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Overview of current development in electrical energy storage technologies and the application potential in power system operation ☆

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HIGHLIGHTS

- An overview of the state-of-the-art in Electrical Energy Storage (EES) is provided.
- A comprehensive analysis of various EES technologies is carried out.
- An application potential analysis of the reviewed EES technologies is presented.
- The presented synthesis to EES technologies can be used to support future R&D and deployment.

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ABSTRACT

Electrical power generation is changing dramatically across the world because of the need to reduce greenhouse gas emissions and to introduce mixed energy sources. The power network faces great challenges in transmission and distribution to meet demand with unpredictable daily and seasonal variations. Electrical Energy Storage (EES) is recognized as underpinning technologies to have great potential in meeting these challenges, whereby energy is stored in a certain state, according to the technology used, and is converted to electrical energy when needed. However, the wide variety of options and complex characteristic matrices make it difficult to appraise a specific EES technology for a particular application. This paper intends to mitigate this problem by providing a comprehensive and clear picture of the state-of-the-art technologies available, and where they would be suited for integration into a power generation and distribution system. The paper starts with an overview of the operation principles, technical and economic performance features and the current research and development of important EES technologies, sorted into six main categories based on the types of energy stored. Following this, a comprehensive comparison and an application potential analysis of the reviewed technologies are presented.

1. Introduction

Global electricity generation has grown rapidly over the last decade. As of 2012, the annual gross production of electricity reached approximately 22,200 TW h, of which fossil fuels (including coal/peat, natural gas and oil) contribute around 70% of global electricity generation [1–3]. To maintain the power network stability, the load balance has mainly been managed through fossil fuel power plants. To achieve the target of reducing CO_2 emissions, future electricity generation will progress with diminishing reliance on fossil fuels, growing use of renewable energy sources and with a greater respect for the environment [3]. However, most renewable energy sources are intermittent in their nature, which presents a great challenge in energy generation and load balance maintenance to ensure power network stability and reliability. Great efforts have been made in searching for viable solutions, including Electrical Energy Storage (EES), load shifting through demand management, interconnection with external grids, etc. Amongst all the possible solutions, EES has been recognized as one of the most promising approaches [4,5].

EES technology refers to the process of converting energy from one form (mainly electrical energy) to a storable form and reserving it in various mediums; then the stored energy can be converted back into electrical energy when needed [4,5]. EES can have multiple attractive value propositions (functions) to power network operation and load balancing, such as: (i) helping in meeting peak electrical load demands, (ii) providing time varying energy

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management, (iii) alleviating the intermittence of renewable source power generation, (iv) improving power quality/reliability, (v) meeting remote and vehicle load needs, (vi) supporting the realization of smart grids, (vii) helping with the management of distributed/standby power generation, (viii) reducing electrical energy import during peak demand periods.

In many scenarios, demand for EES and selection of appropriate EES technologies have been considered to be important and challenging in countries with a relatively small network size and inertia. For example, the UK electric power network currently has a capacity of Pumped Hydroelectric Storage (PHS) at 27.6 GW h [6]. Although PHS facilities have been built worldwide as a mature and commercially available technology, it is considered that the potential for further major PHS schemes is restricted in the UK [6]. Therefore, it is of great importance that suitable EES technologies in addition to PHS are explored. Derived from the study of recent publications, Fig. 1 illustrates various EES technologies with potentials to address the challenges faced by the UK energy systems [4,6,7–9]. Many countries potentially need to address similar challenges which can be solved or improved by suitable EES technologies.

