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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

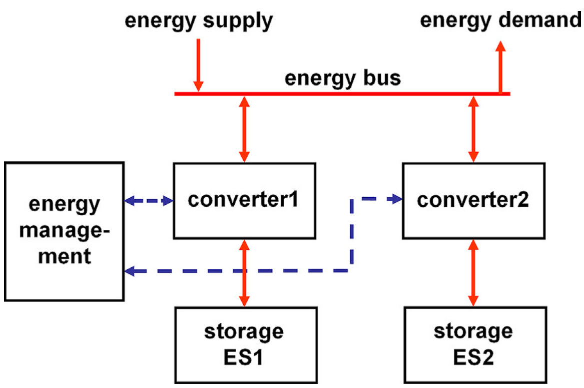

Fig. 1. Basic structure of a HESS.

the context of future HESS-applications. The storage of heat produced from excessive renewable energy (via electric heating cartridges or heat pumps) and from power-to-gas conversion processes (e.g. electrolyser or fuel cell) will increase the overall utilization rate of renewable energies. Moreover, power-to-heat will enable HESS to perform peak shaving and hereby significantly reduce the stress for the other storage components and for the public grid. Optimizing design, control and energy management strategies for HESS at the interface between electricity, heat and gas sector will play an important role and will unfold significant potentials for further improvements of cost, efficiency and lifetime of renewable energy systems.

2.2. Energy storage coupling architectures in HESS

There are different ways for the coupling of the energy storages in a HESS (Fig. 2). A simple approach is the direct DC-coupling of two storages. Main advantage is the simplicity and cost-effectiveness. Moreover, the DC-bus voltage experiences only small variations. Main disadvantage is the lack of possibilities for power flow control and energy management and a resulting ineffective utilization of the storages (e.g. in a supercap/battery-HESS with direct coupling only a small percentage of the supercap capacity can be utilized when operated within the narrow voltage band of the battery). The second energy storage coupling architecture in a HESS is via one bidirectional DC/DC-converter (Fig. 2a and b). The converter can either be connected to the “high-power” or to the “high-energy” storage. In the latter case the “high-energy” storage can be protected against peak power and fast load fluctuations. The DC/DC-converter then operates in current-controlled mode. A drawback of this solution is the fluctuation of the DC-bus voltage, which is identical to the voltage of the “high-power” storage.

The third and most promising coupling architecture consists of two DC/DC-converters. Here the parallel converter topology (Fig. 2d) is very common. The additional DC/DC-converter associated with the “high-power” storage is in charge of the voltage regulation of the DC-bus. It helps to operate the “high-power” storage in a broader voltage band, and hereby the available storage capacity is better utilized. Besides the parallel converter topology also a serial, cascade-type of converter topology is possible (Fig. 2c), which is generally more expensive and more difficult to be controlled. Disadvantages of the two converter coupling architecture are higher complexity and slightly higher

