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The Effect of Demand Side Management on Reliability of Automated Distribution Systems

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Abstract—**Demand side management (DSM) provides power systems with the opportunity to supply electricity to the customers more efficiently and reliably. In a smart grid incorporating automated control and distributed energy systems, an effective DSM can alleviate the peak load and shift part of the demand to off-peak hours. This paper evaluates the impact of DSM on reliability of automated power distribution systems. Unlike the previous research studies, we perform load flow analysis and state enumeration to include actual restrictions of distribution systems such as voltage limits of buses and power flow limits of branches. The effects of demand curve and loading of the system components are also considered. The results of this paper are presented through different case studies and sensitivity analyses.**

Keywords—demand side management; distribution system; reliability analysis; smart grid.

I. INTRODUCTION

Demand side management (DSM) strategies have been used in the power industry for many years [1]. The goal of DSM is to provide efficient usage of the power system assets and reduce electricity costs for customers. In fact, DSM alters the load curves of customers through a variety of programs, such as peak clipping, load shifting, valley filling, energy conservation, etc. [2]. Therefore, electric utilities are recommended to incorporate DSM in their resource planning by performing cost/benefit analysis [3]. The promising infrastructure of the smart grid featuring real-time communication and data flow among electric utilities and customers will support DSMs by providing more efficient load controllability and incentives based on dynamic electricity rates, in the near future [4]. A number of recent research studies have considered the impact of incorporating Distributed Energy Resources (DER), such as electric vehicles [5] and distributed generation-storage systems [6], on DSM and system reliability. The effects of DSM on the adequacy of power generation have been previously studied in the literature [7, 8]. The researchers in [8] indicated that the highest reliability benefit of DSM in terms of outage cost reduction is associated with the large user sectors rather than small residential and agricultural loads. In [9], the authors have discussed the effect of demand response on distribution system reliability, but their work is a conceptual representation of a framework and does not include case study analysis and results. Another study evaluates the effectiveness of two DSM schemes on reliability improvement of a distribution system [10]. However, this research is limited by some specific scenarios and does not include load flow analysis for reliability evaluation.

In this paper, we determine the impact of DSM strategies, such as load shifting and energy conservation, on the reliability of an automated distribution system. Following a contingency in an automated distribution system, the faulted area of the system is quickly isolated and part of the loads in that area may still be restored automatically. The DSM modeled in this research is based on the reduction of system electricity demand due to energy efficient strategies and alleviation of the peak load by shifting the demand to the low-demand hours. There are at least two main reasons why an effective DSM is expected to improve the reliability of a distribution system. First, an effective DSM reduces the loading stress on the system components and, therefore, reduces the probability of failure. Second, applying DSM programs leads to peak load shaving; and, therefore, given a failure and outage of a component in the system, the probability that the grid is still capable of supplying the loads without being overloaded will be increased. In other words, since there is more line capacity available in the system for power restoration when utilizing DSM, fewer loads will be shed. In this research, this aforementioned impact of DSM on the reliability of a distribution system is analyzed using AC load flow, considering the voltage limits of the buses and loading constraints of the branches in the network. This paper considers the sequential operational steps after a fault in an automated distribution system. In addition, it considers different loading levels of the system through the sensitivity analyses performed. This study uses Power Factory DIgSILENT software, and the results are presented using various distribution system reliability metrics.

II. RELIABILITY EVALUATION METHOD

The reliability evaluation of a distribution system is based on load flow study and state enumeration for failures in an automated distribution system. The reliability data, including failure rate and repair duration of the components, are assumed to be the same when using DSM schemes in different case studies. The active and reactive power of the bus loads change on hourly basis and are modeled using a daily load curve.

