2)$$

$$\Phi_i = \frac{R_{pdi} - R_{0i}}{t_{ee} - t_{oe}} \quad \text{(Tripped lines/Hours)} \qquad (3)$$

Another metric is Λ, which represents how low the resilience has dropped due to the event in Phase I. this metric shows the MW lost (4), and total lines tripped (5).

$$\Lambda_o = R_{0o} - R_{pdo} \quad \text{(MW)} \qquad (4)$$

$$\Lambda_i = R_{0i} - R_{pdi} \quad \text{(Tripped Lines)} \qquad (5)$$

In phase II, the metric E describes how significant the degraded state of the grid is after the disturbances, and the unit is Hours for both the operational (6) and infrastructure (7).

$$E_o = t_{or} - t_{ee} \quad \text{(Hours)} \qquad (6)$$

$$E_i = t_{ir} - t_{ee} \quad \text{(Hours)} \qquad (7)$$

In phase III, the restoration phase, the metric Π describes how fast the electric grid was restored. Its unit is MW/Hour for the operational function (8), and number of lines restored/hours for the infrastructure function (9).

$$\Pi_o = \frac{R_{0o} - R_{pdo}}{T_{or} - t_{or}} \quad \text{(MW/Hours)} \qquad (8)$$

$$\Pi_i = \frac{R_{0i} - R_{pdi}}{T_{ir} - t_{ir}} \quad \text{(Restored Lines/Hours)} \tag{9}$$

An example of implementation of the Φ Λ Ε Π metrics to determine is implemented on the simplified Great Britain 29-bus transmission network during a windstorm [22] as shown in Fig-4.

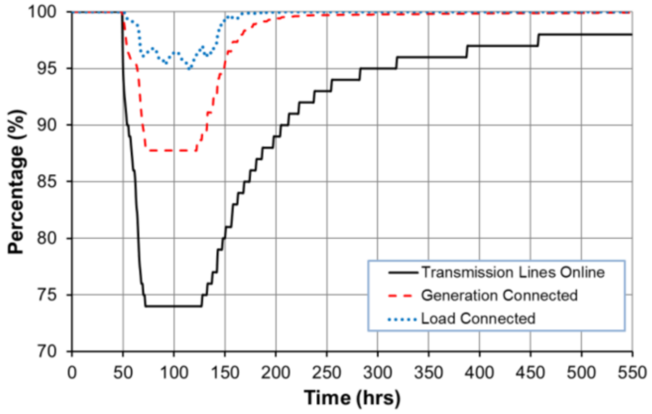


Fig -4: Curve-based Resilience metrics of GB Bus system under Windstorm

In Table-1, the resilience metrics for the 29-bus system [23], simplified GB transmission network is calculated based on the resilience curve in Fig-4.

Table -1: ΦΛΕΠ Metrics for the resilience curve in Fig-4.

Resilience Metric	Transmission Lines	Generation Connected	Load Connected
Φ	-1.083 (% of Lines tripped/hr)	-0.521 (% of MW lost/hr)	-0.249 (% of MW lost/hr)
Λ	26 (% of Line tripped)	12.5 (% of MW lost)	5.99 (% of MW lost)
Ε	53 (Hours)	54 (Hours)	57 (Hours)
Π	0.058 (% of Lines restored/hr)	0.033 (MW restored/hr)	0.072 (MW restored/hr)

3. MODELING

The process of modelling the resilience components of an electrical grids requires modelling of the different stages of resiliency impacting event. Resilience events happen when external factors like earthquakes or windstorms causes the malfunction, tripping and stressing of the different components of the electrical grids such as transmission and distribution lines, outdoors transformers and auxiliary systems [24].

3.1 Modeling Assumptions

The process of modelling weather events and associated impact to the power system is a very complex and demanding process, therefore, certain assumptions were established to ease the modelling and simulation process [25]. The assumptions are:

- The installed generation capabilities will not be impacted by extreme weather events. If the generation units is wind based, then it will trip due to high wind speed beyond design basses of the towers.

- The load does not change prior to the event happening, during and after the restoration of the service.

- The transmission lines are standardly designed structures and follow statistical fragility models, and their tripping or outage is independent from each other.