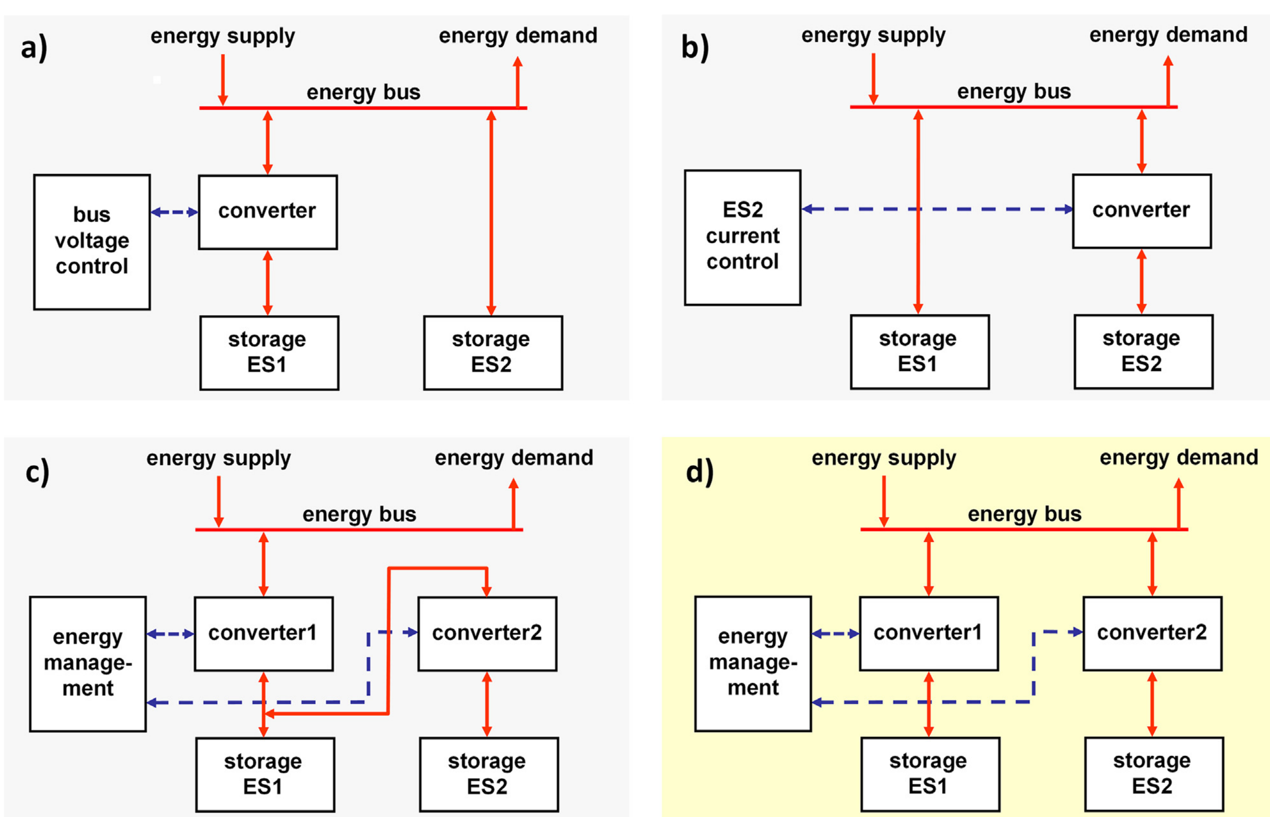

Fig. 2. Basic coupling architectures for HESS: (a) one voltage controlled converter, (b) one current controlled converter, (c) serial connection of two converters, (d) parallel connection of two converters.

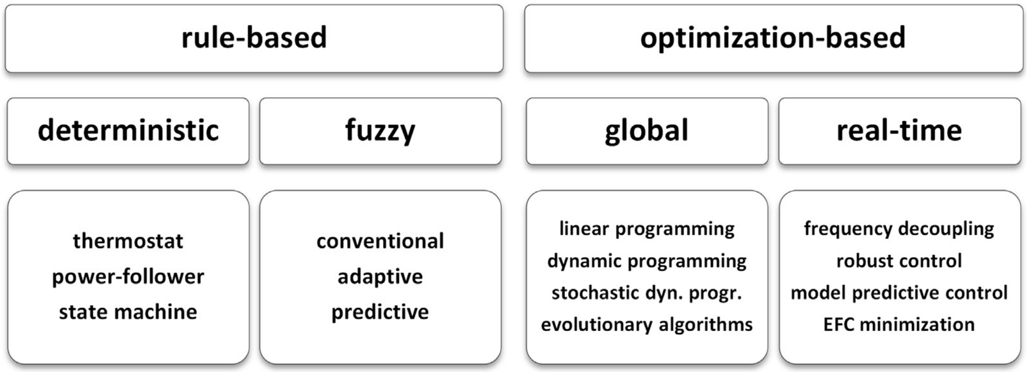

Fig. 3. Control and energy management concepts for HESS.

costs. There are isolated and non-isolated DC/DC-converter topologies available for HESS-applications (e.g. buck/boost, half-bridge, full-bridge) with the trend to highly efficient and cost effective multi-port converters with a reduced number of conversion stages [24].

2.3. Control and energy management concepts for HESS

An intelligent control and optimizing management of the power flow distribution is essential for a good operation of any HESS. Quite a number of different control and energy management concepts have been studied, mostly in the field of hybrid and fuel cell electric cars. Fig. 3 gives an overview of the basic classes of HESS-energy management concepts.

Generally two classes, rule-based and optimization-based energy management concepts, can be distinguished. Rule-based concepts are well suited for real-time applications. The rules are created by an expert or mathematical models. A simple rule-based control strategy for HESS is the “thermostat”-concept. The “high energy” storage ES2 is switched on and off according to a lower and upper state of charge-(SOC)-threshold applied to the “high power” storage ES1. A more advanced concept is based on state machine control [25], which can involve multiple rules (to be defined on the basis of heuristic or expert experience). A further improvement of the rule-based concept is fuzzy logic control. Here the power split between ES1 and ES2 is achieved in a smooth way (no switching) by fuzzy-rules and membership functions [26]. This strategy can be easily tuned to achieve nearly optimal operation. Rule-based energy management approaches can handle measurement imprecisions and component variations quite well.

The main feature of optimization-based approaches is the minimization of a cost function. Optimization-based approaches can be distinguished into global (off-line) and real-time (on-line) algorithms. Frequency decoupling is well suited for real-time applications. It is usually accomplished by a simple low-pass filter or by advanced filter concepts based on wavelet or Fourier transform. The low frequency component supplies the set-point value of the power controller of ES2, the high frequency component is covered by ES1 [27]. Another promising and widely used optimization-based energy management approach is the equivalent fuel consumption minimization strategy (EFCM). It is aiming for the minimization of an instantaneous cost-function (e.g. efficiency or H_2-fuel consumption) [28]. Other energy management approaches are based on classical PI-controllers [29] not requiring expert knowledge and allowing to be tuned easily on the basis of an on-line adaptation law.

