Power-Intensive Energy Storage Systems

Giovanni De Carne, Seyede Masoome Maroufi, Antonio Morandi, and Mattia Simonazzi

Abstract The current energy system requires fast and long-term energy storage delivery. While energy-intensive energy storage systems, like batteries or hydrogen, can provide energy in the long term (e.g., hours or days), their fast dynamic power delivery is either constrained or strongly affects their lifespan. Power-intensive energy storage systems are specific technologies developed for allowing short-term high-power energy delivery. This specific characteristic is particularly useful for compensating fast-dynamic phenomena, such as faults or voltage dips, or optimizing energy-intensive technologies' efficiency and lifespan. This chapter describes the basic principle, operation, and network integration of the two most common power-intensive energy storage systems: the supercapacitor energy storage system (SCES) and the superconducting magnetic energy storage system (SMES). Their system hybridization with energy-intensive ESS is discussed, highlighting the control possibilities.

Keywords Flywheels · Batteries · Energy storage · Power system management · Fuzzy logic · Frequency control · Fluctuations · State of charge · Control systems · Vehicle dynamics · Flywheels · Hybrid energy storage · Power management · Ramp Rate (RR) · State of Charge (SoC)

G. De Carne (✉) · S. M. Maroufi
Institute for Technical Physics, Karlsruhe Institute of Technology, Eggenstein-Leopoldshafen, Germany
e-mail: giovanni.carne@kit.edu

S. M. Maroufi
e-mail: seyede.maroufi@kit.edu

A. Morandi · M. Simonazzi
Dipartimento di Ingegneria dell'Energia Elettrica e dell'Informazione "Guglielmo Marconi", Bologna, Italy

R. Scipioni et al. (eds.), *Hybrid Energy Storage*, Lecture Notes in Energy 47,
https://doi.org/10.1007/978-3-031-97755-8_5

1 Introduction to Power-Intensive Energy Storage Systems

Energy storage devices offer fast, flexible, and controllable bidirectional energy transfer, making them ideal for precise power exchanges with the grid to meet various regulation needs (Mao et al. 2020). In particular, power-intensive ESSs are essential components in modern energy infrastructure, especially as we transition towards more renewable energy sources like solar and wind. These systems are designed to manage high power demands over short durations, critical in stabilizing the grid, enhancing efficiency, and supporting the integration of variable renewable energy (Farhadi and Mohammed 2016).

Battery energy storage systems (BESSs) currently dominate the energy storage landscape due to their high energy density, scalability, flexibility, and efficiency (Barelli et al. 2022; Pelosi et al. 2023). Batteries are advancing rapidly, making their production both cheaper and more environmentally friendly. They are capable of delivering the required power during fast transients (such as during low-inertia frequency disturbances). However, as electrochemical devices, they are vulnerable to degradation, particularly from power surges and deep depths of discharges (DoDs) (Pelosi et al. 2024). As a result, frequent replacements, or, in alternative large oversizing, would be necessary when using BESSs to handle the high-power spikes.

To avoid the need for overly large BESSs in such scenarios, hybridization with short-term energy storage systems like flywheel, Supercapacitor Energy Storage (SCES), and Superconducting Magnetic Energy Storage (SMES), which feature high power-to-capacity ratios, is recommended. These devices can manage high-power spikes, reducing stress on the energy-intensive storage device (Jia et al. 2023; Mongird et al. 2020). Due to their fast response times and high efficiency, high-power energy storage systems are suitable for frequency regulation, voltage control, and oscillation damping in the power grid (Gyuk et al. 2013; Kirby and Hirst 1997). Additionally, combining complementary energy storage technologies in hybrid systems can mitigate the limitations of individual devices, greatly expanding their operational capabilities across various conditions and timeframes (Barelli et al. 2019). Hybrid storage systems combining power- and energy-intensive energy storage, allows to integrate the capability of providing energy for a relatively long period of time (e.g., hours for batteries, days for hydrogen), while extending as much as possible the energy-intensive resource lifetime, by letting the power-intensive resources address the fast- or repetitive transients.

This chapter provides an overview of two well-known power-intensive energy storage systems, such as SCES and SMES, focusing on their basic principles, grid integration, and existing applications and projects.

2 Energy and Power Comparison Among Energy Storage Systems

To better understand the potential of power-intensive energy storage systems, it is important to highlight their difference with energy-intensive systems. Figure 1 presents the specific power (per unit of mass), specific energy (per unit of energy), and Discharge Time (DT) ranges of various energy storage technologies, providing a clear description of their categorization based on performance metrics (Carne et al. 2024).

Technologies like SCES and SMES exhibit high specific power capabilities which reflects their capacity to deliver rapid bursts of energy over short durations from seconds up to a minute. Power density of SCES ranges from 500 to 7000 W/kg (Chatzivasileiadi 2012; Morandi et al. 2008). As for SMES, the power per unit mass ranges between 500 and 2000 W/kg, provided that the magnet (and the power electronics) are designed for withstanding fast charge/discharge operation. However, both technologies are constrained by relatively low specific energy values, with SCES ranging between 2.5 and 15 Wh/kg and SMES between 0.5 and 5 Wh/kg (with only the active mass of the magnet considered) (Cicéron et al. 2017; Mukherjee and Rao 2019; Zakeri and Syri 2015).

In contrast, batteries like lithium-ion are located in a more balanced area, offering a more moderate specific power and higher specific energy, making them versatile for applications and services involving longer (tens of minutes or hours) delivery of moderate (and slowly fluctuating) power (Hu et al. 2017; Milano and Manjavacas

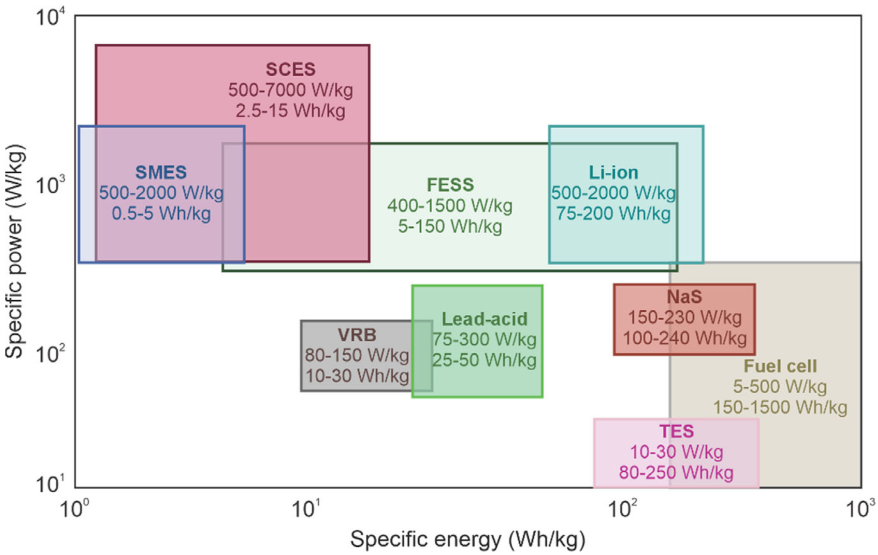

Fig. 1 Comparison between specific energy and specific power and discharge time

2019). Fuel cell storage systems, with their high specific energy but low specific power (5–500 W/Kg and 150–1500 Wh/Kg), are ideal for scenarios requiring large energy reserves for delivery or absorption over long periods (hours or days) (Farivar et al. 2022). The diagram of Fig. 1 highlights the trade-offs between power and energy capabilities, guiding the selection of appropriate storage technologies based on specific application needs.

3 Electric and Magnetic Energy Storage: Basic Principles

Supercapacitors and superconducting magnetic energy storage systems follow two different principles for storing energy. While the first ones store the energy in the form of an electric field, the latter store the energy in a magnetic field, similar to common inductors but with no joule dissipation. For capacitors, the stored electric energy $W_c\ (t)$ at the generic time instant t is expressed by the relation:

$$W_C(t) = \frac{1}{2} C_{vc}(t)^2 \tag{1}$$

where C is the capacitance and v_C the voltage across the capacitor. For SMES, like inductors, the stored electric energy $W_m(t)$ at the generic time instant t is expressed by the equation:

$$W_m(t) = \frac{1}{2} L i_L(t)^2 \tag{2}$$

where L is the inductance and i_L the current through the superconducting inductor. In order to achieve an amount of stored energy that is of interest for practical applications the capacitor must be characterized by a large capacitance and the inductor by a large inductance, and, moreover, they should be able to withstand large voltage and current, respectively. Furthermore, they should be able to operate with no or very reduced losses. Common capacitors based on conventional technologies only reach limited values of capacitance and can only store limited energy. Similarly, conventional inductors, also have limited inductance and are also characterized by Joule losses due to winding resistance. Recent technological advancements in the field of electrochemistry and superconductivity have provided capacitors and inductors that are suitable for energy storage. Due to their superior performance with respect to their conventional counterpart, this new generation of electrical components are referred to as “supercapacitors” and “superinductors” (or more commonly superconducting inductors or SMES), respectively.

By assuming a time interval from t_0 to t during which the storage device exchanges a power $P(t)$ with the grid, the stored energy $W(t)$ is:

$$W(t) = \int_0^t P(\tau)\mathrm{d}\tau \tag{3}$$

where $W(t_0)$ is the energy stored at the initial instant t_0. Based on energy conservation, by neglecting any power loss (both intrinsic in the storage device and in power converters), the capacitor voltage can be expressed as:

$$v_c(t) = \sqrt{v_c(t_0)^2 - \frac{2}{C}\int_{t_0}^{t} P(\tau)\mathrm{d}\tau} \tag{4}$$

and the inductor current as

$$i_L(t) = \sqrt{i_L(t_0)^2 - \frac{2}{L}\int_{t_0}^{t} P(\tau)\mathrm{d}\tau} \tag{5}$$

In Fig. 2 an example of the capacitor voltage or inductor current profiles during a discharging and subsequent charging phase is shown. At the initial time instant t_0 the storage device was charged, being assumed $v_C \neq 0$ and $i_L \neq 0$, then the two variables follow the trend described by (4) and (5) according to the power profile $P(t)$.

An important difference between electric and magnetic storage, and their respective power conditioning circuitry, is the stand-by operation. In fact, in order to maintain constant stored energy (and, hence, constant charge and voltage) of a capacitor, open circuit operation with zero current must be applied ($i_C = 0$). In contrast, to maintain constant stored energy (and, hence, constant magnetic flux and current) in an inductor, short circuit operation with zero voltage should be applied ($v_L = 0$).

