ECONOMIC EVALUATION OF ENERGY STORAGE USED FOR RELIABILITY IMPROVEMENT IN DISTRIBUTION NETWORKS

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ABSTRACT

Recent advances in energy storage technologies and their increased deployment in power systems have improved the network flexibility and brought a number of economic benefits. Apart from typical energy storage applications during the network nominal operation, energy storage can significantly improve the quality of service under fault conditions and increase principal reliability indices. However, economic aspects of energy storage operating under these conditions have been seldom studied. This paper addresses the cost-benefit issues of energy storage integration for distribution network reliability improvement purposes. A novel methodology is proposed that calculates both technical and economic reliability indices for a distribution network and then uses them to determine the benefits of energy storage integration. Technical parameters and investment cost of different energy storage technologies are considered. Finally, a benefit-cost ratio index is defined to analyse and quantify the investment proportion that can be recovered by this specific reliability improvement.

INTRODUCTION

Energy storage integration will bring significant advantages to distribution systems such as peak shaving, increase in renewable generation penetration and available ancillary services and also improved reliability of supply [1]. All these benefits have to be included in energy storage evaluation during distribution system planning. The benefits of energy storage installations are commonly evaluated for the network nominal operating conditions and less attention has been paid to the possible reliability improvements during network faults.

Network component failures cause interruptions to customers and affect their reliability of supply. In addition, these interruptions have a significant economic impact [1]. Restoration actions are applied in order to reduce the negative impacts. Among these options, energy storage systems accompanying DGs represent a choice to restore the supply. This is principally done by providing power to the areas isolated by faults that cannot be connected to alternative feeders (islanded operation) [2]. Therefore, the contribution of energy storage to reliability has to be assessed during the network planning stage.

Two main probabilistic approaches are typically used to assess the reliability of distribution networks: analytical and Monte Carlo simulation (MCS) [3]. MCS approach has been widely used to assess energy storage in reliability studies for distribution systems [5][6]. It has the advantage of simple evaluation of the chronological operation of energy storage during faults. However, it requires long computation times and, in this respect, the analytical approach represents a more computationally-efficient alternative to MCS [3]. Yet, the main drawback of analytical techniques is in the modelling the energy storage. It requires increased complexity to address the chronological performance of energy storage over the fault duration [7]. Despite this, several analytical models have been also proposed to evaluate energy storage in reliability studies [8], [9]. Therefore, analytical techniques can be applied to gain computational efficiency when a large number of reliability improvement scenarios are analysed.

Several studies have been performed to assess the contribution of energy storage to distribution network reliability [5], [6], [8], [9]. These studies focus mainly on the technical analysis but the related cost-benefit analyses have been seldom studied. In [5] the reliability improvement provided by an energy storage system in a distribution network was analysed and it was found to be unprofitable. In [6] the cost of energy-not-supplied for different sizes of energy storage was evaluated, demonstrating that the costs can be significantly reduced. However, the investment in the technology was not assessed. Further, more detailed studies are required to assess the proportion of the energy storage investment that can be recovered by the reliability improvement as well as the related implications of energy storage size and technology.

In this paper, a novel cost-benefit analysis for the reliability improvements offered by energy storage is presented and a new methodology proposed for its assessment. The analysis takes into account the cost of energy-not-supplied and the energy storage investment. Different sizes and technologies of storage devices are evaluated and compared. The cost of energy-not-supplied is determined by the existing analytical reliability assessment techniques that model the operation of energy storage. Finally, the proposed method is applied to a real distribution network in order to quantify the economic contribution of energy storage systems to reliability.

METHODOLOGY

Figure 1 shows the proposed methodology used for the cost-benefit analysis of energy storage in reliability studies. The methodology evaluates different energy storage options considered for reliability improvement. For each option, the reliability indices of the network are calculated by using a specific method able to assess the contribution of energy storage. Then, an economic assessment is performed to determine the benefit obtained from improving reliability and the investment cost of the energy storage option evaluated. As a result, the methodology provides the benefit provided by the reliability improvement and the amount of the energy storage investment that is recovered by this benefit.