- The restoration time can be modelled and calculated for each type of transmission line, and randomly generated failure time and restoration times are assumed to simplify the process of calculating the metrics of the reliability and resilience.

3.2 Windstorm Modeling

Wind speed is a stochastic value, that can be modelling in a statistical model that will reflect its behaviour during the season. The behaviour of wind speed is calculated based on either Weibull distribution or Rayleigh distribution [26]. In this case, the Weibull representation for wind speed is:

$$f\left(V_{wind}\right) = \frac{K^0}{C^k} \cdot V^{K^0 - 1} \cdot e^{(-V/C)^{K0}} \tag{10}$$

Using MATLAB, the Weibull distribution for wind speed is shown in Fig-5, and the distribution for wind speed based on changes in value of K0 is shown in Fig-6.

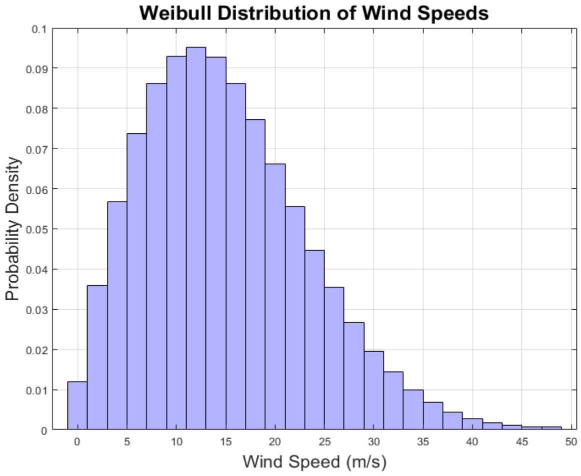


Fig -5: Weibull Distribution of Wind Speeds

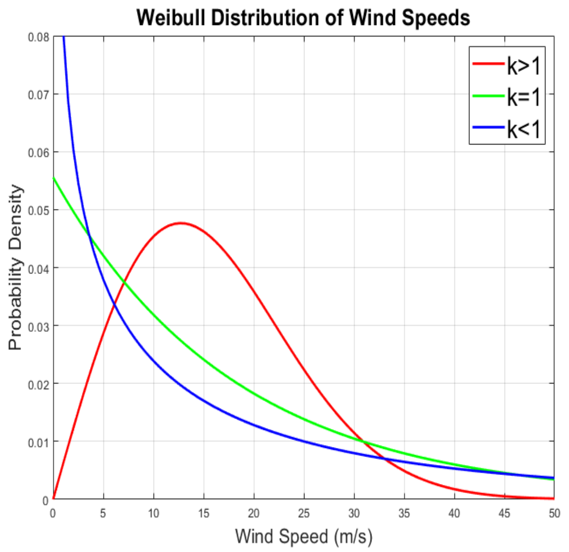


Fig -6: Wind Speed Distribution with Different values of K

3.3 Transmission Line Fragility Curve

The next component that needs to be modelled is the fragility curve of grid components like Transmission & Distribution lines, Transformers, generation units, and substation [28]. Some of those curves have mathematical expressions that were derived either by simulation and analytics, or empirical data. One model was analytically obtained through regression analysis of transmission lines failure based on the wind speed [29]. The fragility curve (11) is plotted using MATLAB in Fig-7.

$$P_w = \frac{1}{1+e^{(13.476-0.293w)}} \tag{11}$$

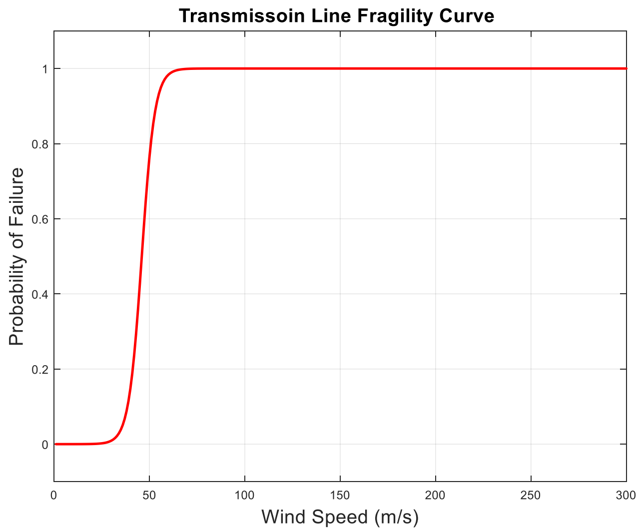


Fig -7: - Fragility Curve for OHL from equation K

Equation (13), and Fig-8 describe the fragility curve of transmission and distribution towers done through analyzing the structure of the transmission line during high winds. It