From a practical point of view, it is simple to create nearly ideal open circuit condition through power electronic circuitry in the OFF state, while the short circuit

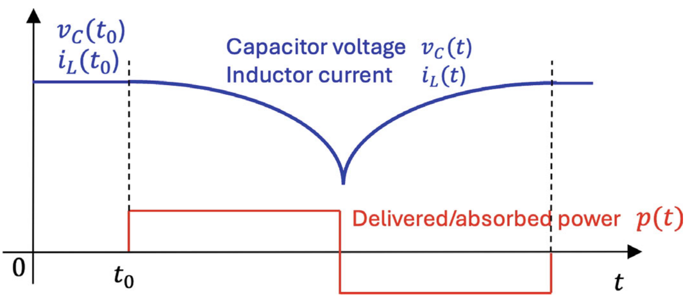

Fig. 2 Capacitor voltage or inductor current profile (blue curve) during a discharging and subsequent charging phase

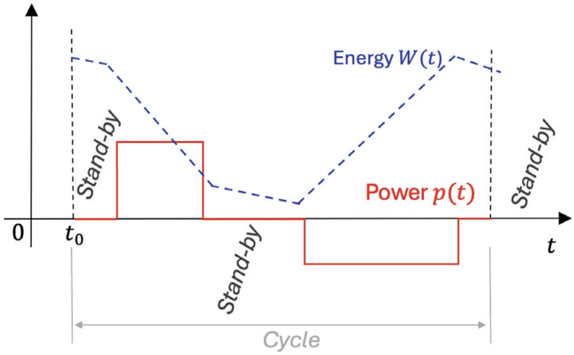

Fig. 3 Power (red curve) and energy (blue curve) profiles during a discharging and subsequent charging with stand-by phases

is more problematic since dissipation is unavoidable in power electronic components in ON state transporting a current. As a practical consequence, electric storage is suitable for applications in which long standby phases are involved, while magnetic storage is not.

Figure 3 shows a possible charge–discharge cycle for a capacitor or and inductor energy storage device. The considered cycle consists of a power delivery (positive power according to generator convention) and a power absorption (negative power) phase with the same total energy, interleaved by stand-by phases. The figure highlights that part of the energy of the device is lost in the stand-by phases due to both possible intrinsic phenomena in the storage devices and due to additional losses in the system. In order to assess an overall energy balance of practical electric or magnetic energy storage systems, all sources of power consumption must be considered. These include intrinsic dissipation in the storage device, dissipation in the power converters, dissipation during stand-by and possible auxiliary power that is required to maintain proper operating conditions.

The latter is particularly important in magnetic energy storage through superconducting inductors whereby cooling power must be constantly provided to keep the material at the proper cryogenic temperature required for superconductivity. Similarly, temperature control must also be provided for supercapacitors (and batteries) through ventilation and heat exchangers to prevent excessive temperature. However, in the former case the energy required is much higher due to the need to reach and maintain very low temperature, in the order of 77 K (− 196.15 °C) at most.

During cycling operation, in which the energy W_{del} is delivered to the grid and the energy W_{abs}, that takes all the loss mechanisms into account, is supplied to the device during the charging phase, the round-trip efficiency of the storage can be defined as:

$$\eta = \frac{W_{del}}{W_{abs}} = \frac{W_{del}}{\frac{W_{del}}{\eta_i \eta_c} + P_{aux}\Delta t + P_{standby}\Delta t_{standby}} \tag{6}$$

where η_i and η_c are the intrinsic and the converters' efficiency respectively, P_{aux} is the required auxiliary power (e.g., for cooling purposes) and $P_{standby}$ the power consumed during the stand-by phase with duration $\Delta t_{standby}$.

3.1 Grid Integration by Means of Power Electronics

In order to exchange energy with the power grid, capacitor and inductors must be interfaced through a proper power conditioning circuit able to control their voltage or current, as it is schematized in Fig. 4.

As explained above, despite being both power-intensive energy storage systems, supercapacitors and SMES work with two different principles. From the electrical point of view, supercapacitors can be assumed as voltage sources (Sect. 5.4.1 provides a detailed modeling of it). To regulate the energy flow between the SCES and the grid, a DC–DC converter is combined with a DC/AC front-end converter. The DC–DC converter performs two tasks: (i) transforms the DC voltage from the variable one of the SCES (dependent on their state of charge) to the constant one of the front-end converter DC links; (ii) regulates the current at the SCES side I_{sces}, and thus its power exchange. The DC link is then connected to a DC–AC front-end converter, that regulates the power flow between the AC and DC side, in order to keep the DC voltage V_{dc} at the nominal value. As a result, a controlled power flow is established between the SCES and the grid.

On the other side, a SMES can be assumed as a constant current source. While the front-end converter performs the same tasks as the SCES one, the DC–DC converter regulates instead the SMES voltage V_{smes} in order to extract a certain amount of energy from the SMES. In this case a controlled power flow is established between the SMES and the grid as a result.

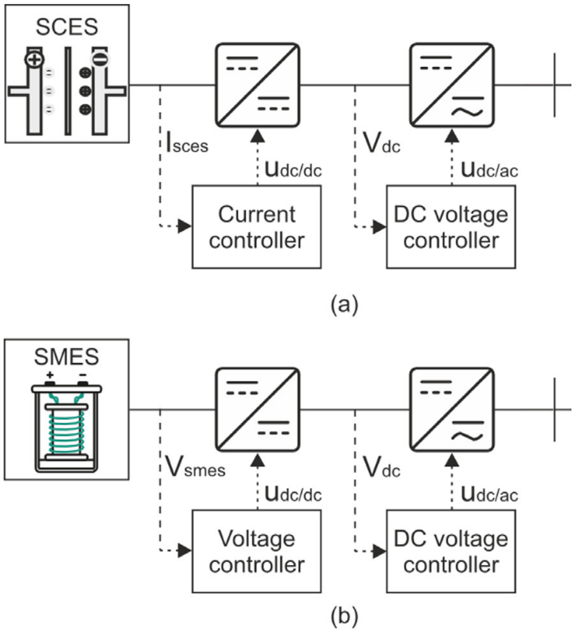

Fig. 4 Schematic representation of the grid connection architecture of **a** an electric storage device, i.e., a Supercapacitor Energy Storage (SCES) and **b** a magnetic energy storage device, i.e., a Superconducting Magnetic Energy Storage (SMES)

In the following, the SCES and SMES technologies are described in more detail, focusing on the specific modeling, services, and applications in power systems.

4 Supercapacitor Energy Storage Systems

4.1 SCES Modelling

This section introduces the most used modelling approaches for SCES (De Carne et al. 2022). The supercapacitor models consist of 4 main contributions (Fig. 5): (i) the main RC branch and (ii) its series RC elements, (iii) the parallel RC branches, and (iv) the leakage resistor branch.

Main RC Branch

The RC branch represents the basic behavior of the supercapacitors and describes the storing of electrostatic energy. It consists of a resistive element R in series with a capacitor $C(V)$ that accounts for the non-linear behavior of the capacitance, that is linearly dependent on the voltage:

$$C(v) = C_0 + k \cdot v \tag{7}$$

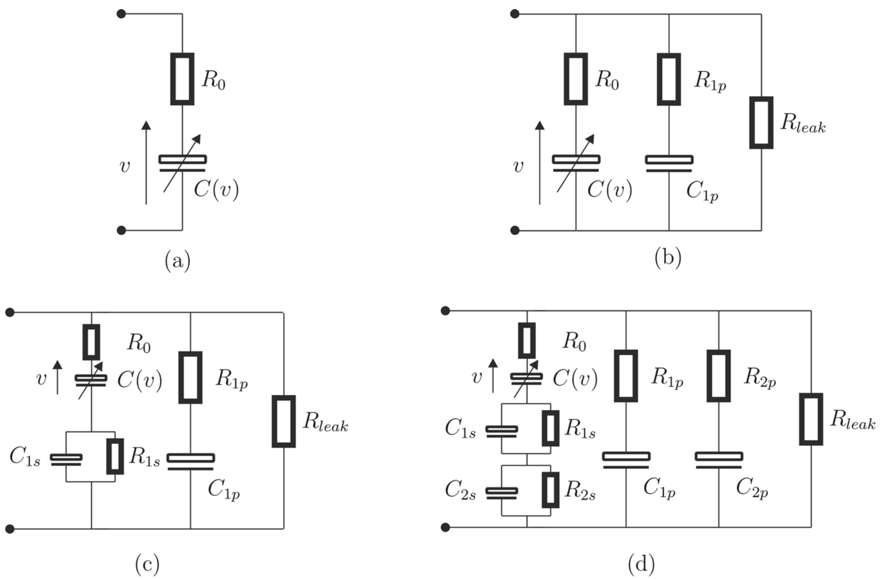

Fig. 5 Supercapacitor models proposed in literature (De Carne et al. 2022): **a** RC, **b** single parallel (1P) branch, **c** single parallel and single series (1P + 1S) branches, **d** double parallel and double series (2P + 2S) branches model

where C_0 is the supercapacitor main capacitance, and k describes the capacitance dependency on the voltage $C(v)$. This model accounts for the static behavior of the supercapacitor, without taking into account the dynamics and internal losses, that require additional modeling details.

Series RC Elements

To consider the fast voltage dynamics across the supercapacitors (e.g., caused by fast power changes), additional RC elements must be included in series to the main branch. These additional RC elements can be modeled as linear, and they target high frequency dynamics (e.g., 1 Hz and above). Despite several elements can be connected in series to represent a large dynamic spectrum, only a few RC elements (usually two) are considered in the main branch. These elements represent mostly the lower part of the high-frequency spectrum (e.g., up to 1 kHz).

Parallel RC Branches

To accurately represent the ion diffusion dynamics through the electrode power, that usually are slower dynamics in the range of seconds, additional parallel RC branches can be added. Similar to the series branches, in common practice up to two parallel branches are considered in supercapacitor models to represent the ion diffusion dynamics.

Leakage Resistor Branch

The supercapacitor cell tends to self-discharge during stand-by operations, although this phenomenon may require days or weeks. To take into account this property, a leakage resistor is usually added in the supercapacitor models.

4.2 SCES: Advantages and Disadvantages

This section describes the advantages and disadvantages in employing SCESs as energy storage solution.

- **Advantages**

SCESs offer several advantages over traditional energy storage systems, making them highly suited for applications requiring rapid power delivery and frequent charge–discharge cycles (Krpan et al. 2021). One of the most notable benefits is their high power density, which allows them to deliver bursts of energy much faster than batteries (Luo et al. 2015). This is especially advantageous in applications such as regenerative braking in electric vehicles or grid stabilization, where quick energy transfer is critical. Additionally, SCES have a long operational life due to their ability to withstand millions of charge–discharge cycles without significant degradation (Carne et al. 2024). This makes them highly reliable for applications where longevity and maintenance-free operation are crucial. Another advantage is their ability to operate efficiently across various temperatures, unlike batteries that may suffer from performance losses or may face severe safety issues in extreme conditions. Furthermore, SCES are eco-friendly as they are typically made from materials that are less hazardous than the chemicals used in traditional batteries (Saikia et al. 2020).

