A FRAMEWORK TO EVALUATE MICROGRIDS AND ENERGY STORAGE FOR INCREASING DISTRIBUTION SYSTEM RELIABILITY

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ABSTRACT

Traditionally, distribution system reliability has been improved by adopting grid hardening measures and adding intelligence into the system. Grid hardening measures are in many cases the most effective solution but they may sometimes not be attractive/feasible due to system specifications, customer preferences, and other reasons. Moreover, in some cases, grid hardening measures such as vegetation management, can also be very expensive or might otherwise not be a viable option. In such cases, a cost-effective solution to reduce customer downtime (and hence SAIDI) may be to leverage strategic placement of storage-enabled microgrid systems. This paper describes EPRI's efforts to develop a framework for utilizing a utility's reliability targets as the yardstick to size, locate and operate storage-enabled microgrids for reliability improvement purposes. The framework is demonstrated using a 44 kV utility feeder as a case study.

INTRODUCTION

Improving distribution system reliability and resiliency has been an area of active research in the past decade [1]. The outcome of these efforts has been a growing interest in microgrids as a solution to enhance reliability and resilience. A microgrid is a group of interconnected loads and distributed energy resources (DER) within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and that connects and disconnects from such grid to enable it to operate in both grid connected or island mode [2],[3]. Typically, utilities have utilized grid hardening techniques (aerial/underground cable, vegetation management etc.) and added system intelligence (adding alternative feeder ties as backup sources and distribution automation (DA)) to improve the reliability of their distribution systems. Grid hardening, although an effective way to improve reliability, may sometimes either not be attractive due to customer preferences, or feasible for other reasons. In such scenarios, system intelligence becomes the main solution. Further, there is a growing interest from utilities and regulators to utilize the islanding capability of storage-enabled microgrids to restore supply to customers affected by unplanned or planned outages, and hence reduce their SAIDI (or CAIDI) numbers. Although techniques such as adding recloser switches; Distribution Management Systems (DMS) functions; fault location, identification and service restoration (FLISR) systems; and lately microgrids have been around for some time, there is limited understanding in how to comprehensively assess the benefits of using each solution by itself or in conjunction with other solutions to make decisions.

This paper takes steps towards proposing such a framework. In this framework, utility reliability targets are used as a benchmark to evaluate reliability improvement options and to ultimately size and locate DERs strategically with an microgrid. The next section describes this framework. Subsequent sections then demonstrate the framework using a real 44 kV utility feeder as a case study. The effectiveness and shortcomings of the framework are discussed and areas for future work are proposed.

ANALYSIS FRAMEWORK FOR RELIABILITY ENHANCEMENTS

The proposed analysis framework for reliability enhancements is illustrated in Figure 1. The framework has the following main parts:

- **Step 1 – Data Gathering**: Gather historical fault data to calculate the feeder baseline SAIDI and SAIFI and component failure rates.
- **Step 2 – Optimal Switch Placement**: Use a switch placement algorithm to optimally place distribution automation switches (with fault current interrupting capability) to minimize customer interruptions.
- **Step 3 – Load Transfer Schemes**: Explore the option of load transfer using neighbouring feeders.
- **Step 4 – Optimal ESS Placement**: Identify section(s) of the feeder to be restored using storage-enabled microgrids based upon reliability objective.
- **Step 5 – Microgrid Analysis**: Compute size of the energy storage system (ESS) based upon the load size of the feeder section to be restored.

The first step involves gathering all the necessary data for the feeder. The necessary data includes fault data, with fault location, over the last three years. This data is used to arrive at the feeder SAIFI and SAIDI numbers that form the baseline upon which improvement is sought. The remaining parts of the framework assess different reliability improvement techniques to meet the utility's SAIFI and SAIDI targets. First, the placement of additional distribution automation switches is assessed. In this paper, an optimal switch placement algorithm developed by Electric Power Research Institute (EPRI) is used [4],[5]. The algorithm identifies the optimal location of a single DA switch to minimize customer interruptions and then calculates reliability improvement achieved by this step. If the set reliability targets are not met, another