2.4. Example of an hierarchical optimizing energy management concept for a fuel cell-battery-hybrid system

Different energy management concepts for HESS have being developed, investigated and experimentally tested including a

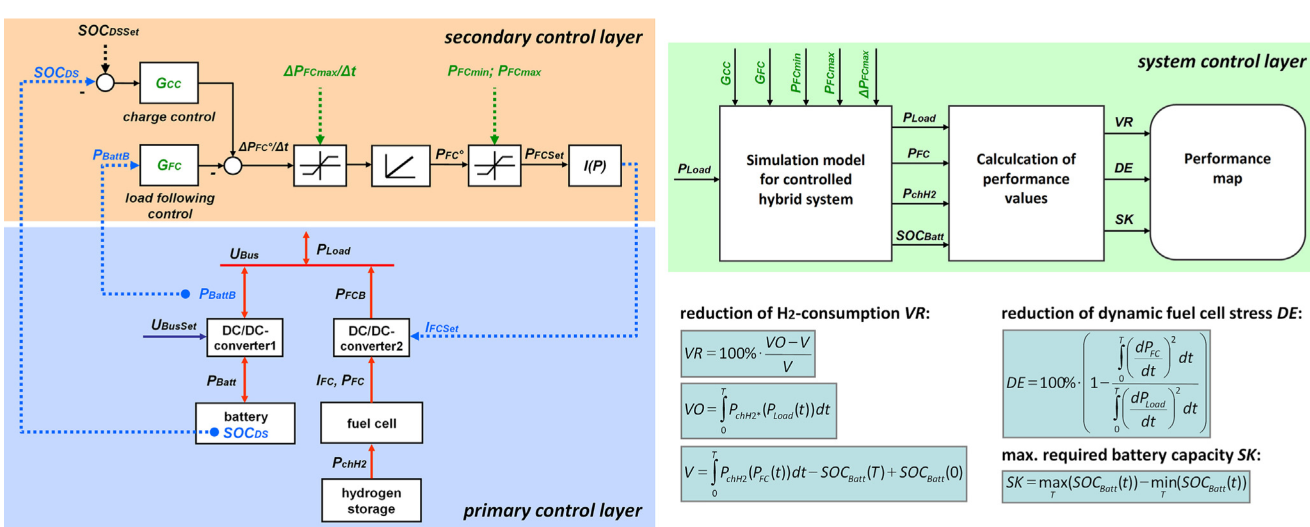

Fig. 4. Hierarchical energy management concept combining left: primary control layer (voltage and current control) and secondary control layer (SOC- and load following control) and right: system control layer (global optimization) [33].

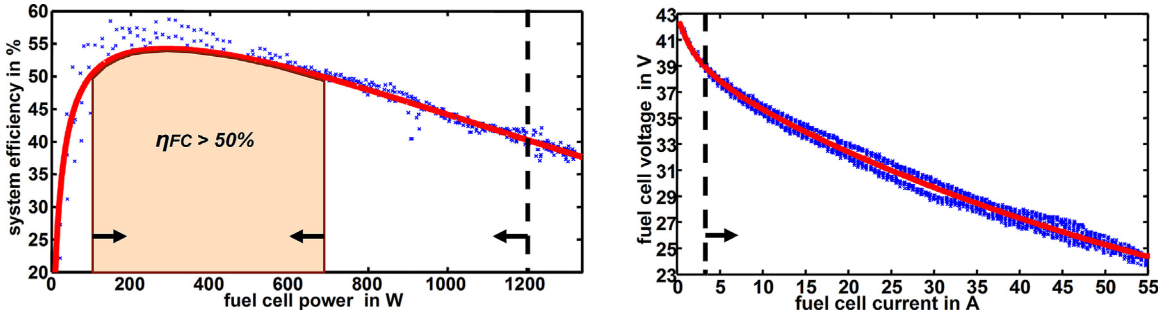

Fig. 5. Left: efficiency-power characteristic, right: voltage–current characteristic of PEM-fuel cell system (NEXA power module), limited operating range leading to improvement of fuel cell efficiency and lifetime.

rule-based approach [30], an approach based on dynamic programming [31] and a combined control- and optimization-based, hierarchical energy management [32], [33], [34], which is illustrated in Fig. 4 for the example of a fuel cell-battery-HESS. This hierarchical concept divides the control and optimization problem into three layers: the primary control of bus voltage and fuel cell current, the secondary control to limit fuel cell operating range and power gradient and to perform battery charge and load-following control, and the system control to optimally adjust the secondary control parameters aiming for the minimization of H_2-consumption and dynamic fuel cell stress parameters.

The primary control plant of the hybrid power supply unit consists of two power electronic converters (left diagram of Fig. 4). DC/DC-converter 1, associated with the battery, is responsible for the fast control of the bus voltage U_{Bus}. Fast changes of the load power P_{Load} are completely covered by the battery and thus, dynamic stress is kept away from the fuel cell. DC/DC-converter2 adjusts the fuel cell output voltage to the bus voltage and runs the fuel cell basically as a current source. The desired fuel cell current I_{FCSet} is calculated by the secondary control (software operating on the energy management unit) and is passed to the primary controller.