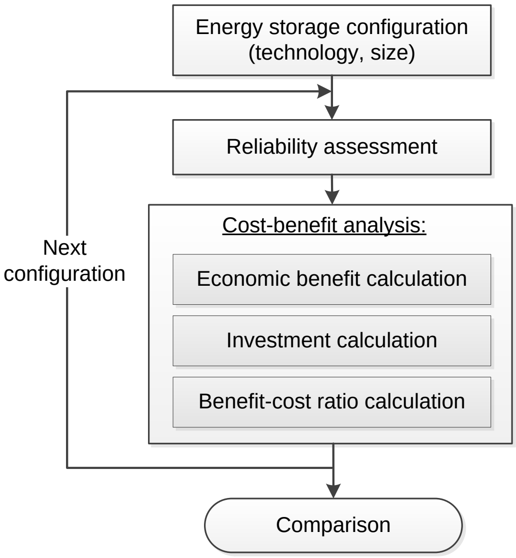

Figure 1. Flowchart of the proposed methodology for the cost-benefit analysis of energy storage in reliability studies

Energy Storage Configurations

Different energy storage configurations are evaluated and they represent the input to the methodology. The configurations are defined by the technology used and its size (capacity and power). The cost-benefit analysis compares all these configurations.

Reliability Assessment

To evaluate the network reliability the methodology proposed in [9] is used. It calculates different reliability indices for the network load points and for specific network regions (area indices). Examples of area indices commonly used in reliability studies are SAIFI (System Average Interruption Frequency Index), SAIDI (System Average Interruption Duration Index) and ENS (Energy-Not-Supplied) [3]. These indices quantify the reliability improvement provided by each energy storage configuration and define network reliability levels. In addition, these indices are used to determine the economic benefit associated with the reliability improvement. In particular, ENS is the principal index used for the economic evaluation this paper as it is described later in the paper.

To calculate the reliability indices, an analytical methodology is applied. The methodology assesses the impact of network faults on customers considering different options to supply restoration in the interrupted areas. One of these options is based on using DGs and energy storage in islanded operation. The DGs can operate with conventional or renewable resources, while energy storage is used to support the generation shortages during faults and reduce the interruption duration. Therefore, the reason behind the reliability improvement provided by energy storage comes from the reduction in the interruption duration and in the energy-not-supplied to the customers. This reliability improvement can be expressed in economic terms and provide useful information regarding the profitability. The procedure for this calculation is described in the following Section.

Cost-Benefit analysis

The cost-benefit analysis proposed in this paper determines the amount of the annual investment that is recovered by the reliability improvement. The annual investment refers to the cost of the energy storage configuration, while the benefit of the reliability improvement to the reduction in the energy-not-supplied provided by the application of energy storage.

The benefit-cost ratio is defined in this paper to represent the ratio between the economic benefit of the reliability improvement and the investment required:

$$Benefit/cost = \frac{BENS}{AIC}$$

where $BENS$ is the annual benefit obtained from energy-not-supplied reduction and AIC is the annual investment cost of the energy storage configuration. They are calculated as described in further text.

Benefit analysis:

The economic benefit of the reliability improvement $BENS$ is determined as the reduction of the customer interruption cost. The following steps are performed to calculate this benefit:

1. The customer interruption cost (CENS) is calculated for each load point i in the network as:

$$CENS_i = \sum_{j=1}^{N_j} ENS_{ij}\, CI_{i,j}$$

Where j and N_j are the index and number of network faults evaluated, ENS_{ij} is the energy not supplied to load point i during fault j, and CI_{ij} is the interruption cost per unit of energy-not-supplied to load point i during fault j. Therefore, the interruption cost is proportional to the amount of energy-not-supplied to customers (ENS_{ij}), while the value of CI_{ij} cost depends on the type of customer interrupted (for example, industrial, residential, commercial) and the duration of the interruption. Details of the criteria used to determine CI_{ij} are given in [10].