- **Disadvantages**

Despite their strength points, SCES also have several limitations that can restrict their usage in specific applications. A significant disadvantage is their relatively low energy density compared to batteries, meaning they cannot store as much energy in the same volume or weight (Song et al. 2014). This limits their effectiveness in applications that require long-duration energy storage, such as powering electric vehicles over extended distances (Lemian and Bode 2022). Additionally, SCES experience higher self-discharge rates than batteries, meaning they lose stored energy faster when unused. This makes them less ideal for applications requiring long-term energy retention. SCESs are also more expensive per unit of energy stored, which can increase the overall cost of energy storage solutions when used in systems requiring large amounts of stored energy (Zakeri and Syri 2015). Lastly, while they excel at providing high power output, they typically need to be paired with other storage systems, such as batteries, in hybrid configurations to efficiently handle both power and energy demands (Sutikno et al. 2022).

4.3 Application in Power System

- **Grid Stabilization**:

In modern power systems, the integration of renewable energy sources (RES), such as wind and solar, plays a crucial role in reducing reliance on fossil fuels and lowering carbon emissions (Dwyer and Teske 2018). However, these renewable sources are typically connected to the grid through power electronic converters, which isolate the energy source from the load, leading to a significant reduction in grid inertia (Nguyen et al. 2018). Grid inertia is essential for maintaining stability during power imbalances, as it helps to absorb disturbances and prevents cascading failures. When grid inertia is low, the system becomes vulnerable to undesirable effects such as load shedding (Sarojini and Kaliannan 2021). In this context, fast-acting energy storage systems like SCES can play a pivotal role. By injecting power immediately after a disturbance or the loss of a generation unit, SCES effectively emulate inertia, providing additional support to the grid. This inertia emulation can be achieved by generating power proportionally to the grid's frequency, ensuring stability. Numerous studies have highlighted the effectiveness of SCES in addressing the challenges posed by low inertia in modern power grids (Kim et al. 2019).

In addition to grid stabilization through inertia emulation, SCES are also valuable for frequency regulation, which is a critical function in balancing electricity supply and demand (Hatziargyriou et al. 2020; Wang et al. 2024). Frequency disturbances can destabilize power grids, especially those with a high share of renewable energy. SCES can absorb or deliver power almost instantaneously, making them ideal for providing short-term ancillary services within the power system (Barton and Infield 2004). Several research works propose using SCES to provide dynamic frequency support in isolated power systems, where they can effectively counteract sudden frequency deviations caused by fluctuations in generation or load (Delille et al. 2012; Tan et al. 2017).

Moreover, voltage regulation is another key area in which SCES finds applications. In power grids with significant penetration of renewable energy, voltage fluctuations can occur due to the intermittent and variable nature of generation from wind and solar sources (Ramirez and Murillo-Perez 2006). With their fast response times, power converters of SCES can be designed and controlled to rapidly inject or absorb reactive power to stabilize voltage levels during such fluctuations (Bensmaine et al. 2015). At the same time, the ability to charge and discharge faster than conventional batteries allow SCES to manage peak loads effectively, thereby adding active power control capability and contributing to grid stability. One notable industrial application is the partnership between TransnetBW and Hitachi Energy in Germany, where SCES are central to the implementation of STATCOM-GFM (Static Synchronous Compensator with Grid-Forming capabilities) systems. These systems provide enhanced voltage regulation by managing reactive power and offering short-term active power support, showcasing the role of SCES in modern grid management (TransnetBW 2024).

Thus, SCES contribute significantly to grid stability through multiple mechanisms grid inertia support, frequency regulation, and voltage stabilization making them indispensable in power systems with a growing share of renewable energy.

- **Electric Mobility**:

SCES are increasingly being integrated into transportation systems due to their unique ability to provide rapid bursts of energy combined with low weight and long cycle life. In electric vehicles (EVs), SCESs complement traditional battery systems by enabling regenerative braking, which captures energy during braking and stores it for later use (Wang et al. 2020). This process enhances energy efficiency, allowing quicker acceleration and smoother deceleration. Additionally, supercapacitors can supply high power during peak demand situations, such as when vehicles require immediate acceleration, thus improving overall performance (Horn et al. 2019). In public transport systems, like electric buses and trams, supercapacitors store energy for short trips between charging stations, allowing for quick recharges at stops and minimizing downtime (Mir et al. 2009; Zhang et al. 2017). Their lightweight design and ability to operate in various temperature ranges make them ideal for use in rail systems, where they can recover energy during braking and use it for acceleration.

Several industrial applications illustrate the effectiveness of SCES in mobility. For instance, Nidec Conversion is developing an all-electric, zero-emission passengers ferry that utilizes fast-charging supercapacitors to enhance performance and sustainability (Nidec Conversion 2024). Sunwin, a state-owned company, is implementing supercapacitors in China and the UAE in their buses to improve energy efficiency and operational capabilities (Shanghai Sunwin Bus Corporation 2024; Enterprises 2024). In Italy, Chariot Motors, in partnership with local company E-CO, is deploying buses in Rome and Turin capable of recovering over 35% of energy during braking (Bus 2024; s.r.l 2024). Furthermore, Skeleton and Siemens are collaborating on train systems that utilize supercapacitors to maximize energy recovery and operational efficiency (Mobility 2024; Technologies 2024).

5 Superconducting Magnetic Energy Storage Systems

Superconducting Magnetic Energy Storage (SMES) systems store energy in the magnetic field generated by a DC current flowing in a resistanceless superconducting coil connected to the grid through suitable power conditioning apparatuses. Conceptual SMES systems were first proposed by Ferrier in 1969 to store diurnal energy in France (Boicea 2014), while the first SMES was realized at the University of Wisconsin in 1971(Adetokun et al. 2022). The first commercial operating device was introduced in 1981 in the 500 kV Pacific Intertie corridor, connecting California to the Northwest region of the United States (Torre and Eckroad 2001). A SMES unit with 10 MW 1 s rating are used since 2008 to prevent power interruptions in a semiconducting manufacturing plant in Japan (Nagaya et al. 2012).

To maximize the current circulating in the in the SMES coil, so to maximize the stored energy, and to prevent joule losses during current circulation that would jeopardize the efficiency of the system, superconducting materials are used for the windings (Morandi et al. 2016; Schoenung et al. 1991). Energy exchange with the grid is then managed by power converters, controlled by algorithms designed to modulate the coil current according to (5) to ensure that the charging and, more importantly, the discharging of the coil occur when needed and with the promptness required. This makes SMES able to store energy with minimal losses (overall efficiency up to 95% or more) and release it almost instantaneously, resulting in a highly efficient and responsive system that can mitigate voltage deeps and brief interruptions, thereby ensuring continuity of service (Schoenung et al. 1991; Vulusala and Madichetty 2018).

5.1 Superconducting Magnet System

A practical SMES system consists of a lossless (or extremely low loss) superconducting magnet and a power conditioning system, required for connecting the coil to the (usually three phase) power grid. The cooling system, required for maintaining the temperature of the coil below the critical value so to ensure that it operates in the superconducting state, is an integral and essential part of the system. SMES systems based on low-temperature superconductors are an established power-intensive storage technology (Filippidis et al. 2021; Boenig and Hauer 1985; Morandi et al. 2008; Ottonello et al. 2006). In these systems the superconducting coil, made of industrially mature NbTi wires routinely used in MRI applications, operates at 4.2 K (− 268.5 °C) and is cooled by immersion in a liquid helium bath, obtained by closed cycle cooling machines. Despite complete and qualified systems have been developed, LTS-SMES technology has failed to find broad market penetration due to the high cost (capital and operational) related to liquid helium. Besides the high cost, liquid helium also implies complicated management, supply (also facing shortage concerns), maintenance and safety (overpressure and explosion risk in the case of quench), which make its use not trivial for grid or industry systems. Improvement of SMES prototypes based on first-generation HTS materials (Bi2223/Ag conductor) and cryogen-free cooling (not using liquid helium) at 20 K have been also proven (Hawley and Gower 2005). However, the high cost of practical 1G-HTS conductors (requiring a high silver content) does not offer prospects for commercial development of this SMES technology.

A drastic improvement in SMES technology, creating a breakthrough increase of both the technical and economic attractiveness, can be obtained today using modern (second generation) HTS materials ReBCO coated conductors. These materials offer much improved transport capacity and magnetic field withstand ability and, moreover, are able to operate at much increased temperature, in the range of 20–50 K and beyond for SMES applications. These characteristics open the way to more compact magnet designs, requiring a much simplified and cost-effective cooling system. The magnesium diboride (MgB2), a superconductor with intermediate electro-thermal performance compared to LTS and HTS and able to operate in the temperature range of 10–20 K, can also be considered as an alternative for SMES applications due to its excellent industrial maturity and low cost (Morandi et al. 2018). HTS-SMES prototypes based on 2G HTS tapes have already been developed and validated in the lab (Cicéron et al. 2018a, b; Hawley and Gower 2005; Ren et al. 2015).

5.2 SMES: Advantages and Disadvantages

- In general, SMES can have significant advantages in terms of power density and response speed, but they also have limitations in energy density and cost, which affect their adoption in various sectors. More specifically, the advantages of SMES technologies are:
- High efficiency: SMES systems can achieve round-trip efficiencies greater than 98%.
- Fast transient dynamics: SMES systems offer very small response times, making them suitable for grid stabilization and power quality applications.

- High power density: SMES can reach very high-power output capability, meaning that it can deliver large amounts of power in short periods.
- Unlimited charge–discharge cycles: SMES systems have no intrinsic degradation over time with cycling (unlike batteries and supercapacitors), offering a long service life.
- Zero carbon emissions: during operations SMES does not contribute with greenhouse emissions and does not involve hazardous materials.

SMES disadvantages can be instead summarized as:

- Cryogenic cooling: SMES systems involve superconductors whose require extremely low temperatures (typically using liquid helium or nitrogen), leading to high operational complexity and costs, including maintenance.
- High initial cost: the superconducting materials, cooling infrastructure, and supporting systems make SMES installations considerably expensive.
- Low energy density: SMES has excellent power density, but it has relatively low energy density, making it unsuitable for long-duration energy storage.

Overall, SMES systems are the best solution for high-power, short-time energy storage. While they offer exceptional efficiency and fast response times, their high costs and cooling requirements still remain significant challenges limiting their large-scale diffusion (Luongo 1996).

