ESTIMATING RESILIENCY OF ENERGY DISTRIBUTION SUPPLY CHAIN BY MONTE CARLO SIMULATION

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ABSTRACT

Reliability indices of power transmission and distribution networks are among the most important parameters which are controlled by distribution system operators. However, the sustainability of the supply in disasters cannot be deduced from reliability metrics. In these cases, resiliency indices can represent the continuity of supply in complex systems such as power distribution networks, when they are subjected to natural disasters such as earthquakes, hurricanes and floods as well as technical incidents like cascading failures in power transmission and distribution networks. In current study, we developed a practical method which can be used to estimate resiliency of power distribution networks.

INTRODUCTION

Natural, Political and economic disasters as well as technical incidents can disrupt normal flow of electricity in a grid. These events have major impacts on company profitability and customers' satisfaction. Thus DSOs should find a way to circumvent disruptions and minimize their impacts on the power delivery. Sustainability of electricity supply chain hinges upon three factors: first, reducing the rate of failure (improving reliability). Second, minimizing the number of customers or activities affected by a disruption (reducing vulnerability) and increasing the ability of the supply chain to cope with a disturbing changes (enhancing resiliency). Supply chain experts have developed a few approaches to improve resilience of a supply chain. Majority of them are based on five concepts: 1- Defining strategic priorities 2- Identifying vulnerabilities of supply chain 3- Proactive action in design and utilization of supply chain components to reduce the length of time and the extent of post-disaster recovery 4-Monitoring resiliency of supply by comparable metrics 5- Being aware of warning signals and carrying out proactive actions to reduce extent of disasters.

The metrics describing the resilience of electricity supply chain are not easy to acquire because there are many factors that affect the time needed to restore a disrupted grid. Analytical methods and simulation are two main approaches used to define and estimate metrics. In analytical methods these metrics are found by identifying and understanding the effects of each factor and interrelations among them. On the other hand, simulation is the imitation of the operation of a real-world system. It needs a model representing the key characteristics or behaviors of the selected system. Although the analytical approach gives a real insight into the factors affecting metrics, it is not possible to develop a practical framework for such a complex problems. Monte Carlo simulation chosen for estimating resiliency indices of electricity distribution supply chain in current study relies on repeated random sampling to obtain numerical results.

In current study, a small part of a power distribution network was selected and disaster scenarios were generated in selected area. Then, the time needed to restore the grid after the emergency events in each scenario was estimated. Finally, the result of simulation was analyzed by statistical techniques. The confidence interval of mean and median and quantiles reflect the resiliency of the grid. This metric can be used in two main applications. The first one is comparison between two grids to identify which one is more resilient and the second one is decision making. When a DSO decided to expand its grid, buy electricity from new producer or enter a contract with a large customer, it is possible to evaluate resiliency of the grid before and after the changes and take corrective actions to maintain or improve the resiliency index.

RESPONSE TO THE RISKS IN POWER DISTRIBUION SECTOR

Risk is defined as the "effect of uncertainty on objectives". Resiliency study is one of the most important aspects of the modern risk management. Any sustainable organization should identify its business risks and chose one of the following responses properly:

1. Ignore or accept the risk.
2. Reduce the probability of the risk.
3. Reduce or limit the consequences.
4. Transfer, share or deflect the risk.
5. Make contingency plans.
6. Adapt to it.
7. Oppose a change.
8. Move to another environment [1].

DSOs have to identify and prioritize the risks. If their expected impacts are negligible due to small probabilities and/or consequences, the cost of remedial action is become economically unjustifiable. Therefore, even the most risk-averse organizations accept some risks.

Distribution system operators normally cannot reduce the probability of risks but they can limit their consequences. For instance, DSOs strengthen their infrastructure in the flood plains. In addition, they can share the disastrous risks with other organization such as transmission system operator (TSO) and municipality. Contingency plans are solutions which are used after the disaster actually occurs. Thus DSOs prepare plans for alleviate the probable events that can disrupt their services. DSOs can adapt to this risks if they are agile enough to respond to changing condition [1]. The risks which are related to power distribution are normally natural like earthquake and flood, so it is not possible to oppose them. DSOs have to work in predefined regions and cannot change it even if something threats the sustainability of energy supply in their domains.

