Proceedings of 10th IOE Graduate Conference
Peer Reviewed
ISSN: 2350-8914 (Online), 2350-8906 (Print)
Year: 2021 Month: October Volume: 10

Transmission Systems Resilience Assessment: A Case Study in Integrated Nepal Power System

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Abstract

The dramatic impacts of earthquake and other natural disasters in the power system is of a growing concern. The impacts are reflected in infrastructure damage, service interruptions, casualties, and the financial burden for recovery. Various countries around the world suffer from loss due to such events. This paper presents a Monte Carlo based simulation to access seismic impact on Integrated Nepal Power System (INPS). The resilience is quantified with demand not served (MW). The framework is a probabilistic approach to quantify the resilience of the transmission system subject to extreme earthquake. The study further provides criticality ranking of transmission lines. This paper aims on helping system operator to access the performance of INPS under seismic attacks and be prepared to deploy proper branch strengthening schemes to enhance resilience of INPS.

Keywords

Integrated Nepal Power System (INPS), High Impact Low Probability (HILP), resilience metric, criticality ranking

1. Introduction

Electrical power system is the foundation of today's world that supports a variety of other prominent infrastructures such as transportation, communication, health, education and so on. The increasing and huge cost of power system outages due to natural disasters along with the severe impact on various field and personnel security cannot be neglected. Therefore, it is a high time to think beyond reliability and move the focus on the analysis and assessment of power system resiliency.

A symposium held between NRC[1], EPRI[2] and NARUC[3] on July 24-25, 2014 opened the doors for researchers in power system in the field of resiliency [1]. The symposium discussed on the ways to make America's power grid strong and resilient from a wide range of natural disturbances. From then until now, various other countries are exploring ways to make their power system withstand and recover from any disturbances i.e. the focus is on making a resilient power system.

UNISDR[4] defines resilience as the capability of the system which is subjected to risk to accept, withstand, respond, adapt and recover from the effects of a hazard, in a effective and suitable manner, comprising of the maintenance and repair of its vital fundamental structures and purposes [2]." Although there have been several power system resilience definitions, quantification metrics, methodology for its evaluation and enhancement, there is still no standard definitions of power system resilience, its quantification and suitable alternative or enhancement techniques. Therefore, there is an urgent need to explore about the current practices, research gaps and challenges to contribute in building a universally accepted definition, quantification, and evaluation methods. Many people confuse resiliency analysis with reliability analysis in the power system that has been done over the decades. It is true that reliability analysis and resiliency analysis are linked and in order to be resilient, the system must be reliable first. However, resiliency analysis incorporates additional concepts that include being prepared for, operating satisfactorily and recovering back quickly from any major disruptions irrespective of the cause of

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[1] National Research Council

[2] Electric Power Research Institute

[3] National Association of Regulatory Utility Commissioners

[4] United Nations International Strategy for Disaster. Reduction

disturbance. Resiliency is the ability of a system to withstand and recover from any extreme event.

The concept of n-1 or even n-2 contingency analysis is not new in power system industry. The design and study of power systems including design in generation and transmission systems is being done to make the system reliable for predictable events adopting different contingency analysis techniques. But, now it is time to think out of the box and prepare ourselves for the events that are unpredictable. Is the power system prepared for the changes and disturbances for which there are no set standards? Can it withstand and recover quickly from the events it has never experienced? Understanding that we cannot prevent the disasters, but we can prepare for, operate through and recover from each disturbance while learning in the process is the key to resiliency.

2. Resiliency and INPS

Although a new concept, many countries around the world are researching about resiliency analysis in their power system. They have a dedicated research team in this area. However, there have not been any studies made in our country even though Nepal is also very prone to natural disasters. 2015 Nepal earthquake, recurring landslides and flood every year are the examples that Nepal does not fall far from the vulnerability of natural disasters. Therefore, it is a high time and a task of a high importance to study the resiliency assessment of Nepalese power system.

In the resiliency white paper, EPRI has determined that the power system needs to be more resilient, flexible and connected [3]. There can be various reasons to ensure resilience in any power system. First, increasing cost of power system outages due to natural disasters plays a vital role in need of resiliency analysis [4]. Also, the impact of loss of services on personal security and safety cannot be neglected. This mandates a proactive disturbance handling and recovering strategy in power system that goes beyond traditional reliability-oriented perspective, which is based on High Impact Low Probability (HILP) events [5].

