Electrical Power and Energy Systems 104 (2019) 724–733

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Risk assessment in planning high penetrations of solar photovoltaic installations in distribution systems

Mauricio E. Samper[a,*], Fathalla A. Eldali[b], Siddharth Suryanarayanan[b]

[a] Institute of Electric Energy, CONICET – UNSJ, San Juan, Argentina
[b] Colorado State University, Fort Collins, CO 80523, USA

ARTICLE INFO

Keywords:
Distributed energy resources
Energy storage
Power system planning
Renewable energy integration
Risk analysis

ABSTRACT

The stochastic nature of several renewable energy resources adds a layer of complexity to the planning of the distribution networks. Distributed energy storage is a potential solution for buffering the intermittent supply of energy from such stochastic resources and increasing reliability. This paper quantifies the benefit of investing in battery energy storage systems (BESS) along with relatively high solar photovoltaic (PV) penetrations to defer capital-intensive investments in distribution system assets. Uncertainties in the load growth and the solar PV generation are considered in the assessment of risk by using modified risk-adjusted cost ratios. Furthermore, the size and allocation of BESS in the network system are optimized by applying a heuristic algorithm. The results are demonstrated via simulations on a typical Latin American distribution network. Simulation results indicate that the flexibility of BESS for distribution planning lies in closely accommodating the growth demand and distributed PV integration.

1. Introduction

Battery energy storage systems (BESS) are integrated with distribution networks to help buffer the stochastic energy generated by renewable energy resources (RER) such as solar photovoltaics (PV). The combination of RER and BESS holds the potential for deferring capital investment on electricity grid assets by performing peak-shaving, peak-shifting, and minimizing the financial risk that limits investments in delivery networks expansion [1–3].

There is a correlation between the selections of the size and the location of energy storage systems (ESS). In the literature, several studies focused on finding the optimal choice of energy storage technologies and their dispatch profiles in order to improve supply reliability or to shave and shift the peak demand [4–6]. The work in [7] presents a heuristic planning tool using genetic algorithm (GA) to make the decision of sizing and allocating ESS in the distribution network. This intents to help the distribution system operator (DSO) to solve the problem of operating voltage rise due to high penetration of solar PV systems. The study shows that single-phase residential distributed energy storage might be more financially viable than the three-phase aggregated energy storage at the head of the feeder or at the substation.

Reference [8] proposes an optimal sizing of a hybrid energy system technique with RER independent of BESS. It calculates the net present value (NPV) to compare against the transmission line extension plans to ensure cost-effectiveness. The paper uses response surface methodology to optimize and ensure break-even of the hybrid system and its location in comparison with transmission line extension. It is worth mentioning that the paper considers the stochasticity of the input variables when solving the optimization problem.

Reference [9] presents a methodology to optimally size BESS on a microgrid system that has a variety of RER by including BESS in the unit-commitment formulation. This optimization is based on cost benefit analysis. The paper builds a mathematical model for both microgrid modes of operation (i.e., the grid-connected and the islanded modes) and uses mixed linear integer programing (MLIP) to minimize the total cost.

In [10,11], the papers attempt to examine the potential of using BESS in the low-voltage side of the distribution grid to defer upgrades needed to increase the penetration of PV. In [10], a multi-objective function is proposed to combine three objectives, which include the combination of maintaining voltage level, shaving peak demand, and minimizing the total cost. The work in [11] attempts to find the optimal sizing and location of distributed BESS. The aim of the optimization technique is to minimize the total cost considering price arbitrage and adopting different tariffs. GA is used to find the solution of the optimization problem.

From the literature, several goals are targeted by employing BESS such as peak shaving [6,12], minimizing the total cost [9,11],

---

[*] Corresponding author.

E-mail addresses: msamper@ieee.org (M.E. Samper), Fathalla.Eldali@colostate.edu (F.A. Eldali), sid@colostate.edu (S. Suryanarayanan).

https://doi.org/10.1016/j.ijepes.2018.07.052
Received 22 November 2017; Received in revised form 14 June 2018; Accepted 22 July 2018

minimizing power losses in the distribution grid [13], and deferring investment [14].The main objective of this work is the assessment of risk in deferring capital-intensive investments in distribution grid assets in lieu of investments in BESS technologies, considering the stochasticity associated with the solar PV generation and the load growth. The expected flexibility of BESS options enables the system to closely follow the growths in demand and PV integration.

In capital asset management and investment portfolios, some risk-adjusted ratios (RARs) such as Sharpe ratio (SR) and Sortino ratio (SOR) are usually used for assessing returns of an investment per unit risk [15]. Hence, the objective in investment studies is to find the highest value of these ratios. In this work, we attempt to target the lowest total cost per unit of risk for distribution grid planning using modifications to such RARs.

The contributions of this work are: (i) a risk-based optimization framework for distribution expansion planning; (ii) two modified RARs for investment risk assessment; (iii) the analysis of investing in BESS on a real distribution network in Latin America along with high PV penetrations; considering actual data of solar-weather conditions and associated load data, cost values, and projected growth rates. This work builds on the initial results from our previous work [16,17]. In [16], we proposed an initial study of investing in BESS for supporting high penetration of PVs installed by the customers, without considering uncertainties. In [17], we quantified improvements in wind power forecasts by deferring ancillary services using newly developed metrics for RARs. In this paper, we further modify the new metrics from [17] to fit the application, and consider uncertainties along with the original framework from [16] to provide a comprehensive approach to assessing risk in distribution planning.