$$P_w = \frac{1}{1+e^{(50.527-1.351w)}} \tag{12}$$

Fig -8: Fragility Curve for Transmission line Tower

3.4 Time to Repair (TTR) Models

Following the degradation and failure of power system component, it is important to establish a reasonable Time to Repair (TTR) model based on either statistical data or analytical methods, empirical or based on expert opinion [29]. Equation (13) shows the TTR for overhead lines impacted by wind speed based on random event and uniformly distributed wind speed using MATLAB.

$$TTR = \begin{cases} TTR_{\text{normal}}, & w_{\max} \le 20 \text{ m/s} \\ k_1 \times TTR_{\text{normal}}, & 20 \text{ m/s} < w_{\max} \le 40 \text{ m/s} \\ k_2 \times TTR_{\text{normal}}, & 40 \text{ m/s} < w_{\max} \le 60 \text{ m/s} \end{cases} \tag{13}$$

The TTR_{normal} is usually 10 hours for the lines, and 50 hours for the towers. When the wind speed is between 20 m/s and 40 m/s, the TTR_{normal} is multiplied a $k_1 = U(2, 4)$, and when the wind speed is between 40m/s and 60m/s, the TTR_{normal} is multiplied by factor $k_2 = U(5, 7)$. Fig-9 shows the uniform distribution implied by equation (13) and the time to fix broken lines or transmission lines obtained using MATLAB script.

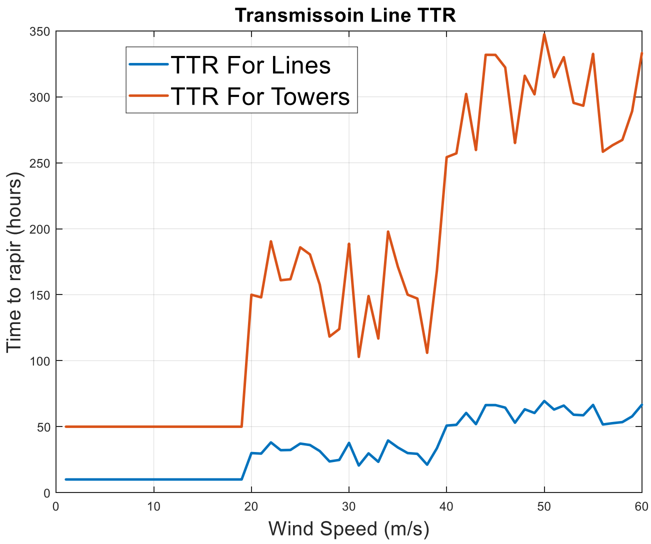


Fig -9: TTR for Transmission line & Tower during high winds

4. SIMULATION

In this section, the simulation of a base case will be conducted, then another simulation of base case with added NPP is conducted. In Both cases the resilience metrics will be obtained and compared.

4.1 Base Case

In this section, the power flow analysis will be conducted on a benchmark test system, and a base power result will be obtained for the grid condition prior to the extreme event happening. This can be implemented using different software such as PowerWorld, MATLAB and MatPower. In this section the resilience of a 39-Bus system [30] will be examined using ΦΛΕΠ metrics (Resiliency Curve). Fig-10 shows the bus system obtained from PowerWorld software. This will allow us to know the total connected loads, generation and the chances of violating the restriction of transmission lines limits, and the need for load shedding or isolation of part of the bus system. The results of the power flow analysis using Power World is demonstrated in Table-2.

