A FrameWork For Resilience Performance Analysis of An Electrical Grid

Dilshad Ahmad
Dept. of Electrical Engineering
Indian Institute of Engg. Science & Technology, Shibpur
Howrah, India
dilshad1401@ymail.com

Chandan Kumar Chanda
Dept. of Electrical Engineering
Indian Institute of Engg. Science & Technology, Shibpur
Howrah, India
ckc_math@yahoo.com

***Abstract*—Dynamic and diverse disruptions are continuously challenging the functionality of Electrical Grid. Climate change and integration of modern communication technologies in the grid raises new challenges, and past few year events highlight the need to address these challenges especially for the electrical power distribution system. Quick recovery of the grid after an outage is vital in order to minimize its economic, social, and political impacts. Resilience is the terminology that evaluate response and recovery process. This paper proposes a framework for the resilience performance analysis of the electrical grid considering different aspects that evolved around the response of the grid against any kind of disruption. The quality of the outcome after response and speed of the response is affected by the cause of disruptions, need of resources to response against disruptions, the capability of the resources and its performance. Speed and quality of the response are the most used measure of resilience. Relevance of the aspects that considered in the framework is also the part of this study.**

Keywords—distribution system, disruptions, electrical grid, framework, outcome, performance, power outage, relevance, resilience, response,

I. INTRODUCTION

Electricity system is developing from the last century. It has become a measure of economic and social growth of a country. Unscheduled outage due to damage of electrical grid (transmission and distribution) is one of the major obstructions in development of a country. It is expected that the power grid can quickly recover with minimum damage after any schedule or unscheduled outage. Tropical storms, earthquake, tornado, flood, equipments failure, supply shortage, voltage reduction, volunteer reduction are some of the major cause of electricity outage. These events are affecting economy like USA, India heavily. A recent White House committee on science and technology estimates the cost of severe weather-related outages at an annual average of $25 to $70 billion [1]. So resilient grid is the necessary for sustainable development.

Modern smart grid phenomenon evolves both transmission and distribution systems. Moreover, distribution networks historically are behind transmission networks in terms of observability and monitoring system deployment. Resilience analyses need more attention in the area of distribution systems.

Electrical power grid infrastructure and its interactions with biophysical environment within which it operates is a factor of importance [2]. Damage due to outage depends upon length of interruption [3-6], time of day, day of the week, and time of year [4]. Literature [7] Show that outage duration is strongly correlated with the shocks that cause outages. Factors affecting outage duration has primarily involved storm winds and earthquakes [8-11]. Transmission lines, substations, protective devices, and service transformer and environmental conditions (i.e. population density and land cover) are also important factors [12]. Such diverse disruption and its impact is the motivation behind this proposed work.

Economy and safety are two major aspects that help in defining quality of the power system. Productive and protective aspects are two ways of looking into safety . Whereas protective safety is based on protection and prevention against harmful events, productive safety look into the cause of harmful event and system ability to produce acceptable outcome.

The word resilient derive from Latin word resilio which means 'to bounce back'. The resilience analysis definition evolved and expanded across the field over a period of time [13-20]. In 2013 White House defines 'Resilience is the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. . . . [It] includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents'.

There are different perspectives to look on resilience measure. For a state resilience measure with economic perspective has more important where as for a utilities the perspective of availability of backup power has more importance. There are different levels of decision making and no single set of metric can support need of all. But across all level of decision making the metric ought to be organized within a considerable measurement framework.

There are many kind of events (storm, earthquakes etc.) that causes damage to electrical grid. Each event needs some expertise to deal with it. Single metric cannot explain resilience corresponding to each event. Different kind of metric are present for resilience analysis based on different functionality. The proposed framework has objective to choose metrics on the basis of events to study the resilience performance.

The proposed framework consists of event list for which utilities has prepared response, recourse management allocation for the corresponding event, capability of the resource, threshold point of response initiate and response end, performance of the system corresponding to response, outcome

978-1-5090-0035-7/16/$31.00©2016IEEE

and verifications. Relevance is the another important aspect of the whole preparation that is a part of framework. Under these five major blocks the framework included all kind of aspect related to electrical distribution system like economic, monitoring, human resources, environmental, traditions.
The rest part of this paper is organized is as follows.

- The cause of outage is explained in section II
- The framework itself is explained in section III.
- In section IV different kinds of metrics has been reviewed.
- A case study to explain the importance of decision making on IEEE 9 bus system is performed in section V.
- Section VI concludes the paper.

