Energy Storage Systems for Transport and Grid Applications

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***Abstract*—Energy storage systems (ESSs) are enabling technologies for well-established and new applications such as power peak shaving, electric vehicles, integration of renewable energies, etc. This paper presents a review of ESSs for transport and grid applications, covering several aspects as the storage technology, the main applications, and the power converters used to operate some of the energy storage technologies. Special attention is given to the different applications, providing a deep description of the system and addressing the most suitable storage technology. The main objective of this paper is to introduce the subject and to give an updated reference to nonspecialist, academic, and engineers in the field of power electronics.**

***Index Terms*—Batteries, compressed air energy storage (CAES), energy storage, flywheel, fuel cell, power conversion, power electronics, renewable energy, supercapacitors, superconductive magnetic energy storage (SMES), thermoelectric energy storage (TEES).**

I. INTRODUCTION

DUE to environmental and geopolitical concerns, there has been a renewed push to minimize the use of hydrocarbons for electric energy generation and transportation. These concerns have lead to the proliferation of electricity generation using both grid-tied and stand-alone renewable energy resources such as wind turbines and photovoltaic arrays. However, the intermittent nature of these resources introduces issues with system stability, reliability, and power quality. The issue of sporadic availability of renewable resources can be addressed by introducing energy storage systems (ESSs) to (partially) decouple energy generation from demand. In addition, the ESSs can be used to address the power quality issues by providing ancillary services to the grid. Large ESSs are routinely used alongside renewable generation such as wind to stabilize the power output.

Transportation electrification is seen as an effective way to substantially reduce the overall use of hydrocarbons. Electrified vehicles with plug-in capability contain an energy storage element that is capable of storing power from the grid. If this power is produced using renewable energy sources (RESs), the overall reduction in the use of hydrocarbons is substantial. In addition to diminish the use of hydrocarbons to propel vehicles, the introduction of plug-in vehicles presents numerous small distributed energy storage resources that can be used to stabilize the grid locally. The main objective of this paper is to review the technologies used for energy storage in utility and transportation applications and to present the latest advances and developments at the component and system level as well as to discuss some implementation issues.

This paper is organized as follows. Section II presents a review of the energy storage technologies that are considered for use in utility and transportation applications. In certain cases, no single energy storage technology is capable of satisfying application requirements effectively. In such a case that hybrid ESSs are used, they electronically combine two or more energy storage technologies. This kind of systems is discussed in Section III. Section IV presents the energy storage requirements of transportation and utility applications. A link is made between the energy storage capabilities and application requirements. Section V reviews the power converters that are used to interface the ESSs with the application, and finally, Section VI concludes this paper.

II. REVIEW OF ENERGY STORAGE TECHNOLOGIES

ESSs, discussed in this paper, convert electrical energy to some form of energy that can be stored and released as needed. The choice of the ESS for an application will depend on the application power and energy ratings, response time, weight, volume, and operating temperature. Table I summarizes the characteristic parameters of different energy storage technologies; these values have been extracted from [1]–[3].

A. Batteries

1) Lead Acid: The use of lead acid batteries for energy storage dates back to mid-1800s. Lead acid battery cell consists of spongy lead as the negative active material, lead dioxide as the positive active material, immersed in diluted sulfuric acid electrolyte, and lead as the current collector.

During discharge, lead sulfate is the product on both electrodes. If the batteries are overdischarged or kept at a discharged state, the sulfate crystals become larger and are more difficult to break up during recharge. In addition, the large lead sulfite crystals disjoin the active material from the collector plates. Due to the production of hydrogen at the positive electrode, lead acid batteries suffer from water loss during overcharge.

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TABLE I
ENERGY STORAGE SYSTEMS

Type	Energy Efficiency $(\%)$	Energy Density (Wh/kg)	Power Density (W/kg)	Cycle Life (cycles)	Self Discharge
Pb-Acid	70–80	20–35	25	200–2000	Low
Ni-Cd	60–90	40–60	140–180	500–2000	Low
Ni-MH	50–80	60–80	220	< 3000	High
Li-Ion	70–85	100–200	360	500–2000	Med
Li-polymer	70	200	250–1000	> 1200	Med
NaS	70	120	120	2000	–
VRB	80	25	80–150	> 16000	Negligible
EDLC	95	< 50	4000	> 50000	Very high
Pumped hydro	65–80	0.3	–	$>$ 20 years	Negligible
CAES	40–50	10–30	–	$>$ 20 years	–
Flywheel (steel)	95	5–30	1000	> 20000	Very high
Flywheel (composite)	95	> 50	5000	> 20000	Very high

Distilled water is sometimes added to flooded lead acid batteries to mitigate this problem. Maintenance-free versions use a valve to minimize the water loss by allowing hydrogen and oxygen recombination. Current collectors in lead acid batteries are made of lead, leading to the low energy density (in watt–hours per kilogram). In addition, the lead is prone to corrosion when exposed to the sulfuric acid electrolyte.

Lead acid batteries are still prevalent in cost-sensitive applications where the low energy density and limited cycle life are not an issue and where ruggedness and abuse tolerance are required [4], [5]. Such applications include automotive starting, lighting, and ignition (SLI) and battery-powered uninterruptible power supplies (UPSs). SLI applications make use of flat plate grid designs as current collectors, while more advanced batteries use tubular designs. Recent advances aim to replace lead with lighter materials such as carbon to increase power and energy density.

2) Li-Ion: In lithium-ion (Li-ion) batteries, the lithium ions move between the anode and cathode to produce a current flow [6].

The main advantages of this battery technology are high energy-to-weight ratios, no memory effect, and a low self-discharge. Main applications include portable equipment, laptops, cameras, mobile telephones, and portable tools. Due to its high energy density, Li-ion is proving to be the most promising battery technology for plug-in hybrid and electric vehicle (EV) applications. However, the price of Li-ion batteries is still high for many applications. The price issue may become more contentious given the limited lithium resources. Although there is an ongoing debate regarding the available worldwide lithium reserves, its widespread use for vehicle batteries will gradually deplete the known resources, leading to increasing raw material costs [7], [8].

The technical characteristics of the basic cell, its density and voltage, depend on the chemistry used. The specific energy density is about 200 W · h/kg, double the energy density of nickel metal hydride or nickel–cadmium batteries.

The cell of this battery can be operated with higher current level than other cells, but some problems have to be solved. The internal resistance can produce internal heat-up and failure. Therefore, to ensure safe operation, it is mandatory to use a battery management system to at least provide overvoltage, undervoltage, overtemperature, and overcurrent protection. In addition, more advanced systems provide cell voltage balancing that ensures that all batteries operate at the same voltage and, therefore, state of charge [9]–[11].

3) NiCd/NiMH*:* NiCd batteries were the chemistry of choice for a wide range of high-performance applications between 1970 and 1990. Recently, they have been replaced by Li-ion and NiMH chemistries in many applications. The NiCd battery uses nickel oxyhydroxide for the positive electrode and metallic cadmium for the negative electrode.

NiCd batteries have a higher energy density and longer cycle life than lead acid batteries but are inferior to chemistries such as Li-ion and NiMH. Other disadvantages of NiCd batteries compared to NiMH include the following: 1) shorter life cycle; 2) more pronounced "memory effect;" 3) toxicity of Cd that requires a complex recycling procedure; 4) lower energy density; and 5) flat discharge curve and negative temperature coefficient that may cause thermal runaway in voltage-controlled charging.

For the reasons mentioned earlier, nickel metal hydride batteries have gained prominence over NiCd batteries in the recent past. NiMH batteries use nickel oxyhydroxide for the positive electrode and metallic cadmium for the negative electrode.

NiMH batteries have been the chemistry of choice for EV and hybrid EV (HEV) applications in the 1990s and 2000s, respectively, due to their relatively high power density, proven safety, good abuse tolerance, and very long life at a partial state of charge [4], [5]. One of the disadvantages of NiMH chemistry is the relatively high self-discharge rate, although the introduction of novel separators has mitigated this problem.

When overcharged, NiMH batteries use excess energy to split and recombine water. Therefore, the batteries are maintenance free. However, if the batteries are charged at an excessively high charge rate, hydrogen buildup can cause cell rupture. If the battery is overdischarged, the cell can be reverse-polarized, leading to capacity reduction.

4) NaS*:* Sodium sulfur batteries consist of molten sulfur at the positive electrode and molten sodium at the negative electrode separated by a solid beta alumina ceramic electrolyte.

The electrolyte allows only the positive sodium ions to go through it and combine with the sulfur to form sodium

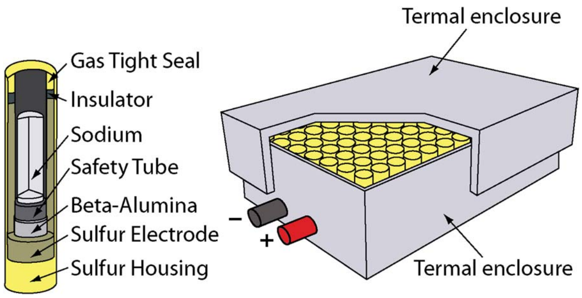


Fig. 1. NaS battery cell and package.

polysulfides. During discharge, positive sodium ions flow through the electrolyte. The battery operating temperature is in the range of 300 °C–360 °C. Therefore, NaS batteries need to be heated externally for optimal operation.

NaS batteries exhibit high power and energy density (over four times that of the lead acid battery), high Coulombic efficiency, good temperature stability, long cycle life, low cost, and good safety [12]–[14]. The batteries are made of abundant and low-cost materials, making them suitable for high-volume mass production. Great achievements have been made during the last two decades, particularly under the collaboration of Tokyo Electric Power Company (TEPCO) and NGK Insulator, Ltd., (NGK). A NaS cell design developed by NGK is shown in Fig. 1, [15]. These batteries can be used for load leveling, emergency power supply, or UPS applications, being suitable to a number of markets, including industrial applications, commercial owners, and wind power generating systems. For example, they are used in a substation update demonstration project at Charleston, VA, by American Electric Power [16]. The batteries generate up to 1.2 MW of power for up to 7 h, easing the strain on an overloaded substation.

5) FBs: Flow batteries (FBs) are a promising technology that decouples the total stored energy from the rated power. The rated power depends on the reactor size, while the stored capacity depends on the auxiliary tank volume. These characteristics make the FB suitable for providing large amounts of power and energy required by electrical utilities. FBs work in a similar way as hydrogen fuel cells (FCs), as they consume two electrolytes that are stored in different tanks (no self-discharge), and there is a microporous membrane that separates both electrolytes but allows selected ions to cross through, creating an electrical current. There are many potential electrochemical reactions, usually called reduction-oxidation reaction or REDOX, but only a few of them seem to be useful in practice. The main technologies that are used currently are summarized in Table II, [17]–[22].

Fig. 2 shows a schematic of an FB. The power rating is defined by the flow reactants and the area of the membranes, while the electrolyte tank capacity defines the total stored energy. Note that, in a classical battery, the electrolyte is stored in the cell itself, so there is a strong coupling between the power and energy rating. In the cell (flow reactor), a reversible electrochemical reaction takes place, producing (or consuming) electric dc current. At this time, several large- and small-scale demonstration and commercial products utilize the FB technology.

