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Resilience Assessment of Electric Power Systems: A Scoping Study

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***Abstract*—Electric distribution planning and research have been focused on the reliability and flexibility of electric supply at the consumer end. Due to increase in weather related outages, natural disaster like hurricanes, earthquake etc. in recent years, ample research has been sprouted to enhance the resilience of the power grid. This paper presents the concept of resilience in Infrastructure systems, measuring methods, framework for developing resilience indices. Additionally, the paper also presents a Resilience Assessment Methodology (RAM) and Model for resilience analysis of Power Systems.**

Keywords—Resilience;threat; Reliability, Catastrophes;Electric Power Restoration;

I. Introduction

The design, maintenance and operation of Electric Power systems has been conventionally driven by crucial reliability principles. This in turn allows the system to deal with known contingencies and threats so as to provide reliable power supply to the consumers on a continual basis. During the last decade, occurrence of several natural disasters such as 2012 Hurricane Sandy, 2011 Japan Earthquake Blackouts etc. and its impact on power systems have forced researchers and power engineers to thing beyond the conventional principles of Reliability for keeping the system secure. In recent years there has been tremendous progress in developing methods for analyzing natural catastrophes related outages in power systems. Due to complexity of the problem and its interdisciplinary approach, research are carried out widely across different disciplines. The paper is structured into six sections. Section I deals with the overview of research. Section II gives a brief description about Concept of Resilience in Power Systems. Section III details about the Resilience Assessment Methodology. Sections IV discuss about Resilience Indices and its Formulation. Section V and VI describes about a Model for Resilience analysis for power systems and Conclusions respectively

II. Concept of Resilience

Resilience refers to "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes ability to withstand and recover from deliberate attacks, accidents or naturally occurring threats or incidents."[1]

Resilience describes the state of the service being provided by the system in response to a threat. The crucial queries while finding resilience would be whether the supply has been disrupted, how much amount of the supply has been disrupted, how fast is the supply restoration. Therefore resilience describes the degree of disruption across multiple dimensions like type, quality, time and geographical location rather than divaricate state of the system [2].

Fig.1. presents a theoretical response of an energy system to a disruption. The Percentage of service provided is shown along the y-axis, which can be measured in terms of electricity delivered, gallons of fuel shipped, economic output generated by energy, or other metrics. The threat could be a natural disaster or terrorist attack. The time of disruption and rate of service decline would depend on the nature of the event, design of the system, and mode with which the system is operated

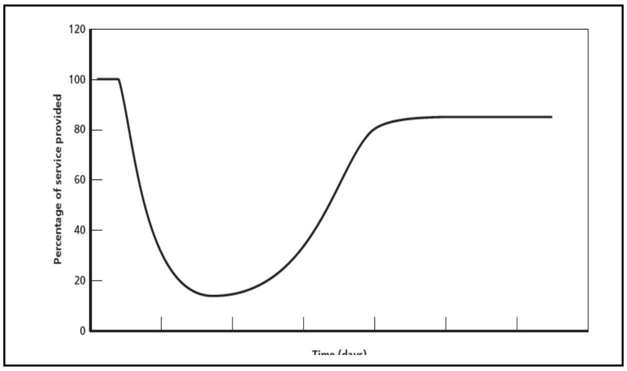

Fig.1. State of service from a system in response to a disruption

The characteristic of the system depends on its design features and by the way it is operated.For example a power system which is designed with more redundancy, operated with multiple faults incorporating a restoration design may experince a lesser disruption so would be more resilient in comparison with other system

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Fig.2. describes a system with different design features like amount of redundancy, back up protection, recovery etc

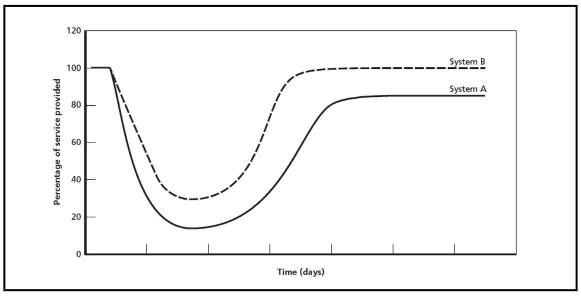

Fig.2. Systems with different Resilience to same disruption

Different inputs or resources may lead to different level of resilience at different costs.

Fig.3. illustrates a system with additional resources which is possible to recover a grid after a catastrophe, with more efficient resources.

