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Hybrid energy storage systems of energy- and power-dense batteries: a survey on modelling techniques and control methods

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Abstract

The impact of global warming and climate change has forced countries to introduce strict policies and decarbonization goals toward sustainable development. To achieve the decarbonization of the economy, a substantial increase of renewable energy sources is required to meed energy demand and to transition away from fossil fuels. However, renewables are sensitive to environmental conditions, which may lead to imbalances between energy supply and demand. Battery energy storage systems are gaining more attention for balancing energy systems in existing grid networks at various levels such as bulk power management, transmission and distribution, and for end-users. Integrating battery energy storage systems with renewables can also solve reliability issues related to transient energy production and be used as a buffer source for electrical vehicle fast charging. Despite these advantages, batteries are still expensive and typically built for a single application – either for an energy- or power-dense application – which limits economic feasibility and flexibility. This paper presents a theoretical approach of a hybrid energy storage system that utilizes both energy- and power-dense batteries serving multiple grid applications. The proposed system will employ second use electrical vehicle batteries in order to maximise the potential of battery waste. The approach is based on a survey of battery modelling techniques and control methods. It was found that equivalent circuit models as well as unified control methods are best suited for modelling hybrid energy storages for grid applications. This approach for hybrid modelling is intended to help accelerate the renewable energy transition by providing reliable energy storage.

Keywords: hybrid energy storage system; multiple grid applications; battery control methods; energy- and power-dense batteries; second use batteries

1. Introduction

Research on alternative energy sources and energy storage methods is increasing rapidly due to greater awareness of climate change and pollution from fossil fuels [1]. To combat the situation, many governments are enacting strict emissions reduction policies [2]. The objective of such policies is to achieve a sustainable energy transition with reliable, safe, robust, and efficient power grid operation coupled with a zero-emission transportation system. Because of government subsidies encouraging private parties in the power sector, there has been a record growth of renewable energy sources (RES). This growth is driven by wind and solar photovoltaic systems, which in 2020 increased by 12% and 23%, respectively [3]. However, RESs are subjected to varying environmental and weather conditions, which can lead to an imbalance between supply and demand, causing reliability and stability issues for grid systems. To overcome this issue, the utilization of energy storage systems (ESS) will be fundamentally important for the increased deployment of RESs. For a given application, the selection of an appropriate energy storage system is subjected to lifespan, response time, energy and power ratings [4]. Generally, ESSs are categorized based on the storage type:

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electrochemical (batteries), electrical (supercapacitors and superconducting magnetic energy systems (SMES)), mechanical (compressed air energy systems (CAES), pumped hydro, flywheel), hydrogen (fuel cells), and thermal (thermal energy storage systems) [5]. Fig.1 illustrates an overview of ESS technologies in the power system and applications are categorized as bulk power management level, transmission, and distribution (T&D) level, and end-users.

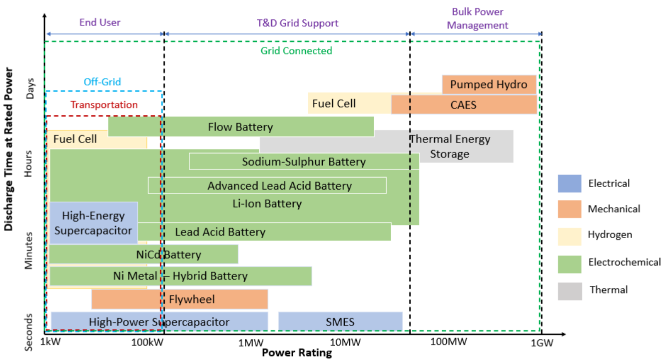

Fig. 1. Overview of different energy storage systems based on power rating [6],[5].