The main function of the secondary control is the limitation of the fuel cell operating range and the fuel cell power gradient $\Delta P_{FC}/\Delta t$ with the goals to minimise H_2-consumption as well as stress and aging of the fuel cell. The typical efficiency-power-curve of a PEM-fuel cell shows an efficiency maximum at partial load (Fig. 5). The efficiency drops for operating points at extreme partial and peak load. At extreme partial load additional stress and accelerated aging occurs due to high electrode potentials and corrosion of the catalyst carbon support layer. At peak load stress and accelerated aging occurs due to problems with heat and water removal, possible membrane flow field flooding, current density fluctuations, and corrosion of the carbon support layer due to increased reactant gas humidity.

The basic structure of the secondary controller is also given in the left diagram of Fig. 4. The load following controller G_{FC} has the goal to minimise the difference between load and fuel cell power and is thus aiming to minimise the losses, which would occur at frequent charging and discharging of the battery. The charge controller G_{CC} insures that the battery never exceeds its minimum and maximum state of charge boundary. Both controllers have one common actuating variable, the fuel cell power gradient $\Delta P_{FC}^{\circ}/\Delta t$. It is limited to a maximum value $\Delta P_{FCmax}/\Delta t$, defined by the system

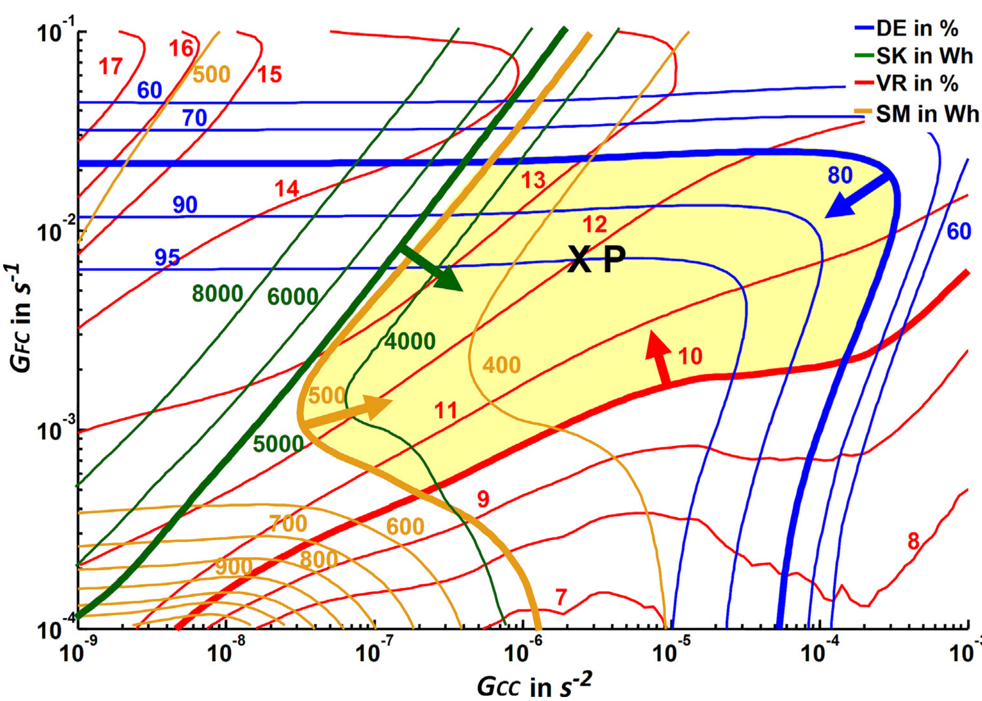

Fig. 6. Influence of the secondary control parameters on the optimization results.

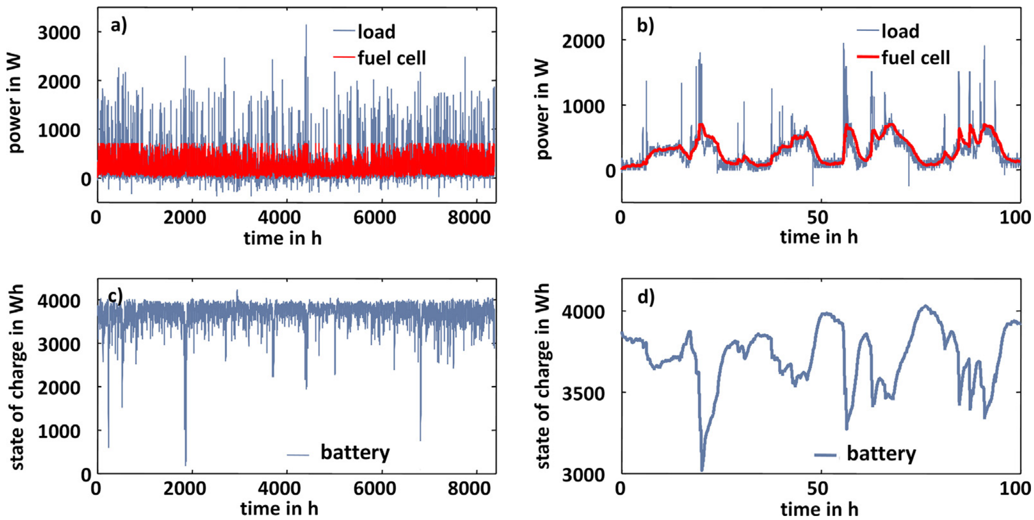

Fig. 7. Optimal split of load into fuel cell and battery power (operation at point P Fig. 6).