TABLE II
FB CHARACTERISTICS

Technology	Potential	Efficiency
Zinc Bromide (ZnBr), [17]	1.8	70 %
Vanadium Redox (VRB), [18], [19]	1.2 – 1.6	80 %
Polysulphide Bromide (PSB), [20], [21]	1.5	
Zinc-Air, [22]	1.6	50 %

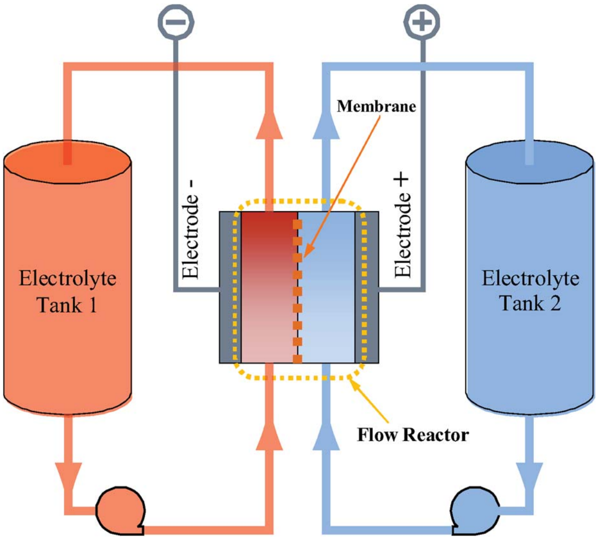


Fig. 2. FB cell.

The main advantages of the technology include the following: 1) high power and energy capacity; 2) fast recharge by replacing exhaust electrolyte; 3) long life enabled by easy electrolyte replacement; 4) full discharge capability; 5) use of nontoxic materials; and 6) low-temperature operation. The main disadvantage of the system is the need for moving mechanical parts such as pumping systems that make system miniaturization difficult. Therefore, the commercial uptake to date has been limited.

B. EDLCs

Electrochemical double-layer capacitors (EDLCs) work in much the same way as conventional capacitors in that there is no ionic or electronic transfer resulting in a chemical reaction (there is no Faradic process) [23], [24]. In other words, energy is stored in the electrochemical capacitor by simple charge separation. Therefore, the energy stored in the electrochemical capacitor can be calculated using the same well-known equation that is used for conventional capacitors

$$Q = CV = \frac{A\varepsilon}{d}V. \qquad (1)$$

As for the conventional capacitor, the capacitance C is proportional to the area A of the plates and the permitivity of the dielectric ε and is inversely proportional to the distance d between the plates. EDLCs are designed to have a very high electrode surface area and use high-permitivity dielectric. The electrode surface area is maximized by using porous carbon as the current collector, allowing a relatively large amount of energy to be stored at the collector surface. Therefore, EDLCs attain very high capacitance ratings (kilofarads versus milli- and microfarads for conventional capacitors). The two electrodes are separated by a very thin porous separator and immersed in an electrolyte such as propylene carbonate. Due to the high permeability and close proximity of the electrodes, EDLCs have a low-voltage-withstand capability (typically 2–3 V).

EDLCs store energy by physically separating unlike charges. This has profound implications on cycle life, efficiency, energy, and power density. EDLCs have a long cycle life due to the fact that (ideally) there are no chemical changes on the electrodes in normal operation. EDLCs have superior efficiency: It is only a function of the ohmic resistance of the conducting path. EDLCs also provide exceptional power density, since the charges are physically stored on the electrodes. Conversely, energy density is low since the electrons are not bound by chemical reactions. This lack of chemical bonding also implies that the EDLCs can be completely discharged, leading to larger voltage swings as a function of the state of charge.

C. Regenerative FCs

FCs are electrochemical conversion devices that consume hydrogen and oxygen to produce water and electricity. FCs are a critical component of the proposed "hydrogen economy," a concept wherein hydrogen would be produced by some process, for instance, electrolysis of water, and then used as fuel [25]. Regenerative FCs or unitized regenerative FCs are devices that combine the function of the FC and the electrolyser into one device. The hydrogen is stored as gaseous fuel for future use to generate electricity. In principle, all FCs can work as regenerative FCs, but they are typically optimized to perform only one function. Combining the two functions reduces the system size for applications that require both energy storage (production of hydrogen) and energy production (production of electricity).

Current research aims to use polymer electrolyte membrane FCs with hydrogen or methanol as the main fuel. The issue is to design a system that is efficient in both hydrogen and electricity productions; current FC designs are less efficient in hydrogen production than other methods such as conventional electrolysis [1]. Unitized FCs have been proposed for aerospace applications that are not cost sensitive and require the highest possible energy density.

Like conventional FCs, regenerative FCs experience life degradation in dynamic applications. Therefore, these devices are often coupled with EDLCs or other ESSs to smooth the changes that the regenerative FCs suffer.

D. CAES

Compressed air energy storage (CAES) is a technology that stores energy as compressed air for later use. Energy is extracted using a standard gas turbine, where the air compression stage of the turbine is replaced by the CAES, thus eliminating the use of natural gas fuel for air compression. System design is complicated by the fact that air compression and expansion are exothermic and endothermic processes, respectively. With this in mind, three types of systems are considered to manage the heat exchange.

1) Isothermal storage, which compresses the air slowly, thus allowing the temperature to equalize with the surroundings [26]. Such a system works well for small systems where power density is not paramount.
2) Adiabatic systems, which store the released heat during compression and feed it back into the system during air release. Such a system needs a heat-storing device, complicating the system design.
3) Diabatic storage systems, which use external power sources to heat or cool the air to maintain a constant system temperature. Most commercially implemented systems are of this kind due to high power density and great system flexibility, albeit at the expense of cost and efficiency.

CAESs have been considered for numerous applications, most notably for electric grid support for load leveling applications [26]–[28]. In such systems, energy is stored during periods of low demand and then converted back to electricity when the electricity demand is high. Commercial systems use natural caverns as air reservoirs in order to store large amounts of energy; installed commercial system capacity ranges from 35 to 300 MW.

E. Flywheel

Flywheel ESSs (FESSs) store energy in a rotatory mass. This concept has been utilized for some time to stabilize the output voltage in synchronous generators. Recent advances in power electronics and material engineering have made this technology attractive for a number of other applications such as transportation and power quality improvement [29].

Flywheel systems are characterized by being able to provide very high peak power. In fact, the input/output peak power is limited only by the power converter. FESSs have high power and energy density and virtually infinite number of charge–discharge cycles. Therefore, they are typically employed in transportation and power quality applications that require a large number of charge–discharge cycles [30], [31]. In addition, FESSs enable relatively simple state monitoring, as "state of charge" is a function of readily measurable parameters such as flywheel inertia and speed [32].

Fig. 3(a) shows the different parts of a FESS, designed with a separate motor and generator. However, the typical FESS has only one machine that serves as a motor/generator unit as shown in Fig. 3(b).

The key factor that determines the technology used to build each component is the maximum rotational speed of the flywheel. Depending on this speed, the FESS can be classified as low- and high-speed FESSs [33]–[38]. The border between the two systems is around 10 000 r/min. The rotational speed not only determines the material, geometry, and length of the flywheel but also the type of electrical machine and the type of bearing [39], [40]. Due to the technological requirements, the high-speed systems are more complex, but as the total energy stored in the flywheel depends on the square of the rotational speed, high-speed flywheels provide higher energy density.

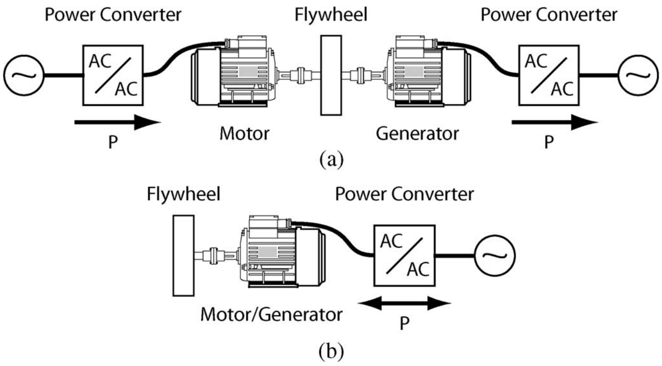


Fig. 3. Different parts of a FESS. (a) General scheme with two machines. (b) Typical construction with only one machine.

Other design considerations include performance, safety, and reliability of the system [41]–[43].

F. SMES

Superconductive magnetic energy storage (SMES) consists of storing energy in the magnetic field created by a direct current flowing through a superconducting coil. The coil is cryogenically cooled to a temperature below its superconducting critical temperature. The first SMES system was proposed in [44]. The construction can be a solenoid or a group of two or more solenoids in order to cancel the magnetic field around them.

SMES provides one of the highest densities of any power storage method. Its main advantage is high storage efficiency, above 90% (not including the refrigeration system, which requires approximately 1.5 kW continuously per megawatt–hour of storage capacity) [45]. An additional advantage is the high dynamic response that permits response time in the range of milliseconds.

G. TEES

Thermoelectric energy storage (TEES) for solar thermal power plants consists of a synthetic oil or molten salt that stores energy in the form of heat collected by solar thermal power plants to enable smooth power output during daytime cloudy periods and to extend power production for 1–10 h after sunset [46]. End-use TEES stores electricity from off-peak periods through the use of hot or cold storage in underground aquifers, water or ice tanks, or other storage materials and uses this stored energy to reduce the electricity consumption of building heating or air conditioning systems during times of peak demand.

III. HYBRID ESSs

Certain applications require a combination of energy, power density, cost, and life cycle specifications that cannot be met by a single energy storage device.

To implement such applications, hybrid energy storage devices (HESDs) have been proposed. HESDs electronically combine the power output of two or more devices with complementary characteristics. HESDs all share a common trait, combining high-power devices (devices with quick response) and high-energy devices (devices with slow response).

Proposed HESDs are listed next, with the energy-supplying device listed first, followed by the power-supplying device:

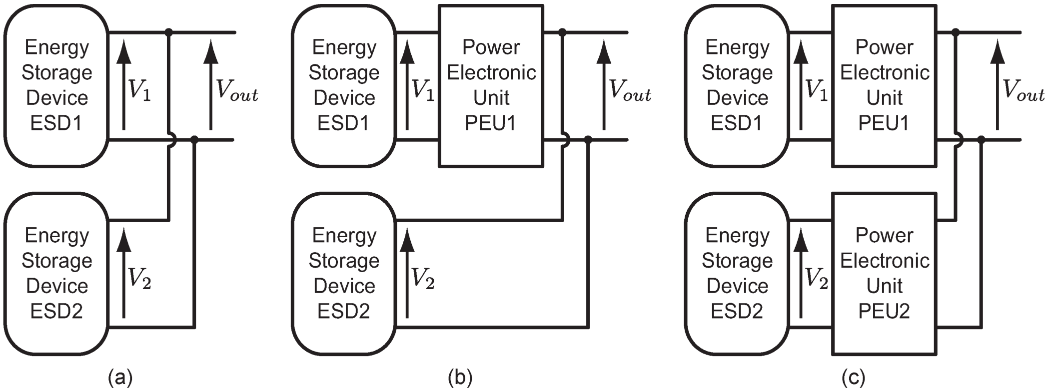
1) battery and EDLC [47]–[53];
2) FC and battery or EDLC [54]–[56];
3) CAES and battery or EDLC [26];
4) battery and flywheel [57];
5) battery and SMES [58].

