Energy storage technologies application Potentials

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Renewable energy sources (RESs) such as wind and solar are frequently hit by fluctuations due to, for example, insufficient wind or sunshine. Energy storage technologies (ESTs) mitigate the problem by storing excess energy generated and then making it accessible on demand. While there are various EST studies, the literature remains isolated and dated. The comparison of the characteristics of ESTs and their potential applications is also short. This paper fills this gap. Using selected criteria, it identifies key ESTs and provides an updated review of the literature on ESTs and their application potential to the renewable energy sector.

Keywords: intermittent energy sources ; energy storage applic ; energy storage application ; characteristics of ESTs ; comparison of ESTs ; selection criteria of ESTs

1. Introduction

Nowadays, renewable energy generation capacity is growing at a rapid rate globally. Data from the International Renewable Energy Agency (IRENA) showed that, at the end of 2019, global RESs generation capacity amounted to 2537 GW. Hydropower accounted for the largest share of the global total, with a capacity of 1190 GW (excluding pure pumped storage); this is followed by wind energy (623 GW), solar energy (586 GW), bioenergy (124 GW), geothermal energy (14 GW), and marine energy (500 MW) [1]. Among renewable energy sources' (RESs') generation capacity, wind and solar energy continued to dominate renewable capacity addition in 2019 [1]. However, energy supply from such sources is often hit by fluctuations due to, for example, insufficient wind or sunshine. It is, therefore, necessary to maintain the power fluctuation of a power system integrated with a large amount of RESs such as wind and solar. Energy storage is a crucial means that mitigates such increased fluctuations or power quality problems by providing voltage support, smoothing their output fluctuations, balancing the power flow in the network, and matching supply and demand. Additionally, ESTs are offering ancillary grid services like frequency control, energy time-shifting, power quality improvement, load leveling, peak shaving, facilitation of RESs grid integration, network expansion, and overall cost reduction and operating reserves [2][3][4][5] Moreover, with the increase of the production of power or energy from RESs, it becomes much important to look at methods or techniques of selecting the appropriate type of ESTs for RESs grid integration application. Hence, the relationship between ESTs and its application is interdependent; a knowledge of the technical characteristics of each ESTs as well as their application potential in RESs are very important toward technology adoption. Furthermore, industry and engineering are producing a variety of ESTs, but the breadth and depth of these technologies are coherently reviewed and synthesized.

2. Overview of Energy Storage Technologies

There are various ESTs available for storing energy for RESs applications, including those based on mechanical, electrical, and electrochemical processes. Above all, the main services that the storage must provide will determine the best-adapted technology. All ESTs have their advantages and disadvantages, therefore which are the most appropriate in different circumstances and able to be adopted for RESs grid integration is the focus of this study. Following subsections cover, a review of the advantages, disadvantages, and application potential of all selected ESTs such as mechanical, electrical, and electromechanical energy storage system for RESs utility grid integration are briefly reviewed. The detailed technical characteristics data for all selected ESTs are presented in section four.

2.1. Mechanical Energy Storage

Mechanical energy storage systems are stored energy as potential energy in PHS and CAES, and as rotational kinetic energy in FES. Among the mechanical energy storage system, the PHS system is the most dominant and widely implemented energy storage system in the world; it accounts for around 92.6%(171.03 GW) of all currently deployed forms of energy storage[6][7][8][9][10][12][15][16][18][19][20][21][22][23][24][25]. PHS is a matured technology with a large volume, long discharge duration, high efficiency, long life, the relatively low capital cost per unit of energy (see Tables 2–4), highly reliable, flexible, low operation, and maintenance cost. Additionally, the rating of PHS is the highest all over the available ESTs (10–5000 MW); hence, it is generally applied for energy management. The PHS system has also application potential in RESs such as for wind power grid integration. On the other hand, since the PHS system has a slow response time, it is not appropriate for suppressing wind fluctuations [17]. The major limitations of PHS system are its dependence on topographical conditions and large land use, long development time, and long payback periods[13][26].

CAES is one of the largest energy storage systems [5–300 MW] next to the PHS systems [13]. It has a rapid start-up time, long discharge duration, low capital costs, and moderate efficiency (see Tables 2–4). The major limitations to the implementation of the CAES system are its dependence on favorable geography [13], fossil fuel combustion, and CO2 emission problem during operation conditions [27]. CAES system has application potential in renewable energy such as in wind energy for energy management purposes, due to the high power and energy capacity rating of the storage [17].

FES systems have low maintenance, no carbon emission, no toxic components, high cycle life, very fast response, high cycle efficiency (90–95%), very short discharge duration, and high power density [3][11][28][29]. However, FES suffers from idling losses when the FES is on standby. This can lead to a relatively high self-discharge rate (up to ~20% of stored capacity per hour) [11][27]. In addition to this, FES have low storage capacity and high cost [3]. The most common FES application areas are power quality improvement of grid systems such as frequency and voltage regulation, uninterruptible power supply (UPS), transportation, spacecraft, military, and grid-integration of RESs such as for suppressing fast wind power fluctuation [17][28].