5.2.1 SMES Modeling

As seen in the previous sections, SCESs consist of many supercapacitor cells or small modules arranged in series or parallel in order to reach the required voltage, current, and power rating. Modeling of individual supercapacitor cells is crucial to accurately reproduce the overall behavior of system. Concerning SMES, although intense modeling efforts are required in the design phase of the coil, the interaction of the SMES with the converters and the grid can be well reproduced, at least for the typical time-scale of power exchange cycles, by representing the coil as a simple inductor. This is due to the fact that the superconducting windings are embedded in one unique cryostat with two current leads connecting it to the external environment at room temperature. Overall, the SMESs form a two-terminals component which can be modeled as an ideal inductor. Indeed, further phenomena that occur into the coils during operations (i.e., AC losses) do not significantly affect the terminals behavior of the SMES in normal conditions. Of course, these phenomena, which would require complex modeling, are duly considered in the design phase of the SMES system. It is to be pointed out that the ideal inductor model only holds in normal operating conditions, during which all the thermal and electromagnetic parameters are within the design range. If special operating conditions need to be investigated more complex models need to be introduced. For example, quench phenomena involving overheating would require distributed non-linear resistive network, whereas investigation of fast voltage transients would require distributed L-C circuits.

6 Hybrid Energy Storage Systems

Hybrid energy storage systems (HESS) represent an advanced approach to energy management. They integrate multiple energy storage technologies to harness their complementary attributes. Typically, HESS combines high power-density devices, such as SMES and SCES, with high energy–density devices, such as batteries (Liu et al. 2024; Zhu et al. 2012). With their rapid charge/discharge capabilities, high-power devices can manage short-term fluctuations and peak power demands, while high-energy devices are suited for long-duration energy storage and stable power delivery over extended periods (Etxeberria et al. 2010). The potential of HESS lies in its ability to provide both immediate power response and sustained energy delivery. For example, supercapacitors can handle high-power transients that last seconds to minutes, such as during grid frequency stabilization or rapid acceleration in electric vehicles (Jia et al. 2023; Sun et al. 2017). Meanwhile, batteries or other high-energy storage technologies deliver the required energy over a longer duration, ensuring consistent power supply even under variable load demands (Rouholamini et al. 2022). This synergy leads to increased system efficiency, reduced stress on individual storage components, and an extended lifecycle for the energy storage system as a whole (Li et al. 2021). Among implementations of HESS, in wind applications, battery/supercapacitor HESS has been introduced to improve efficiency and reduce costs by extending battery life (Sarrias-Mena et al. 2014). A SMES/battery HESS was considered to stabilize fluctuating loads in railway substations (Ise et al. 2005; Zhou et al. 2010) demonstrated that combining short- and long-term ESS improves renewable energy penetration in power systems. Additionally, (Gee et al. 2013) described how SCES can extend battery life in off-grid wind systems, with similar methods successfully predicting battery lifetime in other studies (Guan et al. 2014; Li et al. 2015).

6.1 Power Electronics Integration

HESS are usually composed of two energy storage systems with different voltage, current and power ratings, and that may behave differently as voltage or current sources. Power electronics converters allows storage systems to be integrated in the same system and to control optimally the energy flow. This section provides a brief overview of the possible power electronics connection of hybrid energy storage systems, considering 4 potential connection architectures as in Fig. 6.

AC Coupling

This coupling connects two HESS separated devices in the AC side. It means, that the power- and energy-dense devices can be of different vendors, and eventually work at different voltage rates (e.g., connected with a transformer), and they are coupled only from an energy management point of view. Despite it requires several power

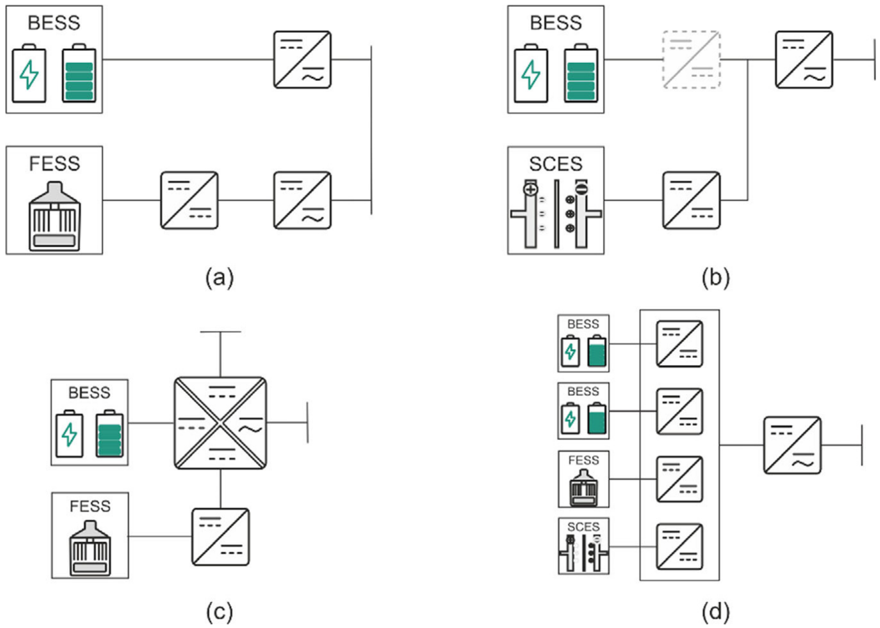

Fig. 6 HESS power electronics integration considering different energy storage technologies, including BESS, SCES and other power-intensive storage systems, such as Flywheel (FESS). Different architectures are considered: **a** AC coupling between BESS and FESS, **b** DC coupling between BESS and SCES, **c** multi-port coupling between BESS and FESS, **d** multi-level coupling with BESS, FESS, SCES

conversion stages, this coupling approach is widely spread in industrial application, due to its design flexibility (e.g., it can be easily scaled up).

DC Coupling

The DC coupling exploits the DC nature of many energy storage systems (e.g., batteries, supercapacitors, SMES, FESS) to reduce the number of dedicated conversion stages (Lo Franco et al. 2021). The HESS are interfaced in a common DC link, by means of DC/DC converters (isolated and not), that regulate the power exchange in each storage system. A common DC/AC converter interfaces the DC link to the AC system. The main advantage of using DC coupling lies in the efficiency and in the material saving: there are fewer conversion stages, leading to lower losses and a reduced need for semiconductor and passive components. This translates automatically in potentially lower bill of materials, and thus costs.

Multi-port DC Coupling

An innovative concept pursued recently is to enable the DC coupling by means of the magnetic stage of dual active bridge (DAB) DC/DC converters (Kheraluwala et al. 1992). This approach, employing usually Multiple-Active-Bridge (MAB) converters, transfers energy in AC form in medium- or high-frequency transformers (up to hundreds of kHz), and reconvert it in DC at multiple terminals. The main advantage in using this approach lies in the compactness of the solution. With respect to direct DC coupling, fewer conversion stages are required to connect several different HESS technologies. This aspect is particularly important for on-board systems, where safety is guaranteed by the galvanic insulation (Pereira et al. 2021), and a reduced weight and space enables smaller footprints.

Multi-level Coupling

Multi-level converters offer the possibility to connect directly to high voltage grids by means of low voltage components. Topologies, such as Cascaded H-Bridge and Modular Multi-level Converter, are composed of a series-connection of low voltage cells, that include usually capacitive elements. Recently, several works (Hillers et al. 2015; Jiang et al. 2021), envisioned the idea to connect the energy storage elements directly at cell level, decreasing the need for further DC/DC stages. This idea, pursued for HESS in several works, has its own challenges, particularly in the control and protection (i.e., no power flow control in case of fault).

6.2 Services and Applications

As mentioned above, HESS can manage optimally the energy delivery in the short- and long-term, allowing to extend their capability in offering services. In the following, several examples are provided, where HESS can play an important role in the energy management. A review of existing projects on the development of SCES and SMES is presented in the next section, followed by the discussion of a selected application case.

- **Renewable Energy Integration**:

Renewable energy generation, unlike conventional fossil fuel plants, is influenced by weather conditions and time of day, leading to times when power output either falls short of or exceeds demand (Deguenon et al. 2023). Grid operators must continuously manage these fluctuations in to prevent frequency imbalances, voltage instabilities, and power outages (Khalid 2024). HESSs are crucial in mitigating these issues by storing surplus energy during peak production and supplying it when production is low (Adeyinka et al. 2024; Kebede et al. 2022).

- **Electric Vehicles (EVs)**:

Due to uncertainties surrounding future energy resources and environmental, economic, and political challenges, energy efficiency policies and clean energy adoption have gained significant focus. In the private transport sector, options such as fuel cell (FC) vehicles, hybrid electric vehicles (HEVs), plug-in HEVs (PHEVs), and battery electric vehicles (EVs) are being proposed to replace or enhance internal combustion engines (ICEs), with all these alternatives incorporating electric propulsion systems to reduce dependence on ICEs. The power output of the primary sources in these vehicles, typically batteries or fuel cells, are limited by their charge/discharge cycles and may struggle to meet high power demands during short periods, such as acceleration. FESS, ultra-capacitors, and SMES are commonly recommended for power-based energy storage in EV applications (Bazzi et al. 2018; Rezaei et al. 2022).

- **Electric Trains**:

In comparison to other modes of transportation, electrified rail offers benefits such as high capacity, punctuality, and environmental sustainability. However, the growing global focus on enhancing railway use and energy efficiency has led to rising planning, investment, and construction costs of the powering infrastructure. Recently, there has been increasing interest in optimizing the use of ESSs to recover more regenerative energy and boost traction efficiency (González-Gil et al. 2013; Ise et al. 2005). Among different ESSs, batteries are still a common choice for absorbing regenerative energy in certain electrified sections. Still, they have significant limitations, including reduced energy efficiency and a limited cycle life (Vazquez et al. 2010). Given the current state of ESSs, no single type can fully meet the demands of modern electrified railway systems, such as long cycle life, cost-effectiveness, and balanced power and energy densities. As a result, HESSs offer a superior solution (Babu et al. 2020).

- **Marine Transportation**:

Traditional ships typically rely on diesel-powered internal combustion engines for propulsion. Still, these engines emit pollutants that harm the environment and human health. With growing environmental regulations, electric ships have gained prominence in the future of shipbuilding and maritime operations. Strategies such as optimized vessel routing, increased electrification supported by ESSs, renewable energy integration, and alternative fuels have been identified as effective ways to significantly reduce emissions from electric ships. Currently, most electric ships use lithium-iron phosphate batteries for energy storage (Banaei et al. 2020). However, power fluctuations during voyages can result in high current impacts that accelerate battery aging. Furthermore, the reliance on a single energy source can compromise the ship's power grid reliability. However, the potential of HESS to reduce operating costs is a reassuring factor. By combining different energy storage technologies, HESS can leverage their complementary strengths to create more efficient systems. SCES, with their fast charging, long cycle life, and high-power density, are ideal for handling high current charging and discharging. Effective energy management strategies can further extend battery life and lower operating costs, making the economic viability of all-electric ships a promising prospect (He et al. 2021).

