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Optimal placement, sizing, and daily charge/discharge of battery energy storage in low voltage distribution network with high photovoltaic penetration

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HIGHLIGHTS

- Calculating optimal sitting, sizing, and scheduling of battery simultaneously.
- Detailed cost/benefit analysis including all possible battery benefits and costs.
- Mitigating impact of high photovoltaic penetration and increasing economic benefit.
- Simulation was performed using real data and low voltage distribution network.
- Reduction environmental emission is considered and converted to economic benefit.

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ABSTRACT

Proper installation of rooftop photovoltaic generation in distribution networks can improve voltage profile, reduce energy losses, and enhance the reliability. But, on the other hand, some problems regarding harmonic distortion, voltage magnitude, reverse power flow, and energy losses can arise when photovoltaic penetration is increased in low voltage distribution network. Local battery energy storage system can mitigate these disadvantages and as a result, improve the system operation. For this purpose, battery energy storage system is charged when production of photovoltaic is more than consumers' demands and discharged when consumers' demands are increased. Since the price of battery energy storage system is high, economic, environmental, and technical objectives should be considered together for its placement and sizing. In this paper, optimal placement, sizing, and daily (24 h) charge/discharge of battery energy storage system are performed based on a cost function that includes energy arbitrage, environmental emission, energy losses, transmission access fee, as well as capital and maintenance costs of battery energy storage system. All simulations are carried out in DIgSILENT and MATLAB linked together. Results show that by using the proposed approach, overvoltage and energy losses are decreased, reverse power flow is prevented, environmental emission is reduced, and economic profit is maximized.

1. Introduction

Recently, utilization of renewable energy sources (RES) in electrical networks is getting inevitable due to the global energy tension and environmental concerns of fossil-fuel-based electricity generation [1].

Photovoltaic (PV) generation is growing very fast while its cost is dropping rapidly [2]. Single phase rooftop PVs (< 10 kW) owned by utility customers are being installed in low voltage (LV) distribution networks. The penetration of such PV systems is increased in many places throughout the world, including Iran, due to solar radiation, gradual elimination of energy subsidies, and government incentives.

Utilizing PV systems can help to reduce the dependence on conventional power plants, improve voltage profile, and decrease energy losses [3]. However, in the case of high PV penetration in LV distribution network, reverse power flow may occur when the PV production exceeds the consumers' load [4]. This situation may lead to overvoltage, increase of total harmonic distortion (THD) and fault current, blinding of protection and false tripping, risk of islanding operation [5], and decrease reliability [6].

To reduce the negative impacts of high PV penetration, there are

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two main approaches including conventional (commercially available) and emerging mitigation methods [1]. Reconductoring and on-load tap changing (OLTC) are examples of conventional methods. Emerging methods include reactive power (VAR) control by PV inverters, distributed energy storage systems (DESSs), coordinated control between utility equipment and PV inverters, installation of devices such as dynamic voltage restorer (DVR) and distributed static compensator (DSTATCOM), etc.