The immediate response time, high power density, and fast charging and discharging capabilities are characteristics of ESSs using power-dense (PD) systems. Supercapacitors, SMES, flywheels, and high-power batteries will come under this classification. ESSs using energy-dense (ED) systems can provide energy for longer periods of time. ESSs included in this category are CAESs, fuel cells, pumped hydro energy systems, thermal energy storage systems, and high-energy batteries. The selection of a single type of ESS from Fig.1 is either ED or PD. For instance, CAES has high discharge time at rated power but suffers from poor response time. SMES will respond in seconds to minute but they have a low energy density. As a result, the typical ESS approach of using only one energy storage technology that cannot handle complex grid management and multiple grid applications frequently results in an inefficient system where energy delivery does not always meet demand. To address this, a hybrid energy storage system (HESS) that provides multiple grid applications is required. HESS is a combination of two storage systems that satisfy both ED and PD requirements. As an example, a flywheel (PD) with batteries (ED)[7], pumped hydro (ED) storage with batteries (PD) [8], fuel cells and batteries [9], two different battery types [10], ultracapacitors (PD) with batteries (ED) [11], etc. Fortunately, due to lower maintenance, battery storage systems are one of the least complex choices for HESSs, which means that batteries have the potential to play a crucial societal function for robust energy storage.

In one industry report, battery storage was identified as serving up to 13 applications in the electrical grid for three different stakeholder groups (utility services, customer services, and independent system operators/ regional transmission organization services)[12]. . G. Reid et al., in [13] proposed 14 applications and four stakeholders (commercial & industrial, utility, residential and off-grid) for second use batteries. Synthesizing this information, stakeholders can be identified as “in-front-of the-meter”, “behind-the-meter”, and “off-grid” [14], which require different PD and ED applications. Typical PD applications are frequency stability, spinning /non-spinning reserve, peak shaving while typical ED applications are black start, energy arbitrage and backup power [15].

In terms of applicability, lithium-ion (Li-ion) batteries have shown the largest market potential in recent years due to their continually growing capacity, technological capability for stationary and transport applications, as well as falling costs due to production efficiencies and improvements. Li-ion battery applications are also wide ranging, from electronic gadgets and computers to electric vehicles (EV) to stationary ESS thus Li-ion batteries dominate the market. Initiatives from different zero-emission vehicle mandates, government subsidies to enhance EV sales, and drastic development of battery technology increased the penetration of EVs on the global market. The International Energy Agency (IEA) estimates that there will be 10 million EVs globally and Europe’s new EV registrations more than doubled to 1.4 million, representing a market share growth of 10% compared to the previous year [16]. Germany registered 0.39 million new EVs, and France registered 0.185 million and the United Kingdom more than doubled to reach 0.176 million. In terms of new vehicle share, EVs represent 75% of total new vehicles in Norway, 50% in Iceland, 30% in Sweden, and 25% in the Netherlands [16]. With the increasing use of EVs, there will be a huge quantity of decommissioned batteries available in the future and these EV batteries will still have 70%-80% of the initial charge capacity [14]. Based on the type of cell chemistry and design, second use ED batteries will still be useful for low demand stationary applications, such as ESSs, thus reducing the need for new battery production for ESSs [14]. Recent studies also show that second use ED batteries provide a cost-effective and long-term solution for future ESSs [17].

The deployment of EV charging stations lead to new peak loads, which require PD energy storage to reduce charging time by delivering higher power when required. Conventional supercapacitors can deliver the required peak power for a short period of time (0.3 Sec - 30 Sec) [18] but not long enough for EV charging, which may require high power for upwards of 20 minutes per vehicle charged. To balance the expected high loads and increased time span (from a few minutes up to several hours), PD batteries are better suited than SCs.

Wider utilization of batteries in future ESSs are still difficult due to economic challenges like high cost and low lifespan [19]. Despite the large drop in Li-ion battery prices over the past few years due to mass production and technology improvements, current prices for new ED batteries are still prohibitively expensive for widespread deployment. HESSs, which combine ED second use batteries with new PD batteries, have the potential to improve battery economics by enlarging the range of applications (possibly also by simultaneously serving them) while reducing overall system costs compared to new ED batteries [20].

Attempting to combine two distinct Li-ion battery types in a HESS is new and the knowledge base is limited. To address this gap, an initial system investigation is required. To assess the performance of such a HESS, mathematical models are needed. Such models can be used in simulation studies and are required to run physical and electrical applications. The next section of this paper presents a survey of modelling and control methods for a HESS that repurposes spent EV batteries.