7 Existing Projects with Power-Intensive HESS

As the energy landscape continues to evolve, numerous projects are exploring the potential of power-intensive HESS to meet the growing demand for robust and efficient energy solutions (Babu et al. 2020). These projects, from early planning stages to ongoing developments, address critical challenges such as grid stability, renewable energy integration, and peak load management. This section provides an overview of some key projects either underway or in the planning phase, offering insights into their objectives and anticipated outcomes to harness the potential of HESS in power-intensive applications.

- **Duke Energy HESS at Rankin Substation in Gaston County, N.C. (2016)**: Featuring a 100-kW/300-kWh battery and ultracapacitors. This system integrates Aquion Energy's Aqueous Hybrid Ion batteries with Maxwell Technologies' high-speed ultracapacitors for rapid energy response. The HESS aims to enhance solar power management by smoothing fluctuations, extending operational life, and enabling load shifting (Duke Energy 2016).
- **Skeleton Technologies' SuperBattery HESS (2023)**: Energy storage solution combining the benefits of supercapacitors and batteries. This hybrid technology leverages supercapacitors' high-power density and rapid charge/discharge capabilities with the high energy density and long-term storage capabilities of batteries. The SuperBattery is designed for applications requiring high-power energy storage, such as automotive and renewable energy in industrial sectors. Key features include excellent cycle life, fast charging and discharging, and robust performance in varying temperatures (Skeleton Technologies n.d.).
- **Beyonder and ABB Lithium-ion Capacitors (LiC) HESS (2024)**: Beyonder and ABB partnering to enhance product development, production, and market strategies for the large-scale production of Beyonder's LiC, utilizing key components from both companies. They aim to discover more cost-effective and sustainable methods for delivering energy storage solutions to the power grid while supporting emissions-free solutions at airports, ports, heavy transport, and fast charging stations (Beyonder 2024).
- **V-ACCESS—Vessel Advanced Clustered and Coordinated Energy Storage Systems**: The EU funded V-ACCESS project aims to integrate, in addition to battery, a 100 kW SCES system and 100 kW SMES system to match vessel's operative conditions. The project, involving 14 EU companies and research institutions with SKELETON and ASG companies as SCES and SMES technology providers respectively, investigates how these short-term energy storage technologies can operate together with batteries and how it can be ensured that they can effectively mitigate battery degradation. Suitable control of the power flows and DC integration strategies, as well as safety assessment and systems' marinization, are fully developed in the project to reach the objectives.

8 Case Study: Power Management in Hybrid Energy Storage Systems

This section offers a case study for hybrid energy storage systems, where a dynamic energy storage system, i.e., a SCES or SMES studied in this chapter, is associated with a battery energy storage system. The complementary power and energy characteristics of SCES or SMES and lithium-ion batteries enable advanced grid services with enhanced power response, energy capacity, and cycling capability while extending the system's lifetime. SCES or SMES can handle continuous, high-power, short-duration demands efficiently, protecting the battery from excessive stress while the battery provides the energy density required for sustained, longer-duration energy supply. Careful monitoring and management of State of Charge (SoC) and ramp rate are important because they directly affect system performance and longevity. High ramp rates can cause stress on the components, while extreme SoC levels (either too low or too high) can reduce efficiency or risk depletion, respectively. Simplifying the SoC and ramp rate categories to critical thresholds ensures effective real-time decisions without unnecessary computational complexity. Therefore, effective real-time power management and carefully considering storage components' SoC and ramp rates are essential to optimize performance.

As a reference case for investigating the cooperation between SCES/SMES and batteries, we consider the work Maroufi et al. (2025) which explores a novel Moving Average (MA) and Fuzzy Logic-based power management approach for a hybrid energy storage system designed to provide grid services. In Maroufi et al. (2025), a flywheel system is considered a power-intensive storage system. The developed methodology is extended to supercapacitors and SMES here. This method optimally distributes power between the two technologies by addressing key limitations: the supercapacitor's and SMES SoC and the battery's ramp rate. By employing Moving Averages for dynamic energy demand adjustments and Fuzzy Logic controllers for precise power redistribution, the system minimizes imbalances in SoC and ramp rates.

As shown in Fig. 7 the controller integrates fuzzy logic and moving average techniques to optimize power set-points, dynamically adjusting to the rate of change in the battery's power output and the SoC of the flywheel (can be SCES or SMES). Fuzzy logic is particularly suited for this application due to its flexibility and intuitive handling of nonlinear variables, enabling the determination of the moving average window length based on real-time conditions. This adaptability ensures that the system can respond effectively to rapid fluctuations in power demand while maintaining SoC and ramp rate levels within optimal ranges. Furthermore, by carefully managing the trade-off between prioritizing power response and SoC control, the HESS remains available for additional grid services. Unlike conventional methods, this integrated approach directly manages the HESS's output power, ensuring optimal overall performance under dynamic grid conditions.

In order to obtain the HESS power profile, real-world data from southern Germany, spanning three months and summarized into a representative day profile through an

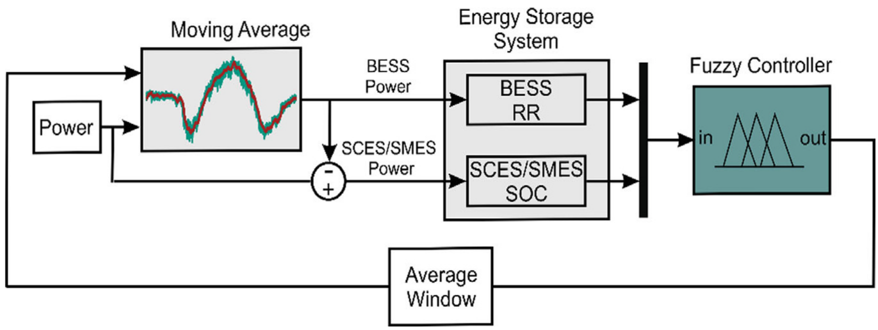

Fig. 7 Control scheme for HESS including the moving average and fuzzy logic stages

enhanced motif discovery algorithm, were employed. This power profile, derived from reference (Karrari et al. 2022), identifies the most recurrent daily consumption patterns within the target time series with a 1-s time step. The input data, collected during the summer of 2018 from four distinct 10/0.4 kV substations, captured high levels of PV generation critical for the sizing analysis. These substations were selected based on their relative voltage sensitivity to changes in active power as proposed in (Karrari et al. 2020). Figure 8 demonstrates the division of this input power using a 10-min moving average. For this particular input dataset, the moving average output varies within a range of ± 160 kW, while the difference between the input signal and the moving average filter output falls within a range of ± 30 kW.

In the following performance metrics, when the high-energy density storage (Battery Energy Storage) is fixed at 500 kWh, but the high-power density storage (e.g., SCES or SMES) varies in capacity, are compared. The three cases were

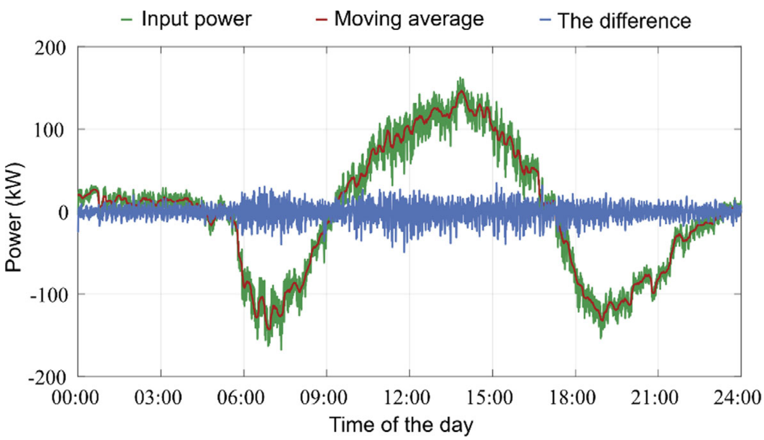

Fig. 8 The profile of the input power, the moving average filter, and the difference between them adapted from (Karrari et al. 2022)

conducted when the high-power density storage had capacities of 3.5, 7.0, and 10.5 kWh. These ratings can be met based on the present state of the art for the SCES and SMES (mostly in the 3.5 kWh case) systems. The following key observations highlight the impact of the SCES/SMES energy capacity:

1. **Effect on Average Window**: Fig. 9 shows how the size of the high-power density storage influences the Moving Average window length used in the power management strategy during a time interval of one day Systems with lower energy capacity in the high-power density storage required shorter average windows, as they have limited ability to buffer energy fluctuations. For instance, SCES or SMES necessitate more frequent power adjustments to accommodate rapid changes in demand. It is also noteworthy that SCES and SMES, with their higher power density compared to flywheels, are more effective in handling sharp power spikes. However, their lower energy capacities mean that the Moving Average window must adapt dynamically to prevent overloading.
2. **Effect on State of Charge (SoC)**: Fig. 10 shows how the SoC dynamics of the high-power density storage are impacted by its energy capacity during a time interval of one day. Smaller capacity devices reach lower SoC levels during the day because they deplete faster under equivalent power demands. While supercapacitors and SMES discharge more rapidly due to their higher power density, their ability to recharge quickly ensures they remain viable for high-frequency power adjustments. This characteristic differentiates them from flywheels, which may have slower response times in comparison.
3. **Effect on Ramp Rate of High-Energy Density Storage (Battery)**: Fig. 11 shows how a decrease in the energy capacity of the high-power density storage impacts the power ramp rate of the battery. With smaller high-power density storage, the system relies more heavily on the battery to respond to fast power fluctuations, leading to higher ramp rates. The higher power density of SCES and SMES helps to mitigate this effect to some extent by absorbing rapid fluctuations more effectively than flywheels. However, their limited energy capacity means that their ability to sustain prolonged support is reduced.

This case study highlights the intricate balance required in designing hybrid energy storage systems. Supercapacitors and SMES, with their superior power density compared to flywheels, excel in handling rapid power fluctuations but are limited by their lower energy capacities. By leveraging power management strategies like Moving Average and Fuzzy Logic, it is possible to mitigate these limitations and ensure system efficiency.