Table -2: Load Flow Reuslts for the bus system in Fig-10

Name	Volt (kV)	Angle (Deg)	Gen (MW)	Gen (Mvar)	Load (MW)	Load (Mvar)
1	1.05	-26.62	0	0	0	0
2	1.06	-24.43	0	0	0	0
3	1.05	-26.8	0	0	322	2.4
4	1.04	-23.79	0	0	500	184
5	1.06	-19.55	0	0	0	0
6	1.06	-18.32	0	0	0	0
7	1.05	-20.56	0	0	233.8	84
8	1.04	-21.14	0	0	522	176
9	1.05	-21.16	0	0	0	0
10	1.05	-18.16	0	0	0	0
11	1.05	-18.25	0	0	0	0
12	1.03	-18.94	0	0	7.5	88
13	1.04	-19.53	0	0	0	0
14	1.04	-22.9	0	0	0	0
15	1.03	-28.69	0	0	320	153
16	1.05	-29.65	0	0	329.4	32.3
17	1.05	-28.94	0	0	0	0
18	1.05	-28.54	0	0	158	30
19	1.06	-29.7	0	0	0	0
20	0.99	-31.08	0	0	680	103
21	1.04	-29.01	0	0	274	115
22	1.06	-26.4	0	0	0	0
23	1.05	-25.93	0	0	247.5	84.6
24	1.05	-29.93	0	0	308.6	-92.2
25	1.06	-23.38	0	0	224	47.2
26	1.06	-25.85	0	0	139	17
27	1.05	-28.41	0	0	281	75.5
28	1.05	-22.36	0	0	206	27.6
29	1.05	-19.61	0	0	283.5	26.9
30	1.05	-22.03	250	90.96	0	0
31	0.98	-1.59	1404.1	614.07	9.2	4.6
32	0.98	-10.4	650	61.18	0	0
33	1	-28.27	174.86	57.12	0	0
34	1.01	-25.9	508	144.78	0	0
35	1.05	-24.32	274.14	132.28	0	0
36	1.06	-18.13	560	69.3	0	0
37	1.03	-16.62	540	-17.82	0	0
38	1.03	-12.56	830	8.26	0	0
39	1.03	-27.95	1000	127.14	1104	250

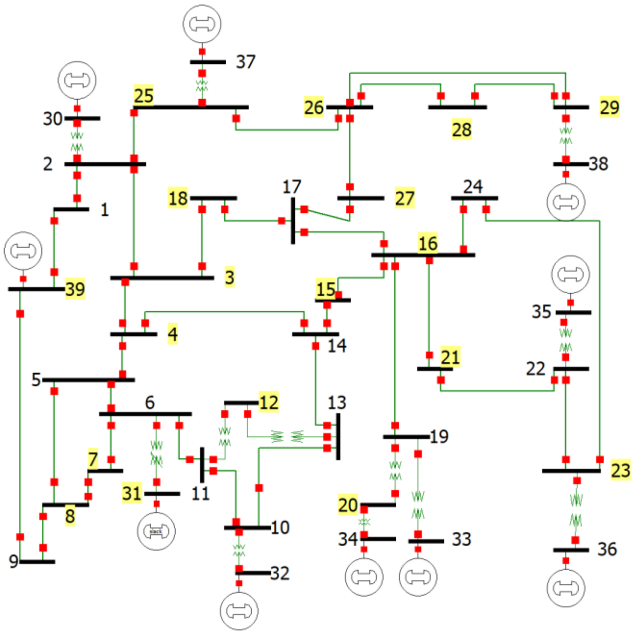


Fig -10: 39-Bus system under study

Using MATLAB and the models that were obtained in the previous section, the windspeed of each section of the bus-system is randomly chosen following a uniformly distributed number. Each square represents a zone with a certain wind speed. The color scale can provide information of how fast the wind and the colored square is tell the location. Based on this, the line failure sequence will be created. Fig-11 shows the bus system with the wind-speed color grid.

