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Energy storage systems for PV-based communal grids

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ABSTRACT

In this paper energy storage systems used with PV power generators are reviewed with a focus on batteries. Merits and demerits of different storage technologies are compared. Batteries are further reviewed, modelled and simulated, with a focus on the four most common battery technologies used with PV systems, i.e., lead-acid (Pb-acid), lithium-ion (Li-ion), nickel-metal-hydride (Ni-MH), and nickel-cadmium (Ni-Cd). Pb-acid batteries are the cheapest and most widely available but they also have the lowest charging/discharging cycles. Ni-MH and Ni-Cd batteries have many similar characteristics with the latter being the most temperature resistant of all batteries. However, these technologies are not widely available and are quite expensive compared to Pb-Acid batteries. Li-ion batteries have the fastest charging/discharging cycles and highest efficiencies of up to 99%. However, they are also the most expensive and are also not widely available in developing communities; the merits and demerits of the four battery technologies mentioned above are compared in a table.

1. Introduction

Energy storage systems are used in decentralized power systems for energy management, i.e., load levelling or peak shaving, for power bridging, and for power quality improvements [1–4]. Energy management functions require the energy storage systems to serve for long durations compared to the other functions [1–4]. Power bridging functions require energy storage systems to serve for few seconds to few minutes [1–4]. For power quality improvements, the energy storage systems are required for only fractions of a second [1–4]. The main energy storage technologies include pumped hydro, compressed air energy storage (CAES), flywheels, superconducting magnetic energy storage (SMES), and electrochemical storage [5–9].

In pumped hydro systems excess energy during low demand periods is used to pump water from a lower reservoir into an uphill reservoir from where it can be used to generate electricity during high power demands by natural flow of water through turbines back to lower reservoir. In CAES systems compressed air is used to feed a gas turbine to generate electricity when necessary. In flywheels energy is stored in form of mechanical kinetic energy and is then converted back into electricity by use of a 4-quandrant power converter. SMESs store energy in magnetic fields using superconducting coils with high magnetic fields. The stored energy can be discharged as electric current by connecting it to a load. Electrochemical storage systems store energy as chemical energy which can then be converted into electricity through chemical reactions. They include fuel cells, supercapacitors, and batteries.

Table 1 compares the different energy storage technologies discussed above. It is noteworthy that batteries have a wider range in all aspects of comparison. This is because there are very many types of batteries that are commercially available, with each type optimizable for different purposes and applications.

Batteries are the main energy storage devices used with PV power systems. They are also used to operate PV systems near their maximum power points (MPP), to power electrical loads at stable voltages, and to supply surge currents to electrical loads and inverters. The two main classes of batteries are primary batteries and secondary batteries. Primary batteries cannot be recharged and are thus not applicable in PV systems. Examples include carbon-zinc and lithium batteries used in consumer electronics. Secondary batteries can be recharged and are thus used in PV systems. The most common battery types used with PV systems are lead-acid, lithium-ion, nickel-metal-hydride, and nickel-cadmium.

1.1. Lead-acid (Pb-acid) batteries

The positive electrode in a Pb-acid battery is composed of lead dioxide (PbO_2) while the negative electrode if composed of porous lead (Pb). The electrolyte is composed of 6 molar sulphuric acid (H_2SO_4).

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Table 1
Energy storage technologies comparison [5–9].

	Supercapacitors	Batteries	Flywheels	SMESs	Fuel Cells	Pumped Hydros	CAESs
Charge Time	1–30 s	0.3–5 h	0.5–2h	0.1–5 h	0.3–5 h	10–50 h	1–50 h
Reverse Time (S)	0.01	0.01	0.1	0.01	360	10	360
Energy Density (Wh/kG)	1–10	30–130	5–50	10–50	20–30	0.2–0.7	20–50
Power Density (W/kg)	10^3–10^5	10–10^2	10^2–10^4	10^3–10^4	10^2–10^3	Not relevant	Not relevant
Rated Power (MW)	0.01–5	0.01–90	0.1–10	1–50	0.01–90	500–5000	100–1000
Life Cycle	>10^6	10^3	10^4–10^6	>10^6	10^3	10^4–10^6	10^4–10^5
Efficiency	>95%	60–99%	85–90%	>95%	40–60%	70–85%	75–80%
Capital Cost (£/kW)	300–500	300–3000	3000–5000	700–3000	700–3000	700–2000	700–1500
Cost/Cycle (₵ /kWh)	2–20	9–100	3–20	6–100	6–100	0.1–1.5	2–5
Sitting Requirement	Close to load	Close to load	Close to load	Substations/ generators	Close to load	Geological consideration	Geographical consideration

During discharge the following reactions occur at the electrodes:

a) Positive electrode: $PbO_2 + SO_4^{-2} + 4H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O$
b) Negative electrode: $Pb + SO_4^{-2} \rightarrow PbSO_4 + 2e^-$
c) Overall: $Pb + PbO_2 + 2SO_4^{-2} + 4H^+ \rightarrow 2PbSO_4 + 2H_2O$

Reactions at the positive and negative electrodes lead to formation of lead sulphate coats around the electrodes which lead to reduction of the acid electrolyte. Since lead sulphate is a poor conductor, further reactions are limited; charging of the battery forces electrons to flow from the positive electrode to the negative electrode, reversing the 'sulphation' process [10].

