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# Reliability-Driven Optimum Standby Electric Storage Allocation for Power Distribution Systems

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**Abstract**—Integration of distributed energy resources (DER) has become an indispensable aspect of the future smart grid. The significant and valuable impact of these resources is expected to lead toward a more reliable and efficient power system. As the number of distributed generation and storage systems increases, the availability of sensitive and critical loads may be improved by allocating a portion of electricity storage capacity as a reserve. The goal of this paper is to determine the optimum standby storage capacity in a smart grid based on reliability indices such as the Expected Interruption Cost (EIC) of the system using particle swarm optimization (PSO). To include the actual restrictions of the power distribution system, we perform load flow analysis and simulate a sequential post-fault scenario for every outage of the components. The results from different case studies show that standby electricity storage can become cost efficient at certain load points of the distribution system.

**Keywords**—distributed energy resources; electric storage system; interruption cost; reliability analysis ; smart grid.

## I. INTRODUCTION

Distributed electricity generation and storage systems will play a critical role in the reliability and efficiency of the emerging smart grid. In fact, distributed energy resources (DER) can contribute to peak load alleviation, investment deferral, voltage regulation, power loss reduction, etc [1]. The infrastructure of the smart grid, incorporating real-time communication and control commodities, can well accommodate the efficient operation of these energy resources [2]. Renewable DERs used in a distribution system are usually a combination of distributed intermittent generation, such as photovoltaic (PV) or wind generation, and a storage system, such as a battery [3]. Electricity storage systems are generally used to smooth out the volatilities of renewable generation. In addition, they may be employed to shift the peak load, trade electricity in a dynamic pricing scheme, provide ancillary services, etc. [4, 5]. However, the electricity stored can also be used as an online backup resource in case of a failure to avoid the interruption of the critical loads of the system. In fact, uninterruptible power supplies (UPS) have been used for a long time in sensitive and high priority facilities, such as data centers [6]. In this paper, we increase the primary storage capacity of a distributed generation-storage system determined in the planning phase and allocate the excess capacity for standby electricity storage. The goal is to determine the optimum allocation of the standby electricity storage from a reliability perspective considering load interruption costs.

Optimal placement of DER in distribution power systems has been extensively studied in the literature [7- 9]. In addition, many researchers have studied the optimum sizing of energy storage for distributed generation, such as wind power [10] and photovoltaic systems [11]. Therefore, rather than focus on the optimal placement of distribution resources, this paper concentrates on determining the additional electricity storage capacity of a DER system whose optimum location and primary capacity have been determined in a smart grid in order to improve network reliability. When a contingency occurs, standby stored electricity prevents the interruption of a larger number of customers at the installation load point. In addition, the stored electricity can reduce system loading even with a contingency on its neighboring feeders; and relieving the power line loading could improve power restoration. Using cost/benefit analysis, the condition upon which the standby storage becomes beneficial is specified; and subsequently, the optimum capacity of such energy storage is determined using particle swarm optimization (PSO) method.

A method for determining the optimum size of backup storage from a reliability perspective has been reported in [12]. However, this study does not include the network topology and the costs incurred due to interruptions in the system. Xu et al. [13] have evaluated the impact on reliability and the economics of energy storage with different control strategies using the Monte Carlo simulation approach. This research, however, neither considers the power flow constraints of a distribution system nor the load point reliability indices.

In the approach presented here, the reliability evaluation of distribution systems with standby electricity storage is based on power flow study and state enumeration. The failure probabilities of the distribution system components are used to generate simulation contingencies. Each contingency is handled through the scenario including fault clearance, fault isolation, power restoration, system overload detection, load shedding, etc. Notably, load profiles and customer interruption costs are considered in the analysis. Sensitivity analyses are carried out using DIGSILENT Power Factory software to determine the profitability condition of the standby electricity storage. Then, the optimum standby storage capacities are calculated at the DER integration points of the distribution system using the PSO method, and the results are presented.