RESILIENCY IN POWER DISTRIBUTION

"Ability of an organization to anticipate, prepare for, and respond and adapt to incremental change and sudden disruptions in order to survive and prosper" is definition of "organizational resilience" in British Standard, BS 65000 [2]. The operations of the power distribution infrastructure are interdependent. Therefore, disruption cascading effect will increase the time needed to network restoration. In addition, natural disasters like earthquake and flood damage not only power transmission and distribution networks but also roads, communication links and other facilities which are needed for service recovery.
Pommerening [3] has compared resiliency and protection. The summary of this comparison can be seen in Table 1.

Table: differences between protection and resiliency[2]

Aspects	Protection	Resilience
Activity planned	Hardening structures	Redesigning processes
Subject focus	Asset-driven	Services-driven
Value proposition	Cost-centred	Benefit-centred
Network character	Insulated	Interdependent
System coupling	Loose	Tight

Distribution system operators like other organizations should enhance the resilience of their operation by a proper proactive approach. Therefore, they should be aware of their risks, vulnerabilities and their current capabilities to deal with them. Private sectors are in charge of expanding and utilizing the power distribution network. Therefore, investment in the grid relies on pragmatic reasons. There are three crucially important questions required quantified measure of resiliency. First, how does a distribution system operator know that the resiliency of distribution network needs improvement? Second, how can the DSO justify the expense of improving resiliency and finally, how can the DSO choose optimum solution with limited resources. The solutions of these questions are based on metrics that show resiliency of the grid [4].
There are many factors that have significant impacts on resiliency. Consequently, obtaining the metrics is complicated procedure. The approaches which are used to acquire resiliency metrics categorized into two groups:
1- Analytical methods which are based on identifying and understanding the effect of each factors and interrelation among them.
2- Simulation methods that imitate the operation of a real world system over time. In current study Monte Carlo simulation was chosen for calculating resiliency indices.

MONTE CARLO SIMULATION

Monte Carlo simulation is a computerized mathematical technique. In this approach, the factors that have inherent uncertainty are identified and a model that can show the relations between factors and results is developed. In the next step, a range of value is generated for each factor based on probability functions, and then the results of the model for each set of value are calculated. The calculations are performed for each set of value. In this procedure, the possible results of the model are obtained. Finally, the probability of each possible result is calculated. The calculation may be performed tens of thousands time if the number of uncertain factors or the ranges specified for them are considerable.
Monte Carlo simulation has many advantages that can be useful in estimation of resiliency indices in the power distribution network. First, Monte Carlo simulation is very flexible. When a proper model for resiliency problem is developed we can modify the relation between the factors and the level of factors uncertainty in order to estimate the resiliency after network expansion, reconfiguration or reconstruction as well as changing the network utilization policy. Second, it is possible to perform sensitivity analysis and determine which factor has the biggest impact on resiliency of the grid. Finally, the result of simulation not only shows the most probable outcome but also determines the probability of other results. In addition, the output of simulation can be shown graphically.

MATHEMATICAL MODELS OF THE NETWORK RESTORATION

In Monte Carlo simulation, hundreds or thousands scenarios are generated. In each scenario, the damaged components should be found and repaired optimally. There are many issues that should be considered in the mathematical modeling of network resiliency:
1- The subtransmission and distribution network is a graph. Substations, transformers and switches are vertices and cables and overhead lines are edges of this graph.
2- When the power flow in this graph is disrupted, some of these edges and vertices should be checked because the roots of the disruption can be located in these places. Sometimes, the damage happens in only one edge or vertices and other parts of network are intact but in the major disasters, many parts of grid are adversely affected.
3- The control room engineers usually don't know the exact place of damaged network components. Therefore they send a field crew to check the place where the probability of failure is high enough. They prioritize the field crew schedule based on historical failure rate, customers' calls and the time needed for reaching to that place, repairing or replacing damaged components. When all damaged components are repaired/replaced and energy distribution is completely restored it is not necessary to inspect other part of the grid.

