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A review of supercapacitor modeling, estimation, and applications: A control/management perspective

Lei Zhang[a,b,1], Xiaosong Hu[c,d,*,1], Zhenpo Wang[a,**], Fengchun Sun[a], David G. Dorrell[b]

[a] Collaborative Innovation Center for Electric Vehicles in Beijing & National Engineering Laboratory for Electric Vehicles, Beijing Institute of Technology, Beijing 100081, China
[b] Faculty of Engineering and Information Technology, University of Technology, Sydney, Sydney 2007, Australia
[c] The State Key Laboratory of Mechanical Transmissions, Chongqing University, Chongqing 400044, China
[d] College of Automotive Engineering, Chongqing University, Chongqing 400044, China

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ABSTRACT

Supercapacitors (SCs) have high power density and exceptional durability. Progress has been made in their materials and chemistries, while extensive research has been carried out to address challenges of SC management. The potential engineering applications of SCs are being continually explored. This paper presents a review of SC modeling, state estimation, and industrial applications reported in the literature, with the overarching goal to summarize recent research progress and stimulate innovative thoughts for SC control/management. For SC modeling, the state-of-the-art models for electrical, self-discharge, and thermal behaviors are systematically reviewed, where electrochemical, equivalent circuit, intelligent, and fractional-order models for electrical behavior simulation are highlighted. For SC state estimation, methods for State-of-Charge (SOC) estimation and State-of-Health (SOH) monitoring are covered, together with an underlying analysis of aging mechanism and its influencing factors. Finally, a wide range of potential SC applications is summarized. Particularly, co-working with high energy-density devices constitutes hybrid energy storage for renewable energy systems and electric vehicles (EVs), sufficiently reaping synergistic benefits of multiple energy-storage units.

1. Introduction

Energy storage systems play an important role in a diverse range of industrial applications [1,2], as either bulk energy storage or distributed transient energy buffer. Specific energy, specific power, lifetime, reliability, and safety are among the main criteria considered when picking energy storage [3]. Rechargeable batteries, especially lithium-ion batteries, are currently a popular option due to their high energy density and acceptable cycle life [4]. Nevertheless, they have limits of relatively low power density and relatively high internal resistance that could heavily curtail their power-delivery capability under large current loading. Moreover, battery life is highly susceptible to high current-rate and transient loading conditions [5]. In order to overcome these shortcomings, redundant design is often adopted in practice for pulse and peak power fulfillment, which inevitably incurs additional expense. On the other hand, supercapacitors (SCs), also known as ultracapacitors (UCs) or Electric Double-Layer Capacitors (EDLCs), are being actively studied and unanimously envisaged as a promising energy storage technology, owing to their desirable merits including high power density and high degree of recyclability [6,7]. They have additional advantages, such as low internal resistance, wide operating temperature window, and high efficiency, despite that they have relatively low energy density [8]. These advantageous characteristics render them particularly suitable for working independently or in tandem with other high-energy devices for power sinking/sourcing in real plants [9].

In order to ensure efficient, safe, and reliable operation of SC systems, an enabling management system is necessary [10]. Its main tasks include cell equalization management, thermal management, power control synthesis, safety supervision, and so on, all of which hinge on systems and control engineering. For example, accurate and efficient modeling is fundamental for management system development regarding electrical, thermal, and aging issues [11]. Besides, precise state estimation provides insights for cell non-uniformity

* Corresponding author at: Chongqing University, No. 174, Shazhengjie, Shapingba District, Chongqing 400044, China.
** Corresponding author at: National Engineering Laboratory for Electric Vehicles, 5 Zhongguancun South St. Haidian District, Beijing 100081, China.
E-mail addresses: xiaosonghu@ieee.org (X. Hu), wangzhenpo@bit.edu.cn (Z. Wang).
[1] L. Zhang and X. Hu equally contributed to this work.

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suppression and optimal power control of SC systems. There is a large body of literature reporting on advances in SC modeling, state estimation, and their industrial applications. This paper provides a comprehensive survey of SC studies in the recent literature, with the primary objective to systematically summarize the state of the art in SC modeling, state estimation, and industrial applications from a control/management perspective. Three prominent contributions distinguish our endeavor from existing review articles [12–15]. First, we review virtually all the modeling approaches applied to SCs, including electrochemical, equivalent circuit, intelligent, and fractional-order models, especially underscoring the most recent modeling outcomes. Second, we cover the latest literature on State-of-Charge (SOC) estimation and State-of-Health (SOH) monitoring, and highlight the influencing factors that impact SC health. Third, we elucidate a broad variety of SC applications, especially focusing on the energy management development of SC-involved systems. This paper is anticipated to manifest research progress in the subject of SC management, catalyze novel transformative modeling/control ideas, and unlock more application opportunities.

The remainder of the paper is structured as follows: Section 2 gives a short overview of SC fundamentals. Section 3 reviews SC modeling approaches. The SOC estimation and SOH monitoring techniques are summarized in Section 4, followed by introducing SC industrial applications in Section 5. Section 6 summarizes the key points of this paper.

