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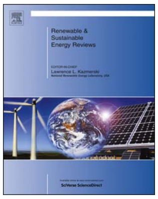

Energy storage planning in electric power distribution networks – A state-of-the-art review

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ABSTRACT

In the past decade, energy storage systems (ESSs) as one of the structural units of the smart grids have experienced a rapid growth in both technical maturity and cost effectiveness. These devices propose diverse applications in the power systems especially in distribution networks. Despite offering numerous applications, the ESSs are new devices characterized by high investment costs. Besides technological advancement, optimal ESS planning and scheduling is one of the effective ways to reduce the costs and justifying high investment costs by taking their benefits out as much as possible. During the past few years, various studies have been conducted by the researcher to address the problem of optimal ESS planning in distribution networks. In this context, various models, methods, and considerations have been proposed to enhance the functionality of optimal planning process. The aim of this paper is to review the problem of optimal ESS planning including optimal bus location, power rating, and energy capacity determination in the distribution networks. In order to facilitate continuing and growing research in this field, a comprehensive literature survey and classification of the related studies followed by research gaps and future opportunities is provided.

1. Introduction

During the past decades, electric power industry has experienced unprecedented technological developments resulting in innovation in the various parts of the utility. Moreover, growing demand for the electricity in the modern society alongside with sustainability and environmental concerns is driving the development and implementation of a new power delivery system. With the advent of smart grids concept, distribution networks continue to move quickly toward becoming smarter and more secure subject to the technical and economic constraints. New technologies have been a great driver in the smart grid deployment and development, especially in distribution networks [1,2]. Over the last years, energy storage systems (ESSs) as one of the fundamental requirements of the smart grid advancement and implementation have seen a rapid growth in both technical maturity and cost effectiveness [3].

Applications of the ESSs in various subsystems of the power systems and especially smart grids are considered and reviewed well in the literature [4–7]. Distribution network as one the structural units of electric power system certainly get benefits from achievable applications of the ESSs in this network. Applications of the ESSs in the distribution networks can be generally summarized as arbitrage or load leveling [8,9], renewable energy integration, smoothing, and time-shift [10–12], renewable energy capacity firming [13], network congestion relief and upgrade deferral [14,15], emission reduction [16], transient and steady-state voltage control [17,18], load following and frequency control [19], and loss reduction [20].

High costs associated with the installing ESSs, especially high investment costs, is the main obstacle to develop these useful devices. Although new technological advancements have been provided to mitigate this problem, but the ESSs are not yet comparable to other conventional equipments in the distribution network.

One of the practical solutions to overcome this obstruction is to take all applications out of the ESSs at the same time. In other words, extracting multiple synergic applications of the ESSs can help to increase their benefits, enhance cost effectiveness, and justify high investment costs. This can be achieved by an optimal investment plan for the ESSs in the distribution network. The new came into sight problem is an optimization problem aiming at finding optimal bus location, power rating, and energy capacity of the ESSs in a distribution network. The objective of the problem is to maximize the benefits achieved by the applications of the ESSs in the network subject to the

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technical limitations of the network and the ESSs.

This new optimization problem has been attracting more attention over the last years [21–51] and a variety of models, methods, and consideration has been developed. In this context, this paper reviews the problem of optimal ESS planning in distribution networks. It should be noted that in the problem in hand the planning means not only sizing in terms of power rating and energy capacity but also sitting of the ESSs in a distribution network with buses and lines. The ESS planning in a single bus network (single node model) which refers to only ESS sizing is not the focus of this paper because this problem has already been widely reviewed [52–55]. The work in [56] performs a review of ESS planning in distribution networks, but, this work has been merged ESS planning in the network and ESS planning in the microgrid. It should be kept in mind that most of the ESS applications in the distribution network including voltage control, loss reduction, congestion alleviation, and network expansion deferral will be achieved only in a network constrained framework. Therefore, combining this problem with ESS planning in microgrid results in lessening the details of the work. In addition, numerous new works have been published after that works. In this regard, this paper offers a detailed and updated review of the network constrained ESS planning in distribution network.

To this end, high quality research works are surveyed and classified in details in order to facilitate continuing research in this field. Table 1 shows list of the reviewed works together with the publication date and the associated journal title. As the table shows, number of the publications is increased year by year. The growing number of the works demonstrates importance of the topic.

Considering the components of the optimization problem in hand, ESS planning in distribution networks, in addition to the contributions of the reviewed works, the review content is classified as follows. After this introduction and in Section 2, various commercial ESS technologies and modeling details used by the researchers in the planning problem are evaluated. In Section 3, those applications of the ESSs which are employed in the problem and the associated objective functions are considered. Joining ESS planning with other solutions in the network, various objective types in terms of single or multi-objective, and also multi-stage planning concept are also dealt with in this section. Network modeling in addition to the solution methods and uncertainty modeling and management issues are investigated in Section 4. Finally, Section 5 offers conclusion remarks of the work.