4- Sometimes, a field crew cannot find or repair damaged parts and network control engineers send expert team with special equipment. For example, skills, practices and tools which are needed for maintenance of subtransmission substations are different from maintenance of underground distribution cables. Therefore, the workload of field crew is not equal in the disasters.

Mathematicians have introduced two problems that related techniques can be used for estimating restoration time of power distribution networks after disastrous events. The Vehicle Routing Problem (VRP) which is a set of problems focused on services to vertices is the first one. The standard problem is the generalization of famous travelling salesman problem (TSP) and for the first time appeared in a paper by George Dantzig and John Ramser in 1959 [5]. The main question of this problem is "What are the optimum routes for a fleet of vehicles to service delivery in predefined nude?" and can be solved by integer programming and combinatorial optimization. The objective of standard VRP is to minimize the total route cost and studies showed that it is NP-hard problem. The second class of problem is Arc Routing Problem (ARP). Services in arc routing problems are distributed in through edges instead of vertices. A subset of graph edges that required services are selected and the objective of standard ARP is finding a route that includes the selected edges while minimize unnecessary movement. In network restoration problem, city streets are edges in the graph and the streets that the failed cables and overhead lines systems located on them are selected edges that required services. It is obvious that both vertices and edges in power distribution grids need attention after disasters. In other words, the optimum solution of distribution system restoration must be encompass visiting certain vertices (substation, transformers and switches) as well as traversing certain edges (cables and overhead lines) by proper field crew. When distribution network is completely restored, the vertices and edges in the service queue are simply ignored. The General Routing Problem (GRP) which is combination of VRP and ARP can be modified to find near-optimal solution. The probabilistic model of power distribution system restoration after disastrous evens is rather complex and cannot be explained in current paper. However, it was used to find near-optimal solution in each scenario.

METHODOLOGY

The procedure of estimating resiliency indices can be divided into five steps:

1- Selecting scope of study: resiliency analysis of the whole distribution network which includes thousands of transformers and hundreds of thousands of consumers cannot be performs in monolithic model. Therefore, it is necessary to neglect less important details.

2- Defining multivariate probability distributions and describing the dependency between random variables which are related to network components failure in disasters. Sometimes, this step is omitted because there is not enough data to fit probability distribution to historical data. When we have not historic data, we cannot compare resiliency of two different grids but it is possible to compare resiliency of same network after modification.

3- Generating disaster scenarios.

4- Finding near optimal solution for network restoration for each scenario by solving stochastic GRP.

5- Statistical analysis for estimating resiliency metrics. Mean and median and %90, %95 and %99 percentiles are main metrics used to evaluate resiliency of power distribution systems. These percentiles shows that the time needed to restore distribution services in the selected percentage of scenarios. The combined resiliency index is a weighted sum of three selected percentile indices and system restoration mean time and system restoration median time.

The more resilient system has smaller resiliency indices. In addition, the mean and median confidence intervals play an important role in comparing resiliency of two different grids or comparing two utilization strategies of a same grid. If the mean confidence intervals of two systems overlap each other, there are not enough evidences claiming meaningful difference between resiliencies of these systems. The same idea is valid for median confidence intervals

CASE STUDY

In current paper we selected small portion of power distribution network that includes one 40MW central subtransmission substation, 13 medium voltage feeders and three adjacent subtransmission substations. Although these medium voltage feeders usually are supplied with central substation, it is possible to supply them with adjacent substations if it is necessary. In addition, there is not a distributed generation (DG) unit in this area but we added two 1MW DGs to increase the complexity of the model. These 13 medium voltage feeders supplies hundreds of transformers and tens of thousands of residential and commercial customers. The scope of this study is limited to medium voltage level. Five hundred scenarios (Table 1) were generated and the near-optimal system restoration solution was generated for each scenario. The resiliency study was performed for original network and current utilization program as well as modified utilization strategy including vendor managed inventory and using trailer mounted diesel generators.

The T (Time) which was used in statistical analysis is the time needed to restore medium voltage feeders to normal condition. In other words, medium voltage feeders and all intact transformers are completely energized or their customers supplied with diesel generators.