2. The benefit introduced by energy storage is defined as the difference between the interruption cost obtained for the case without and with energy storage in the network. It is calculated at each load point as:

$$BENS_i = CENS_i^{NS} - CENS_i$$

where $BENS_i$ is the benefit on reliability provided by the energy storage and $CENS_i^{NS}$ is the interruption cost in the network without energy storage.

3. Then, the overall benefit of energy storage ($BENS$) is calculated for a network area by aggregating the benefits of all loads points as:

$$BENS = \sum_{i=1}^{N_i} BENS_i$$

Cost analysis:

The annual investment cost of energy storage (AIC) is calculated as the ratio between its total investment cost (IC) and its lifetime:

$$AIC = \frac{IC}{Lifetime}$$

The investment cost is calculated as described in [11] and includes the costs of the energy storage technology and the power converter used. These costs mainly depend on the size of the energy storage system.

The lifetime is obtained from the technical specifications provided by the manufacturer. This parameter predominantly depends on the energy storage technology and its operating conditions.

RESULTS

Test Network Description

The proposed methodology is applied to a real 11 kV distribution network in Spain shown in Figure 2. The reliability of this network has been also studied in [12] but not the profitability and the associated cost-benefits. Thus, the proposed methodology was applied to analyse the profitability of energy storage integration in the network. The study addresses only the impact of energy storage when used to improve the reliability of the network and calculate the associated cost-benefits.

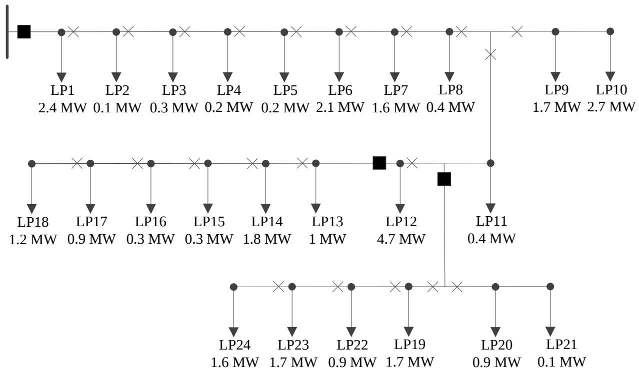

Figure 2 Single-line diagram of the test network [12]

The type of customers in the network is residential with the exception of loads LP6, LP14 and LP19 that were industrial. The study assumes a penetration of DGs in the network as shown in Table 2.

TABLE 1. Related-reliability parameters of DGs

DG	Location (bus)	Technology	DG	Location (bus)	Technology
1	13	Diesel	4	19	Wind
2	16	Solar	5	20	Solar
3	17	Wind	6	23	Diesel

Two energy storage devices are installed in LP17 and LP19 in order to improve the reliability of system. Different power and capacity ratios are used to represent the size of the energy storage devices with respect to the capacity of the renewable DGs installed in the network.

Three types of energy storage technologies (batteries) are evaluated: lead-acid, lithium-ion and vanadium redox flow. The technical parameters of battery technologies are shown in Table 2 including their SOC limits, efficiency and lifetime in years. Charge and discharge efficiencies were assumed to be equal, while the lifetime is determined from technical information in [11] and assuming normal operating conditions in the network. The costs for these technologies are 126 $/kWh for Lead-Acid, 240 $/kWh for Lithium-Ion, and 298 $/kWh, 1312 $/kW for Vanadium Redox flow and the cost of the power converter 70 $/kW. These costs have been obtained from the recommendations given in [11].

TABLE 2. Parameters by energy storage technology

	min SOC	max SOC	η	Lifetime
Lead-acid	0.4	1	0.7	4.5
Lithium-ion	0.1	0.9	0.9	5
Redox flow	0.2	0.8	0.75	13

Energy Storage Size and Technologies

In this section the profitability provided by the three energy storage technologies was evaluated. All the energy storage technologies had the same size. The initial SOC was assumed to be equal to the average value of the normal operating condition (SOC^{I}=0.6). Figures 3, 4 and 5 show the benefit-cost ratio results for the three storage technologies.