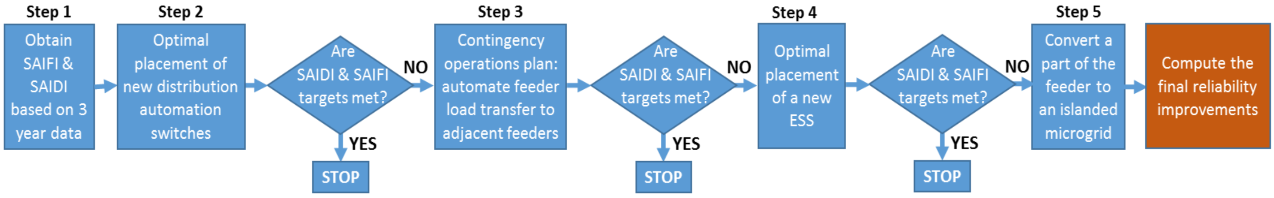

Figure 1 Analysis framework for reliability enhancements

switch is placed on the feeder (keeping the first switch in its location) and the calculation is repeated. This is repeated as many times as reasonable. At some point, the dollar value per incremental reliability improvement becomes too high (and customer interruptions cannot be further significantly reduced) to justify this approach. At this point, it may become more economic to restore sections of the feeder by alternate methods such as load transfer. In distribution planning this is achieved through engineering judgement. In the proposed approach, the instance where the load transfer option should be investigated is obtained from the analysis framework. This calculation often boils down to a simple calculation of 'unit reliability improvement achieved per dollar'. The switches placed in Step 2 create further feeder sections. Step 3 then allows the restoration of (a part of) the customer load through load transfer to neighbouring feeders. Since the algorithm described in Step 2 does not automatically consider such a transfer, this step has to be done manually at present, using help from the distribution engineer.

The upgrades required to existing distribution infrastructure to enable load restoration with other feeders (if any) dictate the costs per unit reliability improvement in this case. SAIFI and SAIDI numbers are recalculated and then compared against the targets at this stage. Finally, when Step 2 and Step 3 fail to achieve the set targets, restoration of customer load through DER placement is proposed. In this step, sections of the feeder, isolated due to a fault are re-energized through a microgrid of DERs that are operated in islanded mode. The reliability improvement required at this stage dictates the size of the microgrid and sometimes more than one microgrid may need to be created on the same feeder to achieve a given target. The size and mix of DERs required for each microgrid is part of a separate analysis where the main objective might be dictated by economics.
The following subsections demonstrate each step of the framework using a real North American 44 kV distribution feeder as a case study.

ANALYSIS OF A CASE STUDY FEEDER

Case Study Feeder Description

The framework introduced above was applied to a real North American 44kV distribution feeder. The 60km long feeder serves roughly 10,000 customers with a peak load of ~25 MW. A single line diagram of the feeder is shown in Figure 2. The feeder has a substation breaker, two tie points to neighbouring feeders, and a protective switch on a lateral as shown (near "DS5"). Due to dense vegetation, ~70% of the total faults on the feeder have occurred within the first 30% of the feeder length. However, due to customer and stakeholder relations in the area, extensive vegetation trimming is not a feasible grid hardening measure on the feeder.

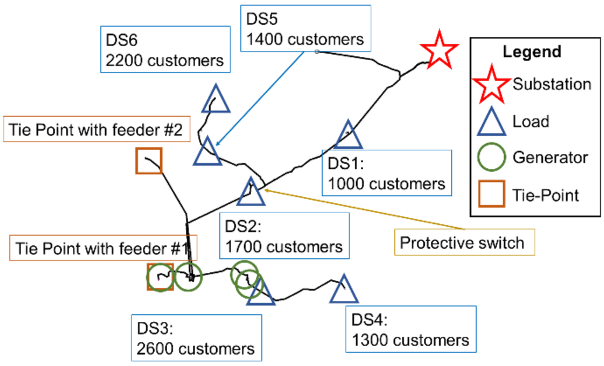

Figure 2 Simplified one-line diagram for the feeder studied

Using Historical Data

Since grid hardening was not a feasible measure on the feeder, added intelligence and microgrid operation were considered as possible reliability improvement solutions. Three years' worth of fault data was used to calculate the SAIFI and SAIDI of the existing feeder since utilities are expected to maintain these quantities as a three year moving average [6]. Data sets longer than 3 years were also not considered representative because of changes to infrastructure over time. Calculations indicated that the feeder had a SAIFI of 3.34 interruptions/customer and a SAIDI of 17.6 hrs/customer. The resulting CAIDI of 5.3 hrs/interruption was used as the 'average repair time' in the analysis. These numbers are considerably higher than the targets for this study which are a SAIFI of 2 interruptions/customer and SAIDI of 5.5 hrs/customer. Finally, the historical data was coordinated with geographical locations of each fault to arrive at the 'failure rate (λ)' assigned to each line section of the feeder [7],[8]. The following formula was used for this calculation:

$$\lambda = \frac{Total\ faults\ on\ line\ section}{Total\ length\ of\ line\ section} * (\%\ perm.faults),$$

where '% permanent faults' indicates the percentage of the line section faults that were permanent. The results represents a three-year window of permanent faults occurring on each kilometre-long section of the feeder.

Optimal Switch Placement

An OpenDSS model of the feeder was created based on the utility CYME model. Each line section in the OpenDSS model was assigned a failure rate and an average repair time. Then, an optimal switch placement algorithm [4],[5] was applied to this simulation. Considering failure rates of the feeder elements, this algorithm finds optimal distribution automation switch placements to minimize customer interruptions. As expected, the marginal reliability improvement obtained with each additional switch was observed to reduce as additional switches were added. The feeder already has one recloser. Adding a second protective switch reduces SAIFI from 3.34 to 3.09 interruptions/customer while SAIDI was reduced from 17.6 to 16.3 hrs/customer. Another additional switch placed on feeder further could only cut SAIFI down to 3.07 and SAIDI to 16.2. These results are summarized in Table 1.

Table 1 Results of optimal switch placement

No. of Switches	SAIFI	SAIDI
1	3.34	17.6
2	3.09	16.3
3	3.07	16.2

Load Transfer

The two additional switches placed on the feeder sectionalize the feeder into four zones illustrated in Figure 3. Step 2 was not sufficient in reaching the reliability objectives on the feeder. Therefore, load restoration using adjacent feeders was considered. The two ties to neighbouring feeders indicated in Figure 3 are capable of picking up load between DS2 and DS4 (Zone 4). However, the switches at these locations are currently not automated. Further, changes to the protection coordination and control logic are required to utilize the tie points under contingencies. Placing two automatic switches at the tie points provides the capability of transferring load at DS3 and DS4 to neighbouring feeders during contingency conditions. It was calculated that this solution would further reduce SAIFI to 1.9 interruptions/customer and SAIDI to 10.03 hrs/customer. At this point, SAIFI meets the set target but SAIDI was still considered unacceptably high.

DER Placement

Figure 3 shows that Zone 1 is connected to the substation and Zone 4 can be energized through neighbouring feeders. Thus, to reduce the feeder SAIDI to the set target value of 5.5 hrs/customer, Zone 2 and Zone 3 shown in Figure 3 were considered as candidates for islanded operation of DERs. The utility indicated their interest in utilizing Energy Storage System (ESS) for this particular exercise and hence ESS was considered as a candidate to enable islanded operation of Zones 2 and 3. Using the system load curve and spot load data, the peak load demand in each of these two zones, over a period of 5.3 hrs (average restoration time for this feeder) was calculated. Assuming that these two zones could then be effectively picked up by the ESS and operated as microgrids, the SAIFI and SAIDI was recalculated. The results are shown in Table 2.

Table 2 Results of DER placement

BESS Location	SAIFI	SAIDI
Zone 3	1.48	7.81
Zone 2	0.98	5.22
Zone 2 and Zone 3	0.56	2.98

Placing an ESS in Zone 2 and operating it as a microgrid reduces the feeder SAIFI and SAIDI under the set reliability targets. The financial cost of all of these reliability solutions was calculated next.

Cost Assessment

The feeder peak load is approximately 25 MW. Zone 2 (Zone 3) peak load was estimated to be ~25% (~20%) of the system peak load. To supply Zone 2 (Zone 3) for 5.3 hrs during the peak load requires an ESS with a capacity