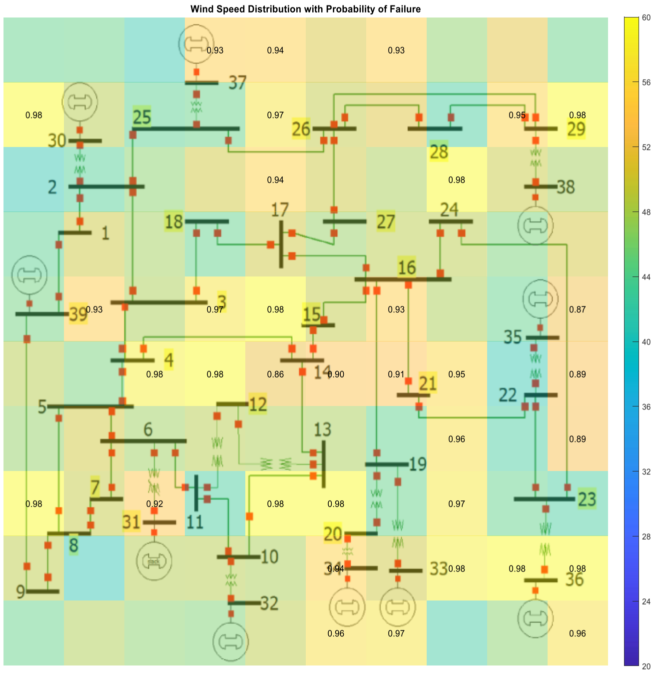
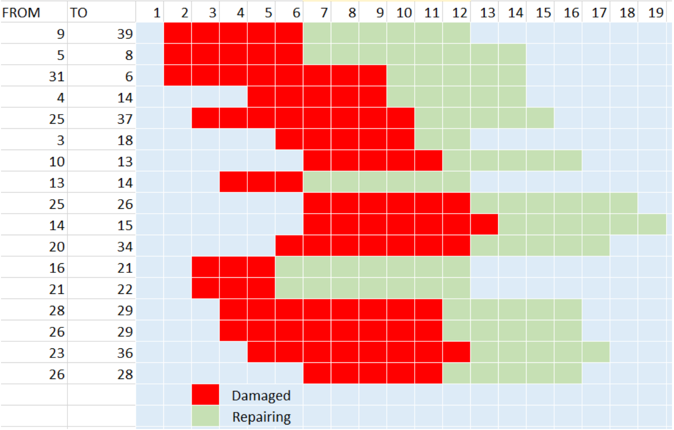


Fig -11: 39-Bus system under study with color map indicating windspeed and probability of failure.

The failure of transmission lines, and the planning and restoration phase are demonstrated in Fig-12.



FROM	TO	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
9	39		🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩							
5	8		🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩					
31	6		🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩					
4	14					🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩					
25	37			🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩				
3	18						🟥	🟥	🟥	🟥	🟥	🟩	🟩							
10	13							🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩			
13	14				🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩							
25	26							🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	
14	15							🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
20	34						🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩		
16	21			🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩							
21	22			🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩							
28	29				🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩			
26	29				🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩			
23	36					🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩		
26	28							🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩			
				🟥	Damaged															
				🟩	Repairing															

Fig -12: Impacted Transmission lines and their Failure and Restoration Timeline.

4.2 Base Case Simulation Results

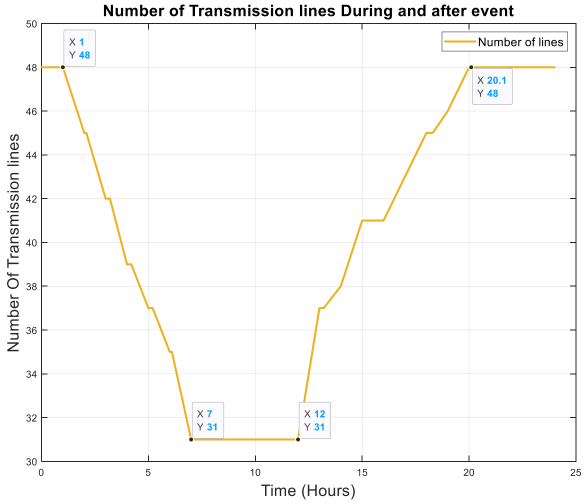


Fig -13: Loss of Transmission line during windstorm for the base case

Table -3: Resilience Metrics for Fig-13

Resilience Metric	Transmission Lines
Φ	-2.8 (% of Lines tripped/hr)
Λ	35.4% (% of Line tripped)
Ε	6 Hours (Resourcefulness)
Π	4.372% (% of Lines restored/hr)