## II. STUDY APPROACH

The distribution system studied consists of a number of DER systems connected at different load points. In this study, DER systems comprise a renewable generation system with electricity storage, where a portion of each storage capacity may be reserved as standby electricity. In case of a failure affecting the feeder with an integrated DER, the standby resource quickly switches in and saves part of the load from being interrupted. The standby stored electricity may also be used when a contingency has occurred at the neighboring feeders in order to alleviate the loading on the lines and prevent load shedding. Each load modeled has a load profile and an interruption incremental cost curve known as the Sector Customer Damage Function (SCDF). When a load is interrupted due to a contingency or a load is shed because of an overload/voltage violation during power restoration, the expected interruption cost is calculated based on the interrupted power, duration of the interruption, and the SCDF, as denoted by (1).

$$LPIC = \sum_{i=1}^I m_i \cdot SCDF(d_i) \quad (1)$$

where  $m_i$  and  $d_i$  are the interrupted power and the duration of the interruption  $i$ , respectively;  $I$  is the total number of interruptions at the load point, and  $LPIC$  is the Load Point Interruption Cost in dollars per year. Some of the other reliability indices calculated in this study are Load Point Interruption Frequency ( $LPIF$ ), Load Point Interruption Duration ( $LPID$ ), Load Point Energy Not Supplied ( $LPENS$ ) for the DER-connected load points, Expected Interruption Cost ( $EIC$ ), System Average Interruption Duration Index ( $SAIDI$ ), and System Average Interruption Frequency Index ( $SAIFI$ ), as the system reliability indices [14].

For reliability and failure cost evaluation, all failures associated with power lines, transformers, and load connections are considered; and each scenario is studied with the state enumeration approach, using power flow, in the DlgSILENT software. The summation of the system  $EIC$  and the levelized cost of standby energy storage represent the system incurred Total Cost, which is compared over different scenarios. Figure 1 shows the flowchart of the study approach. The optimum capacities of the standby storage systems are determined by using sensitivity analysis and the PSO method. In fact, in each iteration and for each particle of the PSO, reliability of the distribution system is evaluated in order to find the set of standby storage capacities which minimizes the Total Cost as the objective function.

$$\text{minimize: Total Cost} = EIC + \sum_{k=1}^N C_{store}(Cap_{L_k}) \quad (1)$$

where  $C_{store}$  represents the cost of the standby electricity storage as a function of its capacity  $Cap_{L_k}$  at the load point  $L_k$ , and  $N$  is the total number of DER-connected load points.

## III. SIMULATED TEST SYSTEM

The single line diagram of the distribution system studied is shown in Figure 2 where four DER systems will be connected at the load points, LP1 to LP4, to generate the base case study.

The system has two voltage levels of 33 and 11 kV, and each load point connected to an 11 kV node aggregates the demand of a number of low voltage customers.

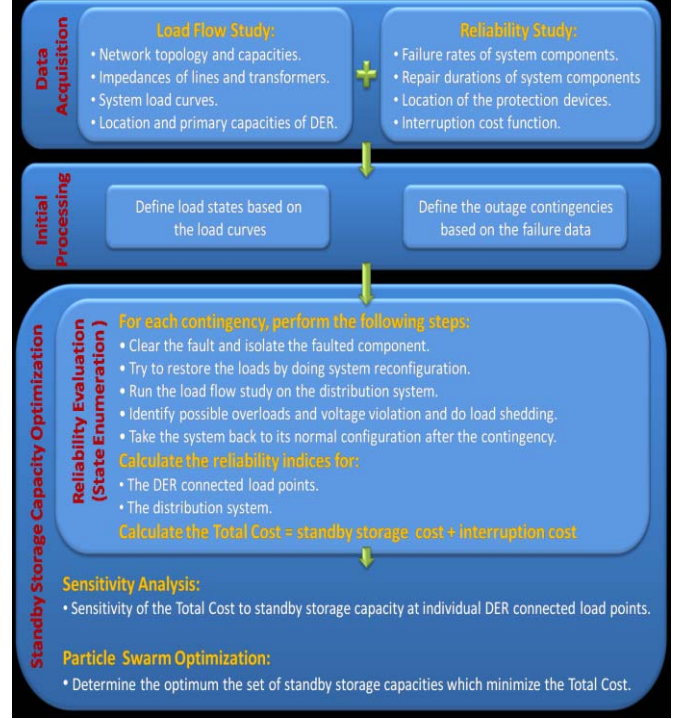


Figure 1. Flowchart of the study approach.