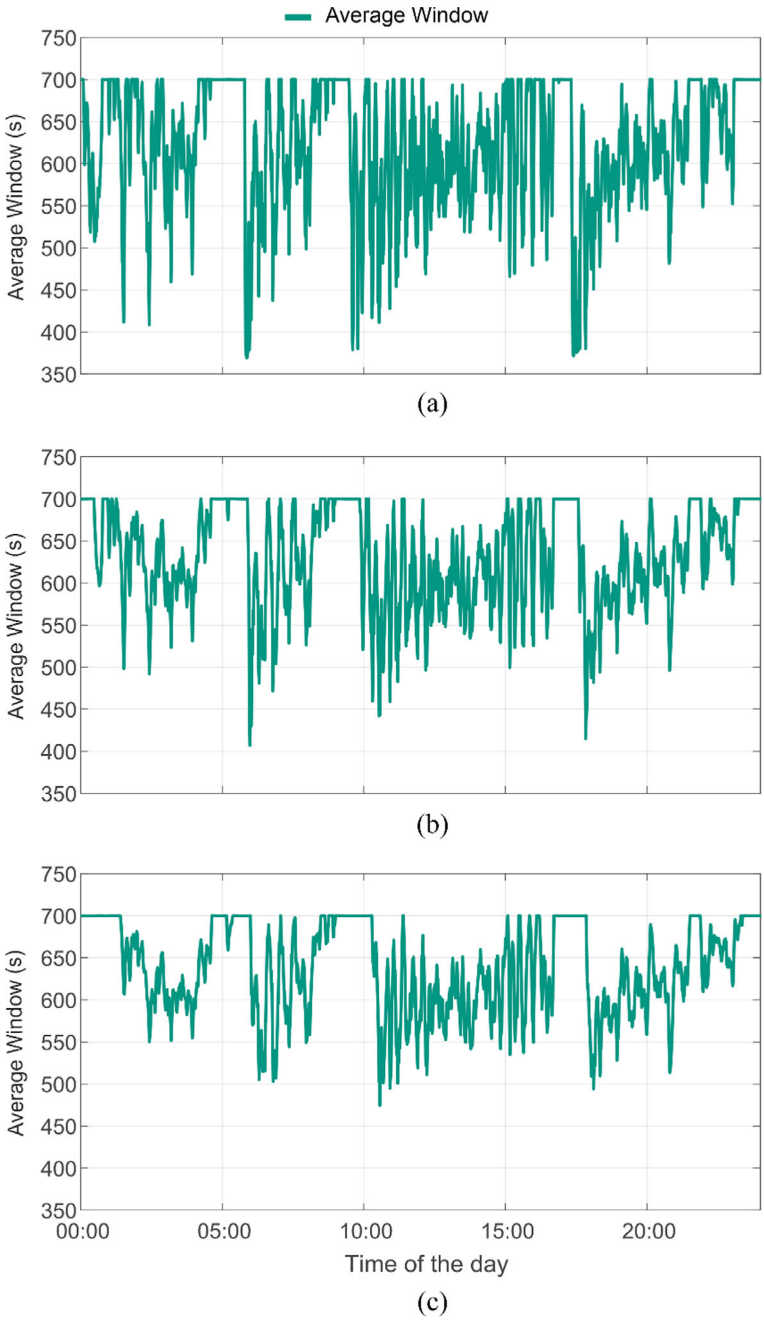

Fig. 9 Average window length of the moving average filter for different energy capacities of the high-power density storage **a** 3.5 kWh **b** 7.0 kWh **c** 10.5 kWh

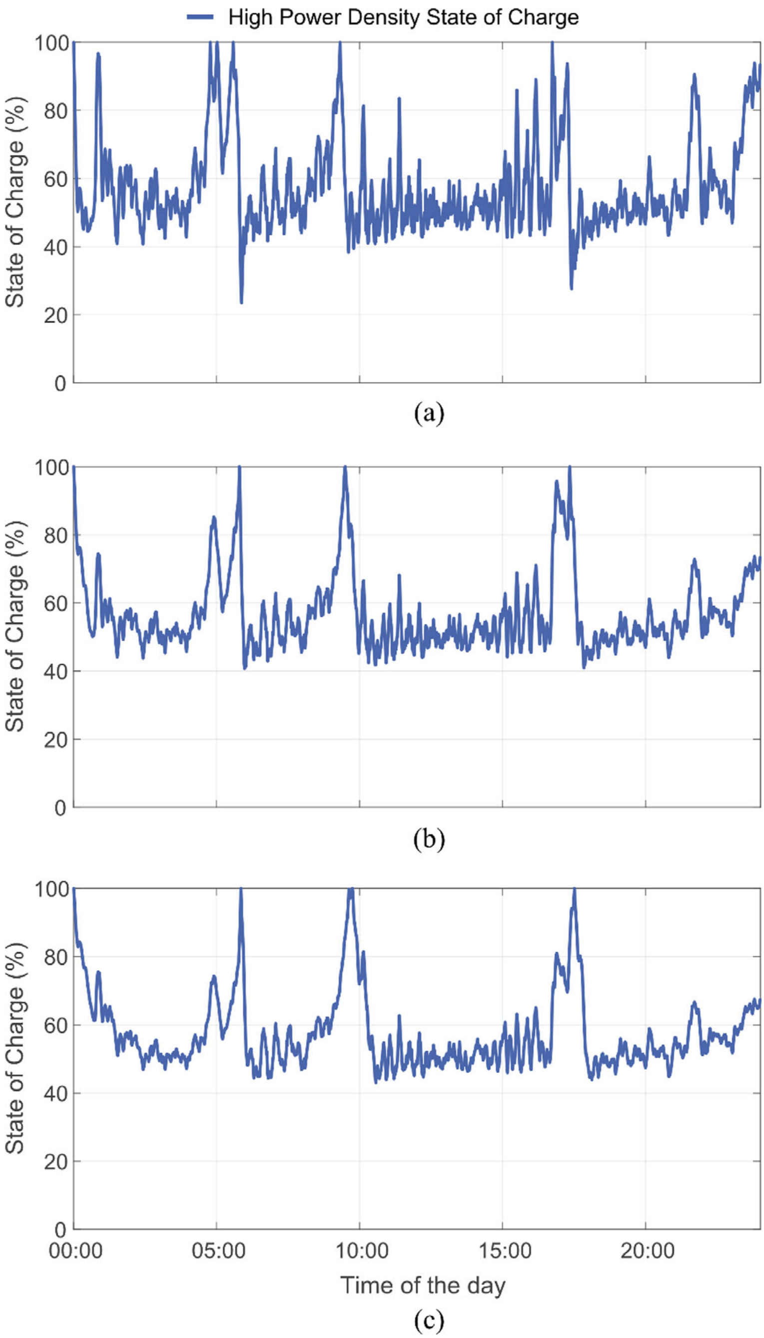

Fig. 10 State of charge of the high-power density storage for different energy capacities of the high-power density storage **a** 3.5 kWh **b** 7.0 kWh **c** 10.5 kWh

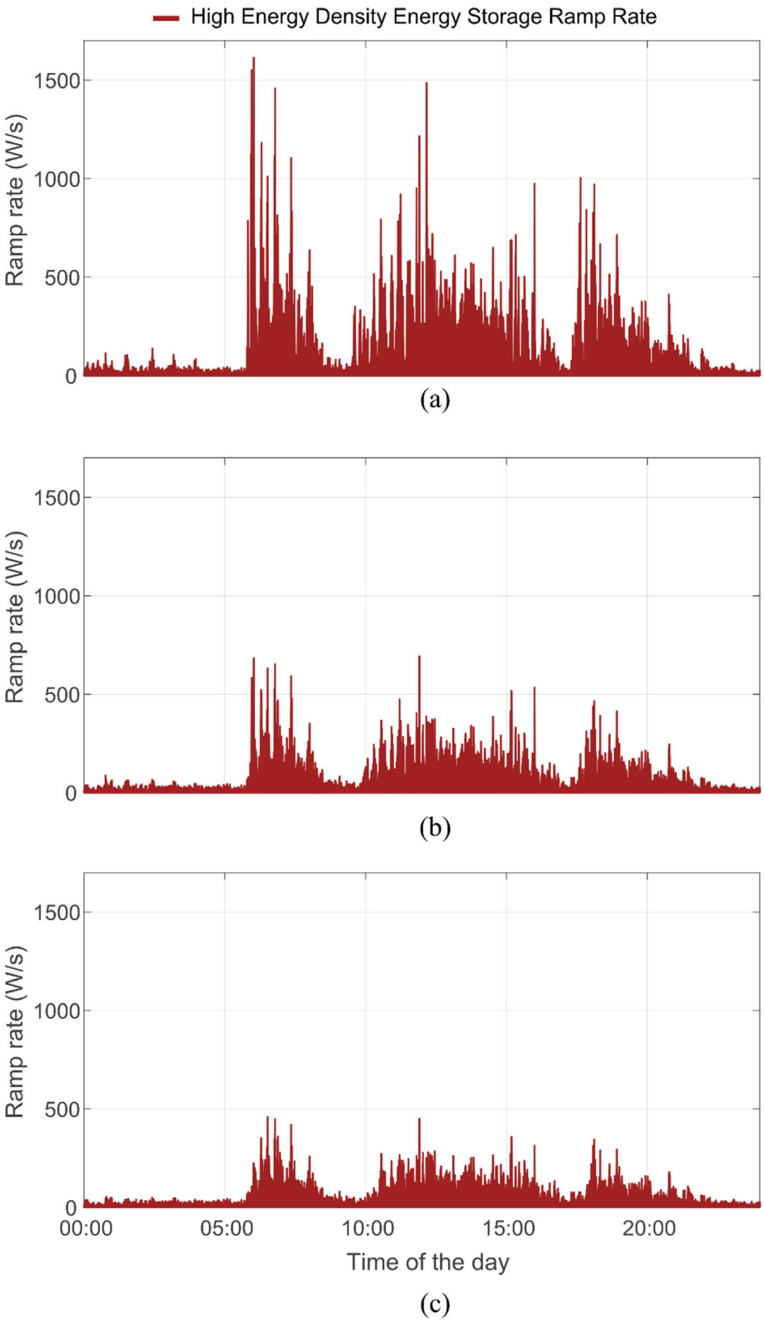

Fig. 11 Ramp rate of battery for different capacities for high-power density storage **a** 3.5 kWh **b** 7.0 kWh **c** 10.5 kWh

Acknowledgements The work of Giovanni De Carne and Seyede Masoome Maroufi was supported by the Helmholtz Association under the program "Energy System Design" and the Helmholtz Young Investigator Group "Hybrid Networks" (VH-NG-1613).

