Renewable and Sustainable Energy Reviews 91 (2018) 1205–1230

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Overview of energy storage systems in distribution networks: Placement, sizing, operation, and power quality

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ARTICLE INFO

Keywords:
Energy storage systems
Power quality
Energy storage system allocation
Energy storage system sizing
Energy storage system operation
Hybrid meta-heuristic optimisation
Energy security

ABSTRACT

The deployment of energy storage systems (ESSs) is a significant avenue for maximising the energy efficiency of a distribution network, and overall network performance can be enhanced by their optimal placement, sizing, and operation. An optimally sized and placed ESS can facilitate peak energy demand fulfilment, enhance the benefits from the integration of renewables and distributed energy sources, aid power quality management, and reduce distribution network expansion costs. This paper provides an overview of optimal ESS placement, sizing, and operation. It considers a range of grid scenarios, targeted performance objectives, applied strategies, ESS types, and advantages and limitations of the proposed systems and approaches. While batteries are widely used as ESSs in various applications, the detailed comparative analysis of ESS technical characteristics suggests that flywheel energy storage (FES) also warrants consideration in some distribution network scenarios. This research provides recommendations for related requirements or procedures, appropriate ESS selection, smart ESS charging and discharging, ESS sizing, placement and operation, and power quality issues. Furthermore, this study identifies future research opportunities in relation to challenges for optimal ESS placement planning, development and implementation issues, optimisation techniques, social impacts, and energy security.

1. Introduction

Present distribution networks face a critical period of change driven by various interrelated factors; for example, greenhouse gas (GHG) reduction targets, demand management, power congestion, power quality requirements, integration of renewables, and network expansion and reliability [1–11]. The U.S. Electric Power Research Institute (EPRI) estimated the annual cost of outages to be $100 billion USD, due to disruptions occurring in the distribution system [12]. Energy storage systems (ESSs) are increasingly being embedded in distribution networks to offer technical, economic, and environmental advantages. These advantages include power quality improvement, mitigation of voltage deviation, frequency regulation, load shifting, load levelling and peak shaving, facilitation of renewable energy source (RES) integration, network expansion and overall cost reduction, operating reserves, and GHG reduction [13–16,6,17–20]. As reported in [21–23], ESSs are expected to effectively relieve the problems posed by power oscillations, abrupt load changes, and interruptions of transmission or distribution systems.

Governmental efforts to reduce emissions have forced the power sector to reduce its reliance on conventional fossil fuel-based power generation in favour of renewable energy [24–30], largely in the form of wind and solar [31,32]. Even though power generation from renewable energy is more environmentally sustainable, a high reliance on renewable energy can make power distribution systems less reliable [33,19]. ESSs can support renewable energy by providing voltage support, smoothing their output fluctuations, balancing the power flow in the network, matching supply and demand [34–39,18,40–43,21,44–46], and helping distribution companies (network operators and energy retailers) to meet demand reliably and sustainably. These operational challenges can be mitigated by the appropriate utilisation of grid-integrated ESSs [39,23,46,25,26,47–49]. Therefore, there is a great potential for using ESSs, from the viewpoint of both utilities and customers.

Unfortunately, misusing or mislocating ESSs in distribution networks can degrade power quality and reduce reliability as well as load control while also affecting voltage and frequency regulation. Research on ESS technologies, development, applications, and benefits is reported in [41,50,51,17–19,52,34,37,40,53,44,54–62,25,26,47,48,46]. In [34,44,54], several ESS options and their prospects for RES

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https://doi.org/10.1016/j.rser.2018.03.068
Received 16 November 2016; Received in revised form 22 March 2018; Accepted 22 March 2018
1364-0321/

