Transmission System Resilience: A Detailed Analysis of Key Factors, Metrics, and Methods

Saranga Abeygunawardane, Visvakumar Aravinthan
Department of Electrical and Computer Engineering
Wichita State University
Wichita, USA
saranga.abeygunawardane@wichita.edu,
visvakumar.aravinthan@wichita.edu

Chanan Singh
Department of Electrical and Computer Engineering
Texas A&M University
Texas, USA
singh@ece.tamu.edu

***Abstract*—Assessing and enhancing transmission system resilience is vital for ensuring an uninterruptible electricity supply during extreme events. Identification of key considerations and suitable metrics or methods can be considered as an essential step in developing more effective frameworks for transmission system resilience evaluation and enhancement. In order to facilitate this, we analyze five factors considered in transmission system resilience namely, the performance of the transmission system, impacts of transmission system outages on consumer wellness, electrical utility's expenditures on damage recovery and resilience enhancement, dependencies between infrastructure systems, and criticality of loads. Further, we examine metrics and methods utilized in existing transmission system resilience studies to incorporate these factors. By identifying existing challenges and providing useful suggestions for future directions, our study contributes to the advancement of transmission system resilience assessment and enhancement frameworks, strategies and decisions.**

Keywords*—*extreme events, key factors, literature review, metrics and methods, power transmission systems, resilience

I. INTRODUCTION

Power transmission systems serve as essential infrastructure for guaranteeing a consistent supply of electricity to power consumers and critical facilities. In case where major power plants in a specific grid fail during an extreme event, its transmission system's ability to transfer power from neighboring areas becomes critical. A failure to do so can result in significant impacts as witnessed in the Texas power outage in 2021 [1]. Therefore, with the increase in extreme weather events, there is a growing emphasis on analyzing and strengthening the resilience of power transmission systems [2].

According to existing definitions, resilience of power transmission systems deals with its capability to foresee, withstand, recover from, and adapt to extreme situations through continuous improvement [2]. Although the definitions of transmission system resilience more focus on the ability of the power system to perform under extreme situations, research on power transmission system resilience considers several related factors [3], [4], [5], [6], [7], [8], [9]. Analyzing such factors along with the metrics and methods used to incorporate them in existing studies is crucial for developing effective methods and frameworks for assessing and enhancing the resilience of power transmission systems.

Although there are many reviews published in the literature, our analysis is different from them. Most of these literature reviews have wide scopes [10], [2], [11]. While reviewing various aspects in power system resilience, [2], [11] and [10] classify resilience metrics used in the both transmission and distribution systems together. However, due to the complexity of power systems it is impractical to assess the resilience of an entire power system, and resilience assessment and enhancement is separately performed for transmission and distribution systems. Factors that need to be considered and most suited metrics and methods to incorporate them can be different for these two functional zones. Resilience metrics used at the transmission level and the distribution level have been separately considered and categorized in the review presented in [12], based on the techniques employed in studies to quantify resilience. Some review papers have more specific scopes [13-15], yet they are different from the scope of this paper. However, none of the published literature reviews conducts a detailed analysis on factors need to be considered in evaluating and enhancing resilience of the either transmission systems or distribution systems, and metrics/methods suit to incorporate them. This paper partly addresses the above-mentioned drawback by limiting the scope of this study to transmission system resilience, but provides a detailed analysis on key factors, and metrics and methods used to incorporate them.

This paper aims to analyze five factors considered in transmission system resilience, together with the metrics and methods used to incorporate them. These factors include the performance of the transmission system, impacts of transmission system outages on consumer wellness, electrical utility's expenditures on damage recovery and resilience enhancement, dependencies between infrastructure systems and criticality of loads. Moreover, associated challenges are discussed and suggestions are provided for future work.

The paper is organized as follows. Section II of this paper provides an overview on factors considered in

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transmission system resilience. Section III reviews existing literature on transmission system resilience, in relation to metrics and methods used to incorporate these factors. In section IV, existing challenges are discussed and suggestions are provided for future work. Section V provides the conclusion.

II. Factors Considered in Assessing and Enhancing Transmission System Resilience

As can be seen in Fig.1 there are five main factors considered in transmission system resilience studies.

1) **Performance of the transmission system**
Extreme events can cause severe damages to various components of power transmission systems such as overhead transmission lines, towers, transformers, etc. Such damages interrupt the performance of transmission systems causing wide spread, long duration outages [16], [17], [18]. Therefore, resilience assessment and enhancement frameworks have given a special attention to quantify and improve the performance of transmission systems, under the presence of extreme events.