For HESD applications, batteries can serve as either the energy or power-supplying device, as shown in the list earlier. Also note that the studies in [54]–[56] consider FCs rather than regenerative FCs. However, the system operation principle would be identical for the regenerative FC, with the difference that the FC would be bidirectional. However, HESDs have been proposed for utilization as an energy source for propulsion applications [47]–[52] or grid support [26], [54]–[56], [58], [59].

In order to combine two or more energy storage devices acting as a single power source, more complex conditioning circuitry is required. Numerous topologies have been proposed to achieve this task ranging from simple to very flexible. In general, the proposed topologies can be grouped into three categories as shown in Fig. 4. A discussion of the merits of each topology and typical uses follows.

Fig. 4(a) shows direct parallel connection of two energy storage devices. This topology requires that the voltage outputs of the two power sources match $(V_1 = V_2)$. Direct parallel connection of batteries and EDLC has been proposed [51]–[53] for low-voltage cost-sensitive applications, such as the automotive 42-V PowerNet system [52]. This system consists of a high power pulse (engine cranking) followed by a constant low power demand over a longer time period (while the vehicle is in operation). A direct parallel connection of batteries and EDLC makes use of the source impedance mismatch, causing the low-impedance ultracapacitor to provide power during high power pulses, while the high-energy battery supplies the long-term lower power demand. The output voltage (V_{out}) varies as the system charges and discharges. The range of power that is used from either energy source is limited by the voltage swing of the other. In other words, individual maximum power point tracking is not possible for each source.

A more complex but flexible solution is to place an additional converter between the two power sources as shown in Fig. 4(b). PEU1 controls the current output of ESD1, allowing its voltage to vary, while ESD2 supplies the remaining power requirement to the load. Therefore, this system allows for the decoupling of the two power sources. Typically, the energy storage device with larger voltage fluctuation is utilized as ESD1. Another criterion may be to put the more sensitive device in place of ESD1 to prolong the life of the system by conditioning the current output of ESD1. Systems that make use of this topology include battery and EDLC [49], [50]; FC and battery or EDLC [55], [56]; and SMES and battery [57]. The commonly used topology for combining the two systems is the single-leg (two switches in series) converter which can act as a boost in the forward and as a buck in the reverse operation mode [50], [55]. In [49], the authors propose to use a variation of this



(a) (b) (c)

Fig. 4. Topologies for HESDs.

system, where the battery and EDLC are connected to the load one at a time, allowing the system controller to choose which source should power the load. Source switching results in step changes of the bus voltage, requiring an appropriate flexible modulation strategy. In [56], the authors propose the use of an isolated topology to allow for a larger voltage gain between the input and output. In [57], the SMES device is connected to the middle points of two converter legs, allowing SMES to charge or discharge. The battery is connected to the bus to make use of the relatively invariant battery voltage.

In [26], [48], [54], and [59]–[61], researchers have looked at using the topology shown in Fig. 4(c), where each power source is connected to a dedicated power converter with the converters connected to the common output bus. Such a system provides the highest level of flexibility, since each power source is allowed to operate at its optimal conditions—in essence, maximum power point tracking can be implemented for each source. Having dedicated converters for each power source allows a wide range of topologies and control strategies to be implemented. The simplest topology that allows an acceptable degree of flexibility is to use the single-leg (two switches in series) converter which can act as a boost in the forward and as a buck in the reverse operation mode [59]–[61]. Other topologies have been proposed that introduce a transformer either for isolation or to allow efficient voltage boosting. An overview of the proposed topologies is presented in [59].

IV. APPLICATIONS OF ESSs

ESSs can improve the performance of several applications. They are particularly suitable for transport and utility-scale applications and, in some cases, are the key factor that will determine the adoption of a technology, for example, EVs. Fig. 5 shows the time versus power operational range of the different energy storage technologies. The figure also shows the suitability of various ESSs for both transport and utility applications. In the case of transport applications, time and power ranges are from seconds to hundred of minutes and from tens of kilowatts to tens of megawatts, while in the case of utility-scale applications, time and power ranges are from tens of minutes to hours and from megawatts to gigawatts.

For utility or renewable energy integration, energy storage capacity, power output, and life cycle are key performance criteria. The need for long life cycle has motivated the use of storage systems from reversible physics such as CAES or pumped hydro as an alternative to electrochemical batteries that present problems of ageing and are difficult to recycle. In transportation applications, portability, scalability, and energy and power density are key performance criteria. Therefore, due to their modularity and portability, and in spite of the numerous issues, including limited life, batteries are still considered the most viable option for transport applications. In the following sections, transport and utility applications are discussed in more detail.

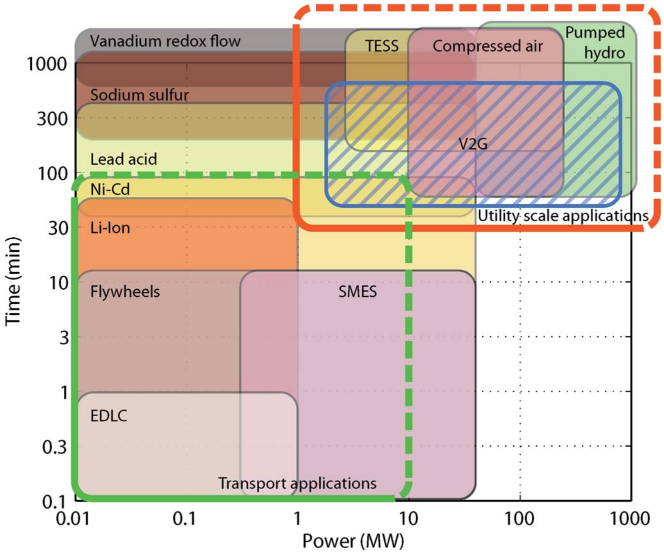


Fig. 5. Storage technology.

A. Transport Applications

1) Road Transport: Due to environmental, geopolitical, and economical concerns, recently, there has been a push to diversify the energy supply for road vehicles. This push has promoted alternatives to the internal combustion engine (ICE), such as FC vehicles (FCVs), HEVs, plug-in HEVs (PHEVs), and battery EVs (BEVs). All these alternatives have in common that ICE is replaced or augmented by electric propulsion. In the case of FCV, onboard FCs consume hydrogen to produce electricity and power the electric motor. The FCV concept

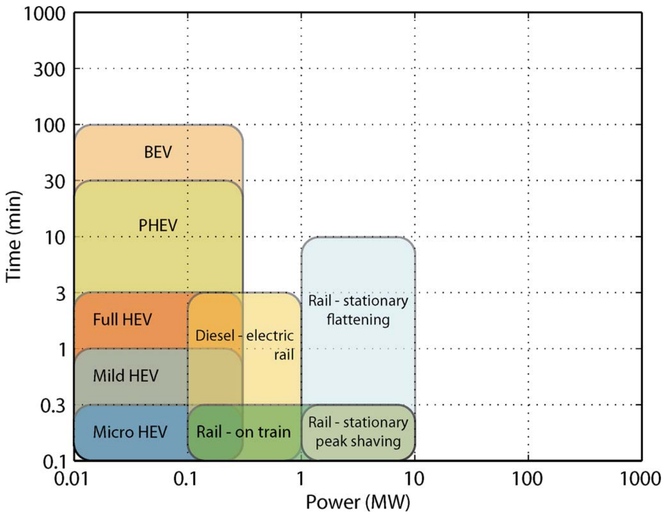


Fig. 6. Transport applications.

is considered as an integral part of the proposed "hydrogen economy" [25]. HEV and PHEV combine the ICE and electric propulsion to propel the vehicle. PHEV provides the option of recharging the onboard energy storage from the power grid. Finally, BEV uses battery energy storage as the only energy source on the vehicle.

Fig. 6 shows the power magnitude and duration requirements for various road transport applications. The plot shows that the energy requirements from the storage system increase from HEV to PHEV to EV. HEVs can be further differentiated by the size of their electric system as will be discussed later in the text. FCV energy storage requirements are similar to that of a HEV. The remainder of this section will look at these vehicles and their energy storage requirements in more detail.

FCVs make use of FCs that convert hydrogen and oxygen into electricity and steam. These vehicles are considered as environmentally benign since hydrogen can be produced using electrolysis—a process that could be powered by RESs. However, even with substantial government and private sector investment to commercialize the technology, no FCV is commercially available. Some of the long-standing technological issues include relatively low energy density of hydrogen (even in the liquid form) compared to petroleum, nonexistent refueling infrastructure, cost and life of the FC, and the detrimental effect of vehicle power profile on the life of the FC [62], [63]. To address the last issue, researchers propose to hybridize the FC with a battery [63], [64], EDLC [64], [65], or a battery/EDLC hybrid [64]–[66]. In such vehicles, the FC would provide the average power demand, while the battery or EDLC would provide peak power.

HEV and PHEV use both ICE and an electric motor to propel the vehicle. The ICE provides the average power, while the electric motor meets the peak power demand. HEV gains efficiency by employing a smaller ICE operating at higher load where the engine is more efficient. The peak power demand is then augmented by the electric motor powered by electric energy storage. The electric energy storage is replenished via regeneration of kinetic energy during braking or by the ICE during low vehicle power demands. Choice of electric energy storage depends on the hybridization factor (HF): relative power of the electric subsystem as a fraction of the total system power [24], [67]. Therefore, an HF of 0 represents a conventional ICE-powered vehicle, while a HF of 1 represents a BEV. This definition allows for the classification of micro-HEV, mild HEV, full HEV, PHEV, and BEV listed in order of increasing HF. Fig. 6 shows that the energy requirements from the battery increase with the HF. With the improvement in the capabilities of electric energy storage devices, the auto industry has been moving to higher levels of hybridization. Currently, full HEVs such as Toyota Prius and Ford Escape hybrid are common. PHEV and BEV are already available from a number of smaller innovative vehicle manufacturers such as Tesla and Aptera; larger automakers such as Nissan and GM plan to sell the GM Volt PHEV and Nissan Leaf EV in the coming year. In the following paragraphs, we look at the energy storage requirements of micro-HEV, mild HEV, full HEV, PHEV, and BEV.

Micro-HEVs typically use an integrated starter generator technology to allow for automatic engine stop/start, limited propulsion assist, and regenerative braking, resulting in moderate fuel economy improvements in city driving. Advanced lead acid batteries are considered to be sufficient to supply this application [68]–[70].

Mild HEVs are fitted with a more powerful electric propulsion system totaling up to 0.25 HF. They are capable of engine stop/start as well as moving the vehicle at low speeds and capturing more regenerative braking energy. Due to the higher power capabilities of the electrochemical system, the energy throughput in the batteries is much higher than that in micro-HEVs. Therefore, advanced lead acid [69], NiMH, and battery/EDLC hybrids [71] are considered for the mild-HEV application. In [72], the author proposes the use of EDLC as the sole electric power source for a mild hybrid. Examples of vehicles in the mild-HEV category include Honda Civic Hybrid and Toyota Camry Hybrid, all of which use NiMH batteries.