2. SC fundamentals

The electric double-layer (EDL) phenomenon was firstly described by Helmholtz in 1853, and patented by Becker (General Electric Company) in 1957, who used porous carbon material with high specific area as electrodes for double-layer structure formation [16]. Nippon Electric Company (or NEC) licensed a SC product as a memory backup device that marked the first commercial application in 1971 [17]. Structurally, the SC consists of two electrodes, a membrane separator, and electrolyte as shown in Fig. 1, which was also illustrated in our previous study [18].

The two electrodes are insulated by the membrane separator and impregnated to the electrolyte. The membrane separator only permits the ion mobility but prevents electric contact. SCs store electrical energy mainly through the formation of the double-layer capacitor structure at the interface between the electrodes and the electrolyte. This energy storage mechanism involves no chemical phase or composition changes, apart from fast and reversible Faradaic reactions existing on the electrode surface, which also contribute to the total capacitance. The characteristic of electrostatic charge transfer results in a high degree of recyclability [19]. Compared to conventional capacitors, the high capacitance of SCs originates from the high specific area of the electrodes, which is largely determined by the used electrode materials and their physical properties (e.g. conductivity and porosity). Advanced electrode materials have been the area of intensive study, and the latest progress has been periodically reviewed in [20,21]. Carbon materials with high specific area, conducting polymers, and metal oxides constitute the main categories for SC electrode materials [22]. Particularly, carbon materials have been successfully utilized in the commercially available SCs because of their advantages such as low cost, high specific area, availability, good conductivity, high electrochemical stability, and wide operating temperature window [23]. The porosity parameters, including pore size and pore-size distribution, equally exert an important influence on the practical SC capacitance, because these parameters can have a major impact on the active electrode surface accessible to the electrolyte. For example, Largeot et al. [24] pointed out that the capacitance culminates when electrodes have the pore size close to the ion size of the electrolyte. Electrolyte is another important component that affects SC performance. The general requirements for the electrolyte encompass large voltage window, high ionic concentration, high electrochemical stability, low resistivity, low viscosity, low volatility, and low cost [25]. Aqueous electrolyte, organic electrolyte, and ionic liquids are mainly used, each with its own strengths and limitations. Generally, SCs with aqueous electrolyte exhibit better performance in terms of capacitance and power delivery, since the aqueous electrolyte can have higher ionic concentration and lower resulting resistance. However, the voltage window of aqueous electrolyte is as low as about 1.2 V, which significantly hinders the improvements of energy and power density, since the SC energy is proportional to the square of the voltage. In contrast, the organic electrolyte can offer a voltage window as high as 3.5 V, making it more preferable in SC manufacturing. Ionic liquid refers to the smelt salt at certain temperature which possesses several desirable properties, including low vapor pressure, large voltage window, high electrochemical stability, and so forth [26].

3. SC modeling

A common framework for describing and analyzing systems is always required by researchers and engineers. This framework is often mathematics, and referred to as mathematical modeling. For SC systems, modeling is essential for design prediction, condition monitoring, and control synthesis. Since a model is, at best, a surrogate for real systems, whose accuracy is subject to the assumptions and requirements, it must be generated for a specific purpose. As such, numerous SC models have been reported in the literature for different purposes, including capturing electrical behavior, thermal behavior, self-discharge, aging simulation, *etc*. For electrical behavior modeling, electrochemical models, equivalent circuit models, and fractional-order models are the most commonly used models. Generally, electrochemical models have high accuracy but low calculation efficiency, since they are able to capture the real reaction process inside UCs at the expense of coupled partial differential equations (PDEs). This hinders their applications in embedded systems for real-time energy management and control. In contrast, equivalent circuit models are derived from empirical experience and experimental data under certain conditions. This renders them inadequate for representingthe UC dynamics under wide-range conditions, thus giving rise to model mismatch issues. Also, their parameters and states lack physical representations so that no internal information is explicitly available. However, the structural simplicity and decent modeling accuracy make them well-accepted for real-time energy management synthesis. The comprehensive SC models for control/management purposes reviewed in this paper are given in Fig. 2.

3.1. Electrochemical models

Helmholtz [27] discovered the EDL phenomenon and described it using a model where all the charges were assumed to be adsorbed at the electrode surface. This is identical to a conventional dielectric capacitor structure [28]. Gouy [29] and Chapman [30] further modified the Helmholtz model to account for the ion mobility in the electrolyte solutions as a result of diffusion and electrostatic forces. Boltzmann distribution equation was adopted to analytically depict the relationship between the ionic concentration and local electrical potential in the diffuse layer. Stern [31] combined the Helmholtz model and the Gouy-Chapman model, and divided the EDL into two characteristically distinct layers, i.e., the Stern layer (Helmholtz layer) and the diffuse layer (Gouy-Chapman layer), as shown in Fig. 3. The Stern layer accounts for the specific absorption of the ions on the electrode surface, whilst the diffuse layer incorporates the Gouy-Chapman model [32]. The total capacitance of EDL can be treated as the Stern layer and diffuse layer capacitances connected in series. An unrealistic ion concentration value may be obtained by deriving the Poission-Boltzmann (PB) equation; this model treats the ions as point charges by ignoring their physical size, but the point-charge assumption is only