Each contingency initiates a scenario handled by simulating the system's automated sequential reactions. The post-fault operational steps include:

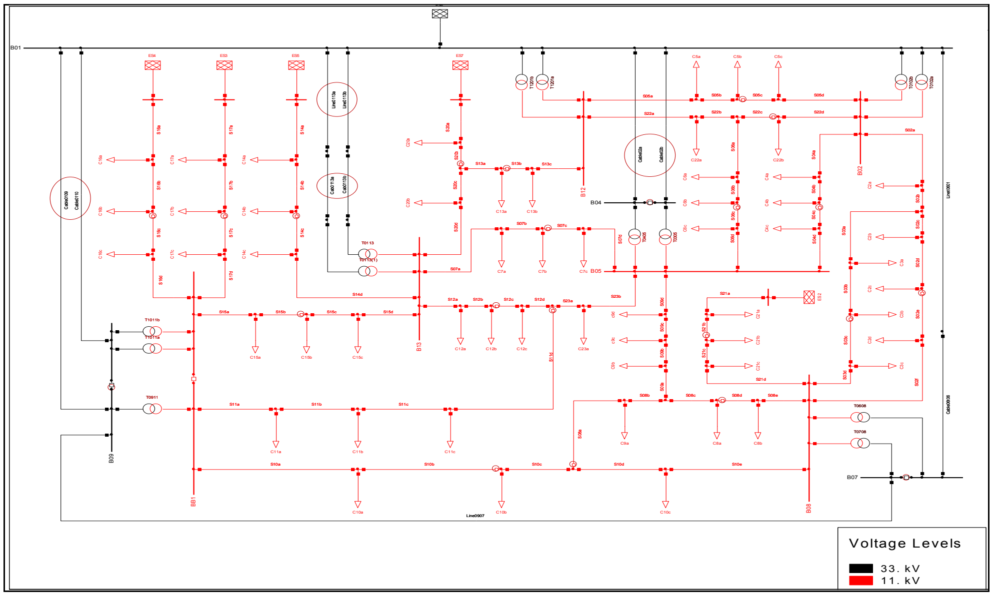

Figure 1. Single line Diagram of the case study distribution system.

- Fault clearance using the protection components.
- Fault isolation by opening separating switches.
- Power restoration by closing normally open switches.
- Load flow study of the restored distribution system.
- Load shedding for overload elimination.
- Load shedding in case of voltage constraint violations.
- Taking the system back to the prefault configuration after the completion of the repair.

After performing contingency analysis using DIgSILENT software and calculating pre- and post-contingency AC power flow, the reliability metrics are calculated and compared for different case studies. The common reliability indices for distribution systems used in this study are System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), Energy Not Served (ENS), and Average Service Availability Index (ASAI) [11].

III. Distribution System Model

The distribution system used for the case studies is an 86-bus system with a mesh topology. The single line diagram of the system is shown in Figure 1. A number of normally open switches are used to separate different feeders and create a radial-operated network during normal conditions. These switches are used to restore the power to the areas disconnected due to a failure. The main bus of this distribution system is a 33kV slack bus, and the loads are distributed on the 11kV buses.

The overall system data is given in Table I. The input data used for the failure rates and repair durations of the system lines, transformers, and buses are given in Table II.

In the simulation process, the loading and voltage constraints used for reliability calculation are defined by (1).

$$\begin{cases} Loading_{Line} < 100\% \\ Loading_{Transformer} < 100\% \\ 0.95\ \text{p.u} < V_{bus} < 1.05\ p.u \end{cases} \quad (1)$$

TABLE I. Distribution System Components

No. of busbars	86
No. of lines	92
No. of transformers	13
No. of loads	56
Avg. No. of customers per load	186
Total peak load	52.08 MW
Total grid power losses	130 kW

TABLE II. Input data for the reliability analysis

Component	Failure rate	Mean Repair duration
Underground Cables	0.01/(km, year)	72 hrs
Overhead Lines	0.015/(km, year)	50 hrs
Power Transformers	0.008/year	96 hrs
11kV Busbar	0.008/year for terminal; 0.015/year per connection	7 hrs
33kV Busbar	0.005/year for terminal; 0.015/year per connection	10 hrs

The load values are diversified at different buses of the distribution system, and they represent different number of customers. However, loads are assumed to be from the same sector; and, therefore, the hourly change of all the loads follow the same pattern as shown in Figure 2.

For the base case study, the system load is selected such that some of the lines and transformers operate close to their maximum loading limit at the peak load. Figure 3 depicts the state of loading of the distribution system branches at the peak load.