II. CAUSES OF OUTAGE [21]

A single event has capability to create major disturbances in the grid but blackouts are not the results of single event and deficiency but the combination of several deficiencies. The following preconditions are the basis for a high power outage risk:

- High loadability limit or High grid utilization
- For better unit commitment and optimal power flow
- Defects due to ageing infrastructure

Under these above mentioned conditions grid vulnerability increases. Now the likelihood of a power blackout for following event is very high:

- Power plant shutdown due to capital maintenance or preventive maintenance or due to supply failures (e.g. cooling water shortage during heat waves)
- Operating personnel failure during maintenance work or switching operations
- Simultaneous grid interruption e.g. short circuit caused by tree contact, excavation work, balloons drifting into power lines, cars hitting utility poles, provisional shutdown due to electrical overloading risk
- Sudden demand of load growth
- Power line and its related electrical equipment may go under breakdown due to natural calamity (e.g. storm, earthquake, snow or ice load, flood, lightning, extreme temperatures)
- Lack of communication between transmission/distribution system personnel and power generation company
- Intentional Cyber attacks

III. THE FRAMEWORK

The literature on RE shows that there are many different opinions about the 'phenomenology' of resilience – which characterizes resilient performance [20]. So instead of considering what resilient performance is, the proposed work considers what enables resilient performance, what makes it possible-and conversely what would make it impossible, if it was missing. This explains the philosophy of the motivation of proposed framework. The proposed framework considered the diverse aspect of power systems disruption and functionality. The first block diagram events set the base for the framework. Other blocks of the framework explain the characteristics of the grid on the basis of choosen events . Since power grid has diverse and continuous challenges as explained in section II it need an organized structure to deal with it. This is what motivated the authors to prepare a framework. In the frame work each block is based on some rational questions on the basis of which required action is to be taken to fulfill the resilient grid objective.

There are two ways of making a framework ; one is strategic in which resources are managed for desire outcome and another is operational in which based on available resources outcome desired. In this thesis mostly strategic perspective is considered because the economy like USA, India, China not only has wide resources but also has the capability to manage the required resources.

A. Events: Background

What are the events (primary causes of outage like tropical storm) for which the utility has a prepared response? How these events were selected (experience, expertise, tradition, regulatory requirements, design basis, risk assessment, industry standard, etc.)

B. Resource Allocation:

In this section the resource allocated for the event response is to be studied. Budgets, number of generators available, man power, smart-grid tech, and question related to monitoring system can be asked in this section. In this section utilities special arrangement for particular event is of major attention

C. Capacity & Capability:

Capacity defines the organized structure of the allocated resource. Type and intensity of the damage to the grid depend upon kinds of event. The capability of allocated resource to handle the event specific damage to grid is desirable. For the event of storm the required capabilities for response is different than in the event of cyber attacks.

D. Threshold:

When is a response activated? What is the triggering criterion or threshold? Is the criterion absolute or does it depends on internal / external factors? Is there a trade-off between, e.g., safety and productivity? Are some important that is associated with this section.

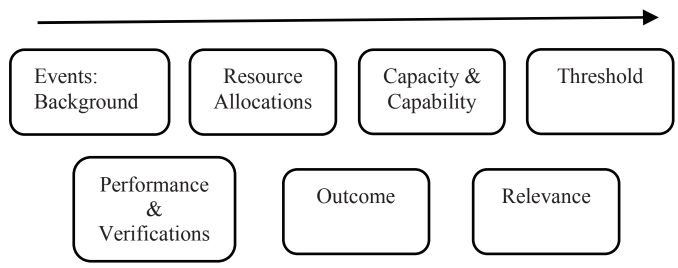

Fig. 1. The Framework

E. Performance and Verification:

This block is dedicated to the analysis of the produce result. After an event recovery does not imply perfect restoration of the system functionality rather it implies that system has returned to a state where it is considered functional. Efficiency, reliability, fault tolerance, robustness are some performance Characteristic measures, which are helpful in verification of the data.

F. Outcome:

The performance through prepared response is acceptable are not. How much system generated the outcome that was seeking to achieve. Reduced damage from disasters, increased economic activity is some measure of outcome.

G. Relevance:

This is the beauty of proposed framework which allow utilities itself to raise question upon his preparation. the most important question that when the response was prepared, when last time it was updated?, And under which circumstances? This analysis provides the ability to learn, to power distribution system.

IV. METRICS

The each block of the above framework has individual characteristics that can be used for resilience metric but that is not enough to make the system resilient. A set of metrics is needed to explain different kind of characteristics at different level. 34 metrics are found in the literature for electrical system with different level of maturity. For this paper only those metrics are reviewing which collected using well-defined methods and at the appropriate timescale. In Table I we listed some references corresponding to the framework blocks. The references that we listed are not only related to electrical grid but also include the wider aspects of the electricity system.

TABLE I. Metrics

Framework	References
Event and Allocated Resource	[22-34]
Capacity and capability	[22], [24-27], [31], [34-45]
Performance and verification	[22], [25], [27-31], [36], [38], [41-42], [45-55]
Outcome	[22], [27-29], [34], [37], [45], [53], [55-58]

V. CASE STUDY

The case study presented here is with the objective to explain the importance of decision making in restoration of line after an outage of several lines. The considered system is IEEE 9-bus test system that represents a portion of the Western System Coordinating Council (WSCC) USA. Fig. 3 shows the grid operation as a function of time. Y(t) is a performance indicator over a period of time. At t_0 system is operating in normal condition. At t_i fault is initiated and at time t_c system completely loss its functionality. t_m is the time at which restoration process started. At t_s system is fully restored. System is fully restored does not mean perfect restoration. It implies that the system has returned to a state where it is considered functional.