References

Adetokun BB, Oghorada O, Abubakar SJ (2022) Superconducting magnetic energy storage systems: prospects and challenges for renewable energy applications. J. Energy Storage 55:105663. https://doi.org/10.1016/j.est.2022.105663

Adeyinka AM, Esan OC, Ijaola AO, Farayibi PK (2024) Advancements in hybrid energy storage systems for enhancing renewable energy-to-grid integration. Sustain Energy Res 11:26. https://doi.org/10.1186/s40807-024-00120-4

Babu TS, Vasudevan KR, Ramachandaramurthy VK, Sani SB, Chemud S, Lajim RM (2020) A comprehensive review of hybrid energy storage systems: converter topologies, control strategies and future prospects. IEEE Access 8:148702–148721. https://doi.org/10.1109/ACCESS.2020.3015919

Banaei M, Rafiei M, Boudjadar J, Khooban M-H (2020) A comparative analysis of optimal operation scenarios in hybrid emission-free ferry ships. IEEE Trans Transp Electrific 6:318–333

Barelli L, Bidini G, Cherubini P, Micangeli A, Pelosi D, Tacconelli C (2019) How hybridization of energy storage technologies can provide additional flexibility and competitiveness to microgrids in the context of developing countries. Energies 12. https://doi.org/10.3390/en12163138

Barelli L, Pelosi D, Longo M, Zaninelli D (2022) Energy storage integration into fast charging stations installed on e-highways. In: 2022 IEEE power & energy society general meeting (PESGM). IEEE, pp 01–05

Barton JP, Infield DG (2004) Energy storage and its use with intermittent renewable energy. IEEE Trans Energy Convers 19:441–448

Bazzi AM, Liu Y, Fay DS (2018) Electric machines and energy storage: over a century of technologies in electric and hybrid electric vehicles. IEEE Electrific Mag 6:49–53. https://doi.org/10.1109/MELE.2018.2849900

Bensmaine F, Bachelier O, Tnani S, Champenois G, Mouni E (2015) LMI approach of state-feedback controller design for a STATCOM-supercapacitors energy storage system associated with a wind generation. Energy Convers Manag 96:463–472

Beyonder (2024) Beyonder and ABB to collaborate on battery technology of the future

Boenig MJ, Hauer JF (1985) Commissioning tests of the bonneville power administration 30 MJ superconducting magnetic energy storage unit. IEEE Trans Power Appar Syst U. S. PAS-104:2. https://doi.org/10.1109/TPAS.1985.319044

Boicea VA (2014) Energy storage technologies: the past and the present. Proc IEEE 102:1777–1794. https://doi.org/10.1109/JPROC.2014.2359545

Bus CE (2024) 12m ultracapacitor chariot E-bus

Carne GD, Maroufi SM, Beiranvand H, Angelis VD, D'Arco S, Gevorgian V, Waczowicz S, Mather B, Liserre M, Hagenmeyer V (2024) The role of energy storage systems for a secure energy supply: a comprehensive review of system needs and technology solutions. Electr Power Syst Res 236:110963. https://doi.org/10.1016/j.epsr.2024.110963

Chatzivasileiadi A (2012) Electrical energy storage technologies and the built environment

Cicéron J, Badel A, Tixador P, Forest F (2017) Design considerations for high-energy density SMES. IEEE Trans Appl Supercond 27:1–5. https://doi.org/10.1109/TASC.2017.2655627

Cicéron J, Badel A, Tixador P, Pasquet R, Forest F (2018a) Test in strong background field of a modular element of a REBCO 1 MJ high energy density SMES. IEEE Trans Appl Supercond 28:1–5. https://doi.org/10.1109/TASC.2018.2820906

Cicéron J, Badel A, Vialle A-J, Pasquet R, Forest F, Chaud X, Tixador P (2018b) Status of the BOSSE project : a 12 T rare earth-BaCuO solenoid used as compact 1 MJ pulse-power SMES. In: Applied superconductivity conference 2018 (ASC'18). Seattle, United States

De Carne G, Morandi A, Karrari S (2022) Supercapacitor modeling for real-time simulation applications. IEEE J Emerg Sel Top Ind Electron 3:509–518. https://doi.org/10.1109/JESTIE.2022.3165985

Deguenon L, Yamegueu D, Gomna A et al (2023) Overcoming the challenges of integrating variable renewable energy to the grid: a comprehensive review of electrochemical battery storage systems. J Power Sources 580:233343

Delille G, Francois B, Malarange G (2012) Dynamic frequency control support by energy storage to reduce the impact of wind and solar generation on isolated power system's Inertia. IEEE Trans Sustain Energy 3:931–939. https://doi.org/10.1109/TSTE.2012.2205025

Duke Energy (2016) Duke energy to put new battery and ultracapacitor system to the test in N.C

Dwyer S, Teske S (2018) Renewables 2018 global status report. In: Reprenewables 2018 global status report

Enterprises ANG (2024) Buses and coaches

Etxeberria A, Vechiu I, Camblong H, Vinassa JM (2010) Hybrid energy storage systems for renewable energy sources integration in microgrids: a review. In: 2010 conference proceedings IPEC, pp 532–537. https://doi.org/10.1109/IPECON.2010.5697053

Farhadi M, Mohammed O (2016) Energy storage technologies for high-power applications. IEEE Trans Ind Appl 52:1953–1961. https://doi.org/10.1109/TIA.2015.2511096

Farivar GG, Manalastas W, Tafti HD, Ceballos S, Sanchez-Ruiz A, Lovell EC, Konstantinou G, Townsend CD, Srinivasan M, Pou J (2022) Grid-connected energy storage systems: state-of-the-art and emerging technologies. Proc IEEE 111:397–420

Filippidis S, Bouhouras A, Poulakis N, Christoforidis G (2021) A review of the cryocooler-based cooling systems for SMES. IEEE Trans Appl Supercond 31:1–13. https://doi.org/10.1109/TASC.2021.3109799

Gee AM, Robinson FV, Dunn RW (2013) Analysis of battery lifetime extension in a small-scale wind-energy system using supercapacitors. IEEE Trans Energy Convers 28:24–33

González-Gil A, Palacin R, Batty P (2013) Sustainable urban rail systems: strategies and technologies for optimal management of regenerative braking energy. Energy Convers Manag 75:374–388

Guan T, Zuo P, Sun S, Du C, Zhang L, Cui Y, Yang L, Gao Y, Yin G, Wang F (2014) Degradation mechanism of $LiCoO_2$/mesocarbon microbeads battery based on accelerated aging tests. J Power Sources 268:816–823

Gyuk I et al (2013) Grid energy storage. Technical report. U.S. Department of Energy

Hatziargyriou N, Milanovic J, Rahmann C, Ajjarapu V, Canizares C, Erlich I, Hill D, Hiskens I, Kamwa I, Pal B et al (2020) Definition and classification of power system stability–revisited & extended. IEEE Trans Power Syst 36:3271–3281

Hawley CJ, Gower SA (2005) Design and preliminary results of a prototype HTS SMES device. IEEE Trans Appl Supercond 15:1899–1902. https://doi.org/10.1109/TASC.2005.849328

He X, Luo B, Deng X, Zhu G, Zhang G, Wang Q (2021) Research on energy management strategy of hybrid energy storage system for electric ship. In: 2021 IEEE 5th conference on energy internet and energy system integration (EI2), pp 4272–4277. https://doi.org/10.1109/EI252483.2021.9713547

Hillers A, Stojadinovic M, Biela J (2015) Systematic comparison of modular multilevel converter topologies for battery energy storage systems based on split batteries. In: 2015 17th European conference on power electronics and applications (EPE'15 ECCE-Europe), pp 1–9. https://doi.org/10.1109/EPE.2015.7309385

Horn M, MacLeod J, Liu M, Webb J, Motta N (2019) Supercapacitors: a new source of power for electric cars? Econ Anal Policy 61:93–103

Hu X, Zou C, Zhang C, Li Y (2017) Technological developments in batteries: a survey of principal roles, types, and management needs. IEEE Power Energy Mag 15:20–31

Ise T, Kita M, Taguchi A (2005) A hybrid energy storage with a SMES and secondary battery. IEEE Trans Appl Supercond 15:1915–1918. https://doi.org/10.1109/TASC.2005.849333

Jia C, Cui J, Qiao W, Qu L (2023) Real-time model predictive control for battery-supercapacitor hybrid energy storage systems using linear parameter-varying models. IEEE J Emerg Sel Top Power Electron 11:251–263. https://doi.org/10.1109/JESTPE.2021.3130795

Jiang W, Ren K, Xue S, Yang C, Xu Z (2021) Research on the asymmetrical multilevel hybrid energy storage system based on hybrid carrier modulation. IEEE Trans Ind Electron 68:1241–1251. https://doi.org/10.1109/TIE.2020.2967723

Karrari S, Vollmer M, Carne GD, Noe M, Böhm K, Geisbüsch J (2020) A data-driven approach for estimating relative voltage sensitivity. In: 2020 IEEE power & energy society general meeting (PESGM), pp 1–5. https://doi.org/10.1109/PESGM41954.2020.9281859

Karrari S, Ludwig N, De Carne G, Noe M (2022) Sizing of hybrid energy storage systems using recurring daily patterns. IEEE Trans. Smart Grid 13:3290–3300. https://doi.org/10.1109/TSG.2022.3156860

Kebede AA, Kalogiannis T, Van Mierlo J, Berecibar M (2022) A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration. Renew Sustain Energy Rev 159:112213

Khalid M (2024) Smart grids and renewable energy systems: perspectives and grid integration challenges. Energy Strategy Rev 51:101299

Kheraluwala MN, Gascoigne RW, Divan DM, Baumann ED (1992) Performance characterization of a high-power dual active bridge DC-to-DC converter. IEEE Trans Ind Appl 28:1294–1301. https://doi.org/10.1109/28.175280

Kim J, Gevorgian V, Luo Y, Mohanpurkar M, Koritarov V, Hovsapian R, Muljadi E (2019) Supercapacitor to provide ancillary services with control coordination. IEEE Trans Ind Appl 55:5119–5127. https://doi.org/10.1109/TIA.2019.2924859

Kirby B, Hirst E (1997) Ancillary service details: voltage control (No. ONRL/CON-453). Oak Ridge National Laboratory, Oak Ridge, TN, USA

Krpan M, Kuzle I, Radovanović A, Milanović JV (2021) Modelling of supercapacitor banks for power system dynamics studies. IEEE Trans Power Syst 36:3987–3996. https://doi.org/10.1109/TPWRS.2021.3059954

Lemian D, Bode F (2022) Battery-supercapacitor energy storage systems for electrical vehicles: a review. Energies 15. https://doi.org/10.3390/en15155683

Li J, Gee AM, Zhang M, Yuan W (2015) Analysis of battery lifetime extension in a SMES-battery hybrid energy storage system using a novel battery lifetime model. Energy 86:175–185. https://doi.org/10.1016/j.energy.2015.03.132

Li X, Ma R, Yan N, Wang S, Hui D (2021) Research on optimal scheduling method of hybrid energy storage system considering health state of echelon-use lithium-ion battery. IEEE Trans Appl Supercond 31:1–4. https://doi.org/10.1109/TASC.2021.3117752

Liu Y, Han X, Xing Z, Li P, Liu H, Jiang Z (2024) Research on control strategy of hybrid superconducting energy storage based on reinforcement learning algorithm. IEEE Trans Appl Supercond 34:1–4. https://doi.org/10.1109/TASC.2024.3420314