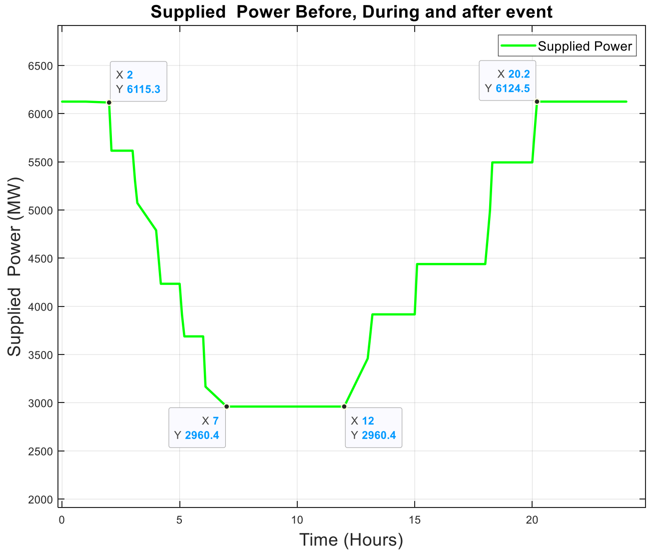


Fig -14: Loss of load during the extreme event.

Table -4: Resilience Metrics for Fig-14

Resilience Metric	Transmission Lines
Φ	-10.32 (% of Load lost/hr)
Λ	51.6% (% of lost Loads)
E	5 Hours (Resourcefulness)
Π	6.45% (% of load restored/hr)

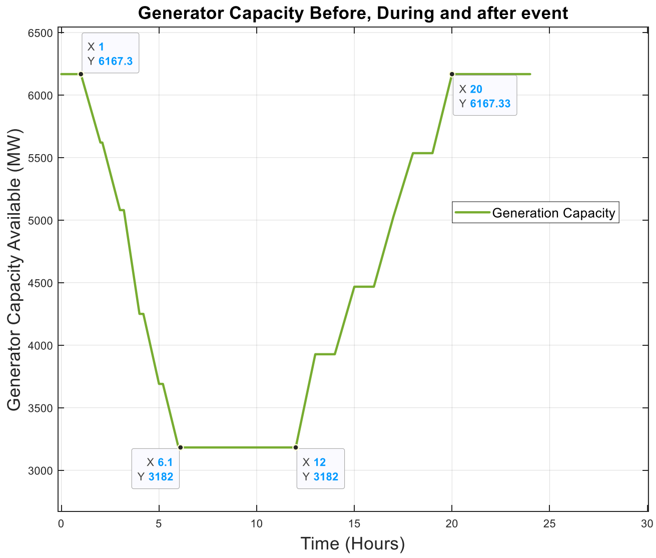


Fig -15: Loss of Generation Capacity during the extreme event.

Table -5: Resilience Metrics for Fig-15

Resilience Metric	Transmission Lines
Φ	-12.16 % (% of Capacity lost/hr)
Λ	48.6% (% of lost Capacity)
E	6 hours (Resourcefulness)
Π	6.1% (% of Capacity restored/hr)

4.3 Base Case with NPP Simulation

Next step, the same bus system will be modified to include a nuclear power plant. The idea of having an NPP to supply the base load of the grid is considered a resilience hardening or enhancement method. Typically, in other grids, distributed energy resources like microturbines or battery system are used in order restore part of the grid in the form of microgrids [108]. In this section, the NPP will have a based load equivalent of 2400 MW using two VVER-1200 reactors, instead of the generators in Bus 31, 32, 33 and 34. The connection with the grid will be hardened transmission lines that will ensure connection with the grid even during high winds. The system under study will be modified to be the one in Fig-16.