Table 1
List of the reviewed works.

Ref #	Date of Publication	Journal Title
[21]	Nov 2010	IEEE Transactions on Power Systems
[22]	Jun 2013	IEEE Transactions on Smart Grid
[23]	Jan 2014	IEEE Transactions on Power Systems
[24]	Jul 2014	International Journal of Electrical Power and Energy Systems
[25]	Sep 2014	IEEE Transactions on Power Systems
[26]	Sep 2014	Electronics Letters
[27]	Sep 2014	IEEE Transactions on Smart Grid
[28]	Jan 2015	IEEE Transactions on Power Systems
[29]	Nov 2015	Energy Conversion and Management
[30]	Nov 2015	IEEE Transactions on Smart Grid
[31]	Nov 2015	International Journal of Electrical Power and Energy Systems
[32]	Dec 2015	Energy
[33]	Jan 2016	IEEE Transactions on Power Systems
[34] [35]	Apr 2016[a]	IEEE Transactions on Smart Grid
[36]	Apr 2016	Journal of Renewable and Sustainable Energy
[37]	May 2016	IEEE Transactions on Power Systems
[38]	May 2016	IET Generation, Transmission & Distribution
[39]	Aug 2016	IEEE Transactions on Smart Grid
[40]	Aug 2016	IEEE Transactions on Smart Grid
[41]	Sep 2016	IET Renewable Power Generation
[42]	Oct 2016	Energy
[43]	Dec 2016	Applied Energy
[44] [45]	Jan 2017[a]	IEEE Transactions on Sustainable Energy
[46]	Jan 2017	IEEE Transactions on Sustainable Energy
[47]	Mar 2017	Applied Energy
[48]	Mar 2017	Journal of Modern Power Systems and Clean Energy
[49]	Apr 2017	Solar Energy
[50]	May 2017	Renewable and Sustainable Energy Reviews
[51]	Jul 2017	Electric Power Systems Research

[a] Two-part publication.

2. Energy storage technologies and modeling for planning

2.1. Energy storage technologies

Energy storage systems (ESSs) in the electric power networks can be provided by a variety of techniques and technologies. The ESS technologies include pumped hydraulic storage (PHS), compressed air energy storage (CAES), flywheel energy storage (FWES), superconducting magnetic energy storage (SMES), battery energy storage system (BESS), and supercapacitor or ultracapacitor energy storage (SCES). Today, these technologies are very popular and used for various applications in the power systems [57].

In general, storage systems are categorized based on two factors namely storage medium (type of the energy stored) and storage (discharge) duration. In the first type classification, the ESSs are divided to mechanical, chemical, and electrical storage systems based on the form in which the energy is stored. The mechanical energy storage can also be divided into kinetic and potential. Also, the electrical energy storage is divided into electrostatic and magnetic energy storage. The pumped hydraulic storage and compressed air energy storage, flywheel energy storage, ultracapacitor, superconducting magnetic energy storage, and battery energy storage are belong to potential mechanical, kinetic mechanical, electrostatic electrical, magnetic electrical, and chemical storage categories, respectively.

Base on the second criterion, i.e. storage or discharge duration, storage technologies are divided into two main categories including long-term and short-term storage. The long-term storage, also known as centralized bulk storage, large-scale, or grid-scale storage, is a relatively large storage installation suitable for storing large amounts of electricity. In this case, the storage capacity ranges from a few to hundreds of megawatts and the unit can supply power to the grid with discharge durations more than 8 h. The pumped hydro, compressed air energy storage, and large-scale batteries belong to this category. Considering the long discharge duration and energy capacity, this type of storage is fitted to the long-term energy management applications such as energy arbitrage, congestion management, expansion deferral, and long term voltage control. Second type of storage in this classification is known as short-term or transient storage. The flywheel energy storage, superconducting magnetic energy storage, ultracapacitor, and small-scale batteries fit in this category. Considering short-term response, this type of storage is suitable for frequency regulation, short-term voltage control, transient renewable energy smoothing, and power quality improvement.

The energy storage used in the distribution networks should met some specific requirements in this network. Implementation of the large-scale storage plants like pumped hydro storage and compressed air energy storage involve special geographical and footprint requirements which cannot be achieved in distribution networks. Also, short-term storage technologies including flywheel, ultracapacitor, and superconducting magnetic energy storage are characterized by short discharge duration and very low energy density. Therefore, these technologies cannot provide long-term and high energy density requirements of the energy management solutions in the distribution