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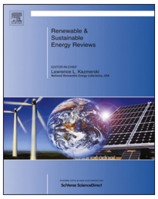

Redox flow batteries for the storage of renewable energy: A review

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ABSTRACT

The need for grid-connected energy storage systems will grow worldwide in the next future due to the expansion of intermittent renewable energy sources and the inherent request for services of power quality and energy management. Electrochemical storage systems will be a solution of choice in many applications because of their localization flexibility, efficiency, scalability, and other appealing features. Among them redox flow batteries (RFBs) exhibit very high potential for several reasons, including power/energy independent sizing, high efficiency, room temperature operation, and extremely long charge/discharge cycle life. RFB technologies make use of different metal ion couples as reacting species. The best-researched and already commercially exploited types are all-vanadium redox batteries, but several research programs on other redox couples are underway in a number of countries. These programs aim at achieving major improvements resulting in more compact and cheaper systems, which can take the technology to a real breakthrough in stationary grid-connected applications.

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1. Introduction

For more than two hundred years the rapid development of industrial societies has relied on the exploitation of huge reserves of low-cost fossil energy. Resources formed over hundreds of millions of years have been burned in a relatively short time, with substantial environmental impact. Nowadays, electric energy demand exceeds 20×10^3 TWh/year and is growing at a rate of about 3% per year. Electrical energy is mainly produced in large fossil-fuel (approx. 2/3 of total), nuclear and hydroelectric power plants [1,2]. In the long term, this choice appears to be unsustainable. The growing demand for energy, particularly from large newly industrialized countries, and the increasing attention to environmental problems call not only for the optimal use of conventional sources, but also for their gradual replacement with environmentally-friendly renewable sources. Such policies, claimed for decades by scientists, have been finally embedded into the funding programs of central administrations in all industrialized countries.

Renewable sources, except hydropower, currently provide 4% of electricity production mainly from wind and solar energy, but their penetration is estimated to grow by more than 25% by 2030 [3].

Unlike conventional power plants, wind, solar, and other renewable sources are intermittent because they generate electrical power according to the time and climatic availability of the resources. Power variability ranges from the hourly time-scale related to the daily sun-light through the year, typical of photovoltaic (PV) systems, down to the min–s time-scale that is characteristic of wind generators.

The integration of primary energy sources with different features requires more attention in the design, control and management of the electric grid [4]. Traditional grids, which have not been designed to meet these goals, are often unable to provide satisfactory performance and recent studies have suggested that the grid can become unstable if power from these sources exceeds 20% of the whole generated power without adequate compensating measures, namely energy storage [5,6].

These issues call for complementing energy generation from renewable sources with energy storage systems capable of storing production surplus during some periods and of coping with higher demand in others [7–9].

Energy storage can also be useful in reducing electricity costs for distributors and consumers when electric companies apply policies of hourly pricing.

The use of energy storage on a large scale, both in a few large plants and in many small/medium size systems, allows to substantially limit the need of upgrading generating plants on the base of peak demand evolution, following instead a strategy of investment deferral.

Energy services can be basically grouped into two main categories, *power quality* and *energy management* (Fig. 1). The former refers to charge/discharge cycles on the short timescale (s–min) and includes sag compensation, power smoothing, grid stabilization, and frequency regulation. The latter concerns charge/discharge cycles on the long timescale (min–h), includes load leveling, load following, power balancing, peak shaving, and time shifting, and also contributes towards improving the grid load factor. *UPS* (uninterruptable power supply) is an energy storage service with intermediate features. Therefore, depending on the service, operating times range from the timescale of fractions of a second, with response times in the order of milliseconds, to several hours [10,11]. Moreover, power ranges from few kilowatt for domestic utilities to some gigawatt, for large plants.

Storage technologies capable of providing such performance will be essential parts of smart grids which are expected to spread in the near future. A recent authoritative report has forecasted investments exceeding $ 10 billions/year on energy storage technologies by 2020 [12].

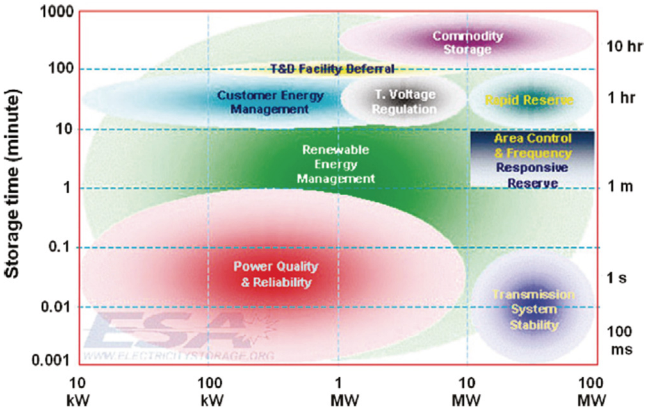

Fig. 1. Allocation of different energy storage requirements in the power—discharge duration diagram (*source*: Electricity Storage Association [13]).

2. Energy storage technologies

Economically convenient and technically competitive storage solutions must ensure not only response time and storage capacity suitable for meeting both the generation and grid needs, but must also show a long lifetime and be able to withstand a large number of charge/discharge cycles. Present-day technologies are characterized by different levels of development and are suitable for different storage and localization needs [14,15]. The best performing storage systems for electric energy applications are listed in Table 1 and described below, while design and operating features are reported in Table 2.

2.1. PHES (pumped hydro energy storage)

Hydro-pumped storage is by far the most exploited at present (127 GW of the total 128 GW worldwide storage capacity) [16]. Hydro-pumped plants operate efficiently when exceeding 20 MW and 50 MWh and top power reaches 3 GW at present (Bath County Pumped Storage Station, US-VA). However, they cannot respond to fast power demand, and are suitable for high-power long-time services, namely for energy managements [17,18]. Moreover, plants can only be sited in mountain regions with suitable differences in water levels, have an environmental impact, and are often threatened by long-term reservoir filling with sedimentary depositions. These drawbacks limit wider diffusion of PHES in several countries [19].

2.2. CAES (compressed air energy storage)

Compressed-air storage is suitable for large plants and is also prone to site issues. In fact, both large-scale existing plants are of the underground type, i.e. they store compressed air in huge underground caves. Huntorf, Germany, started in 1978 and rated 290 MW and 900 MWh, exploits two caverns of 310×10^3 m^3 at -655 to -800 m pressurized up to 66 bar [20]. McIntosh, US-AL, started in 1991 and rated 110 MW and 2800 MWh, uses a 560×10^3 m^3 cavern at -460 m pressurized up 74 bar [21]. In short, they cover similar energy management service as PHES. R&D activities, such as the ADELE project (200 MW, planned to be operational in 2013), are aimed at overcoming present limitations by resorting to an adiabatic operation (A-CAES, retaining the compression heat for reuse in the expansion phase [22]) in order to improve round-trip efficiency and by considering “aboveground” storage in tanks, even if all these solutions involve higher investment costs [23,24].

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