Lo Franco F, Morandi A, Raboni P, Grandi G (2021) Efficiency comparison of DC and AC coupling solutions for large-scale PV+BESS power plants. Energies 14. https://doi.org/10.3390/en14164823

Luo X, Wang J, Dooner M, Clarke J (2015) Overview of current development in electrical energy storage technologies and the application potential in power system operation. Appl Energy 137:511–536. https://doi.org/10.1016/j.apenergy.2014.09.081

Luongo CA (1996) Superconducting storage systems: an overview. IEEE Trans Magn 32:2214–2223. https://doi.org/10.1109/20.508607

Mao Q, Gong X, Liu S, Shi D, Wang Z, Liu D (2020) Research on hybrid energy storage system with high power density and high energy density. In: 2020 IEEE sustainable power and energy conference (iSPEC), pp 2022–2027. https://doi.org/10.1109/iSPEC50848.2020.9351054

Maroufi SM, Karrari S, Rajashekaraiah K, De Carne G (2025) Power management of hybrid flywheel-battery energy storage systems sonsidering the state of charge and power ramp rate. In: IEEE Transactions on Power Electronics, vol 40, no 7, pp 9944–9956. https://doi.org/10.1109/TPEL.2025.3546013

Milano F, Manjavacas ÁO (2019) Converter-interfaced energy storage systems: need for energy storage; 2. Technical and economic aspects; 3. Energy storage technologies; Part II. Modelling: 4. Power system model; 5. Voltage-sourced converter model; 6. Energy storage system models; Part III. Dynamic analysis: 7. Comparison of dynamic models; 8. Control techniques; 9. Stability analysis; Part IV. Appendices. Cambridge University Press

Mir L, Etxeberria-Otadui I, de Arenaza IP, Sarasola I, Nieva T (2009) A supercapacitor based light rail vehicle: system design and operations modes. In: 2009 IEEE energy conversion congress and exposition. IEEE, pp 1632–1639

Mobility S (2024) Siemens mobility

Mongird K, Viswanathan V, Balducci P, Alam J, Fotedar V, Koritarov V, Hadjerioua B (2020) An evaluation of energy storage cost and performance characteristics. Energies 13. https://doi.org/10.3390/en13133307

Morandi A, Breschi M, Fabbri M, Negrini F, Penco R, Perrella M, Ribani P, Tassisto M, Trevisani L (2008) Design, manufacturing and preliminary tests of a conduction cooled 200 kJ Nb–Ti μSMES. IEEE Trans Appl Supercond 18:697–700. https://doi.org/10.1109/TASC.2008.921285

Morandi A, Fabbri M, Gholizad B, Grilli F, Sirois F, Zermeño VMR (2016) Design and comparison of a 1-MW/5-s HTS SMES with toroidal and solenoidal geometry. IEEE Trans Appl Supercond 26:1–6. https://doi.org/10.1109/TASC.2016.2535271

Morandi A, Anemona A, Angeli G, Breschi M, Della Corte A, Ferdeghini C, Gandolfi C, Grandi G, Grasso G, Martini L, Melaccio U, Nardelli D, Ribani PL, Siri S, Tropeano M, Turtù S, Vignolo M (2018) The DRYSMES4GRID project: development of a 500 kJ/200 kW cryogen-free cooled SMES demonstrator based on MgB2. IEEE Trans Appl Supercond 28:1–5. https://doi.org/10.1109/TASC.2018.2793661

Mukherjee P, Rao VV (2019) Design and development of high temperature superconducting magnetic energy storage for power applications—a review. Phys C Supercond Appl 563:67–73. https://doi.org/10.1016/j.physc.2019.05.001

Nagaya S, Hirano N, Katagiri T, Tamada T, Shikimachi K, Iwatani Y, Saito F, Ishii Y (2012) The state of the art of the development of SMES for bridging instantaneous voltage dips in Japan. Cryogenics 52:708–712. https://doi.org/10.1016/j.cryogenics.2012.04.014

Nguyen HT, Yang G, Nielsen AH, Jensen PH (2018) Combination of synchronous condenser and synthetic inertia for frequency stability enhancement in low-inertia systems. IEEE Trans Sustain Energy 10:997–1005

Nidec Conversion (2024) Supercapacitor energy storage system for an all-electric ferry—case study

Ottonello L, Canepa G, Albertelli P, Picco E, Florio A, Masciarelli G, Rossi S, Martini L, Pincella C, Mariscotti A et al (2006) The largest italian SMES. IEEE Trans Appl Supercond 16:602–607

Pelosi D, Longo M, Bidini G, Zaninelli D, Barelli L (2023) A new concept of highways infrastructure integrating energy storage devices for e-mobility transition. J Energy Storage 65:107364. https://doi.org/10.1016/j.est.2023.107364

Pelosi D, Gallorini F, Alessandri G, Barelli L (2024) A hybrid energy storage system integrated with a wave energy converter: data-driven stochastic power management for output power smoothing. Energies 17. https://doi.org/10.3390/en17051167

Pereira T, Hoffmann F, Zhu R, Liserre M (2021) A comprehensive assessment of multiwinding transformer-based DC–DC converters. IEEE Trans Power Electron 36:10020–10036. https://doi.org/10.1109/TPEL.2021.3064302

Ramirez JM, Murillo-Perez JL (2006) Steady-state voltage stability with StatCom. IEEE Trans Power Syst 21:1453–1454

Ren L, Xu Y, Liu H, Liu Y, Han P, Deng J, Li J, Chen J, Shi J, Tang Y (2015) The experimental research and analysis of a HTS SMES hybrid magnet. IEEE Trans Appl Supercond 25:1–5. https://doi.org/10.1109/TASC.2014.2368271

Rezaei H, Abdollahi SE, Abdollahi S, Filizadeh S (2022) Energy management strategies of battery-ultracapacitor hybrid storage systems for electric vehicles: review, challenges, and future trends. J Energy Storage 53:105045. https://doi.org/10.1016/j.est.2022.105045

Rouholamini M, Wang C, Nehrir H, Hu X, Hu Z, Aki H, Zhao B, Miao Z, Strunz K (2022) A review of modeling, management, and applications of grid-connected li-ion battery storage systems. IEEE Trans Smart Grid 13:4505–4524. https://doi.org/10.1109/TSG.2022.3188598

Saikia BK, Benoy SM, Bora M, Tamuly J, Pandey M, Bhattacharya D (2020) A brief review on supercapacitor energy storage devices and utilization of natural carbon resources as their electrode materials. Fuel 282:118796. https://doi.org/10.1016/j.fuel.2020.118796

Sarojini RK, Kaliannan P (2021) Inertia emulation through supercapacitor for a weak grid. IEEE Access 9:30793–30802. https://doi.org/10.1109/ACCESS.2021.3058951

Sarrias-Mena R, Fernández-Ramírez LM, García-Vázquez CA, Jurado F (2014) Fuzzy logic based power management strategy of a multi-MW doubly-fed induction generator wind turbine with battery and ultracapacitor. Energy 70:561–576

Schoenung SM, Meier WR, Hassenzahl WV (1991) A comparison of large-scale toroidal and solenoidal SMES systems. IEEE Trans Magn 27:2324–2328. https://doi.org/10.1109/20.133683

Shanghai Sunwin Bus Corporation (2024) Shanghai Sunwin Bus Corporation

Skeleton Technologies (n.d.) Superbattery

Song Z, Li J, Han X, Xu L, Lu L, Ouyang M, Hofmann H (2014) Multi-objective optimization of a semi-active battery/supercapacitor energy storage system for electric vehicles. Appl Energy 135:212–224

s.r.l E-C (2024) E-CO electric & hybrid

Sun L, Feng K, Chapman C, Zhang N (2017) An adaptive power-split strategy for battery-supercapacitor powertrain—design, simulation, and experiment. IEEE Trans Power Electron 32:9364–9375. https://doi.org/10.1109/TPEL.2017.2653842

Sutikno T, Arsadiando W, Wangsupphaphol A, Yudhana A, Facta M (2022) A review of recent advances on hybrid energy storage system for solar photovoltaics power generation. IEEE Access 10:42346–42364

Tan Y, Muttaqi KM, Ciufo P, Meegahapola L (2017) Enhanced frequency response strategy for a PMSG-based wind energy conversion system using ultracapacitor in remote area power supply systems. IEEE Trans Ind Appl 53:549–558. https://doi.org/10.1109/TIA.2016.2613074

Technologies S (2024) Supercapacitors in the Rail Industry

Torre WV, Eckroad S (2001) Improving power delivery through the application of superconducting magnetic energy storage (SMES). In: 2001 IEEE power engineering society winter meeting. conference proceedings (Cat. No.01CH37194), vol 1, pp 81–87. https://doi.org/10.1109/PESW.2001.916869

TransnetBW (2024) TransnetBW beauftragt Hitachi energy mit innovativen STATCOM-GFM-Anlagen [WWW Document]. https://www.transnetbw.de/de/newsroom/pressemitteilungen/transnetbw-beauftragt-hitachi-energy-mit-innovativen-statcom-gfm-anlagen. Accessed 22 Oct 2024

Vazquez S, Lukic SM, Galvan E, Franquelo LG, Carrasco JM (2010) Energy storage systems for transport and grid applications. IEEE Trans Ind Electron 57:3881–3895

Vulusala GVS, Madichetty S (2018) Application of superconducting magnetic energy storage in electrical power and energy systems: a review. Int J Energy Res 42:358–368. https://doi.org/10.1002/er.3773

Wang H, Zhou G, Xue R, Lu Y, McCann JA (2020) A driving-behavior-based SoC prediction method for light urban vehicles powered by supercapacitors. IEEE Trans Intell Transp Syst 21:2090–2099. https://doi.org/10.1109/TITS.2019.2912501

Wang B, Zhu S, Cai G, Yang D, Chen Z, Ma J, Sun Z (2024) Sparse measurement-based modelling low-order dynamics for primary frequency regulation. IEEE Trans Power Syst 39:681–692. https://doi.org/10.1109/TPWRS.2023.3256642

Zakeri B, Syri S (2015) Electrical energy storage systems: a comparative life cycle cost analysis. Renew Sustain Energy Rev 42:569–596. https://doi.org/10.1016/j.rser.2014.10.011

Zhang X, Wang W, He H, Hua L, Heng J (2017) Optimization of the air-cooled supercapacitor module compartment for an electric bus. Appl Therm Eng 112:1297–1304

Zhou H, Bhattacharya T, Tran D, Siew TST, Khambadkone AM (2010) Composite energy storage system involving battery and ultracapacitor with dynamic energy management in microgrid applications. IEEE Trans Power Electron 26:923–930

Zhu J, Qiu M, Wei B, Zhang H, Lai X, Yuan W (2012) Design, dynamic simulation and construction of a hybrid HTS SMES for Chinese power grid. Energy. Available Online 10