2. Survey of modelling and control methods for HESSs

A HESS is designed to take advantage of the most useful features from different battery technologies, which will enhance the overall energy storage lifespan and ensure that the system will not be oversized [21]. The proposed HESS consists of two distinct Li-ion batteries: PD and ED batteries with an advanced battery management system (BMS) and a battery control unit (BCU) as well as DC/AC converters. Fig.2. illustrate the proposed HESS block diagram.

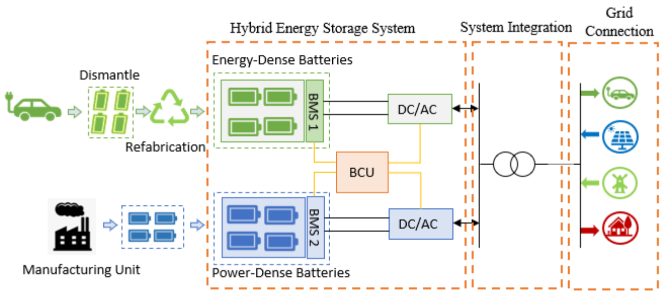

Fig. 2. Proposed hybrid energy storage system block diagram.

The HESS implementation helps to ensure a highly reliable system, a substantial reduction in costs through second use ED batteries, the possibility to meet peak load demands, and improves the robustness and resilience of the existing power system network.

The development of the HESS theoretical approach will require two steps. As a first step, a mathematical model for a hybrid energy storage system will be developed by using two different types of batteries (ED and PD) and tested with different load scenarios. Secondly, advanced battery control algorithms for the HESS will be developed. The function of BCU is to control the charging/discharging while the mathematical battery model is used to do the parameter estimations like state of charge (SOC) and health of the batteries. The control methods within the BCU for multiple grid applications will be implemented by considering end-user requirements. To this end, a survey of battery modelling techniques and control methods has been performed.

2.1. Battery modelling techniques

As per modelling principles, in Meng et al., 2018 [22] modelling methods are classified into four types: 1) *Electrochemical models*, 2) *empirical models*, 3) *data-driven models*, and 4) *equivalent circuit models* (ECM).

Electrochemical models are used to understand the dynamic behavior of the internal cell, such as the reaction between electrodes and electrolytes. Electrochemical reactions are characterized by a set of mathematical partial differential equations. In existing literature, the two main types of electrochemical models used are Pseudo-2D [23] and Single Particle Model [24]. The complexity of modelling depends on the order of the partial differential equation and the number of unknown parameters.

Empirical models comprises a mathematical expression where output voltage is a function of SOC and current. However, the actual battery terminal voltage is a function of open circuit voltage, SOC, current and temperature. The Shepherd model [25] and Unnewehr universal model [26] are simplified empirical models where the nonlinear battery characteristics are represented by reduced order polynomials. Those models perform well for static load currents. The Nernst model [27] exhibit better accuracy by introducing more parameters in the mathematical expression.

By using data-driven algorithms, the battery output voltage can be estimated even without preliminary knowledge of the system. Collection of sample data based on specific application and training of data are crucial steps in the process of data driven models. After the training process of learning algorithms is carried out, data-driven models can established. An offline based neural network training is proposed by [28], where data is collected from the battery charging process. The state variables are the previous battery output voltage and the current SOC. With low training samples [29], a nonlinear battery model is generated by using a least-square support vector machine. The suggested extreme learning machine achieves [30] a smaller error in SOC error and reduced computational costs.

In Hageman et al.,1993 [31], the battery is represented as equivalent electrical components such as a resistor, voltage source related to the SOC, and resistor-capacitor network. In an ECM, the resistor indicates the self-discharge, the voltage source represents the open-circuit voltage, and the RC network (resistor and capacitor are connected in parallel) represents the diffusion process of the cell. The Rint model [32] consists of open circuit voltage and internal resistance. To achieve voltage diffusion in an ECM, the RC network is introduced in Thevenin model [33]. In the realize partnership for a new generation of vehicles (PNGV) model [34], a capacitor is added to the Thevenin model. General, non-linear models [35] are incorporated by the second RC network in PNGV model.