2.2. Electrical Energy Storage

Electrical energy storage systems are stored energy in the same way, like electrical energy and it consists of mainly two types of energy storage: SCES and SMES. Among electrical energy storage systems, SCES has a long lifetime, high cycle efficiency, high power density, a very fast response time (see Tables 2–4), adaptability for diverse environments, and is unaffected by the depth of discharge (DoD) and independent of maintenance [11][14][30][31]. However, the daily self-discharge rate of SCES is high (~5–40%), and the capital cost is also high. Furthermore, SCES has a very short discharge duration and low energy density [30]. Thus, SCES is well suited for short-term storage applications. Moreover, the typical applications of SCES systems are for pulse power, bridging power to equipment, UPS devices, grid-integration of RESs [11][31]. Additionally, SCES can also mitigate fast wind power fluctuations for a short time duration [32].

SMES system has fast response time, very short discharge time, very high efficiency, its cycle life is not affected by the DoD, and a long lifetime [2][7][29][33]. However, SMES units have high capital costs, complicated cooling systems, high daily self-discharge rates (10–15%), and a negative environmental impact due to the strong magnetic field (see Tables 2–4). Due to its fast response time, and short discharge duration, SMES is more suitable for short-term applications, such as power quality problems for large industrial customers and microgrids and intermittent renewable energy mitigation [33].

2.3. Electrochemical Energy Storage

Electrochemical ESTs are the second-highest globally installed energy storage capacity of 9.6 GW [6] (see Figure 1). Among electromechanical ESTs, Li-ion batteries are the most widely installed capacity of 8.5 GW [6]. In this section, a review of the characteristics and application potential of various types of battery energy storage system (BESS) used for grid-scale energy storage, such as Pb-A, Ni-Cd, Na-S, NaNiCl2, Li-ion, and FBES are reviewed.

Pb-A is the oldest, cheapest, well developed, and widely used rechargeable electrochemical energy storage device. The major features of Pb-A batteries include being low cost and simple to manufacture, high reliability, high efficiency, low self-discharge rate, fast response time, easy recyclability, high specific power, and no block-wise or cell-wise battery management system required [34]. Pb-A is a popular choice of energy storage as a backup power supply in a range of kW to tens of MWs for power quality, UPS, data and telecommunication system applications, grid utility application, renewable energy output smoothening, and hybrid electric vehicles application. However, its application for energy management has been very limited due to its short cycle life, low energy density, poor performance at low temperature, high maintenance requirement, and environmental impact [34][35].

Ni-Cd batteries have high efficiency, unaffected by DoD, very low maintenance requirements, small self-discharge rate (10% per month), and operate over a wide range of temperatures (−40 to 50 ℃) [36]. The major limitation of the Ni-Cd battery is its impact on the environment and memory effect problem. Currently, Ni-Cd batteries are used for power tools, portable devices, emergency lighting, UPS, telecoms, and generator starting application purposes. However, Ni-Cd batteries are not implemented in large scale power system applications yet, due to their high cost and memory effect problem.

Na-S batteries have a long lifetime, high energy densities, fast response, high recyclability, and high pulse power capability. In addition to this, Na-S has a power range from several kW to a few MW and an energy range from 100 kWh or higher [37]. The most common application of Na-S battery is for high-power energy management such as the smoothing output power of wind farms, load leveling, and peak shaving [38]. However, the major limitations of Na-S batteries are their high initial capital cost, high-temperature requirements for operations, and high self-discharge per day [35].

NaNiCl2 batteries have higher cell voltage (2.58) compared to Na-S batteries, higher temperature range (270–350 ℃), longer life, higher storage capacity, and are fully recyclable . NaNiCl2 batteries have application potential in RESs such as for smoothing the intermittent RESs in distribution grid integration, peak shaving, and time-shifting [38][39]. However, NaNiCl2 batteries have low energy density compare to Na-S batteries and safety issues due to molten sodium [40].

Li-ion batteries have a low percentage of self-discharge rate not exceeding 8% per month, high energy-to-weight ratios, high cycle life, high cycle efficiencies, a rapid response time (in milliseconds), and low environmental impact [38]. In addition to this, Li-ion batteries have a high power range (1 KW to 100 MW) and energy above 200 MWh [37]. These characteristics make Li-ion batteries good candidates for application where the fast response time, high power and energy density, high cycle efficiency, and lightweight are needed, such as in the renewable energy sector, plug-in hybrid electric vehicle (PHEV), and electrical vehicle (EV) applications. However, the price of a Li-ion battery is high compared to other rechargeable batteries [41][42].

FBES batteries have high response time, very low self-discharge rate, long discharge duration, high efficiency (see Tables 2–4), room temperature operation, low maintenance, and no harmful emission. However, FBES have a low energy density and high manufacturing costs compared to other rechargeable batteries. Currently, some types of FBES like vanadium redox flow battery (VRFB), zinc-bromine flow battery (ZBFB), and polysulfide bromide flow battery (PBFB), have been used or can potentially be used for RESs grid integration as well as for utility grids, such as for load balancing and standby power application [40].

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