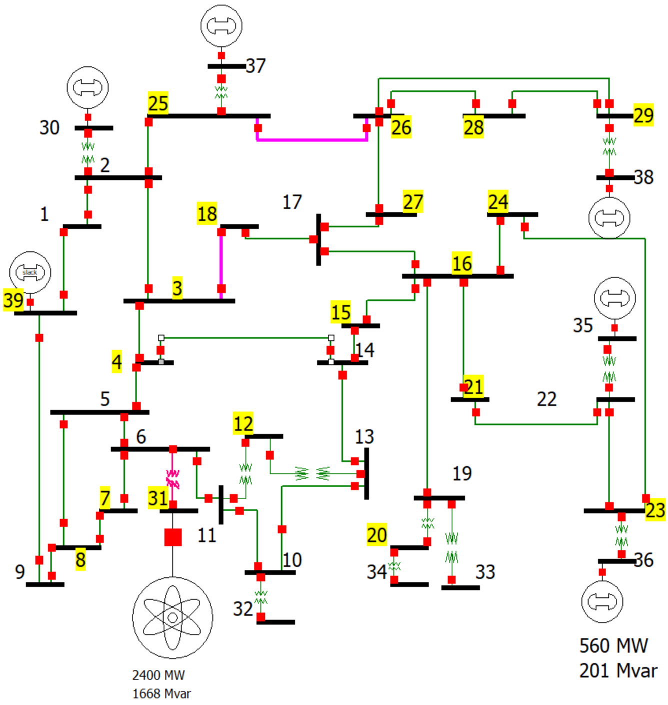


Fig -16: Modified 39-bus system. added a 2400MW NPP

In Fig-17, it can be observed that there is an improvement from the base case to the case with Nuclear Power Plant and hardened transmission lines. The Signiant improvement is for the availability of capacity to service more loads after the extreme event has passed. In the base case, the capacity flatted at 3182 MW, however, in the nuclear case, the capacity reached a minimum of 4269MW for the same extreme event scenario depicted in Fig. 38. This is an improvement of about 34%. Furthermore, in the base, the restored load took 8 hours for full restoration, meanwhile, in the nuclear enhanced case the restoration took 6 hours.

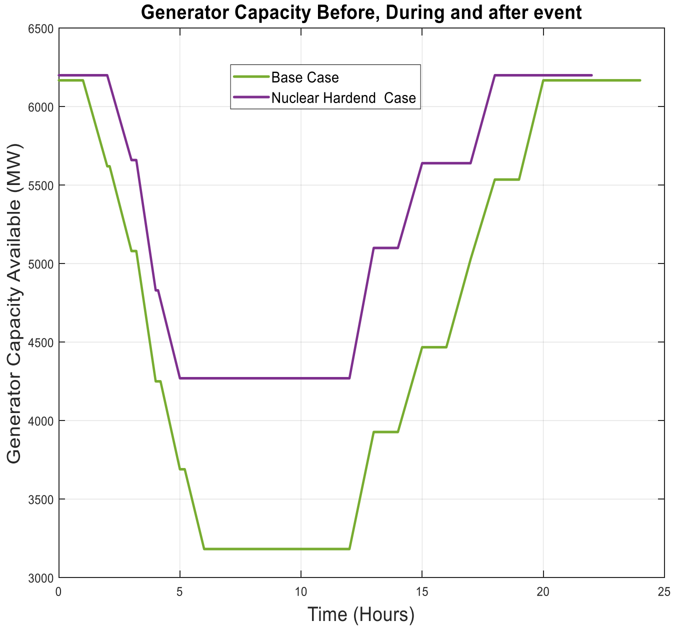


Fig -17: Generation Capacity for Base case and Nuclear Hardened Case

In Fig-18, the supplied load metrics during the extreme events for both base case and the case with NPP installed is shown. The total supplied load went from 6124MW to 2960MW because of loss of transmission lines to the loads, and load shedding due to loss of generation capacity. However, in the NPP hardened case, the supplied load fell from 6124MW to 4062MW for the same extreme event scenario and loss of transmission lines. That is an improvement of about 18% from the base case. In addition to that, the restoration time in the base case took about 8 hours, while in the hardened case it took only 6 hours. This is the impact of both having a nuclear power plant that can sustain the grid during extreme events, and having hardened critical transmission lines that is connected to the critical loads in addition to being a tie connection between different zones in the grid in case some lines fail.

Table-5 shows the comparison between the quantification of the resilience in the base case, and the case with the hardened grid with nuclear power plant.