Since HESSs are electrical systems, ECMs are the most promising modelling techniques. Data sheet values of the used electrical components can directly be implemented into those models. ECMs can also be adapted for other, auxiliary electrical components such as DC/AC convertors [36]. Further, ECMs are the optimal choice in combination with electrical grid management since vital grid parameters are also available as electrical parameters.

2.2. Control methods

Development of control methods is an essential element for the efficient operation of a HESS. The BCU has to optimally manage the power distribution between PD and ED batteries. The choice of the controlling method depends on various factors such as the energy storage application, the system type, the system life span, the operating conditions, and the response time. The BCU should derive the optimal schedule for charging/discharging the HESS by keeping the battery states within their operational limits. To achieve optimized control, different techniques are proposed in the literature. The presented PI control method based on observing the high and low-frequency power components of supply and demand balance in [37] enhances the lifespan of the battery and reduces the high discharge/charge current. Due to the simplicity of the model, the computational burden is lower and fast response times are achieved. The proposed rate limit control method [38] controls the battery charging and discharging by providing a reference current signal. A high pass filter-based droop controller and virtual capacitance droop is developed by [39] to regulate a battery and supercapacitor in a HESS. The proposed controller provides solutions for effective power distribution, avoids voltage imbalance, and controls the SOC of the battery and the supercapacitor In [40], J.P Torreglosa et al implemented an off-grid based wind/solar HESS via model predictive control to observe the SOC and load fluctuations. The proposed control method in [41] aims to minimize the cost of a hydrogen-battery HESS by limiting the level of hydrogen used by allowing for fluctuating SOC of the battery during high power applications. A unified controller developed by [42] contributes to limit the battery charging/discharging rate during power fluctuations in transient and steady state, DC link voltage regulations, and power distribution between systems.

Most of the existing control methods are mainly focusing on HESSs utilizing supercapacitors while limited attention is given to battery control. For a HESS, unified control is best suited, because of better dynamic voltage regulations, efficient power management in sudden disturbances, less execution time, and limiting the surge currents in charge/discharge conditions during transient response. Further, due to its simplicity it allows for an on-site implementation on a physical hybrid energy storage system with limited computational resources.

3. Conclusion and future work

This paper presents a survey of battery modelling techniques and control methods for hybrid energy storage system. Such storage systems combine energy-dense and power-dense batteries into a single system. Thus, both battery capabilities are utilized for maximum reliability of the system. The resultant hybrid energy storage system is designed to utilize second use electric vehicle batteries to reduce the environmental impacts, system costs, and to take advantage of batteries, which have not yet met their end-of-life. The storage system can serve multiple grid applications and thus reduce the battery idling times and therefore increase the economic viability. The survey showed that equivalent circuit models are most suited for modelling hybrid energy storage system. Electrical models allow easy integration into other electrical systems. Unified control methods are best suited for on-site implementation on a hybrid storage system because of their simplicity and thus limited demand on computational resources. An efficient, reliable, and intelligent HESS will be able to tackle the expected increase in renewable energy production by allowing energy to be charged and discharged as needed for a variety of grid applications, especially where existing BESSs lack flexibility and applicability. The use of second use batteries will also contribute to cascading uses of battery wastes within the circular economy and reduce the need for new batteries for ESS solutions. The proposed system is convenient buffer for e.g. residential PV generation combined with a EV fast charging facility. Which enhances the decentralisation and reduce the new peak demand at residential and commercial buildings. Based on PD and ED specifications Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Cobalt Oxide (LCO), Lithium managanese Oxide (LMO), Lithium Nickel Cobalt Aluminium Oxide (NCA) are suitable for ED applications and Lithium Iron Phosphate (LFP) and Lithium Titanate (LTO) for PD applications, however this list is not ended.

Future research on modelling the combination of two different types of batteries should be conducted. The models have to be evaluated with different test cases reflecting potentially feasible grid applications. Subsequently, simulation studies using the proposed hybrid energy storage system model and further developed battery control methods should be tested. Experimental investigations with a physical model using real hardware should be used to verify the simulation results.

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