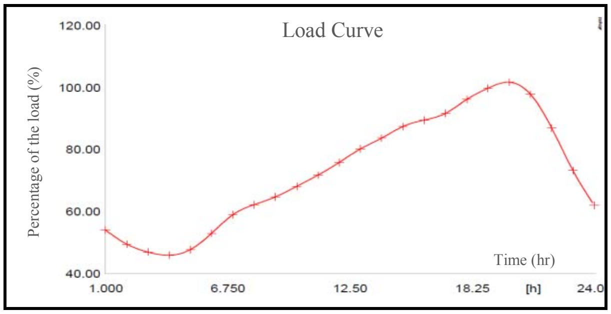

Figure 2. Daily load curve of the loads of the distribution system.

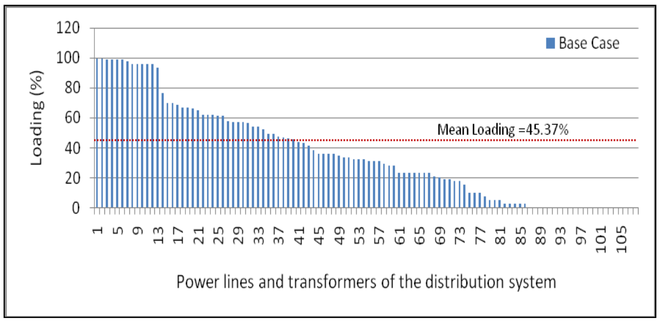

Figure 3. Loadings of power lines and transformers at the peak load.

IV. Case Studies and Results

This section is comprised of different case studies. First, the base case without a DSM is studied; and the reliability indices are calculated. The effectiveness of a DSM strategy depends on both the scheme chosen and characteristics of the distribution system. Therefore, two DSM schemes are simulated; and their impact on the distribution system reliability is obtained. Finally, a sensitivity analysis is performed with different capacities of distribution system components for justification of the previous step results.

A. Base case

In this case, no DSM strategy is employed; and the load curve shown in Figure 2 is applied to the loads. The results of the reliability indices are provided in Table III. The total Energy Not Supplied of the distribution system is almost 76MWh per year; and each customer, on average, experiences 0.25 failures and an interruption duration of 1.9 hours per year.

TABLE III. Reliability Indices for the Base Case Study

SAIFI 1/(Customer, Year)	SAIDI Hr./(Customer, Year)	CAIDI (Hr.)	ENS (MWh/Year)	ASAI
0.245187	1.904	7.767	76.369	0.9997826

B. DSM Scheme 1: Energy Conservation

The scheme used in this case study models the incorporation of various energy efficient strategies and equipment at the customer level as well as the system level such that the overall loading of the distribution system decreases. As a result, it is expected that the reliability of the system be improved.

The load curves for this DSM scheme are shown in Figure 4. Different percentages of DSM load impacts are considered, and the decrease in the system load is uniformly modeled throughout a day using different load scaling factors.

The SAIFI and SAIDI indices have been calculated for each load scaling factor and are shown in Figure 5. The load scaling of "1" means there is no DSM in this scheme. It is observed that as the system bus loads decrease, the reliability of the system improves. As a result of a 10% load reduction, SAIFI and SAIDI decrease by almost 20%.

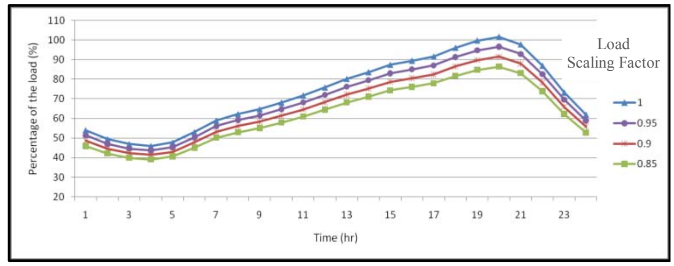

Figure 4. 24-hour load profile with different levels of energy conservation.