Full HEVs or power-assist HEVs offer substantial electric propulsion assistance and limited electric-only range. Electric drive and battery typically operate at voltages above 200 V. Examples of these vehicles include Toyota Prius or Honda Insight. Both vehicles employ high-power NiMH batteries. The batteries are used in a narrow state of charge range but see peak currents of over ten times the ampere–hour rating. Therefore, full-HEV applications can be served by EDLC alone [72] or by a battery/EDLC hybrid energy source [49], [73]–[75]. A number of researchers have focused on optimizing the battery/EDLC control strategy [74] and have proposed novel power electronics topologies for these applications such as multilevel converters [75] and source swapping [49]. High-power Li-ion batteries are also suitable for full-HEV applications. For larger vehicles such as buses, the flywheel/ICE hybrid energy source has also been considered [29].

PHEV is a full HEV characterized by batteries that can be recharged from the power grid. Compared to HEVs, these vehicles provide a much longer all electric range and, therefore, higher overall fuel economy. Thus, PHEVs are essentially BEVs with an onboard ICE generator. Lithium-ion batteries are considered as the chemistry of choice for this application due to the relatively high energy density and high power capability [70], [72].

BEV solely relies on onboard battery energy storage to propel the vehicle. These vehicles have the advantage of a simpler drivetrain than the HEV. However, the power and energy throughput requirements from the battery pack become substantially more demanding than for HEVs and PHEVs. Therefore, there is a major concern about the life of the batteries in these vehicles. The other issue with these vehicles is the long battery recharge time at the prescribed recharge rates as well as the effect on the power grid and the need for a new charging infrastructure [76], [77]. Lithium-ion batteries are considered for this application due to the relatively high energy density and high power capability [70], [72].

2) Rail Transport: Due to periodic acceleration and deceleration as trains move from station to station, their power consumption is very uneven. Therefore, electrically powered railway systems such as trams, subways, and high-speed magnetic levitation trains can benefit from electric energy storage to smooth out the train power demand. ESSs can be installed either at the substation supplying the train network or on the train itself. In addition, when placed at the substation, ESSs can serve as peak-shaving units or as demand-flattening units. As shown in Fig. 6, these constraints greatly affect the energy storage requirements.

Assuming no energy storage or brake resistors on the train, there will be a large power draw from the substation during vehicle acceleration and a similarly large power surge back to the substation when the vehicle decelerates. Attempts were made to minimize the power spikes and flatten the power curve by coordinating train accelerations and decelerations to offset each other [78]; however, managing train movement is difficult, particularly in urban systems. Therefore, the power that must be supplied by the substation is highly irregular.

Installing an energy storage unit minimizes the substation peak power requirements, which improves efficiency by storing the energy that would otherwise be dissipated in the resistor banks. A number of systems have been proposed to serve as the energy sources at the substation level. Typically, these are high-power-density high cycle sources such as EDLC and SMES [79]–[84]. In [79], researchers propose the use of SMES and FBs to flatten out the power demand curve of a high-speed railway system. The SMES provides the pulse power, while the FB supplies the bulk of the energy to completely flatten out the energy demand. Another common approach uses EDLC to minimize the power surge at the substation and to minimize the use of resistor banks at the substation [80]–[82].

Rather than smoothing out the power profile at the substation, onboard energy systems can smooth out the power demand from the train itself. This approach is typically considered for systems that do not have the ability to feed power back to the supply lines. Such trains must have resistor banks on the train itself to be able to slow down the train. An alternative to the resistive bank is an ESS that will provide power to the vehicle during acceleration and would charge up during deceleration. Since this is a high-power application, EDLC systems are commonly used [84]–[87], although other high-power-density storage devices such as flywheels have been proposed [88].

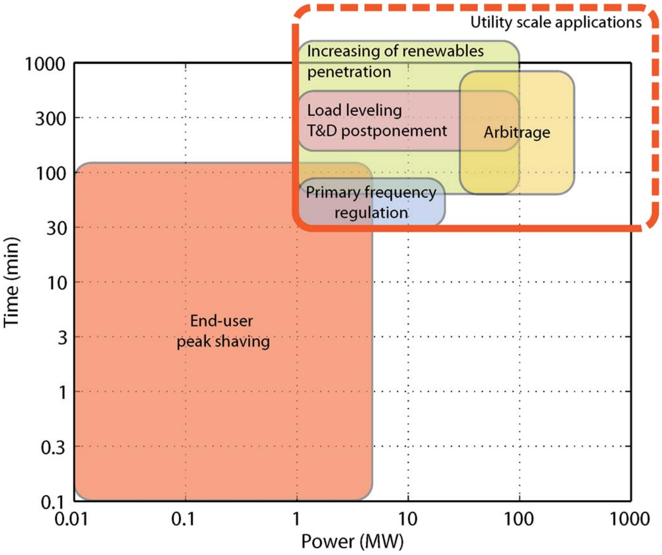


Fig. 7. Utility applications.

Even though most advanced high-speed train systems are electrically powered, there exists a large infrastructure that uses trains powered by diesel generators. To improve the efficiency of these systems, hybridization with energy storage has been proposed. The system operates in a very similar way to the series roadway HEV: A diesel engine supplies the train average demand, while the ESS supplies the peak demand. As shown in Fig. 6, the energy storage requirements for this application are the same as for the HEV in terms of pulse duration; however, these systems are much larger than road vehicles. Proposed systems [91], [92] combine diesel generators with EDLC [93], lead acid batteries, and flywheels [87], [88]. Finally, in [89] and [90], researchers suggest replacing of the diesel generator with an FC hybridized with EDLC [94] or batteries [95].

B. Utility Applications

ESSs are increasing their impact on the utility grid as a solution to stability problems. The main advantage of a storage plant is to contribute to the quality of the grid by maintaining the power constant [46], [96], [97]. The main role of these ESSs is to increase the RES penetration, to level load curve, to contribute to the frequency control, to upgrade the transmission line capability, to mitigate the voltage fluctuations, and to increase the power quality and reliability. Fig. 7 shows the power magnitude and duration requirements for these applications.

1) Increasing RES Penetration: Although RESs are environmentally beneficial, the intermittent nature of two fast growing energies, wind and solar, causes voltage and frequency fluctuations on the grid. That represents a significant barrier to widespread penetration and replacement of fossil-fuel source base-load generation, because integrating renewable sources introduces some new issues on the operation of the power system, such as potential unbalancing between generation and demand [98].

However, intermittent RESs, such as solar and wind, need to be supported with other conventional utility power plants [99]. It is estimated that, for every 10% wind penetration, a balancing power from other generation sources equivalent to 2%–4% of the installed wind capacity is always required for a stable power system operation. Thus, with more penetration of intermittent renewable energy like wind power, the system operation will be more complex, and it will require additional balancing power. This is critical in countries with a large penetration of solar and wind systems, as Denmark or Spain, where it is estimated that approximately 20% and 10% of the electricity generation come from wind power, respectively. A large storage capacity will allow a high percentage of wind [100], [101], photovoltaic [102], and other power plants in the electrical mix contributing to fulfill the objectives for a more sustainable future. In order to integrate RESs, it is necessary to propose a suitable storage system that offers capacities of several hours and power level from 1 to 100 MW.

Nowadays, high-temperature thermosolar power plants are including a TEES, and it is expected that other storage systems will be included in the new generation of RES and the distributed generation sources in general.

Recently, the concept of vehicle-to-grid (V2G) has been introduced. It describes a system in which electric or plug-in hybrid vehicles communicate with the power grid to sell demand respond services by either delivering electricity into the grid or throttling their charging rate. When coupled to an electricity network, EVs can act as a controllable load and energy storage in power systems with high penetration of RESs. The reliability of the renewable electricity will be enhanced with the vast untapped storage of EV fleets when connected to the grid. In Fig. 5, market area for V2G represents 1 million vehicles with 20–50-kWh capacity, where 10% of this capacity is available for utility applications, including integration of RES. The benefits of energy storage applications in RESs have been deeply studied in the bibliography. In [103], the case of a wind farm placed in Portugal with a 144-MW installed capacity has been evaluated. This particular installation produces more energy in off-peak hours than in peak hours, which is a drawback in terms of the renewable Portuguese tariff. A 5-MW and 30-MW · h capacity ESS has been proposed in order to transfer part of the generation to the peak hours and improve the wind farm economical payback. The resultant average wind farm tariff with storage is 2.1% higher than the original one and represents additional 250 k€ income of the annual wind farm turnover. A target price of 60 €/kWh as the storage device purchase cost will allow a payback time of seven years of this system.

2) Load Leveling: Load leveling refers to the use of electricity stored during times of low demand to supply peak electricity demand, which reduces the need to draw on electricity from peaking power plants or increase the grid infrastructure. This application is shown in Fig. 8. $P_{\max}$ is the maximum power that can be delivered to the load by the electrical grid through the existing transmission line. To deliver more power to the load, there are two possibilities, increase the infrastructure and the generator capacity or install an ESS. The ESS allows one to postpone a large infrastructure investment in transmission and distribution network. New technologies, which are not restricted by their geographic limitations, have been proposed as more suitable for load leveling such as TEES and BSS [104].

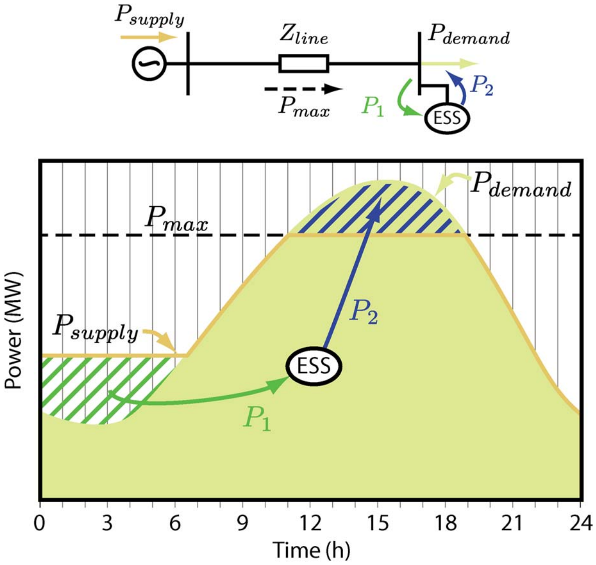


Fig. 8. Basic concept of load leveling through ESS.

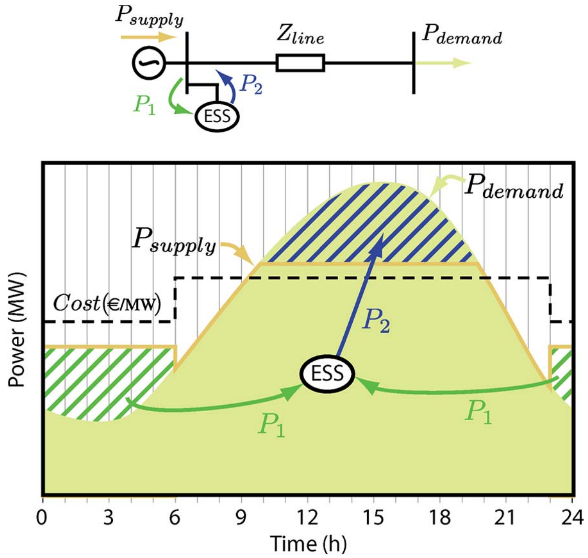


Fig. 9. Basic concept of arbitrage through ESS.