In any power system, transmission lines are the backbone of the system. Transmission system is a critical infrastructure and therefore must always be kept intact and protected in order to prevent the loss of critical services. The financial impact on transmission lines will be higher than on distribution lines when a disturbance occurs in a power system. Therefore, as an inception in resiliency study of Integrated Nepal Power System (INPS), this study focuses on resilience assessment of transmission system in INPS i.e. the lines with voltage level of 66kV or higher.

3. Resiliency metrics

Although there are various literatures with different ways of quantifying power system resilience, there is no standard resilience metrics that is universally accepted up to now. There is still ongoing discussion on setting standard resilience metric and the method to evaluate it. Resilience assessment requires a metric that quantifies the analysis and help in planning alternatives in order to improve grid resilience. The power system performance is being measured by various reliability metrics that provide an evidence based performance indication on response of power system to normal chance failure outages [4]. But, it is difficult to predict and respond to HILP events because their probability of occurrence is lower and hence rare. Therefore, this call for concept beyond the classical reliability oriented view.

There are several literatures that propose the quantification of power system resilience. [6] studies the resilience of power system but there are only a few indictors to compare different proactive measures. [7] quantifies the resilience as per the ability of system to supply to the critical load even after the resources are reduced after the occurrence of HILP events. Likewise, [8] quantifies resiliency as the ability of power system to supply to interrupted loads after HILP event. The proposed resilience metrics do not incorporate the probabilistic trait of HILP events. Most of the proposed metrics are dimensionless and therefore it is difficult to relate to real world applications. There are various optimization based techniques that quantifies resilience on the basis of critical load and restored [9, 10]. But, all these methods focus on the response of system to an event rather than the quantification of resilience for future HILP events.

Therefore, there is not any resilience metric that is universally accepted up to now. Although, there are various literatures in this domain, the proposed approaches do not fulfill the criteria that a standard metric should possess. Some of the proposed metrics focus on system's performance only after facing the disturbance and the measures to take on recovering from a disturbance. These metrics do not provide any idea or significance on the consequences of unforeseen events and are not specific to HILP events.

In light of these considerations, this study presents a paradigm on the basis of Monte Carlo Simulation study to assess the consequences of HILP events on transmission system of Nepal and to measure the effect of such events on system resilience.

There are two approaches to solve the probabilistic reliability problem: analytical methods and numerical methods. Analytical methods are tedious and make the computation extensive and complex. Whereas numerical methods use simulation to solve the problem. Monte Carlo Simulation (MCS) is one of the most common numerical methods. MCS solves the problem by randomly sampling the states until a convergence criterion is met.

Because weather phenomena and their consequences are probabilistic occurrences, MCS is well suited to the analysis and design of systems impacted by them, as revealed by several publications [11]. The resilience analysis in the present work is for a future exceptional occurrence. Monte Carlo Simulation permits for the simulation of such rare events while accounting for the low likelihood of detecting them, resulting in a realistic assessment of the risks associated with such high-impact low-probability events [4].

The framework is further used to identify critical lines in INPS subjected to extreme earthquake. The relative importance of a line with respect to other lines in a system is ranked. Various literatures suggest a subjective view for system resilience because identification of critical lines requires engineering (subjective) judgment [12]. This study is based on Fussel-Vesely (FV) importance measure [13]. This methodology objectively quantifies the criticality of a component in a system based on the loss reduction in the system when that particular component is assumed to be invulnerable. Fussel-Vesely measure suggests a criticality indicator FV-variant which may be defined based on any metric. In this study, FV-variant is expressed in percentage of loss reduction in MW.

Mathematically,

$$FV_i = \frac{L_o - L_i}{L_o} x100\% \tag{1}$$

where,
FV_i = FV variant for component i
L_o = system loss under default configuration
L_i = system loss assuming component i invulnerable
The system average loss is computed as