The main advantages of lead acid batteries include: a) they are low cost as they benefit from maturity of technology, b) they are widely available and thus easy to find parts, and c) they handle abuse (overcharge or over-discharge) better than other batteries [10]. The main disadvantages are that they have shorter shelf-lives compared to emerging technologies and that they are more sensitive to temperatures compared to other brands [10]. They also suffer leakages which can lead to damage of the batteries [10].

1.2. Lithium-ion (Li-ion) batteries

The positive electrode in a Li-ion battery is composed of a lithiated form of a transition metal oxide, usually lithium cobalt oxide ($LiCoO_2$) or lithium manganese oxide ($LiMn_2O_4$) while the negative electrode is composed of carbon (C), usually graphite (C_6). The electrolyte is composed of solid lithium salt electrolytes ($LiPF_6$, $LiBF_4$, or $LiClO_4$) and organic solvents (ether).

During discharge, the following reactions occur at the electrodes, where $x = 1$ or 0:

a) Positive electrode: $LiCoO_2 \rightarrow Li_{1-x}CoO_2 + xLi^+ + xe^-$
b) Negative electrode: $xLi^+ + xe^- + 6C \rightarrow Li_xC_6$
c) Overall: $LiCoO_2 + C_6 \rightarrow Li_{1-x}CoO_2 + Li_xC_6$

During discharge, the cobalt Co is oxidized from Co^{3+} to Co^{4+} while the reverse (reduction) occurs during charging. Li-ion batteries do not accept well a high initial charging current. Also, cells in a battery pack need to be equalized to avoid falling below the minimum cell voltage of about 2.85 V/cell. Therefore, Li-ion batteries need to be initially charged with a constant current profile, and thus the need of a charger. Typical float voltage is above 4 V (usually 4.2 V). Carbonaceous materials used in all Li-ion batteries lead to formation of a solid electrolyte interface (SEI) around the carbon electrodes, as a result of non-reversible chemical reactions between the carbon electrodes and lithium ions. As the SEI gets thicker, it leads to capacity decline and to eventual stoppage of the battery performance [11]. The lifetime and cyclability of Li-ion cell therefore depends on its SEI layer [11].

Advantages of Li-ion batteries include: a) they are lighter and smaller than lead acid batteries of similar capacities, b) they have longer shelf-lives (replacement every 5–7 years as opposed to 1.5–2 years with sealed lead acid), c) they can withstand up to 60 °C without degradation and thus no need for air conditioning, d) they have faster recharge times, 20–25% higher turnaround charge efficiency compared to Pb-acid batteries, e) they have more discharge cycles (5–10×), f) they have a full depth of discharge capability, g) they can be easily and remotely monitored, h) no servicing or watering is required, i) there is no need for hydrogen gas extraction provisions, j) time between recharges is 26 weeks as opposed to 2 weeks for sealed lead acid, k) less cells in series needed to achieve some given voltage and, l) no deposits every charge/discharge cycle and thus 99% efficiency [12]. The main disadvantage of Li-ion batteries is that they are very expensive compared to other technologies.

1.3. Nickel-metal-hydride (Ni-MH) batteries

The positive electrode of an Ni-MH battery is composed of nickel oxyhydroxide (NiO(OH)) while the negative electrode is composed of a metal hydride such as AB2 (where A is titanium and/or vanadium, and B is zirconium or nickel, modified with chromium, cobalt, iron, and/or manganese) or AB5 (where A is a rare earth mixture of lanthanum, cerium, neodymium, and/or praseodymium, and B is nickel, cobalt, manganese, and/or aluminium). The electrolyte is composed of potassium hydroxide (KOH).

During discharge the following reactions occur at the electrodes:

a) Positive electrode: $NiO(OH) + H_2O + e^- \rightarrow Ni(OH)_2 + OH^-$
b) Negative electrode: $MH + OH^- \rightarrow M + H_2O + e^-$
c) Overall: $NiO(OH) + MH \rightarrow Ni(OH)_2 + M$

The electrolyte is not affected because it does not participate in the reaction. Ni-MH batteries do not accept well a high initial charging current and are thus not suitable for charging with a constant-voltage method. Float voltage is about 1.4 V while minimum voltage is about 1 V.

Advantages of Ni-MH batteries include the fact that they are less sensitive to high temperatures than Li-ion and Lead-acid batteries and that they can handle abuse (overcharge or over-discharge) better than Li-ion batteries. The main disadvantages are that more cells in series are needed to achieve some given voltage, compared to similarly sized Li-ion or Pb-acid batteries, and that they are very expensive.