Line power flow and bus voltages are two primary functional indicators in power systems. For this objective any one of them is enough to study. Here voltage at load buses are taken as functionality indicator of performance. Voltage violations is observed by carrying out contingency analysis by causing the outage of three transmission line on a common bus. In this paper the most severe failure is study, by causing outage of lines (2-7), (5-7) and (7-8) at common bus 7. In the system seven voltage violations has been noticed. In this case study two decisions for restoration is analyses.

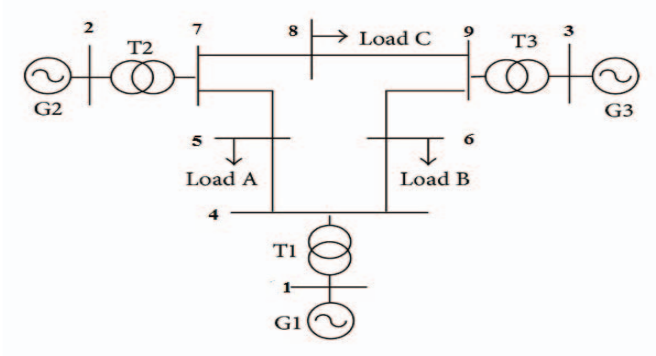

Fig. 2. IEEE 9-bus test system

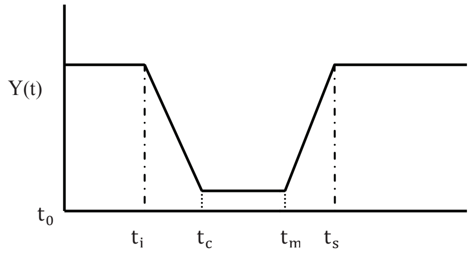

Fig. 3. Grid operation over time

Decision 1: Restore line 7-8 first then 5-7, and 2-7 respectively

Decision 2: Restore line 5-7 first then 7-8, and 2-7 respectively

In this case study it is assumed that only one line can be repaired at a time. First repair started at t_m whereas t_1 and t_2 are other lines repair initiated time. It is also assumed that each line repair time is equal.

TABLE II. Case study

Function(Voltage) At Load Buses		At time					
		t_0	t_c	t_m	t_1	t_2	t_s
Decision 1	5	0.9956	0.9503	0.9503	0.9979	0.9924	0.9956
	6	1.0127	0.9924	0.9924	1.0062	1.0107	1.0127
	8	1.0159	0.9669	0.9669	0.9710	1.0039	1.0159
Decision 2	5	0.9956	0.9503	0.9503	0.9522	0.9924	0.9956
	6	1.0127	0.9924	0.9924	0.9963	1.0107	1.0127
	8	1.0159	0.9669	0.9669	0.9918	1.0039	1.0159

The repair of all three lines completed at t_s. From Table II comparing the two decisions at time $t_1$we find that for decision 1 after restoring line 7-8, the voltage at the load buses 5, 6 and 8 restored to and 0.9710 pu whereas for decision 2 after restoring line 5-7 first the voltage at load buses 5, 6 and 8 are 0.9924 pu, 1.0107 pu, and 0.9918 pu respectively. So decision 1 is suitable for load A and load B at bus 5 and bus 6 whereas for load C at bus 8, decision 2 is better. Load prioritization is very important aspect of distribution system. If we look at the voltage build up at bus 8 (load C) for decision 1 at time t_1 when line (7-8) is recovered, voltage is 0.9710 pu. Whereas for decision 2 at time t_1 when line (5-7) is recovered, voltage is 0.9918 pu. So decision 2 is better for load C because within time t_1 it is able to recover 0.9918 compared to 0.9710pu of decision 1 in other word speed of restoration is faster for load C for decision 2 and speed of restoration is one of the most used notion for resilience, so in one sense the decision making, resilience analysis can be utilized for line outage. From this study it clearly reveals that speed of restoration (most used notion for resilience study) is much depend upon decisions of utilities. There are many factors which affect decision making, are part of proposed framework. Availability of resources, their capacity and capability and previous performances play important role in decision making too.

VI. CONCLUSION AND FUTURE PROSPECTS

Electrical infrastructure is the most critical infrastructure and is in centre in policy making of the countries. Events are inevitable and because of its century old history it is not possible to completely change the whole infrastructure. So to make electrical grid more resilient under these circumstances this paper provides a sustainable framework. This framework gives importance to the almost every possible aspect that help in improving the grid performance. This framework talks about an organized resource with special attention to the specific events and also does the critical assessment of its own work. The proposed framework talks about the broader aspect of resilience in term of its outcome. Relevance is the backbone of this framework which allows the grid to have ability to learn. This paper also explained the importance of load prioritizations during restoration through a case study, which is one of the most important aspects of distribution system.

Government of USA and many European countries has accepted resilient critical infrastructure (i.e. power, water etc.) as the theme of the current decade. On the basis of various aspects that is explained in the framework, utilities and academic can study the current scenario which will be helpful in future events. This framework can be used by utilities to create database which will be helpful in the event of failures. The database can have prepared response based on events.

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