Negative impacts of high PV penetration such as increased voltage magnitude, reverse power flow, and energy losses can be mitigated by optimal placement, sizing and/or charge/discharge scheduling of battery energy storage system (BESS). In this regard, many researchers have studied proper installation of energy storage in distribution networks with high PV penetration. In [7], optimal daily energy profiles of storage systems co-located with PV generation are calculated and it is shown that significant control abilities in peak shaving, voltage stability, and reducing distribution losses can be achieved. Optimal sizing of battery energy storage co-located with PV is evaluated in [8] for the goals such as voltage regulation. In another study, a coordinated hierarchical control scheme is presented for static synchronous compensators (STATCOM) and BESS in order to mitigate the overvoltage problem, but, cost/benefit analysis is not performed for the BESS [9]. Cost/benefit analysis is performed in [10] to determine the optimal location and size (without optimal operation) of community energy storage (CES) by considering energy arbitrage, peak power generation, energy loss reduction, upgrade deferral of transmission and distribution (T & D) systems, CO_2 emission reduction, and reactive power support. BESS is applied in [11] for peak shaving and smoothing the distribution load profile. To achieve these goals, a real time control is developed which performs smoothing and peak shaving, simultaneously. In [11], the economic purpose (price arbitrage) is not considered, therefore, BESS charge/discharge is only calculated for peak shaving. Authors of [12] proposed an algorithm that is capable of integrating sizing, placement, and operational strategies of BESS taking into account energy losses, but, without considering environmental emission. The minimum energy storage required to be installed in LV grid to prevent the overvoltage is calculated in [13]; optimal sizing and placement of BESS is calculated, but, daily charge/discharge is not considered. Authors of [14] proposed optimal sizing (without sitting) of BESS in the residential LV distribution network for peak shaving, valley filling, load balancing, and management of distributed RES. In [15], sizing energy storage based on Open Distribution Simulator (OpenDSS) is proposed, but, optimal sizing, sitting, and charge/discharge are not done simultaneously. Authors of [16] proposed a new framework to integrate CES units in an existing residential community system with rooftop PV units. In [16], the location, sizing, and operational characteristics of CES are calculated to minimize the annual energy loss, enhance load following control, and improve the voltage profile, respectively. In [17], a coordinated control of distributed BESS with traditional voltage regulators including the OLTC and step voltage regulators (SVR) is proposed, but, environmental effects are not analyzed. Authors of [18] discussed optimal sizing and operation of BESS to contribute to local distribution network operation through peak shaving, voltage control, and levelling out power production from RES. The work in [19], optimizes the size of BESS based on a cost/benefit analysis when BESS is applied for voltage regulation and peak load shaving, but, optimal charge/discharge is not taken into account. Optimal planning and operation of energy storage is performed in [20] for peak shaving, reducing reverse power flow, and energy price arbitrage in distribution network with high penetration of RES, but, voltage regulation is not taken into account. In [21], the storage is utilized to compensate long-term and short-term voltage variations originated from sudden change of PV output. The strategy of charge/discharge is presented without any optimization. Authors of [22] determined the soft open point (SOP) of distribution network with the aim of optimal operation of energy storage to mitigate overvoltage arising from high RES penetration. A method is proposed in [23] to optimize the location and size of the DESS. The optimization function is based on best economical investment without considering energy price arbitrage. In [24], by considering high RES penetration, optimal sizing and operation of BESS is proposed to maximize the house independence from the grid and minimize the power flow peaks from and to the grid. An optimization method is developed in [25] for allocation of BESS in distribution system considering capital, land-of-use, and installation costs without taking into account the benefit of energy price arbitrage. Authors of [26] proposed an optimal planning approach for DESS to achieve better economic solution considering total power losses, but, without analyzing environmental effects. In [27], an optimization model is presented to minimize the net present value (NPV) of BESS and energy losses while reduction of environmental emission is not considered. Optimal location, capacity, and power rating of batteries are calculated in [28] to determine the economic technology by considering high RES penetration. Authors of [29] presented a strategy for optimal integration of BESSs by considering voltage regulation and loss reduction without taking into account the benefit of energy price arbitrage. An approach for proper utilization of the energy storage system to mitigate the effects of intermittent nature of PV has been presented in [30], but, optimal BESS planning is not included.

In the present work, it is assumed that distribution system operator (DSO) has got the ownership of BESS. Optimal placement, sizing, and operation of BESS are taken into account in LV distribution network considering high PV penetration. Optimal planning and operation of BESS is performed based on a cost function in order to make the BESS installation economical. In addition, sizing and sitting are done simultaneously with daily charge/discharge. Also, the objectives including energy price arbitrage, transmission access fee, energy losses, and environmental emission are taken into account simultaneously. The objective (cost) function consists of these objectives, and capital and maintenance costs of BESS. In this objective function, loss reduction and environmental benefits are converted to economic benefits. Other technical goals including reverse power flow and voltage regulation are considered as constraints.

Benefits of energy price arbitrage, environmental emission, and transmission access fee are maximized when BESS is charged in low energy price, emission rate, and transmission access fee and discharged while these rates are high. On the other hand, overvoltages that occur due to high penetration of PV are decreased by charging the BESS when PV systems produce maximum energy. Therefore, the optimal charge/discharge of BESS is complicated. In this paper, an auxiliary objective function is defined for increasing energy price arbitrage, reducing transmission access fee and environmental emission, and mitigating undesired impacts of high PV penetration by considering BESS constraints.

DIgSILENT and MATLAB are linked together because modeling of network equipment such as transformer, feeder, load, and power flow study are more accurate and realistic in DIgSILENT while MATLAB provides more powerful optimization tools.

2. BESS modeling

In the case of high PV penetration in LV distribution network, reverse power flow may occur when the PV production exceeds the consumers' load. This situation may lead to overvoltage and increase energy losses [4] (Fig. 1).

BESS can mitigate these disadvantages. Recently, thanks to the technological developments, the price of BESS is decreased, but still is high. As a result, economic, environmental, and technical objectives should be considered for planning and operation of BESS, in order to ensure its affordable utilization. Also, it should be noted that storing energy may take several hours. Furthermore, BESS should charge and discharge during each day. As a result, BESS needs to have features such as efficiency [31], low self-discharge, high cycle life, and low price.