Rechargeable battery technologies like sodium sulfur (NaS) technology are attractive candidates for use in many utility-scale energy storage applications. These advanced battery systems can be utilized with existing infrastructure, helping energy providers to meet peak demands and critical load [105].

3) Energy Arbitrage: Energy arbitrage refers to earning a profit by charging ESS with cheap electricity when the demand is low and selling the stored energy at a higher price when the demand is high, as shown in Fig. 9. This activity can also be used to influence in the demand side, such as using higher peak prices to induce a reduction in peak demand through demand charges, real-time pricing, or other market measures. This function has been traditionally performed by pumped hydro storage (PHS). PHS is appropriate for energy arbitrage because it can be constructed at large capacities over 100-MW range and discharged over periods of time from 100 to 1000 min. These installations allow storage when the demand is low

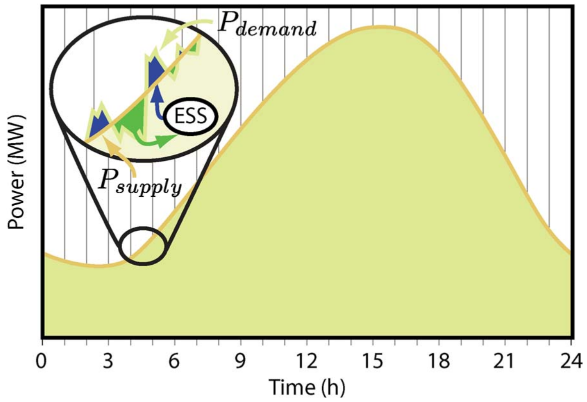
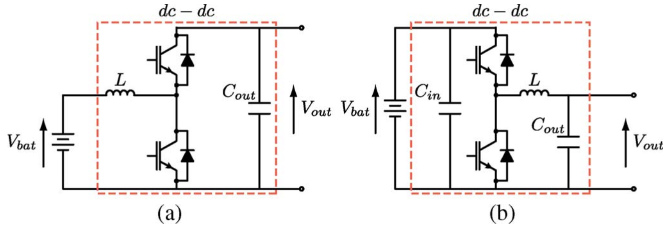


Fig. 10. Basic concept of primary frequency regulation through ESS.



(a) (b)

Fig. 11. Conventional buck–boost dc–dc converter. (a) Battery in the low-voltage side [115]. (b) Battery in the high-voltage side [117].

and the energy is cheap. This ESS is the most widely used energy storage technology at utility scale (100 GW installed worldwide). CAES is also appropriate for energy arbitrage because it can be constructed in capacities of a few hundreds of megawatts and can be discharged over long periods of time.

A new trend for this application is to use the ancillary services that offer the battery of electrical V2G. The large quantity of this V2G expected in a next future could contribute to a new concept of the energy marker [106].

4) Primary Frequency Regulation: This application is shown in Fig. 10. The technical application of ESS includes transient and permanent grid frequency stability support. To contribute to the frequency stabilization during transient, called grid angular stability (GAS) in [107], low- and medium-capacity ESSs are needed. This low-energy-storage requirement is because GAS operation consists of injection and absorption of real power during short periods of time, 1–2 s. This application contributes, for example, to the frequency stability of isolated utilities based on diesel generators [108].

Modern variable-speed wind turbines and large photovoltaic power plants connected to the utility grid do not contribute to the frequency stability as the synchronous generators of the conventional gas or steam turbine do. This creates a new application of ESS that is to be used to emulate the inertia of these steam turbine generators to complement this angular stability deficit [109]. Another solution is to use the power electronic converter of variable-speed wind turbines to emulate the steam turbine inertia using the inertial energy storage of the rotors of these wind turbines [110].

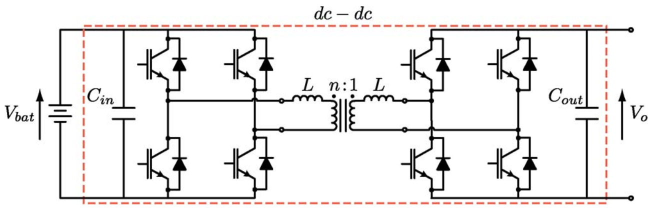


Fig. 12. Isolated dc–dc converter [118].

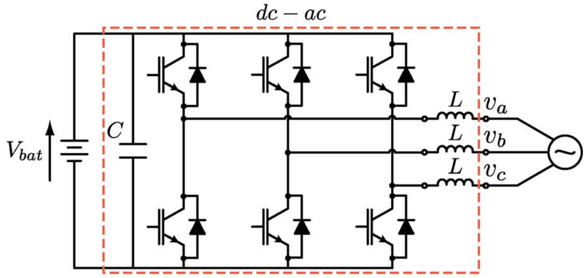


Fig. 13. Conventional ac–dc converter [119], [120].

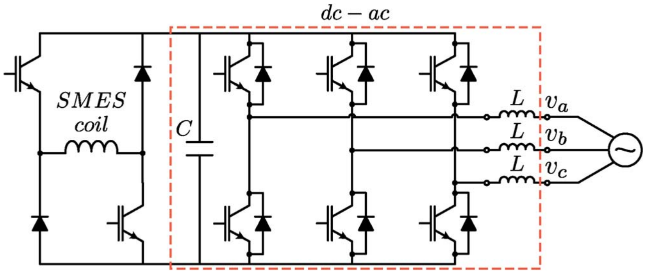


Fig. 14. Power converter to connect an SMES system to the grid [124].

SMESs are getting increasing acceptance in variation applications of damping frequency oscillations [111] because of their higher efficiency and faster response. EDLC, FESS, and BSS are also very suitable for this application.

5) End-User Peak Shaving: There are several undesired grid voltage effects at the end-user level, depending on the duration and variability. Typical voltage effects are long-period interruptions (blackouts), short-period interruptions (voltage sags), voltage peaks, and variable fluctuation (flicker).

To perform peak shaving and prevent against blackouts, the typical approach involves installing UPSs. If an online UPS is installed in series, this isolates the load from the grid, and fluctuations produced by the utility have no effect on the users. However, this solution may not be optimal for all applications. One solution, presented as grid voltage stability in [107], involves mitigating against degraded voltage by providing additional reactive power and injecting real power for durations of up to 2 s. The energy storage needed to protect the load against this voltage degradation is low. The energy storage demanded is even lower in applications with ride-through capability, where the electric load or the generator stays connected during the system disturbance, because part of the energy can be obtained from the grid during the undervoltage period. The voltage flicker is caused by rapid changes of RES and industrial or domestic loads, such as electric arc furnaces, rolling mills, welding equipment, and pumps operating periodically. An ESS can help to reduce voltage fluctuations at the point of common coupling produced by these transitory generators and loads.

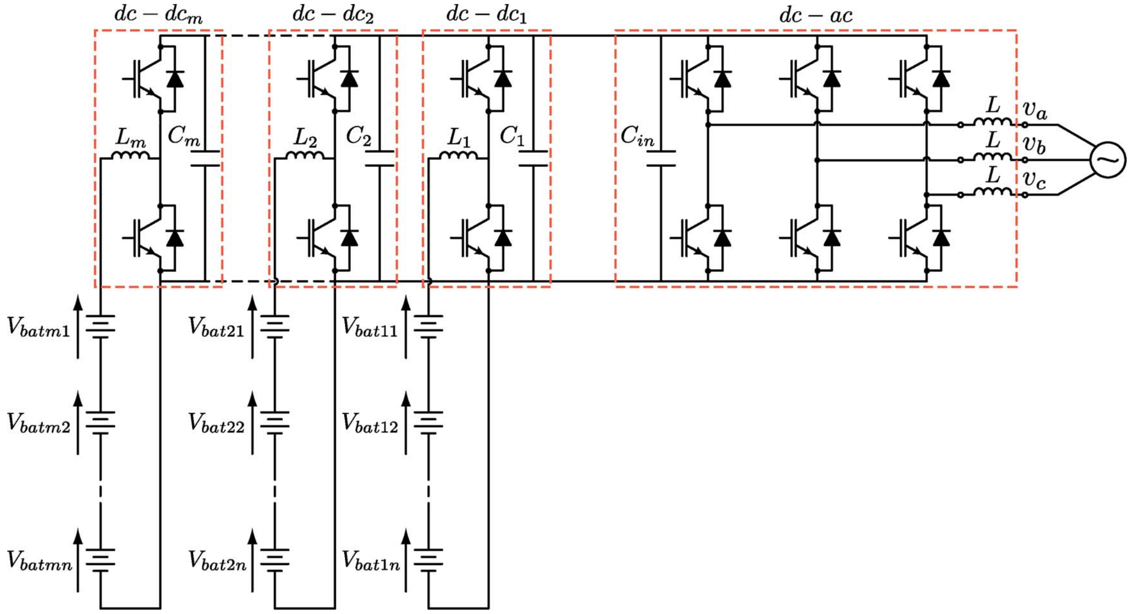


Fig. 15. Connection of several battery modules to the grid [16].

These applications can be supplied by lower energy storage devices such as EDLC [112], [113] and batteries managing the active power plus additional reactive power produced by STATCOM which includes BESS or FESS [35], [114].

V. POWER CONVERTERS FOR ESS

Some energy storage technologies need an additional equipment to adapt their output voltage or current to the required output voltage level or waveform. This is the case of a BESS system connected to the grid, which has to adapt its dc output to the ac voltage level of the grid. Other technologies that have this necessity are EDLC, SMES, FESS, and regenerative FCs.

The device used to perform this task is a power converter. Depending on the storage technology and the application, the power converter has to allow the connection between two different dc voltage level buses, a dc voltage bus and an ac voltage bus, or even connect a current source to a voltage bus. For this reason, the topology used for the power converter depends on both the technology and the application.

In general, power converters applied to ESSs have to present the following features:

1) to manage the energy flow in a bidirectional way, controlling the charging and discharging process of the ESS;
2) to have high efficiency.

Additionally, depending on the application, they have to fulfill the following characteristics:

1) to provide fast response (frequency regulation applications);
2) to have small size and weight (transport applications);
3) to stand high peak power (peak shaving applications);
4) to manage high rated power (load leveling applications).

To connect batteries, EDLCs, or regenerative FCs between two different dc voltage level buses, the most popularly used topology has been the bidirectional boost converter shown in Fig. 11(a). This topology enables connections to a higher voltage bus and can operate properly against voltage fluctuations coming from the ESS [115], [116], for example, the EDLC voltage reduction that halves its voltage to deliver the maximum energy. Another version, the bidirectional buck converter shown in Fig. 11(b), can be suitable for connecting a lower voltage dc bus to these storage technologies [117]. If isolation is needed between the ESS and another stage, a transformer option can be chosen using the bidirectional topology shown in Fig. 12 [118]. This topology is also suitable for high-frequency applications and can be combined with resonant techniques that permit lower size and volume, maintaining a good efficiency.

On the other hand, to connect batteries, EDLCs, or regenerative FCs directly to an ac motor or generator, an inverter has to be used [119], [120]. Fig. 13 shows the case of a BESS connected to the grid through a conventional three-phase two-level converter.