Table 1: Part of generated scenarios

Scenario number	% damage feeder 4	% damage feeder 5	% damage feeder 6	% damage feeder 7	% damage feeder 8	DG1 condition	Main subtransmission	Adjacent subtransmission 1
121	0	2	0	0	0	Failed	Normal	Normal
122	3	0	0	2	2	Normal	63kV line1 failed	63kV line2 failed
123	0	0	0	0	0	Normal	Transformer1 failed	Normal
124	3	7	2	0	1	Normal	Normal	Normal
125	0	3	0	0	2	Failed	Normal	Normal

RESULT

In figure 1, figure 2 and table 2 are the results related to original and modified utilization approaches.

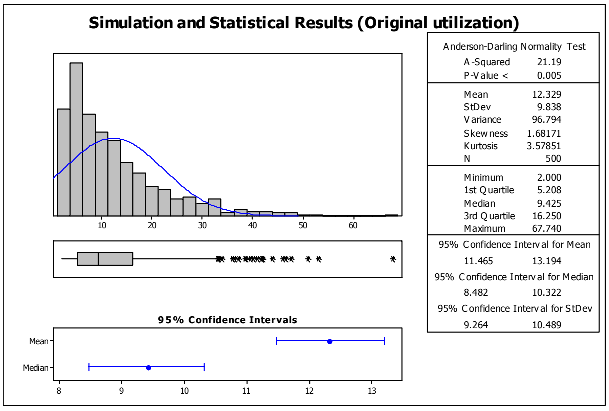

Figure 1: Simulation and statistical results of original utilization approach

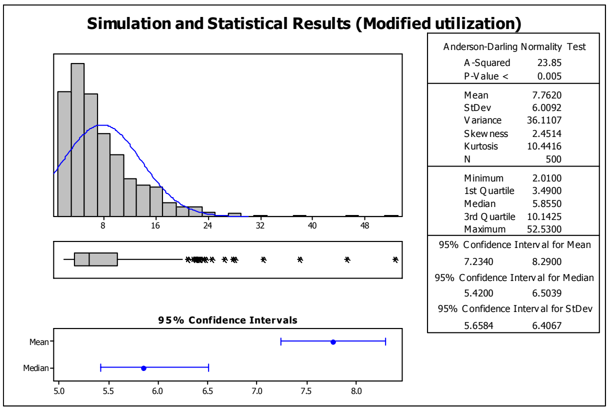

Figure 2: Simulation and statistical results of modified utilization approach

Table 2: Resiliency metrics of power delivery with original and modified utilization approaches

Resiliency Indices (The smaller, the better)	**Original**	**Modified**
90% Percentile (In %90 of scenarios grid functionality was restored within this time)	25.85 hours	15.33 hours
95% Percentile (In %95 of scenarios grid functionality was restored within this time)	32.42 hours	18.64 hours
99% Percentile (In %99 of scenarios grid functionality was restored within this time)	46.19 hours	27.85 hours
Service restoration mean time	12.33 hours	7.76 hours
Service restoration mean time confidence interval	11.5-13.2 hours	7.2-8.3 hours
Service restoration median time	9.42 hours	5.85 hours
Service restoration median time confidence interval	8.5-10.3 hours	5.5-6.5 hours
Service restoration maximum time	67.74 hours	52.53 hours
Combined resiliency index	**237.45**	**155.18**

The comparison of resiliency indices of original and modified utilization strategies in the selected case showed that the modified strategy considerably improved the resiliency of distribution services. The service restoration mean time acquired by the modified strategy was less than the one acquired by the original strategy and the related confidence intervals did not overlap. The similar result was observed in the median. Therefore, we had enough evidence to claim that the resiliency improvement was meaningful.

CONCLUSION

Disasters have great impact on service continuity of power delivery. Quantifying the resiliency level of a grid not only helps distribution system operators to justify the investment required for improving supply continuity after disasters. Monte Carlo simulation is a practical method for estimating the resiliency of power delivery service. This technique not only encompasses all necessary detail and inherent uncertainty of distribution network but also confidence intervals of metrics. These intervals show whether the proposed modification have meaningful effect on resiliency of power delivery or not.

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