$$AverageLoss = \sum_{i=1}^{1000} \sum_{j=1}^{N} (L_j)_i \tag{2}$$

where,
L_j= load loss at jth node in ith iteration
N= number of nodes considered

4. Earthquake Data and Fragility Curve

The design peak ground acceleration values are taken from National Building Code (NBC) 2020 in this study. The building code has design PGA values for various areas of Nepal which provides an estimate on occurrence of earthquake in different areas of Nepal. Hence, the design PGA values for various nodes in the system is taken on the basis of NBC.
Fragility curve is basically a curve of a fragility function. Fragility function can be defined as a function that maps the probability of failure of any component subject to the intensity of a hazard (eg earthquake) [4]. In related literatures, component level fragility curves have been used to model the impacts of any high impact low probability events on power systems. Figure 1 shows fragility curve used in this study that relates the damage probability of transmission lines to The Peak Ground Acceleration (PGA) values. This curve can be mathematically expressed as

$$P(g) = \begin{cases} 0 & \text{if } g < g_{critical} \\ P(g) & \text{if } g_{critical} < g < g_{collapse} \\ 1 & \quad g > g_{collapse} \end{cases} \tag{3}$$

where,
P(g) is the probability of damage state as a function of PGA value g
$g_{critical}$ is the PGA value at which failure probability rapidly increases
$g_{collapse}$ is the PGA value where the component has negligible probability of survival

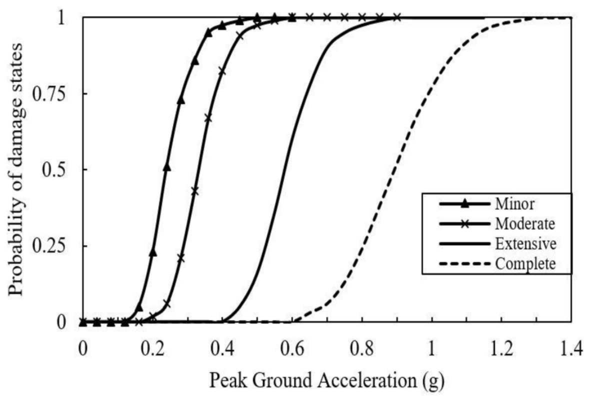


Figure 1: Fragility Curve of transmission lines

5. Research methodology

In the proposed approach, the fragility curve of transmission lines are used to generate probabilistic system loss function. This procedure requires earthquake data and detailed system model as input and it outputs resilience quantification in terms of load loss. Since, earthquake and the impact it can have on a power system are not deterministic, a Monte Carlo Simulation (MCS) method is used to model the probabilistic nature of the earthquake in INPS.

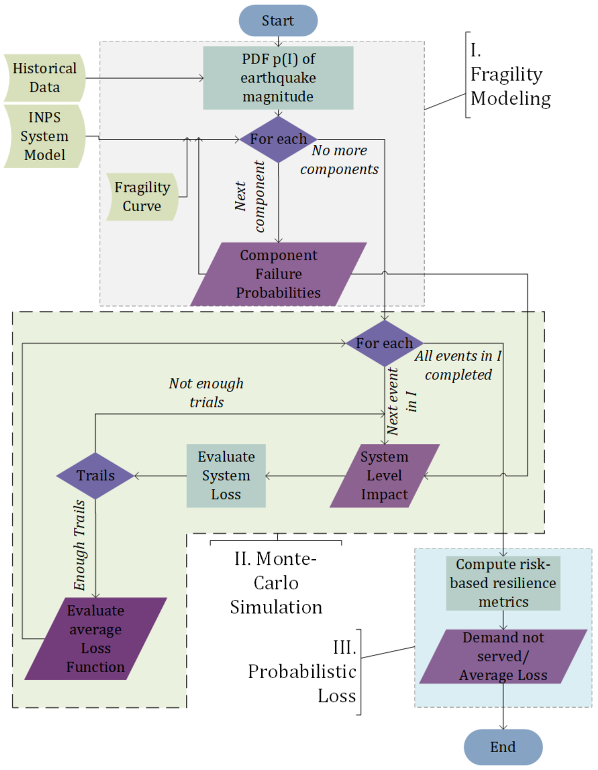


Figure 2: Flowchart of the methodology

Figure 2 shows the plan of action and it has been explained in detail in the following sections.

5.1 System under consideration

The study is performed in Integrated Nepal Power System taken from NEA's annual report. The input parameters such as the conductor type used in various lines, the size of transformers in the substations, load curve and other details are taken from the annual report. Using these data, the system is first modeled in ETAP software and load flow analysis is conducted. The load flow results are compared with standard data for verification. From the load flow report, the bus information along with the power flow in the branches is extracted for further analysis.