The energy flow in a FESS is controlled by the electrical machine attached to the flywheel. Usually, this machine is a three-phase ac motor/generator unit. To control the torque and the speed of this unit, an actuator is needed, as was shown in Fig. 3(b). In general, the motor drive is set up by two ac–dc power converters connected through a common dc link in a back-to-back fashion [121], [122], although other topologies are possible as presented in [123] where authors use a matrix converter.

The SMES technology presents special conditions because it behaves as a current source. Moreover, the current inside the coil flows permanently in only one direction [124]. Therefore, the power converter used for the SMES conditioning system has to be a special topology. Although other topologies are possible to handle this current, the most suitable form is shown in Fig. 14. Here, an asymmetric H-bridge is used to manage the current coming from the dc link of the three-phase converter unit, because only two switches and two diodes are needed to control the current.

Finally, large power systems can be formed by a combination of the topologies described. For instance, a multimegawatt–hour BESS can be built by several strings, and these strings can be connected in parallel to a common dc bus by step-up dc–dc converters. Then, the dc bus is connected to the ac grid by an inverter. This application is shown in Fig. 15, where conventional dc–dc boost converters and conventional three-phase two-level dc–ac converter have been chosen as the power conditioning system [16]. It should be noticed that, for a large rated power system, the dc–ac converter can be implemented using a multilevel topology which is more suitable to manage high amount of power [125], [126].

VI. CONCLUSION

ESSs are the key enabling technologies for transport and utility applications. In particular, the proliferation of energy storage will enable the integration and dispatch of renewable generation and will facilitate the emergence of smarter grids with less reliance on inefficient peak power plants. In the transportation sector, the emergence of viable onboard electric energy storage devices such as high-power and high-energy lithium ion batteries will enable the widespread adoption of plug-in electric and HEVs which will also interact with the smart grids of the future. Mature storage technologies can be used in several applications, but in other situations, these technologies cannot fulfill with the application requirements. Thus, new storage systems have appeared, opening new challenges that have to be solved by the research community. Transport and utility applications operate with a wide range of time versus power storage requirements. The benefits obtained in transport and utility go from technical aspects to economic objectives. For instance, a reduction of CO_2 emissions can be achieved by the use of EVs or increase of profits can be obtained with a load leveling application in a power transmission line. Anyway, the continuous development of the storage technologies and the evolution of their applications will motivate further research to solve the existing issues and improve the ESSs.

REFERENCES

[1] B. Sorensen, *Renewable Energy,* 3rd ed. New York: Academic, 2004.

[2] B. R. Williams and T. Hennessy, "Energy oasis [vanadium redox battery system in power distribution application]," *Power Eng.*, vol. 19, no. 1, pp. 28–31, Feb./Mar. 2005.

[3] D. Y. Goswami and F. Kreith, *Energy Conversion,* 1st ed. Boca Raton, FL: CRC Press, 2007.

[4] J. Larminie and J. Lowry, *Electric Vehicle Technology Explained,* 1st ed. New York: Wiley, 2003.

[5] J. M. Miller, *Propulsion Systems for Hybrid Vehicles*. Stevenage, U.K.: Inst. Eng. Technol., Dec. 2003, ser. IEE Power & Energy Series.

[6] G. A. Abbas Nazri and G. Pistoia, *Lithium Batteries: Science and Technology (Paperback)*. Berlin, Germany: Springer-Verlag, 2009.

[7] W. Tahil, *The Trouble With Lithium-Implications of Future PHEV Production for Lithium Demand*. Martainville, France: Meridian Int. Res., Jan. 2007.

[8] I. Råde and B. A. Andersson, "Requirement for metals of electric vehicle batteries," *J. Power Sources*, vol. 93, no. 1, pp. 55–71, Feb. 2001.

[9] J. McDowall, P. Biensan, and M. Broussely, "Industrial lithium ion battery safety—What are the tradeoffs?" in *Proc. IEEE 29th Int. Telecommun. Energy Conf.*, Rome, Italy, Sep. 6–Oct. 4, 2007, pp. 701–707.

[10] F. Rufus, L. Seungkoo, and A. Thakker, "Health monitoring algorithms for space application batteries," in *Proc. IEEE Int. Conf. Prognostics Health Manage.*, Denver, CO, Oct. 6–9, 2008, pp. 1–8.

[11] T. L. Chern and P. L. Pan, "The research of smart li-ion battery management system," in *Proc. 2nd IEEE Conf. Ind. Electron. Appl.*, Harbin, China, May 23–25, 2007, pp. 2273–2277.

[12] W. Zhaoyin, "Study on energy storage technology of sodium sulfur battery and it's application in power system," in *Proc. Int. Conf. PowerCon*, Chongqing, China, Oct. 22–26, 2006, pp. 1–4.

[13] Y. Bo, Y. Makarov, J. Desteese, V. Viswanathan, P. Nyeng, B. McManus, and J. Pease, "On the use of energy storage technologies for regulation services in electric power systems with significant penetration of wind energy," in *Proc. 5th Int. Conf. EEM*, Lisbon, Portugal, May 28–30, 2008, pp. 1–6.

[14] W. C. Lee, M. F. M. Siam, A. B. Ismail, and Z. F. Hussien, "Modeling and simulation of sodium sulfur battery for battery-energy storage system and custom power devices," in *Proc. Nat. Power Energy Conf. PECon*, Kuala Lumpur, Malaysia, Nov. 29–30, 2004, pp. 205–210.

[15] A. Bito, "Overview of the sodium-sulfur battery for the IEEE stationary battery committee," in *Proc. IEEE Power Eng. Soc. Gen. Meet.*, San Francisco, CA, Jun. 12–16, 2005, vol. 2, pp. 1232–1235.

[16] K. Mattern, A. Ellis, S. E. Williams, C. Edwards, A. Nourai, and D. Porter, "Application of inverter-based systems for peak shaving and reactive power management," in *Proc. IEEE/PES Transmiss. Distrib. Conf. Expo.*, Chicago, IL, Apr. 21–24, 2008, pp. 1–4.

[17] E. Manla, A. Nasiri, C. H. Rentel, and M. Hughes, "Modeling of zinc bromide energy storage for vehicular applications," *IEEE Trans. Ind. Electron.*, vol. 57, no. 2, pp. 624–632, Feb. 2010.

[18] M. Skyllas-Kazacos and C. Menictas, "The vanadium redox battery for emergency back-up applications," in *Proc. INTELEC*, Melbourne, Australia, Oct. 16–23, 1997, pp. 463–471.

[19] C. Blanc and A. Rufer, "Multiphysics and energetic modeling of a vanadium redox flow battery," in *Proc. IEEE ICSET*, Singapore, Nov. 24–27, 2008, pp. 696–701.

[20] D. P. Scamman, G. W. Reade, and E. P. L. Roberts, "Numerical modelling of a bromide-polysulphide redox flow battery. Part 1: Modelling approach and validation for a pilot-scale system," *J. Power Sources*, vol. 189, no. 2, pp. 1220–1230, Apr. 2009.

[21] D. P. Scamman, G. W. Reade, and E. P. L. Roberts, "Numerical modelling of a bromide-polysulphide redox flow battery. Part 2: Evaluation of a utility-scale system," *J. Power Sources*, vol. 189, no. 2, pp. 1231–1239, Apr. 2009.

[22] P. Sapkota and H. Kim, "Zinc–air fuel cell, a potential candidate for alternative energy," *J. Ind. Eng. Chem.*, vol. 15, no. 4, pp. 445–450, Jul. 2009.

[23] P. F. Ribeiro, B. K. Johnson, M. L. Crow, A. Arsoy, and Y. Liu, "Energy storage systems for advanced power applications," *Proc. IEEE*, vol. 89, no. 12, pp. 1744–1756, Dec. 2001.

[24] S. M. Lukic, C. Jian, R. C. Bansal, F. Rodriguez, and A. Emadi, "Energy storage systems for automotive applications," *IEEE Trans. Ind. Electron.*, vol. 55, no. 6, pp. 2258–2267, Jun. 2008.

[25] U. Bossel, "Does a hydrogen economy make sense?" *Proc. IEEE*, vol. 94, no. 10, pp. 1826–1837, Oct. 2006.

[26] S. Lemofouet and A. Rufer, "A hybrid energy storage system based on compressed air and supercapacitors with maximum efficiency point tracking (MEPT)," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1105–1115, Jun. 2006.

[27] S. Lee, Y. Kim, J. Park, S. Moon, and Y. Yoon, "Compressed air energy storage units for power generation and DSM in Korea," in *Proc. IEEE Power Eng. Soc. Gen. Meet.*, Tampa, FL, Jun. 24–28, 2007, pp. 1–6.

[28] D. J. Swider, "Compressed air energy storage in an electricity system with significant wind power generation," *IEEE Trans. Energy Convers.*, vol. 22, no. 1, pp. 95–102, Mar. 2007.

[29] R. Hebner, J. Beno, and A. Walls, "Flywheel batteries come around again," *IEEE Spectr.*, vol. 39, no. 4, pp. 46–51, Apr. 2002.

[30] R. G. Lawrence, K. L. Craven, and G. D. Nichols, "Flywheel UPS," *IEEE Ind. Appl. Mag.*, vol. 9, no. 3, pp. 44–50, May/Jun. 2003.

[31] M. M. Flynn, P. Mcmullen, and O. Solis, "Saving energy using flywheels," *IEEE Ind. Appl. Mag.*, vol. 14, no. 6, pp. 69–76, Nov./Dec. 2008.

[32] EUR 19978 Brochure, Energy Storage A Key Technology for Decentralized Power, Power Quality and Clean Transport, Office for Official Publications of the European Communities, Luxembourg, Geramany, 2001. [Online]. Available: www.cordis.lu/eesd/src/lib_misc.htm

[33] R. S. Weissbach, G. G. Karady, and R. G. Farmer, "A combined uninterruptible power supply and dynamic voltage compensator using a flywheel energy storage system," *IEEE Trans. Power Del.*, vol. 16, no. 2, pp. 265–270, Apr. 2001.

[34] H. Akagi and H. Sato, "Control and performance of a doubly-fed induction machine intended for a flywheel energy storage system," *IEEE Trans. Power Electron.*, vol. 17, no. 1, pp. 109–116, Jan. 2002.

[35] S. Samineni, B. K. Johnson, H. L. Hess, and J. D. Law, "Modeling and analysis of a flywheel energy storage system for voltage sag correction," *IEEE Trans. Ind. Appl.*, vol. 42, no. 1, pp. 42–52, Jan./Feb. 2006.

[36] G. O. Cimuca, C. Saudemont, B. Robyns, and M. M. Radulescu, "Control and performance evaluation of a flywheel energy-storage system associated to a variable-speed wind generator," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1074–1085, Jun. 2006.

[37] R. Cardenas, R. Pena, M. Perez, J. Clare, G. Asher, and P. Wheeler, "Power smoothing using a switched reluctance machine driving a flywheel," *IEEE Trans. Energy Convers.*, vol. 21, no. 1, pp. 294–295, Mar. 2006.

[38] R. Cardenas, R. Pena, M. Perez, J. Clare, G. Asher, and P. Wheeler, "Power smoothing using a flywheel driven by a switched reluctance machine," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1086–1093, Jun. 2006.

[39] H. Liu and J. Jiang, "Flywheel energy storage—An upswing technology for energy sustainability," *Energy Build.*, vol. 39, no. 5, pp. 599–604, May 2007.