control. Hereby the fuel cell is protected against fast load transients. Moreover, the fuel cell power is limited to the optimal operating range (P_{FCmin}, P_{FCmax}). The resulting vector of five secondary control parameters $v_{SC} = [G_{CC}, G_{FC}, P_{FCmin}, P_{FCmax}, \Delta P_{FCmax}/\Delta t]$ is determined by the system control and is subject to adaptation during the optimization problem-solving. Primary and secondary control can be assumed dynamically independent, thus the actual fuel cell power to the bus, P_{FCB}, can be calculated from I_{FCSet}, from the fuel cell power-current- and voltage–current-curve and from the converter efficiency map. The task of the system control is to address and solve the actual optimization problem. The optimization criteria are given in the right diagram of Fig. 4.

Figs. 6 and 7show the simulation results for an example application (measurement data of a 5 kW peak PV-plant and electric load profiles of a four people household). Fig. 6 presents the results of the variation of the secondary control parameters G_{CC} and G_{FC} (at fixed $P_{FCmin} = 0$ W, $P_{FCmax} = 700$ W and $\Delta P_{FCmax}/\Delta t = 5$ W/s). The resulting plot was derived from a variation of 100×100 control parameters with G_{CC} ranging from 10^{-9} s^{-2} to 10^{-3} s^{-2} and G_{FC} ranging from 10^{-4} s^{-1} to 10^{-1} s^{-1} (with logarithmical spacing). For each of the resulting 10,000 control parameter vectors a simulation of the power flow distribution between fuel cell and battery for the complete reference year was performed and evaluated. Fig. 6 shows the resulting contour plot of the four optimization criteria: in red VR, the reduction of H_2-consumption, in blue DE, the dynamic stress reduction of the fuel cell, in green SK, the maximal required battery capacity and in orange SM, the average required battery capacity per day. The bold contour lines correspond to the desired limits of VR $\geq$ 10%, DE $\geq$ 80%, SK $\leq$ 4000 Wh and SM $\leq$ 500 Wh for this example. All vectors (G_{CC}, G_{FC}) of

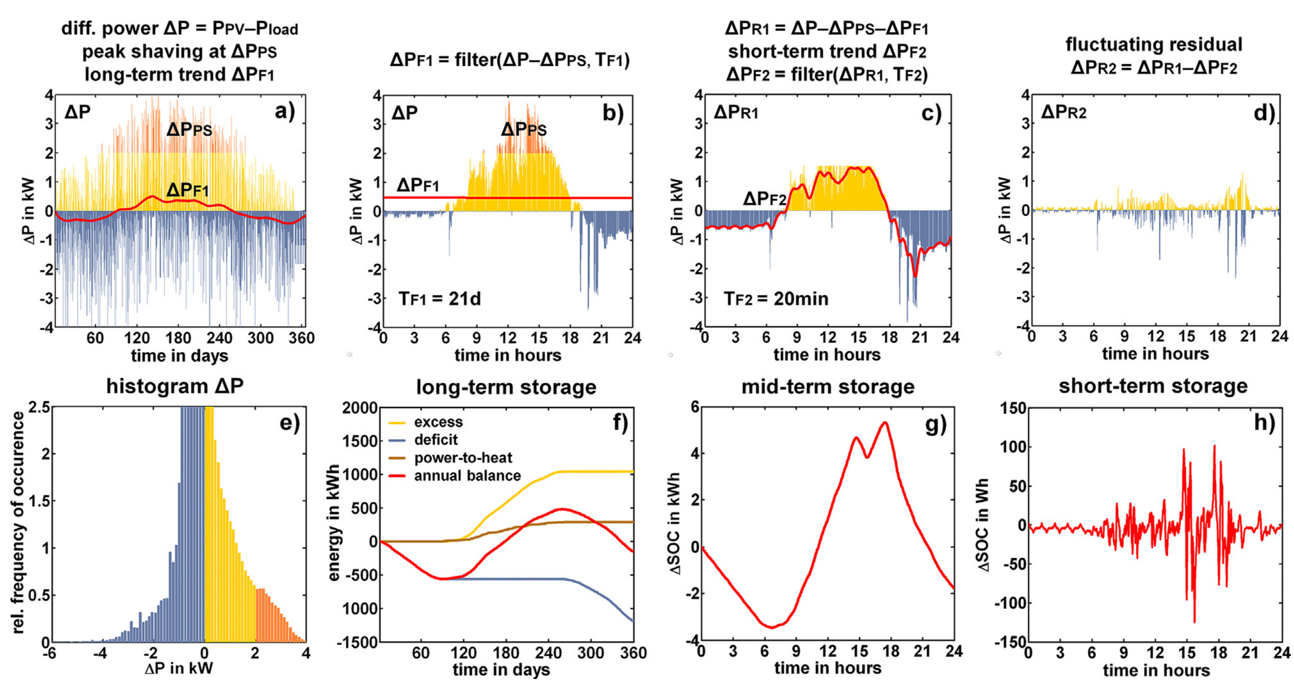

Fig. 8. Example of the power flow decomposition for PV-HESS-application. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

controller gains within the yellow highlighted area guarantee these boundaries and thus facilitate a significant improvement of H_2-consumption and dynamic stress reduction of the fuel cell.