2) **Impacts of outages on electricity consumers**
Widespread long duration outages in transmission networks can impact millions of electricity consumers [10]. Commercial and industrial consumers may experience huge financial consequences [19-21], while domestic consumers experience great inconvenience [22]. Such impacts of transmission system outages on electricity consumers need to be considered in transmission system resilience studies.

3) **Electrical utility's expenditures on damage recovery and resilience enhancement**
In transmission system resilience evaluation, the damage caused by extreme events can be assessed in monetary terms using the amount of money that the utility spends on repairing or replacing damaged infrastructure. On the other hand, utilities make investments on enhancing the resilience of transmission systems. It is important to incorporate both of these cost components in resilience enhancement studies, when resilience improvements are traded-off with costs.

4) **Dependencies between infrastructure systems**
Electricity outages due to failures in transmission systems may affect the operation of other infrastructure systems such as water, gas, communication and transport systems. Dependencies between power transmission system and other infrastructure systems need to be considered in transmission system resilience studies.

5) **Load criticality**
Transmission system outages may affect the functionality of critical loads that provide essential medical and other services to the community. Therefore, the criticality of loads connected to transmission systems need to be considered as a key factor.

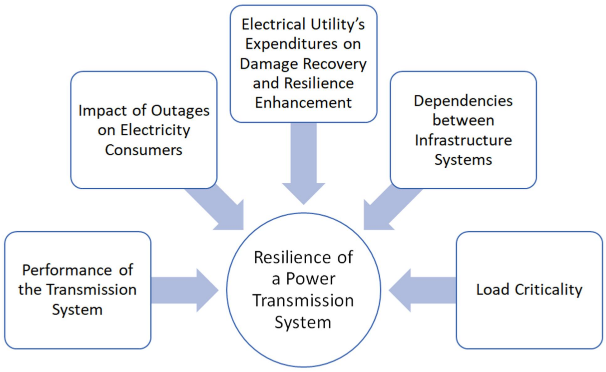

Fig. 1. Factors considered in transmission system resilience studies.

TABLE I. Consideration of Key Factors in Transmission System Resilience Studies

Factor	Evaluation of Transmission System Resilience	Strengthening of Transmission System Resilience
Performance of the transmission system	[23], [24], [25], [26], [27], [3], [4], [28], [29], [30]	[6], [8], [31], [9], [32], [28], [29], [7], [33], [34], [35], [36], [37]
Impact of outages on electricity consumers	[3], [4]	[9], [7], [35], [36], [34]
Electrical utility's expenditures	[3], [5]	[6], [8], [31], [7], [36]
Dependencies between infrastructure systems	[24], [25], [3]	[6], [7]
Load criticality	[23]	[8], [9], [32], [33]

III. Using Metrics and Methods for Incorporating Factors in Transmission System Resilience Studies

In this section, we analyze metrics and methods used to incorporate the above discussed five factors in the literature.

Transmission system resilience evaluation and enhancement studies which consider these factors are tabulated in Table I. This table shows existing trend in incorporating of these factors into existing resiliencestudies.

A. Performance of the Transmission System

As can be seen in Table I, performance of the transmission system under extreme events has been incorporated in many resilience studies. Numerous metrics and methods used to incorporate this aspect can be categorized as follows.

1) Probabilistic metrics: These metrics are widely used in transmission system resilience studies to model uncertainities associated with the failures and repairs of transmission system assets, in the context of extreme events. Three basic categories of probabilistic metrics are employed in transmission system resilience to assess main attributes i.e., the magnitude of load/energy loss, the duration of failure and the frequency of failure [38].

In transmission system resilience evaluation, probabilistic metrics such as "expected power demand not supplied" [3] and "expected energy not served" [29] are used to measure the magnitude of loss of load/energy. In transmission system resilience enhancement, similar metrics namely, "expected unserved energy, weighted expected unserved energy" [8] and "expected load shedding" [31], [37] are employed.

Frequency of outages is quantified in transmission system resilience assessments with the use of probabilistic metrics such as "loss of load frequency" [26], [29] and "time specific interval frequency" [30]. In transmission system resilience enhancement, frequency of outages is not generally quantified.

Transmission system resilience assessments use probabilistic metrics such as "loss of load expectation" [26] and "time specific fractional duration" [30] to measure the duration of outages. Duration of outages is not usually computed in transmission system resilience enhancement studies.