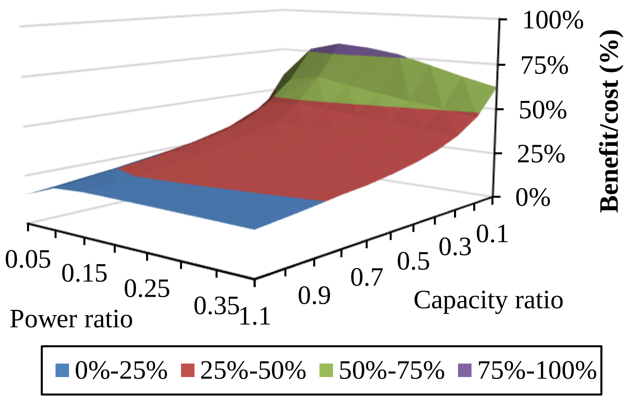

Figure 3. Benefit-cost ratio for lead-acid technology

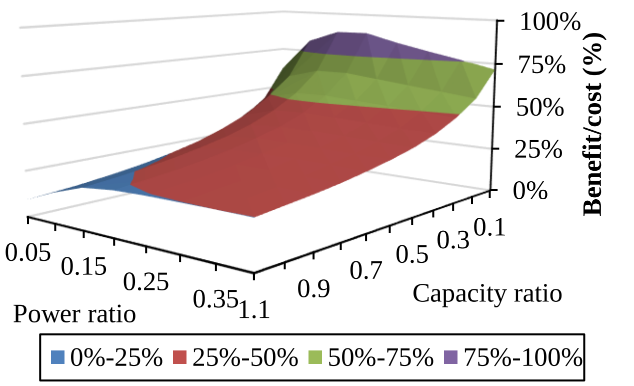

Figure 4. Benefit-cost ratio for lithium-ion technology

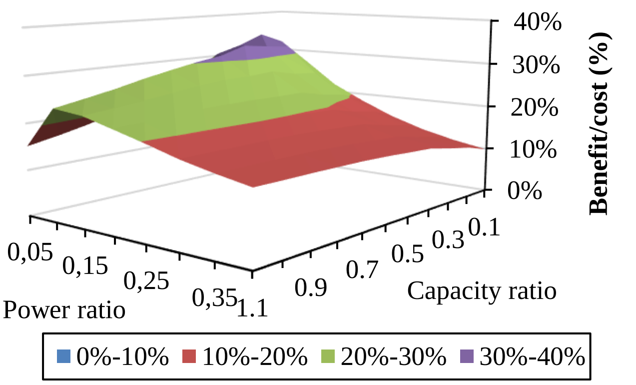

Figure 5. Benefit-cost ratio for vanadium redox flow technology

Results for lead-acid and lithium-ion have similar trends and are highly dependent on the storage capacity. The smaller the storage capacity, the more profitable the energy storage for reliability improvement. This is because small energy storage systems provide more significant reliability improvement when compared to their capacity.

In contrast, the benefit-cost of redox flow technology shows different trends. The storage power has larger influence on the profitability than the storage capacity as its investment cost is higher.

There are significant differences between the benefit-cost ratios of different capacities. For lead-acid, the ratio varied from 88 to 25 % for capacity ratios from 0.1 to 1 respectively (and fixed power ratio of 0.15). In the case of redox-flow, the variation of the benefit-cost ratio were smaller (between 10 and 35 %). The most profitable ratios (between 25 and 33%) are obtained for power ratios between 0.1-0.15 (optimal power ratio).

Reliability benefits

In addition to the benefit-cost ratio, the total economic benefits are compared for the three energy storage technologies. The comparison was performed for a fixed power ratio of 0.15 (this value was within the range of the largest benefit-cost ratios in the previous analysis).