[40] B. Bolund, H. Bernhoff, and M. Leijon, "Flywheel energy and power storage systems," *Renew. Sustain. Energy Rev.*, vol. 11, no. 2, pp. 235–258, 2007.

[41] B. B. Plater and J. A. Andrews, Advances in Flywheel Energy Storage Systems, 2001. [Online]. Available: http://www.powerpulse.net

[42] E. R. Furlong, M. Piemontesi, P. Prasad, and D. Sukumar, "Advances in energy storage techniques for critical power systems," in *Proc. BATTCOM*, Fort Lauderdale, FL, Apr. 29–May 1 2002, pp. 1–8.

[43] N. Bernard, H. B. Ahmed, B. Multon, C. Kerzreho, J. Delamare, and F. Faure, "Flywheel energy storage systems in hybrid and distributed electricity generation," in *Proc. PCIM*, Nuremberg, Germany, May 2003, pp. 121–130.

[44] R. W. Boom and H. Peterson, "Superconductive energy storage for power systems," *IEEE Trans. Magn.*, vol. MAG-8, no. 3, pp. 701–703, Sep. 1972.

[45] R. W. Boom, "Superconductive magnetic energy storage for electric utilities—A review of the 20 year Wisconsin program," in *Proc. 34th Int. Power Sources Symp.*, Cherry Hill, NJ, Jun. 25–28, 1990, pp. 1–4.

[46] A. Oudalov, T. Buehler, and D. Chartouni, "Utility scale applications of energy storage," in *Proc. IEEE ENERGY Conf.*, Atlanta, GA, Nov. 17–19, 2008, pp. 1–7.

[47] M. B. Camara, H. Gualous, F. Gustin, and A. Berthon, "Design and new control of DC/DC converters to share energy between supercapacitors and batteries in hybrid vehicles," *IEEE Trans. Veh. Technol.*, vol. 57, no. 5, pp. 2721–2735, Sep. 2008.

[48] H. Yoo, S. K. Sul, Y. Park, and J. Jeong, "System integration and power flow management for a series hybrid electric vehicle using supercapacitors and batteries," *IEEE Trans. Ind. Appl.*, vol. 44, no. 1, pp. 108–114, Jan./Feb. 2008.

[49] L. Shuai, K. A. Corzine, and M. Ferdowsi, "A new battery/ultracapacitor energy storage system design and its motor drive integration for hybrid electric vehicles," *IEEE Trans. Veh. Technol.*, vol. 56, no. 4, pp. 1516–1523, Jul. 2007.

[50] B. H. Lee, D. H. Shin, B. W. Kim, H. J. Kim, B. K. Lee, C. Y. Won, and J. Hur, "A study on hybrid energy storage system for 42 V automotive power-net," in *Proc. IEEE Veh. Power Propulsion Conf.*, Windsor, U.K., Sep. 6–8, 2006, pp. 1–5.

[51] W. Henson, "Optimal battery/ultracapacitor storage combination," *J. Power Sources*, vol. 179, no. 1, pp. 417–423, Apr. 2008.

[52] J. P. Zheng, T. R. Jow, and M. S. Ding, "Hybrid power sources for pulsed current applications," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 37, no. 1, pp. 288–292, Jan. 2001.

[53] K. Jin, X. Ruan, M. Yang, and M. Xu, "A hybrid fuel cell power system," *IEEE Trans. Ind. Electron.*, vol. 56, no. 4, pp. 1212–1222, Apr. 2009.

[54] Z. Jiang and R. A. Dougal, "A compact digitally controlled fuel cell/battery hybrid power source," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1094–1104, Jun. 2006.

[55] M. H. Todorovic, L. Palma, and P. N. Enjeti, "Design of a wide input range DC-DC converter with a robust power control scheme suitable for fuel cell power conversion," *IEEE Trans. Ind. Electron.*, vol. 55, no. 3, pp. 1247–1255, Mar. 2008.

[56] M. Ortuzar, J. Moreno, and J. Dixon, "Ultracapacitor-based auxiliary energy system for an electric vehicle: Implementation and evaluation," *IEEE Trans. Ind. Electron.*, vol. 54, no. 4, pp. 2147–2156, Aug. 2007.

[57] O. Briat, J. M. Vinassa, W. Lajnef, S. Azzopardi, and E. Woirgard, "Principle, design and experimental validation of a flywheel-battery hybrid source for heavy-duty electric vehicles," *IET Elect. Power Appl.*, vol. 1, no. 5, pp. 665–674, Sep. 2007.

[58] T. Ise, M. Kita, and A. Taguchi, "A hybrid energy storage with a SMES and secondary battery," *IEEE Trans. Appl. Supercond.*, vol. 15, no. 2, pp. 1915–1918, Jun. 2005.

[59] T. Haimin, J. L. Duarte, and M. A. M. Hendrix, "Multiport converters for hybrid power sources," in *Proc. 39th Annu. IEEE PESC*, Rhodes, Greece, Jun. 15–19, 2008, pp. 3412–3418.

[60] H. Matsuo, L. Wenzhong, F. Kurokawa, T. Shigemizu, and N. Watanabe, "Characteristics of the multiple-input DC-DC converter," *IEEE Trans. Ind. Electron.*, vol. 51, no. 3, pp. 625–631, Jun. 2004.

[61] L. Solero, A. Lidozzi, and J. A. Pomilio, "Design of multiple-input power converter for hybrid vehicles," *IEEE Trans. Power Electron.*, vol. 20, no. 5, pp. 1007–1016, Sep. 2005.

[62] S. G. Chalk and J. F. Miller, "Key challenges and recent progress in batteries, fuel cells, and hydrogen storage for clean energy systems," *J. Power Sources*, vol. 159, no. 1, pp. 73–80, Sep. 2006.

[63] S. Aso, M. Kizaki, and Y. Nonobe, "Development of fuel cell hybrid vehicles in TOYOTA," in *Proc. IEEE PCC*, Nagoya, Japan, Apr. 2–5, 2007, pp. 1606–1611.

[64] P. Thounthong, V. Chunkag, P. Sethakul, B. Davat, and M. Hinaje, "Comparative study of fuel-cell vehicle hybridization with battery or supercapacitor storage device," *IEEE Trans. Veh. Technol.*, vol. 58, no. 8, pp. 3892–3904, Oct. 2009.

[65] E. U. Ubong, C. Mizell, G. Slota, and N. Lovria, "Ultracapacitor with Ballard Nexa in a GEM vehicle in a hybrid mode," in *Proc. IEEE Elect. Insul. Conf. Elect. Manuf. Expo*, Indianapolis, IN, Oct. 26, 2005, pp. 317–320.

[66] P. Thounthong, S. Raël, and B. Davat, "Energy management of fuel cell/battery/supercapacitor hybrid power source for vehicle applications," *J. Power Sources*, vol. 193, no. 1, pp. 376–385, Aug. 2009.

[67] S. M. Lukic and A. Emadi, "Effects of drivetrain hybridization on fuel economy and dynamic performance of parallel hybrid electric vehicles," *IEEE Trans. Veh. Technol.*, vol. 53, no. 2, pp. 385–389, Mar. 2004.

[68] S. Schaeck, A. O. Stoermer, and E. Hockgeiger, "Micro-hybrid electric vehicle application of valve-regulated lead-acid batteries in absorbent glass mat technology: Testing a partial-state-of-charge operation strategy," *J. Power Sources*, vol. 190, no. 1, pp. 173–183, May 2009.

[69] J. Valenciano, M. Fernández, F. Trinidad, and L. Sanz, "Lead-acid batteries for micro- and mild-hybrid applications," *J. Power Sources*, vol. 187, no. 2, pp. 599–604, Feb. 2009.

[70] E. Karden, S. Ploumen, B. Fricke, T. Miller, and K. Snyder, "Energy storage devices for future hybrid electric vehicles," *J. Power Sources*, vol. 168, no. 1, pp. 2–11, May 2007.

[71] A. W. Stienecker, T. Stuart, and C. Ashtiani, "An ultracapacitor circuit for reducing sulfation in lead acid batteries for mild hybrid electric vehicles," *J. Power Sources*, vol. 156, no. 2, pp. 755–762, Jun. 2006.

[72] A. F. Burke, "Batteries and ultracapacitors for electric, hybrid, and fuel cell vehicles," *Proc. IEEE*, vol. 95, no. 4, pp. 806–820, Apr. 2007.

[73] H. Yoo, S.-K. Sul, Y. Park, and J. Jeong, "System integration and power-flow management for a series hybrid electric vehicle using supercapacitors and batteries," *IEEE Trans. Ind. Appl.*, vol. 44, no. 1, pp. 108–114, Jan./Feb. 2008.

[74] M. B. Camara, H. Gualous, F. Gustin, A. Berthon, and B. Dakyo, "DC/DC converter design for supercapacitor and battery power management in hybrid vehicle applications-polynomial control strategy," *IEEE Trans. Ind. Electron.*, vol. 57, no. 2, pp. 587–597, Feb. 2010.

[75] L. Shuai, K. A. Corzine, and M. Ferdowsi, "A unique ultracapacitor direct integration scheme in multilevel motor drives for large vehicle propulsion," *IEEE Trans. Veh. Technol.*, vol. 56, no. 4, pp. 1506–1515, Jul. 2007.

[76] K. Clement-Nyns, E. Haesen, and J. Driesen, "The impact of charging plug-in hybrid electric vehicles on a residential distribution grid," *IEEE Trans. Power Syst.*, vol. 25, no. 1, pp. 371–380, Feb. 2010.

[77] K. Dyke, N. Schofield, and M. Barnes, "The impact of transport electrification on electrical networks," *IEEE Trans. Ind. Electron.*, to be published.

[78] Y. V. Bocharnikov, A. M. Tobias, C. Roberts, S. Hillmansen, and C. J. Goodman, "Optimal driving strategy for traction energy saving on DC suburban railways," *IET Elect. Power Appl.*, vol. 1, no. 5, pp. 675–682, Sep. 2007.

[79] S. Suzuki, J. Baba, K. Shutoh, and E. Masada, "Effective application of superconducting magnetic energy storage (SMES) to load leveling

for high speed transportation system," *IEEE Trans. Appl. Supercond.*, vol. 14, no. 2, pp. 713–716, Jun. 2004.

[80] G. Morita, T. Konishi, S. Hase, Y. Nakamichi, H. Nara, and T. Uemura, "Verification tests of electric double-layer capacitors for static energy storage system in DC electrified railway," in *Proc. IEEE SPEEDAM*, Ischia, Italy, Jun. 11–13, 2008, pp. 1017–1022.

[81] L. Battistelli, F. Ciccarelli, D. Lauria, and D. Proto, "Optimal design of DC electrified railway stationary storage system," in *Proc. IEEE ICCEP*, Capri, Italy, Jun. 9–11, 2009, pp. 1017–1022.

[82] A. Rufer, D. Hotellier, and P. Barrade, "A supercapacitor-based energy storage substation for voltage compensation in weak transportation networks," *IEEE Trans. Power Del.*, vol. 19, no. 2, pp. 629–636, Apr. 2004.

[83] S. Hase, T. Konishi, A. Okui, Y. Nakamichi, H. Nara, and T. Uemura, "Fundamental study on energy storage system for DC electric railway system," in *Proc. IEEE Power Convers. Conf.*, Osaka, Japan, Apr. 2–5, 2002, pp. 1456–1459.