Fig. 7a and b shows the difference of the electric load and the PV-power profile (after PV-trend removal) and the optimal fuel cell power profile calculated by the energy management algorithm ($G_{CC} = 2.24 \times 10^{-6}\,s^{-2}$, $G_{FC} = 6.52 \times 10^{-3}\,s^{-1}$, $P_{FCmin} = 0\,W$, $P_{FCmax} = 700\,W$, $\Delta P_{FCmax}/\Delta t = 5\,W/s$). A nicely smoothed and limited fuel cell power profile can be observed. Dynamic fluctuations and peak power are completely covered by the battery (Fig. 7c and d).

HESS design/sizing and energy management optimization problems are usually strongly interdependent. Therefore, intelligent HESS-design algorithms take into account both, component sizes and energy management parameters. A particle swarm optimization algorithm was successfully employed demonstrating good convergence, fast computation speed and an excellent handling of the complex, nonlinear optimization problem [35].

3. HESS for renewable energy applications

3.1. Principle of power flow decomposition

Fig. 8 presents a PV-HESS-example and demonstrates in a simplified manner the decomposition of the difference power ΔP (PV minus load power) for a 5 kW PV-plant and a four-people household (with 4 MWh/a electricity consumption) at a reference site near Chemnitz. The first step is the peak shaving (power-to-heat conversion) for ΔP values greater than the threshold value ΔP_{PS}. The remaining power is low-pass filtered with filter time T_{F1} leading to the long-term trend component ΔP_{F1}. The residual power ΔP_{R1} is filtered with filter time T_{F2} leading to the daily trend component ΔP_{F2}. The residual power ΔP_{R2} contains the remaining fast power fluctuations and part of the peak power. Fig. 8e shows the histogram of ΔP indicating that a significant peak shaving can be realized by converting only a small amount of PV-energy into heat (orange area). Fig. 8f–h) illustrate the cumulated power of ΔP_{F1}, ΔP_{F2} and ΔP_{R2}, corresponding to the state of charge of a virtual long-, mid- and short-term energy storage (a rough estimation of the required storage capacities gives about 1000 kWh, 10 kWh and 200 Wh).

3.2. HESS-configurations for PV-applications

Fig. 9a–d illustrate four HESS-configurations, which can be beneficially employed in the context of decentralized PV-systems. Fig. 9a shows a combination of a power-to-heat unit and a battery. This HESS-configuration can be used for advanced self-consumption optimization integrating a PV-peak shaving functionality and hereby achieving a significant stress reduction and increase of battery lifetime. Additionally, this HESS-configuration can be used for generation and storage of hot water from excessive PV-energy or electricity from the grid at times of low tariffs. Fig. 9b shows an HESS-configuration similar to the previous one with an additional H_2-storage path [17], [38]. Due to the battery, this configuration offers great potentials for the optimization of electrolyser and fuel cell efficiency and lifetime by limitation of operating ranges, number of on-/off-switching and prevention of power gradients and dynamic stress. In this HESS-configuration electrolyser and

