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Hybrid energy storage approach for renewable energy applications

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ABSTRACT

The paper gives an overview of the innovative field of hybrid energy storage systems (HESS). An HESS is characterized by a beneficial coupling of two or more energy storage technologies with supplementary operating characteristics (such as energy and power density, self-discharge rate, efficiency, life-time, etc.). The paper discusses typical HESS-applications, energy storage coupling architectures and basic energy management concepts including a hierarchical control- and optimization-based energy management. Four HESS-configurations, suitable for the application in decentralized PV-systems: (a) power-to-heat/battery, (b) power-to-heat/battery/hydrogen, (c) supercap/battery and (d) battery/battery, are presented along with a principle approach for the power flow decomposition based on peak shaving and double low-pass filtering. A modular experimental test-bed for hybrid energy storage systems is described in its components, structure and functionality.

1. Introduction

The global problems of a rapidly rising CO_2-concentration in the atmosphere, the green-house effect and the related severe changes in world surface temperature and world climate have to be addressed and solved quickly. One important part of the solution will be a fast transition from the antiquated fossil-based energy system to a sustainable, 100%-renewable energy system. Therefore, a further and fast dissemination of PV and wind power is required. PV and wind power fluctuations on an hourly, daily and annual time scale (and with a regional distribution) can be handled, employing a variety of flexibility technologies, such as demand side management, grid extension or energy storage [1]. A number of storage technologies based on electrical, mechanical, chemical and thermal energy storage principles are available with quite different technical parameters and operating characteristics (Table 1,[1–3]). Current system analysis studies indicate energy storage demand on a short-, mid- and long-term time scale [4,5]. At this point, the utilization of the hybrid energy storage system (HESS) approach, integrating storage technologies with supplementary operating characteristics, can be very beneficial. Section 2 discusses typical HESS-applications, energy storage coupling architectures and basic energy management concepts. Section 3 introduces a principle power flow decomposition approach based on peak shaving and double low-pass filtering. Four HESS-configurations, suitable for the application in decentralized PV-systems: (a) power-to-heat/battery, (b) power-to-heat/battery/hydrogen, (c) supercap/battery and (d) battery/battery, are briefly discussed. The paper ends with a short description of a modular HESS-experimental test-bed in its components, structure and functionality.

2. Hybrid energy storage systems

In a HESS typically one storage (ES1) is dedicated to cover "high power" demand, transients and fast load fluctuations and therefore is characterized by a fast response time, high efficiency and high cycle lifetime. The other storage (ES2) is typically the "high energy" storage with a low self-discharge rate and lower energy specific installation costs (Table 1 and Fig. 1). Main advantages of a HESS are:

- reduction of total investment costs compared to a single storage system (due to a decoupling of energy and power, ES2 only has to cover the average power demand)
- increase of total system efficiency (due to operation of ES2 at optimized, high efficiency operating points and reduction of dynamic losses of ES2)
- increase of storage and system lifetime (optimized operation and reduction of dynamic stress of ES2).

2.1. Overview of HESS-applications

Results of a literature review indicate quite a number of promising HESS-applications, e.g.:

- HESS in hybrid and fuel cell powered electric vehicles (supercap/battery-HESS [6–9] or battery/fuel cell-HESS [10,11])

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Table 1
Comparison of different energy storage technologies (advantages highlighted).

	super-cap	SMES	flywheel	pumped hydro	CAES	lead acid battery	lithium-ion battery	NaS battery	VRFB	H2	power-to-CH4
storage duration	seconds to minutes			hours to weeks						weeks to month	
typical capacity	Wh to kWh			MWh to GWh		kWh to GWh (modular)				MWh to TWh	
energy density (Wh/l)	2-20	0.5-10	20-200	0.27-1.5	3-6	50-100	200-350	150-250	20-70	500-2500	1500-4000
power density (W/l)	15000-50000	1000-5000	5000-15000	0.5-1.5	0.5-2	10-500	10-350	140-180	<2	-	-
cycle effiency (%)	77-83	80-90	80-95	75-82	60-70	70-75	80-85	68-75	70-80	34-40	30-35
self-discharge rate (%/day)	≈10-20	10-15	70-100	0.005-0.02	0.5-1	0.1-0.4	0.1-0.3	≈10	0.1-0.4	0.003-0.03	0.003-0.03
response time (ms)	<10	1-10	>10	>3min	3-10min	3-5	3-5	3-5	>1s	≈10min	≈10min
lifetime (years)	15	20	15	≈80	≈25	5-15	5-20	10-15	10-15	5-15	5-15
cycle lifetime (full cycles)	up to 1mill.	>1mill.	>1mill.	10000-30000	8000-12000	500-2000	2000-7000	5000-10000	>10000	1000-10000	1000-10000
costs (€/kWh)	10000-20000	1000-10000	≈1000	5-20	40-80	100-250	300-800	500-700	300-500	0.3-0.6	0.3-0.6
costs (€/kW)	150-200	200-300	≈300	500-1000	700-1000	150-200	150-200	150-200	1000-1500	1500-2000	1000-2000

- HESS-applications in renewable autonomous energy supply systems mainly based on a battery/hydrogen-combination [12–16]
- grid-connected HESS on a household [17], district or regional level (e.g. lithium-ion/redox-flow battery application for the island Pellworm [18] or a hybrid battery system in the M5BAT project [39])
- HESS for large scale wind- and PV-park power management [19,20]
- other specific HESS-configurations, e.g. SMES/battery-HESS [21], CAES/battery-HESS [22] and flywheel/battery-HESS [23]

Batteries, particularly lithium-ion batteries, play a key role in many HESS-applications. They can be utilized both as the "high energy" or the "high power" storage. Supercaps and flywheels are characterized by even higher power densities, efficiencies and cycle lifetimes compared to batteries. Redox-flow batteries are a promising technology due to their storage immanent decoupling of power and stored energy (similar to the hydrogen and power-to-gas storage path) and due to their good cycle lifetime and recyclability. Renewable hydrogen (H_2) and methane (CH_4) are both very promising options for long-term energy storage. Also heat storage and power-to-heat concepts will gain importance in