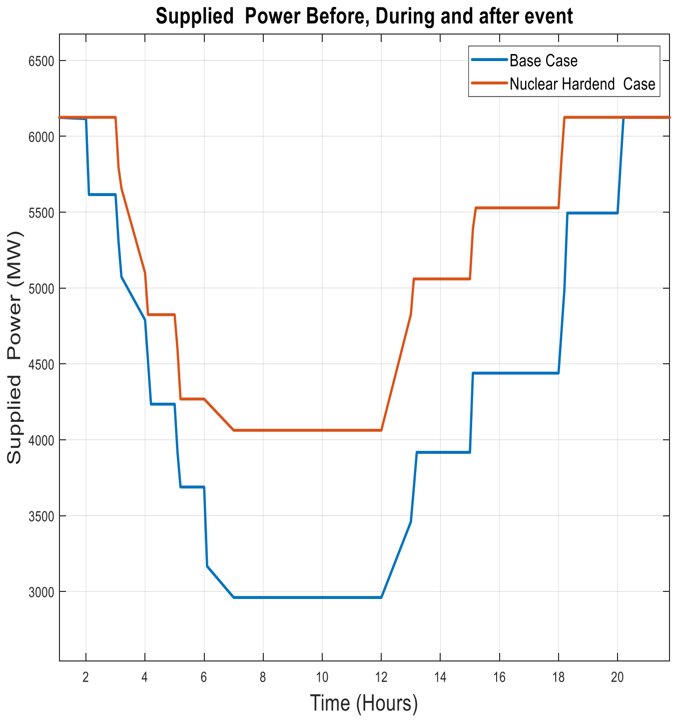


Fig -18: Supplied Load Lost of Base Case and NPP case

Table -5: Resilience Metrics comparison between the base case and the hardened case

Resilience Metric	Generation Capacity	
	Base Case	Hardened Case
Φ	-12.16 % (% of Capacity lost/hr)	-10.3 % (% of Capacity lost/hr)
Λ	48.4 % (% of Capacity lost)	31.1 % (% of Capacity lost)
Ε	6 Hours (Resourcefulness)	5 Hours (Resourcefulness)
Π	6.1 % (% of Capacity Returned/hr)	7.53 % (% of Capacity Returned/hr)

Resilience Metric	Supplied Loads	
	Base Case	Hardened Case
Φ	-10.32 % (% of Load lost/hr)	-8.42 % (% of Load lost/hr)
Λ	51.6 % (% of Load lost)	33.7 % (% of Load lost)
Ε	5 Hours (Resourcefulness)	5 Hours (Resourcefulness)
Π	6.45 % (% of Loads Returned/hr)	8.5 % (% of Loads Returned/hr)

5. CONCLUSIONS

The concept of resilience is still a developing idea that is currently being assessed and studied by both academic and research to identify the correct metrics and evaluation methods, in addition to the precise definition and frameworks. And while the importance of NPPs on the electrical grid is known as a major stability and supply source, NPP's impact on the grid's resilience is under studied, and little research is done to identify the correct metrics and resilience evaluation methods that suites the behavior of a nuclear plant in a grid.

In this paper, the resilience of a 39-bus system is quantified using the ΦΛΕΠ metrics using the simulation results from Power World. The ΦΛΕΠ Metrics are suggested as a method to determine the resilience of a grid during an extreme event, in terms of operational and infrastructural resilience. While the project was able to demonstrate that having a NPP in the grid will improve the resilience of the grid big, good margins, especially in terms of supplying loads and customers during extreme events, there are still more complex scenarios that NPP can be evaluated against such as Cyber Attacks and earthquakes. This project shows that NPP are resilient when it comes to extreme events like high-speed winds or hurricanes. Furthermore, the system that consists of 39-bus system might be a good reflection of a real-life system, that usually consists of hundreds of buses distributed along large geographical areas and exposed to multiple natural phenomena.

In future work, custom resilience metrics need to be included that highlighted the nuclear behavior or the reactors such as Xe poisoning, reactor stability and fuel consumption. In addition to that, the study of the positive impact of NPP when it comes to fuel supply chain resilience, operational advantages and overall idea of excellence that are promoted in the Nuclear Power Plant business. Another important study would consider the economic feasibility of enhancing the resilience of electrical grids.

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