5.2 Earthquake Data

The design peak ground acceleration values are taken from National Building Code (NBC) 2020 in this study. The building code has design PGA values for various areas of Nepal which provides an estimate on occurrence of earthquake in those areas. Hence, the design PGA values for all the buses in the system is obtained. Now, the design PGA is increased by a factor ranging from 0.1 to 3 in order to determine the relevant PGA values to carryout different scenarios for case study of earthquake assessment in the system. In total, resiliency assessment is done for 30 different PGA values.

5.3 Fragility Curve

Figure 1 shows the fragility curve for transmission system used in this study.

The relevant PGA values, obtained from section 5.2, of each bus of a transmission line if averaged in order to obtain the PGA value of that line. The PGA value for each line is plotted on the peak ground acceleration axis of the fragility curve and the corresponding probability of damage is obtained. This is the probability of failure due to a seismic event to each line. The probability of damage for each line is obtained accordingly.

5.4 Quantification of System Loss

MCS has been employed to evaluate the probabilistic impacts of an earthquake event on the transmission system in this study. With the probability of damage as input, Monte Carlo Simulation is done for one line at a time, subject to the range of peak ground acceleration values which is 0.1 to 3 times the design peak ground acceleration value for that particular line.

In this algorithm, a uniformly distributed random number between 0 to 1 is generated.

$$RandomNumber, r \sim U(0,1) \tag{4}$$

These generated random numbers are compared with probability of damage for a particular PGA value to obtain the information whether the line is active or failed. Mathematically,

$$F(g) = \begin{cases} 0 & \text{if P(g) <r} \\ 1 & \text{if P(g) >r} \end{cases} \tag{5}$$

where,
F(g) is the failure function of transmission line
F(g) = 0 means the line is intact and has not failed and vice-versa

A convergence study is done and it has been determined that 1000 Monte Carlo simulations are sufficient to obtain the convergence of system loss function for a given damage scenario. The convergence is verified as shown in figure3. Thus, for the range of peak ground acceleration values, 1000 Monte Carlo simulations have been performed for each value. A loss function is computed for every repetition and then averaged. This facilitates in simulating the system's response to varying degrees of peak ground acceleration. The value of average loss, which is actually the expected resilience loss, is the desired result of the Monte Carlo Simulation. This is repeated for each line in a similar manner.

This value of average loss implies the expected resilience loss in the Integrated Nepal Power System without implementing any resilience enhancement strategy and hence called resilience quantification for the base case. This is the model of INPS's response for different values of peak ground acceleration. The system performance is quantified in terms of load loss in each node as given by equation2.

The input PGA value and the induced losses for each line is noted. This is the base case of the resilience analysis for INPS.

5.5 Criticality Ranking

After quantifying the resilience assessment for the base case in INPS, it is important to figure out the critical lines in the system. Critical lines are the lines which when saved reduces the system loss by a significant amount. This step determines the relative importance of lines. As explained in section 3, this step is based on Fussell-Vesely (FV) importance measure. The criticality assessment is performed for a PGA value of 1.5. Each line is made invulnerable one by one and average loss is quantified for each line. A comparison with the base case provides the reduction in system loss. Equation 1 provides the FV variant for each line. Finally, the criticality assessment is done on the basis of increasing FV value.

6. Result and Analysis

INPS is used to demonstrate the proposed framework. First, several monte carlo simulations are done and as shown in figure 3, 1000 iterations are found to be sufficient for the convergence.