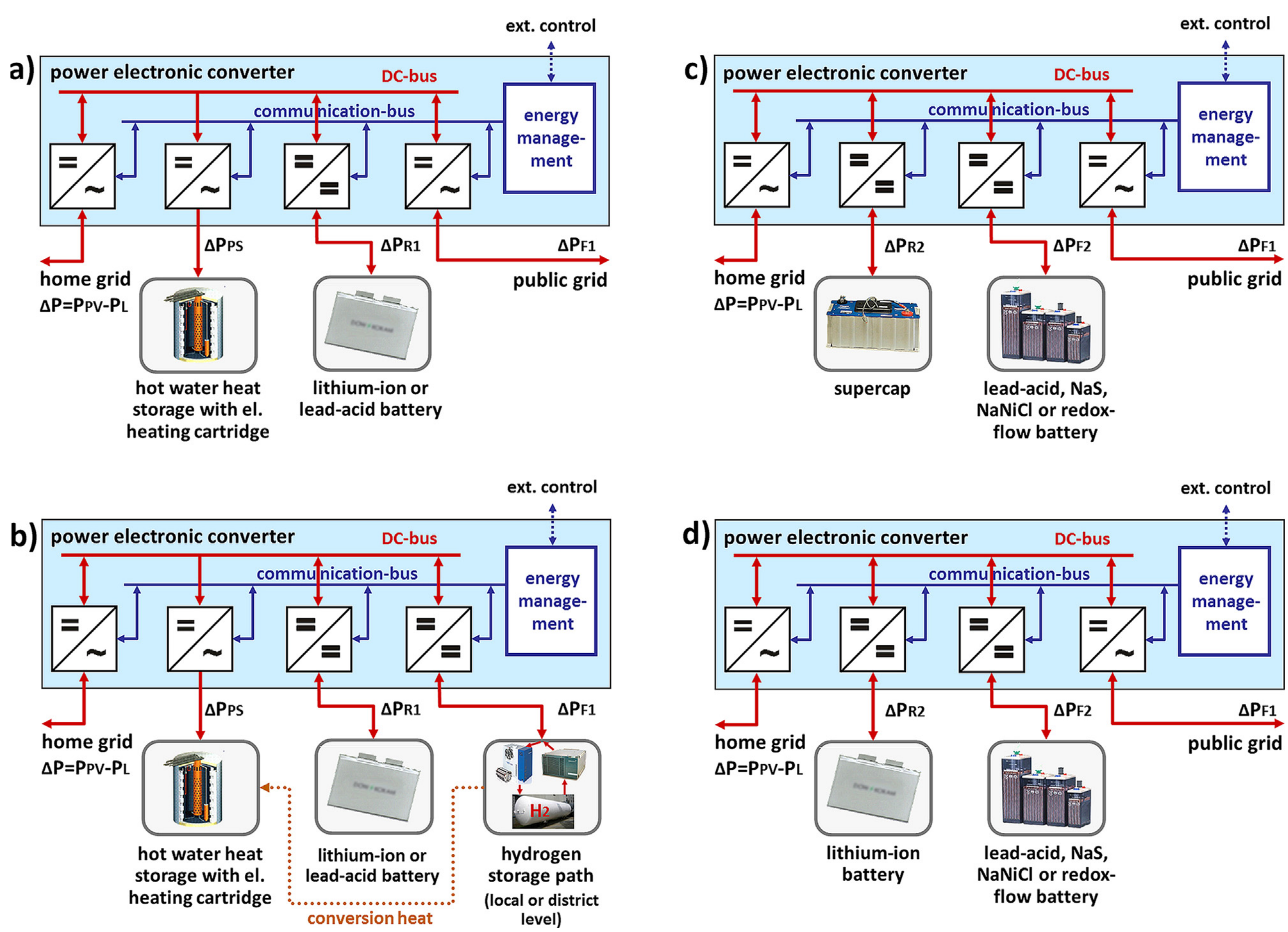

Fig. 9. HESS-configurations for the application in decentralized PV-systems.

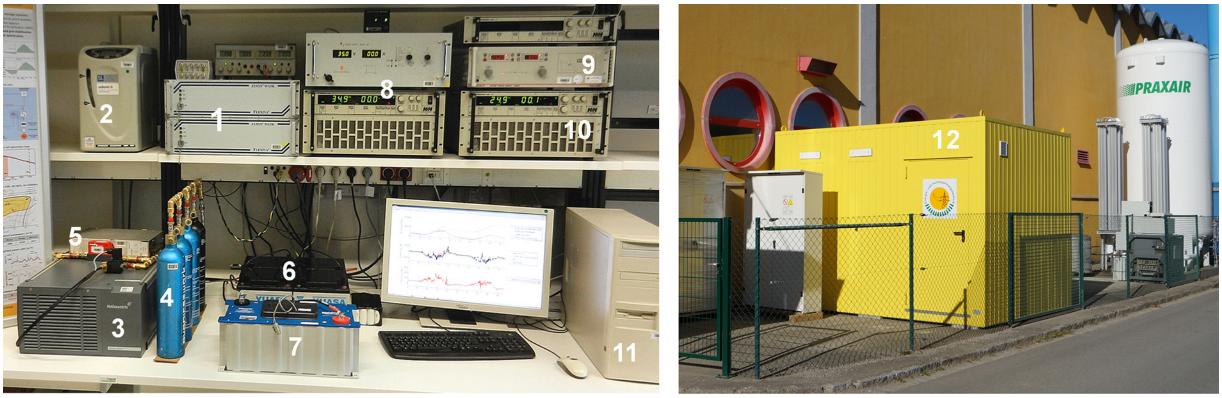

Fig. 10. HESS-experimental test-bed, (1) power converter system, (2) PEM-electrolyser, (3) PEM-fuel cell, (4) H_2-metal hydride storage tanks, (5) fuel cell DC/DC-converter, (6) lithium-ion and lead acid batteries, (7) supercap, (8) virtual battery, (9) virtual fuel cell, (10) virtual electrolyser, (11) energy management PC with Matlab/Simulink control and monitoring software, (12) H_2-storage path.