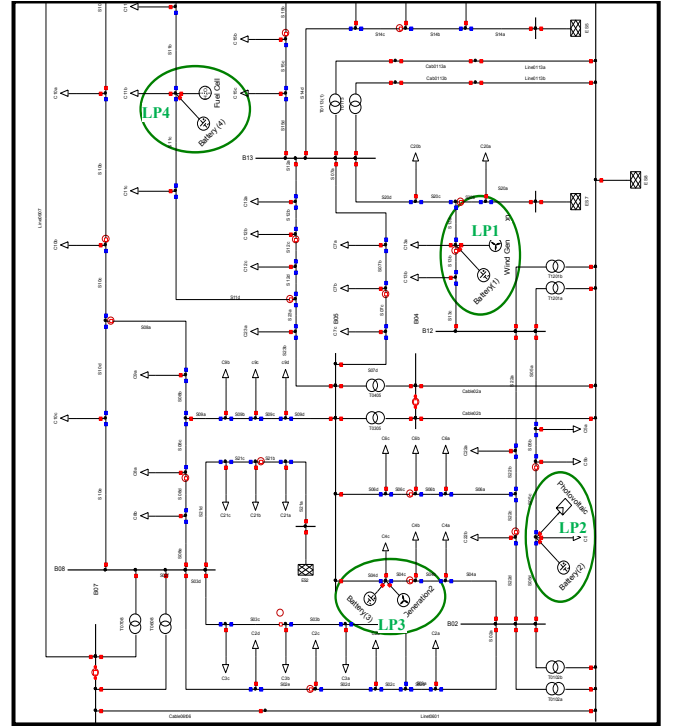


Figure 2. Single line diagram of the case study with four integrated DERs

The statistics of the distribution system components are provided by Table I.

TABLE I. DISTRIBUTION SYSTEM STATISTICS

No. of busbars	86
No. of lines	92
No. of transformers	13
No. of loads	56
No. of customers at LP1	440
No. of customers at LP2	460
No. of customers at LP3	320
No. of customers at LP4	60

The load curves at different load points are binned and represented by load state probabilities for the reliability study. Figure 3 shows the distribution of the active and reactive power demand at LP1 when there is no DER installed in the distribution system. For the purpose of load flow and the reliability study, the DER can be modeled by its impact on the load curve at the point of installation. Presumably, distribution generation reduces the overall load; and the storage system can alleviate the peak load.

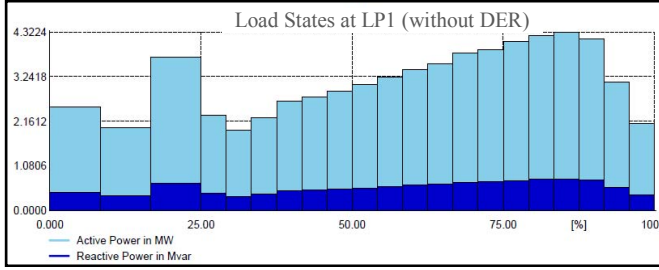


Figure 3. Cumulative percentage of LP1 active and reactive power binned to define load states, without DER in the system.

Figure 4 shows the load distribution for the same load point after the DER installation. The model of the distribution system with DER integration is considered the base case for the reliability study and is used to analyze the effect of additional standby electric storage capacities.

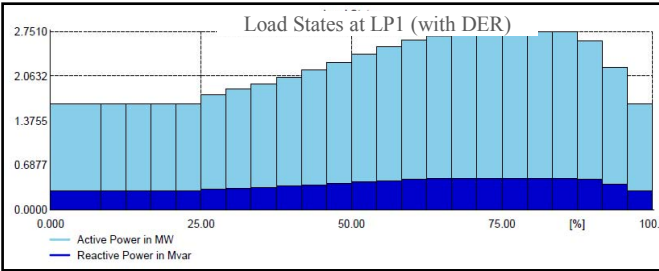


Figure 4. Cumulative percentage of LP1 active and reactive power binned to define load states, with DER in the system (base case).

Table II provides the load flow information on the load points and the total system with and without DER integration.

As depicted in Figure 1, the input data for reliability analysis include the components' failure rates and repair duration as well as the load interruption cost function. These data are provided by Table III and Figure 5, respectively.

TABLE II. LOAD FLOW RESULTS OF THE DISTRIBUTION SYSTEM

Parameters	Without DER	With DER (Base Case)
Peak Load at LP1	4.32 MW	2.75 MW
Peak Load at LP2	3.98 MW	2.53 MW
Peak Load at LP3	2.77 MW	1.76 MW
Peak Load at LP4	0.52 MW	0.33 MW
Total System Peak Load	53.4 MW	48.4 MW
Total System Power Loss	1.4 MW	1.15 MW

Since the cost of interruption could vary for different types of customers, the curve provided in Figure 5 is used as the base load interruption cost function in the study; and each load adopts this cost curve with its own specific scaling factor. Each feeder of the distribution system is equipped with a protection device which is used to clear the fault defined by the contingencies during the reliability evaluation.