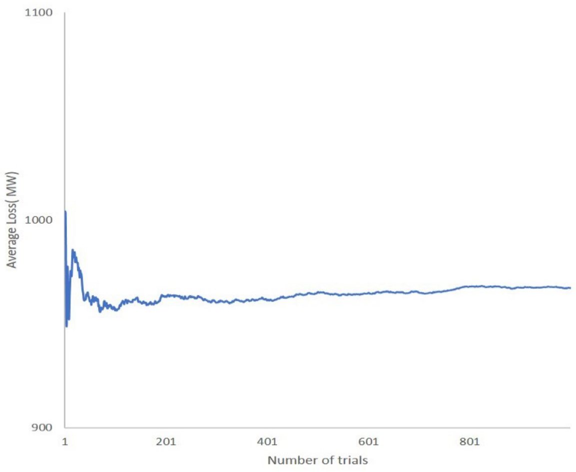


Figure 3: Convergence of MCA

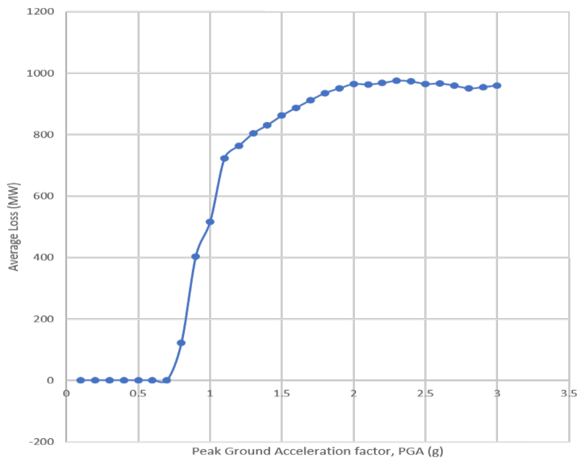
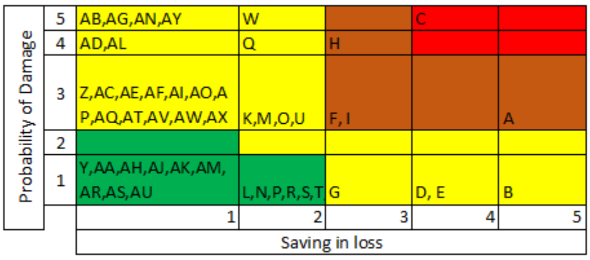


Figure 4: Average loss for different PGA values in INPS

Figure 4 shows average loss for different PGA values in INPS. The framework is run for 30 configurations.

The average loss for each design PGA factor is obtained and plotted. It can be seen that there is negligible load loss up to around 0.7 factor. The average loss increases gradually up to 1.1 times the design PGA. At 1.1 times design PGA, there is a system loss of 750 MW in average. Beyond this point, the rate of increase of average loss is less. This again increases linearly up to 200% of design PGA. Finally, the average loss saturates at around 960 MW.

After performing resiliency analysis for the base case, the criticality ranking of the transmission lines is done. This step is done in order to determine the relative importance of various lines. The results from critical analysis provides which lines need to be hardened with high priority in order to reduce the system loss. Figure 5 shows the criricality ranking table prepared on the basis of critical lines that reduces the expected resilience loss in a system to the greater extend and the probability of that line being damaged by the earthquake with 1.5 times the design PGA factor. This table comprises both the probability of damage and the impact of damage in a system. The lines denoted by the address in the cells of the table is demonstrated in table 1.



Probability of Damage	5	AB,AG,AN,AY	W		C	
	4	AD,AL	Q	H		
	3	Z,AC,AE,AF,AI,AO,AP,AQ,AT,AV,AW,AX	K,M,O,U	F, I		A
	2					
	1	Y,AA,AH,AJ,AK,AM,AR,AS,AU	L,N,P,R,S,T	G	D, E	B
		1	2	3	4	5
		Saving in loss				

Figure 5: Criticality Ranking of transmission lines

In the country like Nepal, where, on one hand, the budget is tight and is a matter of concern, but on the other hand, power system resiliency is of a great importance as well because of recurring natural disasters, criticality ranking helps to prioritize hardening of transmission lines in the limited budget.

From the results, it can be observed lines in red, brown, yellow, and green zones are in the decreasing order of their vulnerability and criticality respectively. The results suggest that line C i.e., line from Kulekhani I to Hetauda is the most critical and vulnerable line in Nepalese Power System. Line C has the highest chance of being damaged from an earthquake and this line also contributes a significant amount in reducing the expected resilience loss in the system.