fuel cell only have to cover the maximum of the long-term trend ΔP_{F1} (Fig. 8). The nominal electrolyser and fuel cell power can be significantly reduced (compared to a power supply without battery) and can be independently chosen from the capacity of the H_2-storage tank. Both measures can lead to significant cost reductions. Moreover, the conversion heat of electrolyser and fuel cell can be utilized leading to high overall system efficiency (electricity and heat). The HESS-configuration of Fig. 9 can be applied for sustainable, zero-emission on- and off-grid applications with different possibilities to place the H_2- and heat storage-path (e.g. building integrated, or centralized on a district or community level, possibly with access to a local heat and/or gas network). The efficiency and lifetime-optimizing energy management algorithm for this HESS-configuration can adapted to larger power-to-gas applications. Fig. 9c shows a HESS-configuration to cover the short- and mid-term range. The supercap here functions as the “high-power” storage, covers peaks, transients and fast power fluctuations. This helps to avoid battery stress (e.g. high charging currents and micro-charging cycles for a lead-acid battery) and as a consequence increases battery lifetime. Fig. 9d shows a similar HESS-configuration only with a “high-power” battery (e.g. lithium-ion or lithium-titanate battery) instead of the supercap. In this case the “high-energy” storage could e.g. be a cheap lead-acid battery (with interesting, supplementary charging/discharging-, SOC- and operating characteristics to the lithium-ion battery). Instead of the lead-acid battery also a redox-flow or a high temperature battery could be utilized to cover the mid-term power fluctuations. The resulting hybrid battery can be beneficial for many renewable energy applications. The configuration requires intelligent charge control (for both batteries) and energy management strategies capable of precise modeling of battery state of charge, state of health and the estimation of the influence of different operating regimes onto the battery lifetime.

3.3. Modular HESS-experimental test-bed

Fig. 10 shows part of the HESS-experimental test-bed which is used for experimental investigation and testing of new control and energy management algorithms for various types of HESS-configurations and different applications [30]. Key component is the modular HESS-power conversion system, which consists of up to eight bidirectional DC/DC- and DC/AC-converters with a nominal power of 2.5 kW and various voltage ranges on the input/component side (0–45 V, 0–60 V, 0–230 V). The converters are coupled via a common 400 V DC-bus. The HESS-power conversion system incorporates a novel power flow control concept, which is characterized by an inner current control loop and an outer voltage control loop, which can either participate in the control of the bus voltage or the voltage at the component side [36,37]. Also current source/sink behavior can be realized by operating the converters within pre-defined voltage limits. All digital controller parameters and set point values can be software programmed and adjusted from a Matlab/Simulink control environment. Here also the emulation of dynamic PV-supply and electricity demand profiles via programmable power supply and load is realized. Different configurations of renewable power sources (e.g. PV or wind), electricity consumers and storage devices (e.g. different types of batteries, supercaps, H_2-storage path or heat storages) can be realized and investigated with the HESS-experimental test-bed. The eight power converters are carried in two module boxes. The DC/AC-converter modules can be operated bidirectional in island or grid parallel mode. Output voltage, current, frequency and phase can be flexibly adjusted. Besides the primary control of converter currents and voltages typically a secondary control layer aims for the optimization of the power flow distribution between the different energy storage devices and therefore integrates intelligent storage charge management, predictive load following control, active limitation of operating range and storage transients, peak power shaving as well as storage and converter condition monitoring. The appropriate control and energy management software is running on a specific energy management-PC under Matlab/Simulink environment. The software communicates with the HESS-power conversion system, the individual energy storage devices as well as the programmable power supplies and loads via RS232- and CAN-bus. Moreover, an AD/DA-process interface allows the synchronous acquisition of additional sensor signals and measurement data (e.g. from H_2-mass flow meter or temperature sensors). The measurement, control and energy management software was designed under Matlab/Simulink and C^{++} employing object oriented programming techniques with timer functions. This allows for a fast and well determined operation of the energy management system at a speed of up to 100 iterations per second.

Additionally, the HESS-power conversion system offers the possibility to integrate so called virtual components. A virtual component is a programmable power source and/or load, which is controlled in its voltage–current characteristic according to a simulation model of a real component (e.g. a battery or a fuel cell). Main advantages of the coupling of real and virtual components are the high flexibility (e.g. a quick change of the battery capacity or type) and the possibility to incorporate virtual H_2-components.

4. Summary and conclusion

Hybrid energy storage systems are an interesting and very promising flexibility technology, which can help to cover short-, mid- and long-term fluctuations in a future sustainable, 100%-renewable energy system. This paper has given an overview of typical HESS-applications, energy storage coupling architectures and basic energy management concepts including a hierarchical control- and optimization-based energy management concept. Four HESS-configurations, suitable for the application in decentralized PV-systems have been presented along with a principle approach for the power flow decomposition based on peak shaving and double low-pass filtering. Particularly the power-to-heat/battery and power-to-heat/battery/hydrogen configuration show great potential for application in sustainable decentralized and regional power supply structures. A modular experimental test-bed for hybrid energy storage systems has been described in its components, structure and functionality. Current research is focusing on the development, investigation and experimental testing of new control- and optimization-based energy management algorithms and optimizing design concepts for HESS.

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