Due to the great potential and the multiple functions of EES, in the literature many authors have reviewed and summarized the EES research and development, demonstrations and industrial applications from different perspectives, particularly in recent years. The paper presented by Ibrahim et al. highlighted the need to store energy for improving power networks and maintaining load levels [10]. A group of characteristics of different EES technologies is given, which can help improve performance and cost estimates for storage systems. However relatively few references are cited in [10]. Chen et al. provided a well-organized and comprehensive critical review on progress in EES systems, which covered various types of EES technologies and their applications/deployment status [4]. The discussion on the selection of appropriate EES candidates for specific applications was relatively brief. Hall et al. also presented a review article concentrating on several EES technologies, i.e., batteries, supercapacitors, superconducting magnetic energy storage and flywheels [11]. Liu et al. provided an insightful review of the advanced materials for several EES technologies [12]. The strategies for developing high-performance hydrogen storage materials and electrochemical lithium-ion battery materials were discussed in detail [12]. The paper also highlighted the prospects in the future development of advanced materials for EES. With the rapid penetration of intermittent renewables, the review articles [13–16] have made effort to assess and summarize the EES options for increased renewable electricity applications. Díaz-González et al. [13] and Zhao et al. [15] focus on the review of EES technologies for wind power applications. A detailed discussion of existing EES applications in wind power is a highlight provided by the article [13], whilst the planning issues, the operation and control strategies of the ESS applications for wind power integration support are summarized by the paper [15]. Furthermore, from a novel viewpoint, Connolly et al. assessed available computer tools for analyzing the integration of renewable energy into various energy systems [17]. Researchers have also reviewed specific aspects of EES systems, such as in [18–22]. For instance, Dunn et al. contributed a high quality review on battery energy storage for the grid applications, mainly focusing on commercially available sodium–sulfur batteries, relatively low cost redox-flow batteries and developing lithium-ion batteries, all with the aim to be used in grid storage [22]. The reviews of the developments and challenges in materials for electrochemical relevant energy storage are presented in [23–25]. For example, Whittingham addressed the current challenges in the subject of electrochemical energy storage materials, which can be summarized as: reducing the cost and extending the lifetime of devices whilst improving their performance and making them more environmentally friendly [23]. In addition, some journals have published special issues dedicated to EES research and development, such as the special issue in 2013 from the Wiley journal Advanced Functional Materials: "Grand Challenges in Energy Storage".

A brief statistical study has been carried out to ascertain the trends in EES related research using the search engine 'Web of Science' and choosing 'Topic' as the search field. Fig. 2 shows the results detailing the number of research papers published in six EES related fields over the past ten years (2004–2013). The titles of the subfigures in Fig. 2 are the input keywords used in the search engine. The results indicate that research in EES in the past ten years has tended to increase, with rapid increases in 2012 and 2013. In particular, research into compressed air energy storage

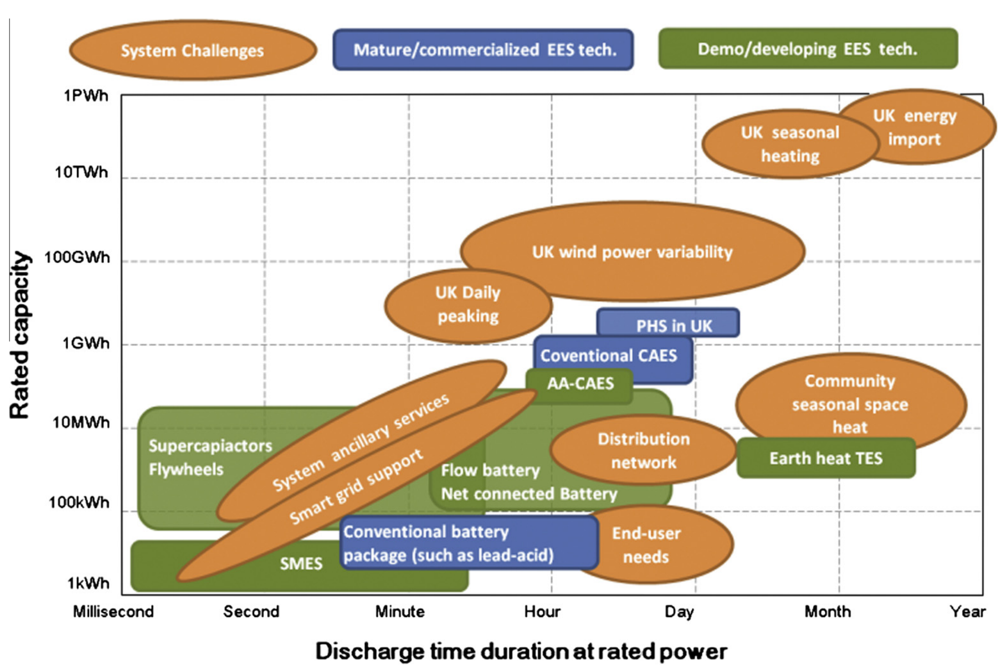

Fig. 1. Electrical energy storage technologies with challenges to the UK energy systems [4,6,7–9].

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