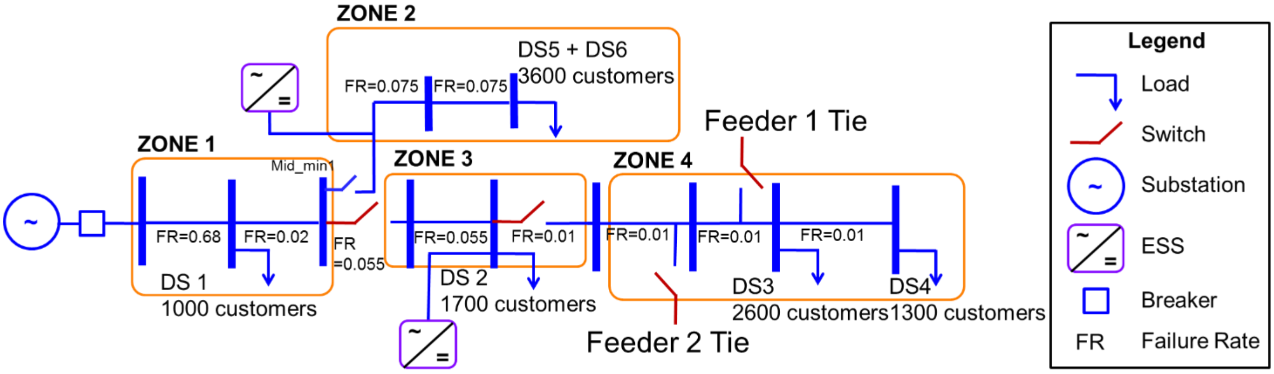

Figure 3 Results of reliability analysis on feeder. Switches added in steps 1 and 2 are shown in red.

of 34.5 MWh (28.5 MWh). The cost of DA switch procurement and installation was assumed to be $100k per switch. The installed cost of the ESS was assumed at $500/kWh.

Based on the values assumed above, the total cost of all the reliability improvement measures was calculated. Figure 4 provides the utility with an intuitive way to compare the costs and benefits of all the analyzed solutions. In Figure 4, the achieved reliability improvements (y-axis) are depicted as a function of the resulting cost (x-axis). Figure 4 (inset) shows that the reliability benefits of optimal switch placement begin to diminish after the third switch has been placed. However, substantial further benefits are achieved by enabling the tie points to the neighboring feeders. The comparative cost of achieving reliability improvements go up substantially thereafter, as ESS is deployed to operate parts of the grid in islanded mode.

DISCUSSION

The case study described in this paper shows that microgrids provide a new tool into the utility distribution planners' toolkit that can support achieving reliability targets. Microgrids may be particularly attractive in improving the reliability of geographically remote feeders, feeders located in dense vegetation areas, feeders with high repair times, or a combination of these factors. However, microgrid costs remain relatively high due to the high capital cost involved in the installation and operation of DERs (and other necessary equipment). The analysed case study feeder has hydro generation but it was not considered in the analysis due to its high variability with season and protection coordination issues.

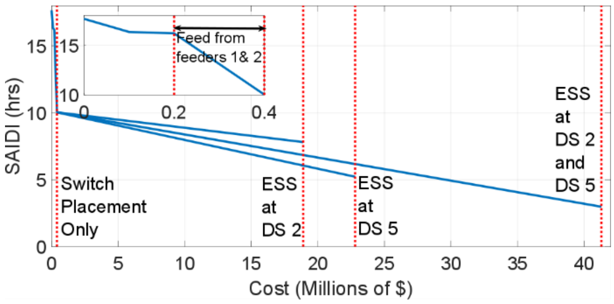

Figure 4. SAIDI improvements achieved with different solutions vs. the associated costs. Inset: reliability improvements achieved by optimal switch placement.

The high microgrid costs could be reduced by 'load prioritization'. Load prioritization refers to classifying the loads within a proposed microgrid based on criticality and implementing a selective load shedding scheme. For example, medical facilities may be assigned the top priority over other loads and would therefore be prime candidates for having access to a microgrid system. Microgrid solutions can also be considered at a community level, and thus some of the responsibility for reliability improvement can be transferred over to either third parties or communities themselves.

FUTURE WORK

Based upon the work presented in this paper, the following avenues for future research have been identified:

- Account for various probability distributions in fault data.
- Analyse the effect of various distribution protection schemes on the size and placement of the microgrid. The same can also be extended to the optimal placement of a switch on the feeder.
- Analyse the effect of variable repair times on different parts of the same feeder.
- Extend the proposed framework to include the microgrid analysis. Automate the process of selecting a DER option, its size and control methodology using a tool such as DER-CAM.
- Implementation of a load prioritization scheme in the reliability framework, especially for cases where the Microgrid size becomes too large.

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