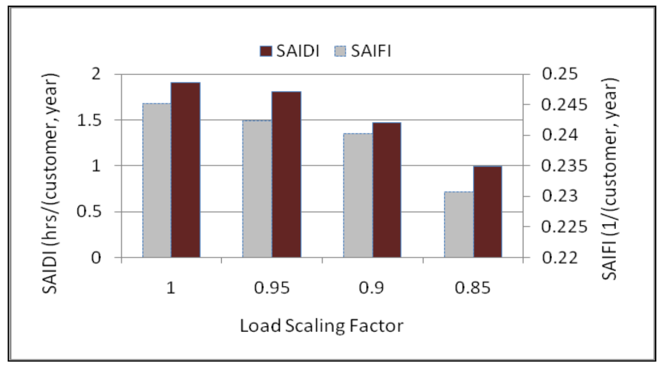

Figure 5. SAIFI and SAIDI with different levels of energy conservation.

Table IV provides the results for this case based on a number of reliability indices.

TABLE IV. Reliability Indices with Different Load Scaling Factors

Scaling Factor	SAIFI 1/(Customer, Year)	SAIDI Hr./(Customer, Year)	CAIDI (Hr.)	ENS (MWh/Year)	ASAI
1	0.245	1.904	7.767	76.369	0.99978
0.95	0.242	1.813	7.485	69.982	0.99979
0.9	0.240	1.47	6.118	51.986	0.99983
0.85	0.231	0.997	4.321	30.045	0.99989

C. DSM Scheme 2: Load Shifting

By using this DSM scheme, the loads are shifted from high-load to low-load hours. So, the peak load is shaved; and the load curve valley is filled. This scheme is modeled using different percentages of load shifting applied to the load curves in the distribution system, as shown in Figure 6. Here, the total demand of the customers is constant.

Figure 7 shows the SAIFI and SAIDI indices for this case where 0% load shifting represents no DSM in this scheme. Unlike what was expected, the results show that the customers, on average, experience higher failure frequency and duration as the loads are shifted by 5, 10, and 15%. Then, these indices decline with a 20% load shifting. In other words, the reliability of the distribution system may get worse with the load shifting DSM.

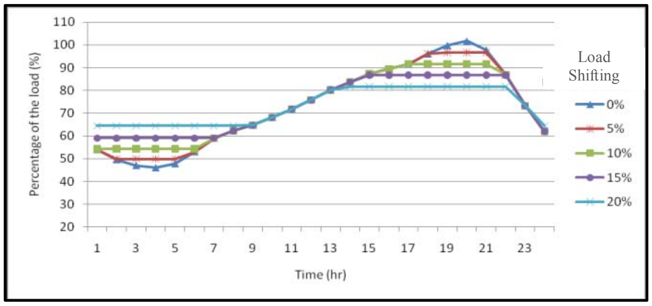

Figure 6. 24-hour load profile with different levels of load shifting.

In fact, the peak shaving scheme of DSM acts toward system capacity relief and improving distribution reliability, as studied in Section IV.B. However, here, the loads filling up the valley can create new overloads in a distribution system subject to a contingency; and, therefore, fewer loads may be restored.

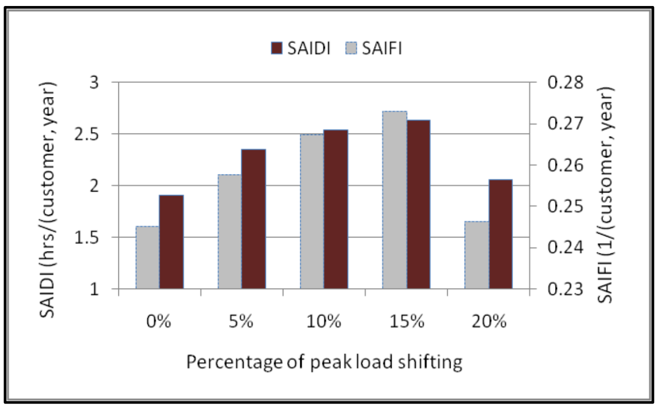

Figure 7. SAIFI and SAIDI with different percentage of load shifting.

The results for the reliability indices with different percentages of load shifting are given in Table V.