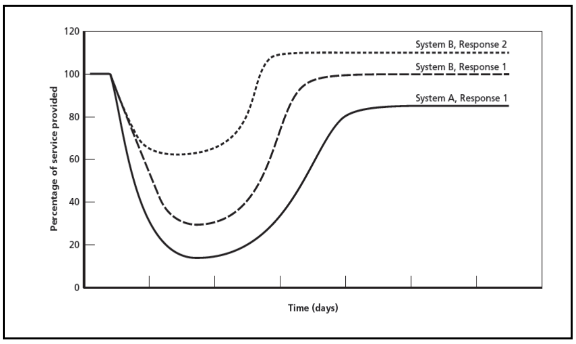

Fig.3. Different responses leading to different Resilience at different costs

The grid may experience repeated disruptions if recovery is not scheduled in time.
If the system is continually maintained and upgraded, the service provided could improve, but at higher cost depicted in response 2 of Figure 2.4.
In case of poor maintenance and upgradation, operation cost might be decreased but output service will eventually decline with time as shown in response 3.

Fig.4. shows the timescale property of Resilience, incorporating the maintenance and upgradation of the system.
Finally, resilience of a system also depends on the timescale behavior.

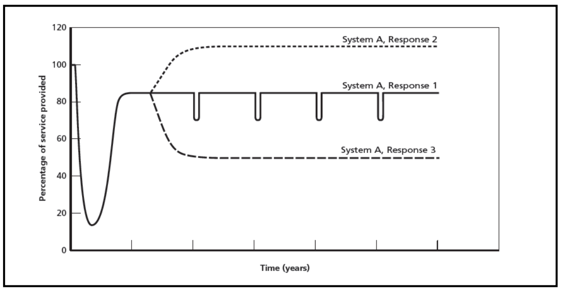

Fig.4. Time dependence of Resilience

III. RESILIENCE ASSESSMENT METHODOLOGY

The Resilience assessment methodology (RAM) can be used for performing base case resilience assessment. Fig.5. depicts the RAM methodology.

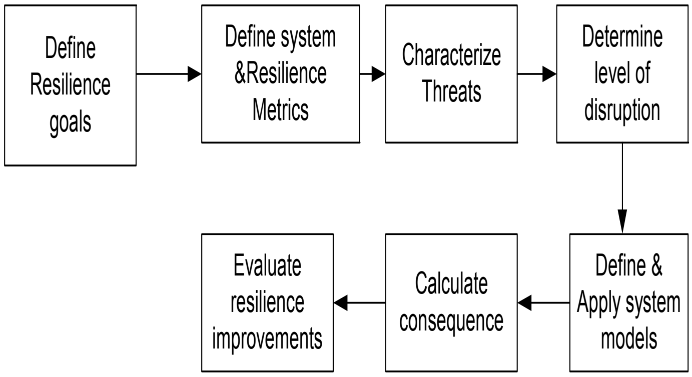

Fig.5. Resilience Assessment Methodology

IV. RESILIENCE INDICES

Power Grid resilience Indices are different from traditional reliability Indices in the context of decision control architectures.
Because the grid, due to growth of renewable and demand, is operating closer to feasibility boundaries, series outages are more likely to cause major blackout. At present, the requirement power systems are to be N-1 secure, capable of absorbing the loss of a single component.
The metrics for resilience of energy systems, natural gas and oil distribution systems are generally not standardized and pressure on how to measure these are lacking. Risk based metrics can be used to assess and measure the progress of ability to plan, operate and recover from weather disasters. Decision support tools incorporating resilience metrics are helpful for public utility commissions and other regulators in making infrastructure investment and rate recovery decisions. Resilience indices take the form of a probability density function (PDF) of the consequence of interest [3]-[5]. There are different approaches for obtaining the PDFs with varying levels of complexity. Figure shows a PDF expressed as probability of consequence versus consequence.

The indices are used to measure both system resilience to extreme events and different investment scenarios for resilience improvement.

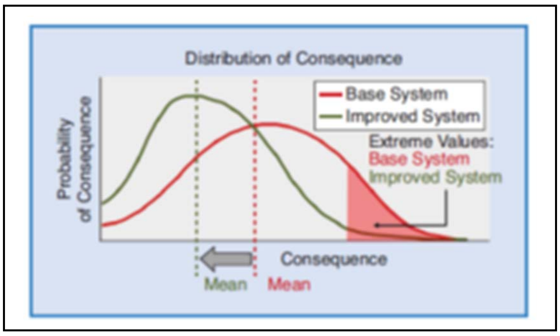

Fig. 6. PDF representation of resilience metric

A. A Framework for formulating Resilience Indices

The framework of a Resilience Index is defined as "the probability of consequence X given threat Y". The framework is independent of type of threat or consequence.

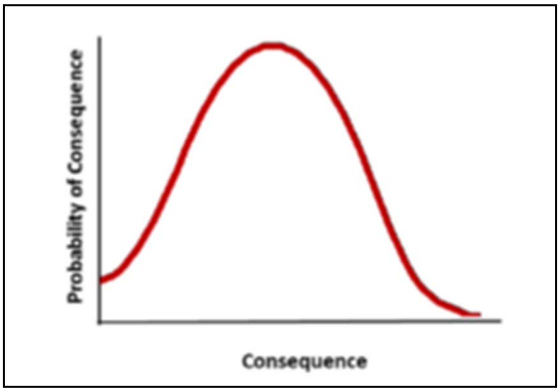

Fig. 7. Probablity distribution of specific consequence to specific threat

Resilience Indices must accomplish certain key aspects. Following are the means for formulating resilience index.