TABLE III. INPUT DATA FOR THE RELIABILITY ANALYSIS

Component	Failure Rate	Mean Repair Duration
Underground Cables	0.01/(km, year)	128 hrs
Overhead Lines	0.015/(km, year)	54 hrs
Power Transformers	0.006/year	116 hrs
11kV Busbar	0.009/year for terminal; 0.015/year per connection	7 hrs
33kV Busbar	0.006/year for terminal; 0.015/year per connection	12 hrs

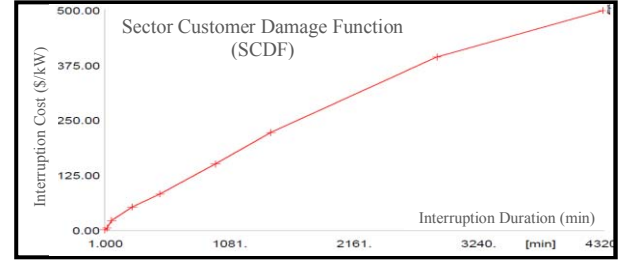


Figure 5. Load interruption cost function for the customers.

#### IV. CASE STUDIES AND RESULTS

This section includes different case studies. First, the reliability of the distribution system in the base case with no standby electricity storage is evaluated. Then, by performing sensitivity analyses, the impact of different standby storage capacities on system reliability and interruption cost is determined. Finally, the optimum capacities of standby energy storage at different load points are calculated using the PSO method.

##### A. Base Case

As previously described, four DER are connected at the specified load points, LP1 to LP4, but no standby storage capacity is available in this case. The results of the system reliability indices are provided in Table IV. The total Energy Not Supplied of the distribution system is 145.5 MWh per year, and each customer, on average, experiences 0.46 failures and interruption duration of 4.02 hours per year.

TABLE IV. SYSTEM RELIABILITY RESULTS FOR THE BASE CASE STUDY

System Reliability Indices (Base Case)				
SAIFI 1/(customer, year)	SAIDI hrs/(customer, year)	ASAI	EENS (MWh/year)	EIC (k\$/year)
0.46	4.02	0.99954	145.5	184

Table V provides the reliability results at the DER-integrated load points. The interruption costs are different at these load points due to variation of their loads, damage costs, and location in the distribution system. The LPENS and LPIC are highest at LP1 and lowest at LP4.

TABLE V. LOAD POINT RELIABILITY RESULTS FOR THE BASE CASE

Location	Load Point Reliability Indices (Base Case)			
	LP1F (1/year)	LP1T (hrs/year)	LP1C (k\$/year)	LP1ENS (MWh/year)
LP1	0.47	3.39	30	8.9
LP2	0.34	3.11	16.2	7.5
LP3	0.36	2.63	7.78	4.3
LP4	0.58	5.24	0.5	1.8

### B. Sensitivity Analysis

Standby electricity storage is added to the LP1 to LP4 nodes in the distribution system, and the effect of different standby storage capacities on the Total Cost of the system is studied using sensitivity analysis. Figure 6 shows the system Total Cost comprised of EIC and levelized costs of different standby storage capacities at LP1. The levelized cost of standby storage is assumed to be 0.3 cents per kWh of capacity, per hour. According to the results, a standby storage of 500 kWh is optimal at LP1. With this standby capacity added to the primary energy storage, the system Total Cost decreases by 2.7%; and the LPIC at LP1 is reduced by almost 30%, compared with the base case.

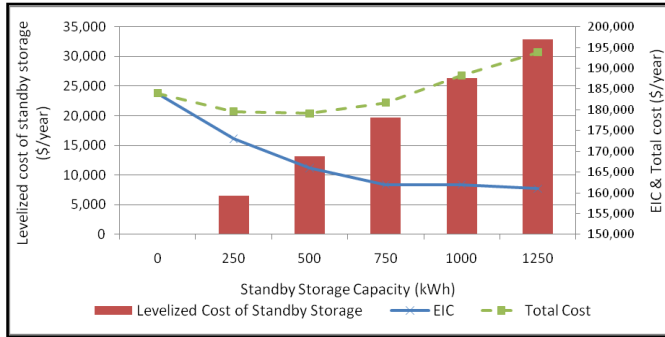


Figure 6. Cost analysis with different capacities of standby storage at LP1.

Figure 7 shows the results of the previous sensitivity analysis where the system Total Cost is displayed for all four DER-integrated load points. The result for each load point is derived based on changing the standby storage capacity at that node while there is no standby storage capacity available at the other load points. This way, the results for each individual load point are compared independent of the changes in the other load points. For each load point, the increment steps of the standby storage capacity are defined by the percentages of that load point's peak load.