[84] A. Xu, S. Xie, Y. Yao, X. Liu, H. Xiao, and J. Feng, "An ultra-capacitor based regenerating energy storage system for urban rail transit," in *Proc. IEEE ECCE*, San Jose, CA, Sep. 20–24, 2009, pp. 1626–1631.

[85] M. Steiner, M. Klohr, and S. Pagiela, "Energy storage system with ultracaps on board of railway vehicles," in *Proc. EPE*, Aalborg, Denmark, Sep. 2–5, 2007, pp. 1–10.

[86] M. Steiner and J. Scholten, "Energy storage on board of DC fed railway vehicles," in *Proc. 35th Annu. IEEE PESC*, Aachen, Germany, Jun. 20–25, 2004, pp. 666–671.

[87] D. Iannuzzi, "Improvement of the energy recovery of traction electrical drives using supercapacitors," in *Proc. EPE-PEMC*, Poznan, Poland, Sep. 1–3, 2008, pp. 1469–1474.

[88] M. B. Richardson, "Flywheel energy storage system for traction applications," in *Proc. IEE Int. Conf. Power Electron., Mach. Drive*, Bath, U.K., Jun. 4–7, 2002, pp. 275–279.

[89] A. Jaafar, C. R. Akli, B. Sareni, X. Roboam, and A. Jeunesse, "Sizing and energy management of a hybrid locomotive based on flywheel and accumulators," *IEEE Trans. Veh. Technol.*, vol. 58, no. 8, pp. 3947–3958, Oct. 2009.

[90] D. Briginshaw, "Hybrid traction system benefits environment: Japan's new energy train project uses a hybrid diesel-electric traction system to achieve major reductions in energy consumption, noxious emissions, and noise," *Int. Railway J.*, vol. 44, no. 12, pp. 32–35, Dec. 2004.

[91] S. Lu, D. H. Meegahawatte, S. Guo, S. Hillmansen, C. Roberts, and C. J. Goodman, "Analysis of energy storage devices in hybrid railway vehicles," in *Proc. IET ICRE*, Hong Kong, Mar. 25–28, 2008, pp. 68–73.

[92] C. R. Akli, X. Roboam, B. Sareni, and A. Jeunesse, "Energy management and sizing of a hybrid locomotive," in *Proc. EPE*, Aalborg, Denmark, Sep. 2–5, 2007, pp. 1–10.

[93] B. Destraz, P. Barrade, and A. Rufer, "Power assistance for diesel-electric locomotives with supercapacitive energy storage," in *Proc. 35th Annu. IEEE PESC*, Aachen, Germany, Jun. 20–25, 2004, pp. 677–682.

[94] A. R. Miller and J. Peters, "Fuelcell hybrid locomotives: Applications and benefits," in *Proc. IEEE/ASME Joint Rail Conf.*, Atlanta, GA, Apr. 4–6, 2006, pp. 287–293.

[95] K. Ogawa, T. Yamamoto, H. Hasegawa, and T. Furuya, "Development of the fuel-cell/battery hybrid railway vehicle," in *Proc. IEEE VPPC*, Dearborn, MI, Sep. 7–10, 2009, pp. 1730–1735.

[96] J. A. Carr, J. C. Balda, and H. A. Mantooth, "A survey of systems to integrate distributed energy resources and energy storage on the utility grid," in *Proc. IEEE ENERGY*, Atlanta, GA, Nov. 17–19, 2008, pp. 1–7.

[97] A. Mohd, E. Ortjohann, A. Schmelter, N. Hamsic, and D. Morton, "Challenges in integrating distributed energy storage systems into future smart grid," in *Proc. IEEE ISIE*, Cambridge, U.K., Jun. 30–Jul. 2 2008, pp. 1627–1632.

[98] J. M. Carrasco, L. G. Franquelo, J. T. Bialasiewicz, E. Galvan, R. C. P. Guisado, M. A. M. Prats, J. I. Leon, and N. Moreno-Alfonso, "Power-electronic systems for the grid integration of renewable energy sources: A survey," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1002–1016, Jun. 2006.

[99] A. Nasiri, "Integrating energy storage with renewable energy systems," in *Proc. IEEE IECON*, Orlando, FL, Nov. 10–13, 2008, pp. 17–18.

[100] S. W. Mohod and M. V. Aware, "Energy storage to stabilize the weak wind generating grid," in *Proc. POWERCON*, Nwe Delhi, India, Oct. 12–15, 2008, pp. 1–5.

[101] T. Tanabe, T. Sato, R. Tanikawa, I. Aoki, T. Funabashi, and R. Yokoyama, "Generation scheduling for wind power generation by storage battery system and meteorological forecast," in *Proc. IEEE PES*, Pittsburgh, PA, Jul. 20–24, 2008, pp. 1–7.

[102] Y. Zhong, J. Zhang, G. Li, and X. Yuan, "Mathematical model of new bidirectional DC-AC-DC converter for supercapacitor energy storage system in photovoltaic generation," in *Proc. Elect. Utility DRPT*, Nanjing, China, Apr. 6–9, 2008, pp. 2686–2690.

[103] S. Faias, P. Santos, F. Matos, J. Sousa, and R. Castro, "Evaluation of energy storage devices for renewable energies integration: Application to a Portuguese wind farm," in *Proc. Int. Conf. EEM*, Lisbon, Portugal, May 28–30, 2008, pp. 1–7.

[104] B. P. Roberts, "Sodium-Sulfur (NaS) batteries for utility energy storage applications," in *Proc. IEEE PES*, Pittsburgh, PA, Jul. 20–24, 2008, pp. 1–2.

[105] D. K. Nichols and S. Eckroad, "Utility-scale application of sodium sulfur battery," in *Proc. IEEE Int. Stationary Battcon*, Marco Island, FL, Apr. 27–30, 2003, pp. 1–9.

[106] A. Y. Saber and G. K. Venayagamoorthy, "Optimization of vehicle-to-grid scheduling in constrained parking lots," in *Proc. IEEE PES*, Calgary, AB, Canada, Jul. 26–30, 2009, pp. 1–8.

[107] *EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications*, Dec. 2003.

[108] F. Schorr and N. Brochard, "Advances in energy-efficient, power quality and energy storage, and implications for utility grid frequency stabilization," in *Proc. IEEE INTELEC*, Rome, Italy, Sep. 30–Oct. 4 2007, pp. 604–608.

[109] G. Costales, A. lara, J M Carrasco, E. Galván, and L. G. Franquelo, "System for conditioning and generating/storing power in electrical distribution networks in order to improve the dynamic stability and frequency control thereof," International Patent WO/2003/023933, Mar. 20, 2003.

[110] G. Costales, A. lara, J M Carrasco, E. Galván, and L. G. Franquelo, "System for using energy stored in the mechanical inertia of the rotor of a wind turbine," International Patent WO/2003/023224, Mar. 20, 2003.

[111] L. Cui, D. Li, J. Wen, Z. Jiang, and S. Cheng, "Application of superconducting magnetic energy storage unit to damp power system low frequency oscillations," in *Proc. Elect. Utility DRPT*, Nanjing, China, Apr. 6–9, 2008, pp. 2251–2257.

[112] H. Chong, A. Q. Huang, S. Bhattacharya, L. W. White, M. Ingram, S. Atcitty, and W. Wong, "Design of an ultra-capacitor energy storage system (UESS) for power quality improvement of electric arc furnaces," in *Conf. Rec. IEEE IAS Annu. Meeting*, Edmonton, AB, Canada, Oct. 5–9, 2008, pp. 1–6.

[113] A. Virtanen and H. Tuusa, "Power compensator for high power fluctuating loads with a supercapacitor bank energy storage," in *Proc. IEEE PECon*, Johor Bahru, Malaysia, Dec. 1–3, 2008, pp. 977–982.

[114] V. Virulkar and M. Aware, "Analysis of DSTATCOM with BESS for mitigation of flicker," in *Proc. IEEE INCACEC*, Perundurai, India, Jun. 4–6, 2009, pp. 1–7.

[115] J. Dixon, I. Nakashima, E. F. Arcos, and M. Ortuzar, "Electric vehicle using a combination of ultracapacitors and ZEBRA battery," *IEEE Trans. Ind. Electron.*, vol. 57, no. 3, pp. 943–949, Mar. 2010.

[116] C. Cecati, A. Dell'Aquila, and M. Liserre, "A novel three-phase single-stage distributed power inverter," *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1226–1233, Sep. 2004.

[117] S. Jaganathan and G. Wenzhong, "Battery charging power electronics converter and control for plug-in hybrid electric vehicle," in *Proc. IEEE VPPC*, Dearborn, MI, Sep. 7–10, 2009, pp. 440–447.

[118] N. M. L. Tan, S. Inoue, A. Kobayashi, and H. Akagi, "Voltage balancing of a 320-V, 12-F electric double-layer capacitor bank combined with a 10-kW bidirectional isolated DC-DC converter," *IEEE Trans. Power Electron.*, vol. 23, no. 6, pp. 2755–2765, Nov. 2008.

[119] P. Goel, B. Singh, S. Murthy, and N. Kishore, "Isolated wind-hydro hybrid system using cage generators and battery storage," *IEEE Trans. Ind. Electron.*, to be published.

[120] L. Maharjan, S. Inoue, H. Akagi, and J. Asakura, "State-of-charge (SOC)-balancing control of a battery energy storage system based on a cascade PWM converter," *IEEE Trans. Power Electron.*, vol. 24, no. 6, pp. 1628–1636, Jun. 2009.

[121] C. Vazquez, M. Lafoz, D. Ugena, and L. García-Tabares, "Control system for the switched reluctance drive of a flywheel energy-storage system," *Eur. Trans. Elect. Power*, vol. 17, no. 6, pp. 537–553, Jan. 2007.

[122] J. Villegas, S. Vazquez, J. M. Carrasco, and I. Gil, "Model predictive control of a switched reluctance machine using discrete space vector modulation," in *Proc. IEEE ISIE*, Bari, Italy, Jul. 4–7, 2010, pp. 3139–3144.

[123] W. Bingsen and G. Venkataramanan, "Dynamic voltage restorer utilizing a matrix converter and flywheel energy storage," *IEEE Trans. Ind. Appl.*, vol. 45, no. 1, pp. 222–231, Jan./Feb. 2009.

[124] R. L. Kustom, J. J. Skiles, J. Wang, K. Klontz, T. Ise, K. Ko, and F. Vong, "Research on power conditioning systems for superconductive magnetic

energy storage (SMES)," *IEEE Trans. Magn.*, vol. 27, no. 2, pp. 2320–2323, Mar. 1991.

[125] J. Rodriguez, L. G. Franquelo, S. Kouro, J. I. Leon, R. C. Portillo, M. A. M. Prats, and M. A. Perez, "Multilevel converters: An enabling technology for high-power applications," *Proc. IEEE*, vol. 97, no. 11, pp. 1786–1817, Nov. 2009.

[126] L. G. Franquelo, J. Rodriguez, J. I. Leon, S. Kouro, R. Portillo, and M. M. Prats, "The age of multilevel converters arrives," *IEEE Ind. Electron. Mag.*, vol. 2, no. 2, pp. 28–39, Jun. 2008.

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