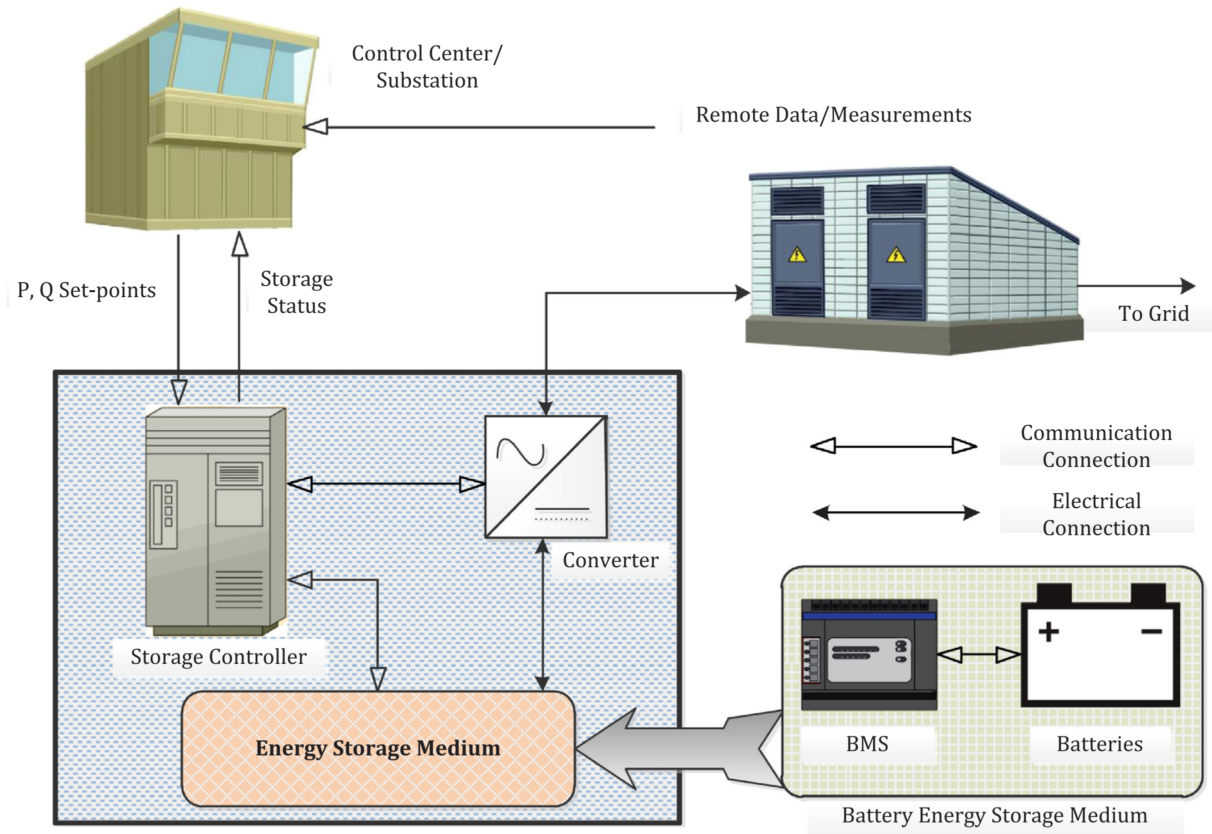

Fig. 1. Conceptual diagram of an ESS.

integration and intermittency are discussed. In [41,37], applications of ESSs for wind energy are studied, while the importance of ESSs for large-scale integration of photovoltaics (PVs) is the focus of [18]. In [25], an ESS, namely, pumped hydro storage (PHS) is used to stable the wind power generation while optimising the generation mix, total CO_2 emissions, and total system costs. [26] investigates the utility-scale application impact of an ESS, e.g., compressed air energy storage (CAES) in a power system scenario considering large RES integration. In [47,48], short term applications of utility-scale ESSs are presented for mitigating negative operational impacts of a high wind-penetrated power system.

An overview of current and future ESS technologies is presented in [53,57,59], while [51] reviews a technological update of ESSs regarding their development, operation, and methods of application. [50] discusses the role of ESSs for various power system operations, e.g., RES-penetrated network operation, load leveling and peak shaving, frequency regulation and damping, low voltage ride-through ability, and power quality improvement. [17] discusses ESS options for some high-power applications, e.g., frequency regulation, voltage control, oscillation damping, and voltage ride-through. [46] presents an economic and technical overview of the role and significance of ESSs and smart grid technologies for future renewable power systems. The policy recommendations and benefits of using ESSs in smart grid are presented in [19] and [52], respectively. Likewise, [58] reviews the various ESSs in terms of innovative technologies, energy policies, and regulatory regimes. The potential of ESSs for various services in distribution networks is reviewed in [55,56], while their operations are discussed in [60]. In [61], research on ESS allocation is reviewed to provide insights into ESS integration issues and challenges in distribution networks along with guidelines for future ESS-related research. In [62], optimal ESS planning is discussed, including optimal ESS locations, energy capacity, and power rating determination in distribution networks.

Although various investigations on ESS options and application benefits are carried out in the literature discussed above, very few studies [61,62] focus on a review of ESS placement, sizing, and operation. However, more emphasis is required on optimal ESS placement, including sizing and operation as well as power quality, and this paper addresses that need. The main contributions of this paper are summarised as follows:

- The paper provides a comprehensive review of ESSs from a distribution network perspective, including ESS benchmarks, ESS technologies and selection, and ESS charging-discharging rules.
- Optimal ESS sizing, placement, and operation are reviewed thoroughly (based on the recent literature) and critically analysed by highlighting the strategies that are used, advantages, and the scope of future research. The paper also discusses tools and their suitability for system modelling, simulation, and analysis, considering ESS applications in distribution networks.
- The paper discusses various issues related to the power quality of distribution networks and their mitigation scopes with ESSs.
- The research verifies the importance of hybrid meta-heuristic optimisation approaches for obtaining optimal solutions, rather than other optimisation techniques.
- The paper identifies the challenges for ESS development and placement and discusses the ESS contributions to energy security and society.
- The research presents several key findings which will benefit researchers by highlighting potentially important directions for future research.The content of this paper is organised as follows: Section 2 describes an overview of ESSs, effective ESS strategies, appropriate ESS selection, and smart charging-discharging of ESSs from a distribution network viewpoint. In Section 3, the related literature on optimal ESS placement, sizing, and operation is reviewed from the viewpoints of distribution network operation and power quality issues. Section 4 discusses the challenges and distribution network performance factors that should maximise the economic and social impact benefits. Finally, Section 5 concludes the paper by highlighting future research recommendations.