Figure 6 shows the economic benefit provided by the reliability improvement (dashed lines, right y-axis) and the corresponding benefit-cost ratio obtained (continuous line, left y-axis).

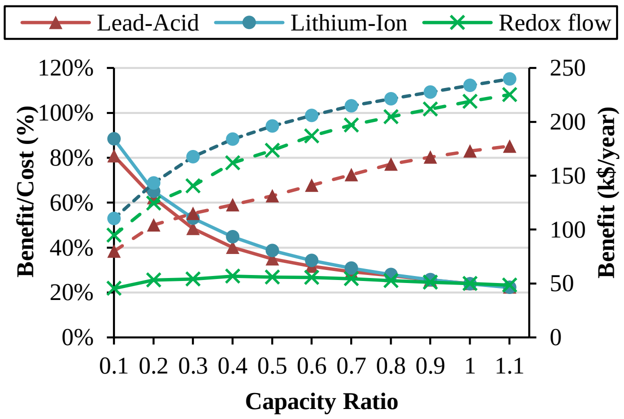

Figure 6. Comparison of benefits (dashed line) and ratios benefit-cost (continuous line) for different energy storage technologies

For all the compared technologies stands the larger the capacity, the larger the economic benefit related to the reliability improvement (as expected). However, in lead-acid and lithium-ion, the investment related to capacity increase is larger than the benefit obtained. This can be observed when benefit-cost ratio and benefit curves are compared. In contrast, the redox flow battery has a more constant benefit ratio between 20-25%.

If we compare the three technologies, lithium-ion provides the largest benefit and lead-acid the lowest. This is because the operating ranges of SOC are larger in ion-lithium than in lead acid technology (from 0.1 to 0.9 for the former, from 0.4 to 1 for the latter). However, the benefit-cost ratios for both technologies are similar as the investment for lithium-ion is larger. Therefore, the cost of the technology is crucial for the cost-benefit analysis.

Impact of State of Charge

The impact of the initial SOC when a fault occurs (SOC^I) is analysed in this section. This parameter is typically assumed as constant in reliability studies [6], however, it is related to the battery operating conditions. To determine the effect of this parameter, different values of average SOC^I (0.4, 0.6 and 0.8) are evaluated and compared. Table 3 shows the average differences of the benefit-cost ratio for the three evaluated values of SOC^I (SOC^I=0.6 is considered as reference).

Table 3. Average variation of benefit-cost ratio with the state of charge SOC^I

	SOC^I = 0.4	SOC^I = 0.8
Lead-acid	-15 %	9 %
Lithium-ion	-5 %	4 %
Redox flow	-5 %	3 %

The results show that the initial SOC has a significant impact on the cost-benefit analysis for the three technologies. They are larger for Lead-Acid technology because of its more constrained operational limits by SOC in comparison with the other technologies (see Table 2). Therefore, this parameter has to be considered in cost-benefit analysis and properly modelled for an accurate evaluation.

CONCLUSIONS

In this paper, a novel cost-benefit analysis is presented for the evaluation of the reliability improvement obtained by energy storage application in distribution networks. The proposed methodology allows the calculation of economic benefits obtained from the reliability improvement only. In this way such contribution can be included in network planning studies and, more importantly, in calculating energy storage payback time. With the expected decrease of energy storage costs the proposed methodology represents a valuable tool for the economic assessment of storage applications.

A case study was used to analyse the economic aspects for different energy storage configurations. The impact of energy storage size and technology as well as the sensitivity of the initial SOC was studied and the comparison was provided. Both economic benefits in absolute terms and benefit-cost ratios were used in the analyses. The principal findings indicate that while vanadium redox flow batteries have higher investment costs they show less sensitivity with respect to storage size. Also, it was confirmed for all the technologies that the larger the capacity, the larger the benefits.

Further studies are required to improve the sensitivity of the proposed methodology and include more techno-economic parameters will be performed in future.

Acknowledgments

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