2) Deterministic metrics: As in probabilistic metrics, there exists three categories of deterministic metrics which are used to measure the three attributes related to the performance of distribution systems.

Magnitude of load loss is measured using a deterministic metric "energy not supplied" in resilience assessment studies in [3] and [4] and using "load shedding" in resilience enhancement studies in [34] and [36].

Deterministic metrics are not commonly used to compute the outage frequency and outage duration in transmission system resilience studies.

3) Resilience curves and curve-based metrics: In a resilience curve, the variation of a metric which measures the performance of the transmission system is plotted against time to illustrate how the performance varies during the extreme event and after the event. Transmission system resilience assessment studies in [23], [24] and [25] obtain resilience curves by plotting "power delivered", "infrastructure operational resilience metric" and "power supply level" with time, respectively. Resilience curves in transmission system resilience enhancement studies in [7] and [33] plot the variation of "percentage of supplied load" and "total load supplied", respectively.

A curve based metric estimates a single value to represent a resilience curve. Transmission system resislience assesments in [25] and [27] compute curve based metrics by considering the areas under the real and ideal resilience curves. In [28], resilience is assessed using several curve based metrics which measures "fastness and level of resilience drop", "the duration in the degraded stage" and "rate of recovery". Curve based metrics are not widely used in transmission system resilience enhancement studies.

4) Other metrics/methods: In addition to above discussed categories, several other metrics have been employed in resilience assessment of transmission grids. Transmission system resilience assessment study in [29], estimates the "percentages of offline transmission lines" to evaluate the grid performance. Some new metrics proposed in transmission system resilience enhancement studies are listed below.

- A new index which evaluates the resilience based on the ability to supply critical loads during the extreme event [9].
- A new index which takes a binary value i.e. 1 or 0, based on the capability of the system to supply the maximum loads during an extreme event, without shedding the most critical loads [32].
- A new metric called "resilience achievement worth" which is given as the percentage of the difference between the value of resilience if the system is 100% resilient and the value of its actual resilience with respect to the actual resilience [28].
- New metrics which calculate the percentage decrease in "expected energy not served" and "loss of load frequency", based on the contribution of individual circuits to the overall system resilience [29].
- "Weighted pre-event and post-event performance loss" [35].

B. *Impact of Outages on Electricity Consumers*

Transmission system resilience evaluation studies in [3] and [5] incorporate the impact of outages on consumers using metrics "cost of power load shedding" and "interruption cost", respectively. In addition to this, some transmission grid resilience enhancement studies have incorporated this aspect by including "cost of load shedding" [9], [7], [36], [34] in the objective function or "the value of lost load" [35] in the performance metric.

C. *Utility Expenditures on Damage Recovery and Resilience Enhancement*

Transmission grid resilience evaluations in [3] and [5] attempt to incorporate the utility expenditures on damage recovery and restoration using "asset damage cost" and "mean restoration cost", respectively.

Transmission systems resilience enhancement studies usually consider utility expenditures on resilience enhancement by considering "investment and operation costs" [6], [8], [31], [36], [7] in the objective function. Some such studies additionally include "penalty for not supplying power" [31], [7] and "repair cost" [7].

D. *Dependencies between Infrastructure Systems*

Dependencies between electricity transmission system and other infrastructure systems have been modelled in several transmission system resilience assessments. In [24], dependencies between power transmission system and water system are incorporated by considering "power supplied to water pumps" and "water required for cooling cycle of generation plants" in the resilience metric. The study in [3] models such dependencies between electricity and gas systems considering "power not supplied to gas compressors" and "gas not supplied for generation plants". Dependencies between electricity and communication networks are modeled in [25] by considering the impact of failure of a communication line on the power system and the failure of a power line on the communication system.

TABLE II. ADVANTAGES AND DISADVANTAGES OF METRICS/METHODS USED IN TRANSMISSION SYSTEM RESILIENCE

Metrics/Methods	Advantages	Disadvantages
Probabilistic metrics	• Capable of including uncertainties associated with the occurrence and impacts of extreme events and the demand for critical services • Provide better estimates	• Complex • High computational burden • More time consuming
Deterministic metrics	• Simple and straightforward • Low computational burden • Less time consuming	• Incapable of modelling uncertainties • May lead to over or under assessments
Resilience curves	• Capable of illustrating the variation of the resilience, as the extreme event propagates and the recovery process progresses with time	• Incapable of modelling uncertainties (A deterministic metric is usually used as the performance function.) • Incapable of providing a specific value for the resilience.
Resilience curve-based metrics	• Capable of providing specific values to represent a resilience curve.	• Incapable of modelling uncertainties (A deterministic metric is usually used as the performance function.)
Using weightages to combine several factors	• Capable of adding dissimilar and dimensionally different concerns together to obtain a single metric	• May allow some concerns to dominate • May allow to add measures of different concerns • Incapable of modelling uncertainties (A combined metric is usually obtained from several deterministic metrics.)
Using several metrics to incorporate several factors	• Allow to separately model different considerations	• May redundantly include some considerations more than once