- Useful in decision making, computational analysis, real time operations etc.
- Mechanism for comparison, when applying a same index to different systems.
- Usable in operation and planning and must be able to judge decisions both in preconfiguring an hazard and planning.
- Development of indices in the framework must be both quantitative and qualitative.
- Index must reflect the uncertainty in the system.
- Indices must highlight, reflect a typical threat oe set of threats, vulnerability and implications on the consumers.
- Resilience indices must incorporate recovery time of the outage.

B. Typical Resilience Indices

1. Lost Revenue Impact (LRI): It represents an economic index that indicates utility's lost revenue.

$$LRI = \sum_t \sum_j C_j (PL^U{}_j - PL^D{}_{j,t}) \times \Delta t \qquad (1)$$

where

$PL^U{}_j$ = *peak load under normal conditions, for j^{th} load*

$PL^D{}_{j,t}$ = *peak load after t^{th} recovery step is completed for j^{th} load*

Δt = *duration of t^{th} step*

C_j = *weighting factor for j^{th} load*

2. Total Restoration (TR):It includes the total resources spent during recovery process, that follow a disaster.

$$TR = \sum_t \left\{ \sum_i \left\{ \begin{array}{l} LC_i \times L_{i,t} + \left(\sum_k UC_k \times R_{pk,t} \right) \\ + \left(\sum_m \left[C_{m,t} - C_{m,u} \right] \times P_{m,t} \Delta t \right) \end{array} \right\} \right\} \qquad (2)$$

where

LC_i = *labor cost in category i per hour*

$L_{i,t}$ = *labor hours worked by person m in category i, during t^{th} repair step*

UC_k = *cost of replacement part in category k*

$R_{pk,t}$ = *amount of replacement parts in category k used in t^{th} repair step*

$C_{m,u}$ = *operating cost of generator under normal condition*

$C_{m,t}$ = *operating cost of generator during t^{th} time step*

$P_{m,t}$ = *hourly power generated by generator m during t^{th} time step*

3. Recovery Resilience(RR): It represents the total effect of the natural disaster on the utility. It results from a particular control algorithm. A weighting factor is used to set the relative preference of LRI and TR.

$$RR = \frac{LRI + \lambda \times TR}{\sum_{t}\sum_{j} C_j (PL^{U}{}_{j})\Delta t} \qquad (3)$$

where

$\lambda = weighting\ factor\ indicating\ the\ relation\ between\ delivered\ powe$

$and\ recovery\ resources$

$\lambda \prec 1;\ priority\ is\ for\ power\ delivered\ to\ load$

$\lambda \succ 1;\ priority\ is\ for\ recovery\ resourses$

$\lambda = 1;\ both\ are\ equally\ important$

V. Model For Resilience Analysis of Power Systems

This section describes a model to evaluate how the priority of recovery tasks and recovery resource constraints affect resilience of power systems and their restoration following a disruption.

A disruptive event that exceeds the N-1 condition; e.g., a hurricane, earthquake etc. that physically compromises the functionality of several components Power system. These components could be generators, transmission lines, substations, transformers, or other equipment contributing to the overall performance of the power system. Multiple components are assumed compromised, as is true in major power disruptions.

The initial physical insult can lead to cascading failures that affect the functionality. Tripped circuits and line failures are examples of cascading failures.

Upon recognition of the disruption, the utility may take actions to limit the cascading failures.

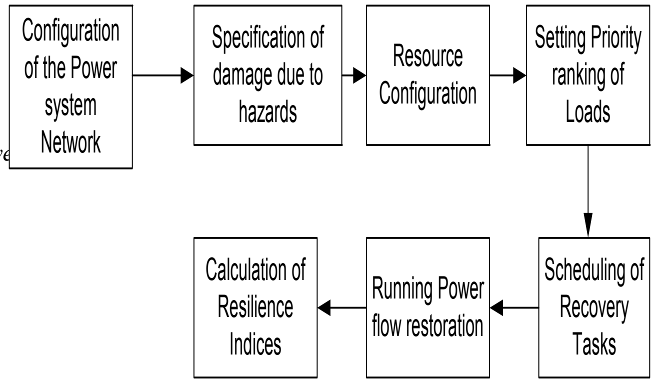

Fig. 8. Flow diagram for Power Restoration

VI. Conclusion

This paper presents the concept of Resilience for Critical Infrastructure systems along with Resilience assessment Methodology. A framework for development of Resilience Indices has been described along with a Model for Resilience analysis of Electric Power Systems. This methodology can be used as a reference for developing catastrophic resilience studies, as it discusses and incorporates the key features for analyzing the effect of natural disasters on Power System Resilience.

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