TABLE V. RELIABILITY INDICES WITH DIFFERENT PERCENTAGES OF LOAD SHIFTING

Load Shift-ing	SAIFI 1/(Customer, Year)	SAIDI Hr./(Customer, Year)	CAIDI (Hr.)	ENS (MWh/Year)	ASAI
%	0.245	1.904	7.767	76.369	0.99978
5%	0.258	2.349	9.113	98.161	0.99973
10%	0.267	2.541	9.506	105.433	0.99971
15%	0.273	2.631	9.64	105.263	0.9997
20%	0.246	2.056	8.343	82.025	0.99976

One of the main factors affecting the reliability of a distribution network, in this case, is the loading of system components. If the system is highly loaded and lines and transformers are operating close to their maximum limit, there is a higher chance that peak load shaving does little in preventing load interruptions compared to valley filling at off-peak hours, in case of a failure. The next case study aims to justify the results and discussion provided with a sensitivity analysis.

D. Sensitivity Analysis

This section evaluates the reliability of distribution systems with different levels of loadings and the load shifting DSM. In order to perform sensitivity analysis, the distribution system, shown in Figure 1, is taken as the base network. Then the capacities of the lines and the transformers of the system are increased to generate the network cases with lower levels of component loadings.

Figure 8 shows the loadings of power lines and transformers with different capacities at peak load. The loadings for the base case are the same as the results in Figure 3; and as the capacities increase, the loading value decreases in the system.

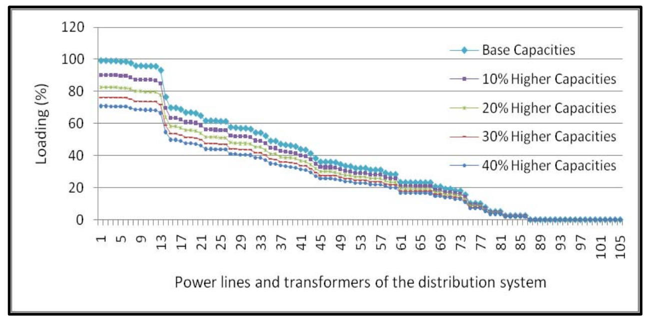

Figure 8. Loadings of power lines and transformers with different capacities at the peak load.

Figures 9 and 10 show the results for SAIFI and SAIDI, respectively. There are a number of observations to point out in these case studies. First, the reliability of distribution system with higher capacities of branch components (while other system parameters are kept unchanged) is generally higher. Second, in a highly loaded distribution system, SAIFI and SAIDI usually rise with higher load shifting. However, there is a turning point where these indices start to decline. As indicated in the figures, this turning point approaches faster and in lower percentages of the load shifting if the distribution system components have higher capacities (i.e., lower system loadings). Third, the degree to which DSM impacts the reliability of a distribution system depends on the system capacity. For example, in the base case, the reliability of the system does not improve even with a 20% load shifting compared with the case where no DSM is applied.

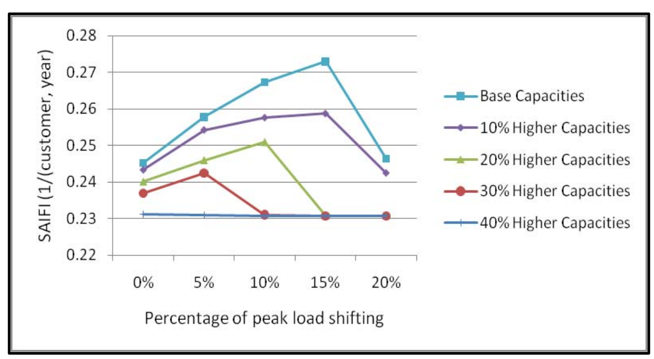

Figure 9. SAIFI with different percentage of load shifting and system capacity increments.

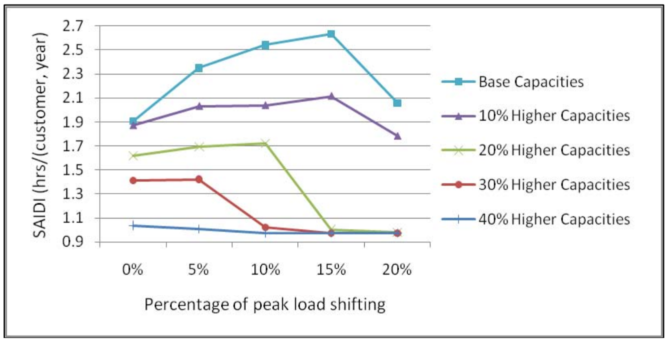

Figure 10. SAIDI with different percentage of load shifting and system capacity increments.