The rest of the paper is organized as follows. Section 2 explains the proposed framework of the optimization problem. Section 3 applies the optimization framework to a case study on a typical Argentinian distribution network. Finally, Section 4 provides the conclusions of the work.

2. Optimization problem formulation

The proposed optimization framework is based on stochastic Monte Carlo simulations (MCS) to take into consideration the uncertainties of the input variables in the distribution planning problem. The original (unmodified) SR considers the expected return (profit), $E[R]$, and the risk, $\sigma[R]$, associated with an investment portfolio as shown in (1) [15]. Further, the SR considers a risk-free rate, rf, which is usually represented by the minimum acceptable rate (MAR) of return on the investments. Note that the values of $E[R]$ and $\sigma[R]$ correspond to the mean and the standard deviation of the returns, respectively. This is under the assumption that the returns are nearly normally distributed, implying the skewness of the probability distribution of the returns is close to zero.

$$SR = \frac{E[R] - r_f}{\sigma[R]} \tag{1}$$

If the skewness of the returns distribution is non-negligible, the use of the downside deviation is better than the standard deviation for risk. In this sense, the original SOR considers those returns falling below a specified target value as the MAR that could be set to rf or zero. Then, the risk in an investment portfolio is evaluated as the target downside deviation (*TDD*) or semi-variance, as shown in (2) [15]

$$SOR = \frac{E[R] - MAR}{TDD[R]} \tag{2}$$

where, *TDD* is the root mean square of the deviations of the underperforming returns from the target return (i.e., MAR), which is mathematically computed as in (3).

$$TDD = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (Min(0, R_i - MAR))^2} \tag{3}$$

where, R_i is the i^{th} return, and N is the total number of returns.

In this work, both a modified Sharpe cost ratio (MSCR) and a modified Sortino cost ratio (MSOR), which are presented in (4) and (5) respectively, are proposed to assess risk in distribution expansion investments. The proposed modifications pertain to considering only the present value of the total costs (C_{Pre}) of –but neglecting the incomes from –the investments in BESS and distribution grid assets, that means for each expansion alternative assessed ($\overline{u}$). Further, it does not consider rf in (4), as it does not pertain to this analysis, and the target MAR in (5) is set to zero. The minus signs in (4) and (5) indicate the consideration of the above assumptions. C_{Pre} is computed in (6) using the following: investment cost for each expansion alternative ($\overline{u}$), C_{Inv}; the cost of energy losses, C_{Loss}; the penalty cost of energy supplied with poor quality (i.e., by violating voltage limits), C_{PQEN}; the penalty cost of violating the ratings of feeders and distribution power transformers by over load energy, C_{OEN}; the discount rate, r; and, the planning horizon, T. In (6) also is considered the total number of MCS, M. The variables t and i correspond to the indexes of the time horizon and MCS, respectively.

$$MSCR = \frac{E[-C_{Pre}(\overline{u})]}{\sigma[-C_{Pre}(\overline{u})]} \tag{4}$$

$$MSOR = \frac{E[-C_{Pre}(\overline{u})]}{-TDD(-C_{Pre}(\overline{u}))} \tag{5}$$

$$C_{Pre}(\overline{u}) = \sum_{t=1}^{T}\sum_{i=1}^{M}\left(\frac{C_{Inv}(\overline{u}) + C_{Loss}(\overline{u}) + C_{PQEN}(\overline{u}) + C_{OEN}(\overline{u})}{(1+r)^t}\right)i,\, t \tag{6}$$

Either the MSCR or the MSOR could be minimized as the objective function of the optimization problem. Based on a simply analysis performed in the previous work [17], in this work the objective function of the optimization method is to minimize the MSOR (5) by considering constraints vis-à-vis load flow, as shown in (7), and later the MSCR is just calculated for the best solutions found (corresponding to the expansion plan). The objective function is the minimizing of MSOR as follows:

$$\text{Min}\left\{\frac{E[-C_{Pre}(\overline{u})]}{-TDD(-C_{Pre}(\overline{u}))}\right\} \tag{7}$$

$$\text{subjectto} IL_{j,t} = IL_{Maxj,t} + \triangle IL_{EXCEj,t} \tag{8}$$

$$IT_{DS,t} = IT_{Max,t} + \triangle IT_{EXCE,t} \tag{9}$$

$$P_{Load,t} + P_{Loss,t} = P_{DS,t} + P_{DER,t} \tag{10}$$

The constraints (8)–(10) represent the line capacity constraint, the DS capacity constraint, and the power balance constraint, respectively. Where, the current that exceeds the capacity of a line (j), $\triangle IL_{EXCE}$, is then used to compute the overload energy, OEN; the maximum capacity of the power distribution substation (DS), IT_{Max}, is determined by the power rating of the transformers, and the current that exceeds the DS capacity, $\triangle IT_{EXCE}$, is also used to compute the *OEN*. In turn, with the power losses, P_{Loss}, the energy losses are calculated; and the nodes with high voltage drops are considered to evaluate the energy supplied with poor quality, P_{QEN}. The power of distributed energy resources (DER) that considers the power injection of both the solar PV distributed generators and the BESS is presented in (10), as well as the possibility of BESS consuming electric energy as a load; along with the power load demand, P_{Load}, and the P_{Loss}, assuming the DS as the slack node.

Each expansion alternative ($\overline{u}$) takes into account the decision variables of the optimization problem, including both conventional reinforcements of networks (such as upgrading feeders, installing capacitor banks, and expanding the DS) and the installation of BESS.