The study in [6] aims to enhance the resilience of transmission systems by replacing overhead transmission lines with underground gas pipes. In this work, the dependency of the power transmission system on the gas network is incorporated by using the investments on gas pipes. The objective function of the model proposed for transmission system resilience enhancement in [7] incorporates the penalty for not supplying power due to failures in the communication system.

E. Load Criticality

Load criticality is considered in the resilience metric of the transmission grid resilience assessment framework in [23] by multiplying the power delivered with weighting factors.

In two transmission system resilience enhancement studies, load criticality is incorporated by allocating weights proportional to the criticality [8], [33]. These weights are used to calculate "weighted expected unserved energy" in [8]. In [33], weights are assigned to each load based on the importance of the load when computing the objective function. In [9], the penalty costs for load shedding is calculated based on the priority of the load. The resilience index is computed in [32] by considering the shedding of most critical loads.

IV. CHALLENGES AND SUGGESTIONS

Challenges identified in relation to selecting and incorporating key factors in resilience evaluation and enhancement at the transmission level are discussed below, along with the suggestions for future work.

- The analysis in this paper reveals that the transmission system resilience studies utilize various metrics and methods to incorporate the performance of the transmission system. Advantages and disadvantages of selecting these metrics for transmission system resilience studies are analyzed in Table II.
- Impact of outages on electricity consumers is incorporated in transmission system resilience assessment and enhancement studies using metrics such as "the value of loss of load" or "the cost of load shedding". These values depend on various factors such as the type of the consumer, the duration of outage, the geographical location etc. Obtaining accurate values to incorporate this aspect in a specific resilience evaluation which leads to important decision making on transmission system resilience enhancement is still challengeable.
- Although resilience assessment studies consider the utility expenditures on repairing damaged transmission infrastructure, many resilience enhancement studies focus only on investment and operational cost that the utility spend on enhancing the resilience of the grid and the penalty cost for not supplying power to consumers. It is important to consider the tradeoff between these cost components with the cost of damages to grid infrastructure caused by extreme events in the absence of resilience enhancement strategies.
- Existing studies attempt to model the dependencies between electricity transmission system and other infrastructure systems such as water, gas and communication systems. However, these studies only consider the dependencies between the power transmission network and one other infrastructure system. Simultaneous modelling of the complex time varying dependencies between the power transmission system and several other infrastructure systems in more accurate and computationally efficient manner requires further work.
- Existing transmission system resilience studies arbitrarily select weightages to prioritize loads based on criticality. Further work is required to develop proper mechanisms to

incorporate load criticality in transmission system resilience studies.

- Existing studies have given a low priority to incorporate consumer perspectives and social equity in transmission system resilience evaluation and enhancement. Although the utilities spend expenditure on enhancing the resilience of transmission systems, that expenditure will ultimately pass on to consumers. Therefore, further discussions are required on the need of incorporating consumer concerns and social equity considerations in resilience studies conducted at the transmission level.

V. Conclusion

This paper highlights the importance of identifying and incorporating key factors in transmission system resilience evaluation and enhancement frameworks. Incorporating all essential considerations using proper metrics or methods is crucial for evaluating transmission system resilience, and making investment decisions on transmission system resilience enhancement, effectively and accurately. This paper examines five main factors, namely, the performance of the transmission system, impacts of transmission system outages on consumers, electrical utility's expenditures on damage recovery and resilience enhancement, dependencies between infrastructure systems and criticality of loads. Further, this work analyzes the metrics and methods used in the literature to incorporate these five factors in transmission system resilience assessment and enhancement frameworks and strategies. The advantages and disadvantages of the metrics used in transmission system resilience studies are analyzed. Existing challenges in relation to incorporating key factors are discussed and suggestions are provided for future work. It has been found that consumer concerns and social equity considerations are not prioritized in resilience studies conducted at the transmission level. This study would provide a better basis for researchers, utilities and policymakers in developing more effective frameworks, strategies and decisions that enhance the resilience of transmission systems.

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