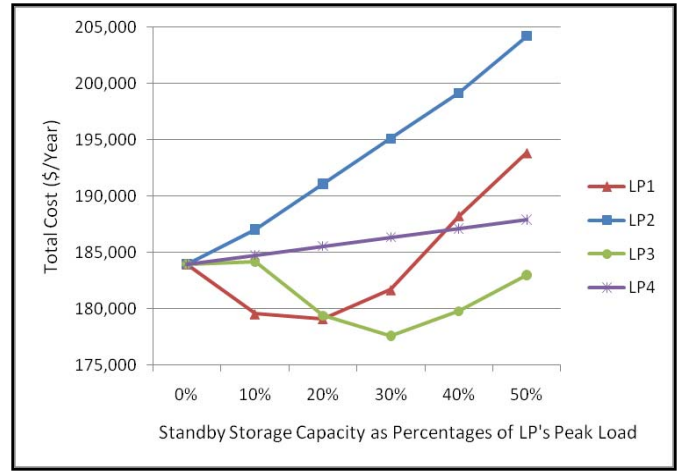


Figure 7. Cost analysis with different capacities of standby storage at all the DER-integrated load points.

According to this figure, standby storage is cost effective only at LP1 and LP3 where the Total Cost could be lower than the base case scenario (0% standby storage capacity).

### C. Optimum Standby Storage Capacities

In the previous section, the impact of the standby storage capacities on the System Interruption Cost was independently studied for each load point. However, in order to calculate the optimum standby capacities, their mutual effect on a distribution system should also be taken into consideration.

Due to the nonlinearity of the system requiring a sequential procedure for analyzing each contingency and reliability evaluation, we use the PSO method to determine the optimum standby storage capacities at all four DER-integrated load points.

Figure 8 shows the results of the optimum standby capacities. The PSO study indicates that no standby storage is beneficial at LP2; but it is optimum to have some standby electricity available at LP1, LP3, and LP4. The EIC of the system with these optimum capacities is \$134,000 per year and the Total Cost adds up to \$159,000 per year, which is less than the Total Costs in the previous section presented in Figure 7.

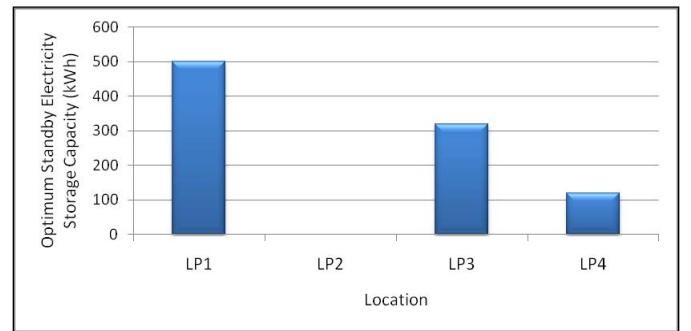


Figure 8. Optimum standby storage capacities at all of the DER-integrated load points.

The load point reliability indices are provided by Table VI. Compared with the base case results in Table V, the load point reliability is improved. The reliability improvement is more



considerable at LP which has the highest optimum standby storage capacity.

TABLE VI. LOAD POINT RELIABILITY RESULTS WITH INTEGRATION OF THE OPTIMUM STANDBY ENERGY STORAGE SYSTEMS

Location	Load Point Reliability Indices (With Optimum Standby Storage Capacities)			
	LPIF (1/year)	LPIT (hrs/year)	LPIC (k\$/year)	LPENS (MWh /year)
LP1	0.47	3.1	20	5.8
LP2	0.34	3.05	16.1	7.35
LP3	0.36	2.62	5.4	3.1
LP4	0.53	4	0.2	0.6

## I. CONCLUSION

The optimum capacities of standby electricity storage were determined at the DER-integration nodes of a distribution system based on reliability analysis and PSO method. The distribution system was modeled in DIGSILENT environment, and the reliability evaluation was based on load flow and state enumeration method.

The goal was to minimize the sum of the system cost of interruption and investments for the standby storage system capacity. The impact of the standby storage at individual load points of the system was studied using sensitivity analysis. Then, the optimum capacities were determined using the PSO method. The results show that allocation of additional storage capacity as a standby electricity resource at specific load points can reduce the total reliability costs. In addition, the calculated indices show the reliability improvement at both the load point and the system level.

It should be noted that the profitability of the standby storage system depends on a number of factors. For example, these capacities may not be beneficial if the cost of the electricity storage system is higher than a certain threshold for a specific distribution system. Therefore, more sensitivity analysis should be conducted to investigate different conditions. The impacts of grid configuration, load priority, load growth, and cost of energy storage system on the optimum capacity and placement of the standby electricity storage will be studied in our future work.

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