On the other hand, in certain loading levels of the system, the reliability may be improved with DSM. For example, in a case in which the capacity of a distribution system is 20% or 30% higher than our base case capacity, SAIFI and SAIDI may be improved if enough load shifting is applied. This impact is more dominant in interruption duration than in frequency.

Finally, the results indicate that if the capacity of the system is high enough (40% higher capacities than the base case), the load shifting has almost no impact on the reliability of the system. This implies that the loading level of the distribution system, in this case, is much lower than a threshold where the shape of the load curve could influence the reliability.

I. CONCLUSION

The impacts of two types of DSM on the reliability of an automated distribution system were studied using a simulation approach. A simulation method was required since the distribution system modeled was nonlinear and complex, especially when considering the load flow study. The distribution system was modeled in DIgSILENT software environment, and the reliability evaluation was based on state enumeration methodology. In this method, different contingency scenarios were defined based on the failure data; and the impact of each failure on the system components and loads was analyzed in order to calculate the distribution system reliability indices.

Based on the results of this paper, the reliability of the distribution system improves if a DSM with energy conservation is applied to the loads. However, with the load shifting approach, the results were case specific. In fact, the overall impact of DSM depends on whether the reliability improving peak load shaving or weakening low load increment is dominant in the system modeled. Through sensitivity analysis, it was determined that, based on the loading condition of a distribution system, load shifting may improve, worsen, or have no significant effect on system reliability. An interesting outcome of this paper is that load alleviation does not necessarily lead to higher reliability of a distribution system, and the loading of the system components plays a key role in this matter.

The impact of different load sectors, load priorities, and diversity of the load on the reliability of a distribution system with DSM will be considered in our future work.

REFERENCES

[1] J. Eto, "The Past, Present, and Future of U.S. Utility Demand-Side Management Programs," Ernest Orlando Lawrence Berkeley National Laboratory, University of California, Dec. 1996.

[2] C. W. Gellings, W. M. Smith, "Integrating Demand Side Management into Utility Planning," *Proc. of the IEEE*, invited paper, vol. 77, no. 6, pp. 908-918, Jun. 1989.

[3] R. Billinton, D. Lakhanpal, "Impacts of demand-side management on reliability cost/reliability worth analysis," *IEE Proc. Generation, Transmission, Distribution*, vol. 143, no. 3, pp. 225- 231, May 1996.

[4] P. Palensky, and D. Dietrich, "Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads," *IEEE Trans. on Industrial Informatics*, vol. 7, no. 3, pp. 381-388, Aug. 2011.

[5] C. Pang, M. Kezunovic, and M. Ehsani, "Demand Side Management by using Electric Vehicles as Distributed Energy Resource," *IEEE International Electric Vehicle Conference (IEVC)*, Mar. 2012.

[6] I. Hernando-Gil, I.-S. Ilie, and S. Z. Djokic, "Reliability Performance of Smart Grids with Demand-side Management and Distributed Generation/Storage Technologies," *3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, Oct. 2012.

[7] D. Huang, R. Billinton, and W. Wangdee, "Effects of Demand Side Management on Bulk System Adequacy Evaluation," *11th Internatonal Conference on Probabilistic Methods Applied to Power Systems (PMAPS)*, Jun. 2010

[8] D. Huang, and R. Billinton, "Effects of Load Sector Demand Side Management Applications in Generating Capacity Adequacy Assessment," *IEEE Trans. on Power Systems*, vol. 27, no. 1, Feb. 2012.

[9] S. Mohagheghi, F. Yang, B. Falahati, "Impact of Demand Response on Distribution System Reliability," *IEEE PES General Meeting*, Jul. 2011.

[10] I. S. Ilie, I. Hernando-Gil, A. J. Collin, J.L. Acosta, and S. Z. Djokic, "Reliability Performance Assessment in Smart Grids with Demand-side Management," *2nd ISGT Europe*, Dec. 2011.

[11] IEEE Standard 1366, "IEEE Guide for Electric Power Distribution Reliability Indices," 2004.