Table 1: Lines and their corresponding address in criticality ranking table

Line	Address
Marsyangdi to Bharatpur (132)	A
Kaligandaki to Butwal (132)	B
Kulekhani I to Hetauda (66)	C
Kusaha to Duhabi	D
Marsyangdi to Suichatar (132)	E
Suichatar (66) to Teku	F
Dhalkebar (132) to Mirchiya (132)	G
Kulekhani II to Matathirtha	H
Matathirtha to Suichatar (132)	I
Gandak to Bardghat (132)	K
Parwanipur (132) to Pathlaiya (132)	L
Balaju (66) to Lainchour (66)	M
Khimti to Lamosangu (132)	N
Chapali (132) to Balaju (132)	O
Lamosangu (132) to Bhaktapur (132)	P
Syaule (132) to Attariya	Q
Mirchiya (132) to Lahan (132)	R
Lahan (132) to Duhabi	S
Dhalkebar (132) to Chandranigahapur (132)	T
Illam (132) to Damak (132)	U
Kusaha to Lahan (132)	V
Shivapur (132) to Lamahi (132)	W
Bhotekoshi (132) to Lamosangu (132)	X
Parwanipur (66) to Birgunj	Y
Suichatar (66) to Patan	Z
Modi to Pokhara (132)	AA
Hetauda (66) to Simara	AB
Patan to Baneshwor (66)	AC
Bharatpur (132) to Damauli (132)	AD
Bardghat (132) to Butwal (132)	AE
Hetauda (66) to Amlekhgunj	AF
Kusum (132) to Kohalpur (132)	AG
Pathlaiya (132) to Chandranigahapur (132)	AH
Chapali (66) to New Chabel	AI
Trishuli to Devighat.	AJ
Damak (132) to Anarmani (132)	AK
Jhimruk to Lamahi (132)	AL
Trishuli (66) to Devighat.	AM
Bharatpur (132) to Kawasoti (132)	AN
Kaligandaki to Syangja (132)	AO
Suichatar (132) to Balaju (132)	AP
Indrawati (66) to Panchkhal (66)	AQ
Syangja (132) to Lekhnath (132)	AR
Lekhnath (132) to Pokhara (132)	AS
Bhaktapur (66) to Banepa (66)	AT
Sunkoshi (66) to Panchkhal (66)	AU
Lainchour (66) to New Chabel	AV
Attariya to Mahendranagar (132)	AW
Pathlaiya (132) to Hetauda (132)	AX
Hapure (132) to Kusum (132)	AY

Similarly, the next vulnerable and critical lines fall in brown zone. There are 4 lines in this area as seen in criticality ranking table. Lines H, F, I, A viz. Kulekhani II to Matatirtha, Suichatar to Teku, Matatirtha to Suichatar, Marsyangdi to Bharatpur respectively fall in brown zone. At this point, the line from Marsyangdi to Bharatpur i.e., line A seems to be the most critical and vulnerable among other three lines. This is because, line A contributes the highest in reduction of expected resilience loss in the system. The probability that this line is damaged due to earthquake is also pretty high. After line A, the next vulnerable and critical line would be line H and F or I respectively.

The next vulnerable and critical zone is yellow. In this zone, it is important to prioritize what is to be considered more important- reduction in expected resilience loss or the probability of the line getting damaged. This zone has a larger number of lines under it. Some of the lines have a very high probability of being damaged in an earthquake event. While the other lines have a huge contribution in reduction of expected resilience loss. While implementing any resilience enhancement strategy in the lines under this zone, it is important to think beforehand what needs to be prioritized more. If the planners want to prioritize the saving in expected resilience loss, line B, D or E, and G needs to be prioritized respectively since they are more critical. Whereas, if the planner wants to focus on the probability of the lines being damaged, other lines in the upper left part of yellow zone needs to be prioritized since they are more vulnerable.

The lines in green zone are considered to be in the least priority for implementation of resilience enhancement strategy if the upgradation of power system needs to be done in a limited budget.

In this way, criticality ranking based on reduction in expected resilience loss and the probability of the lines being damaged is done and it provides a great help in ranking the priority of transmission lines as per our requirements.

7. Conclusion

This paper presents a probabilistic metrics and a detailed simulation approach to quantify the resilience of INPS. The expected resilience loss due to extreme earthquake event is characterized by demand not served. The study is further taken ahead to rank the critical lines in the system. With this information, if in future, there is a limited budget for resiliency enhancement, it can be known which lines to prioritize first. The approach to quantify the effects of earthquake is presented in detail in this paper. From the study, it is observed that making a system resilient will decrease the overall system loss. Few of the resilience enhancement techniques can be infrastructure hardening or implementation of smart technologies in the network. The results from criticality ranking can help in preparing for resiliency enhancement either by hardening such lines or at least preparing a stand by crew members to be dispatched as soon as such disturbance occurs.

Although this paper primarily focuses on the fragility of transmission lines, but the framework can be easily modified to other assets in a power system, such as distribution lines or substations. This framework can also be modified to perform resilience assessment of the system subjected to HILP events such as flood or landslide in case of Nepal.

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