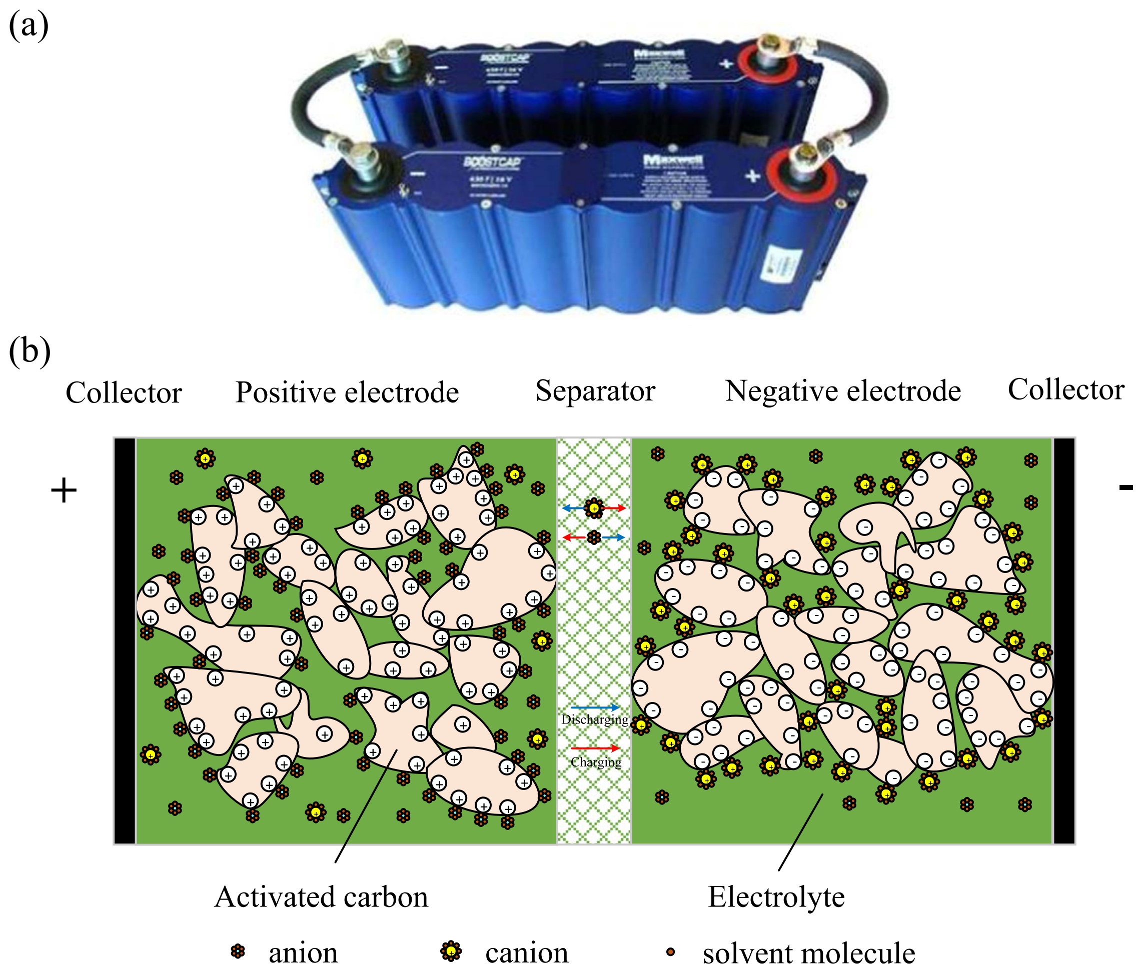

Fig. 1. (a) An example SC module from Maxwell; (b) the SC structure.

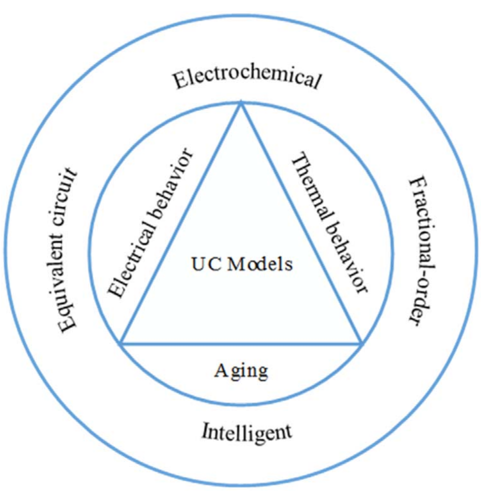

Fig. 2. SC models.

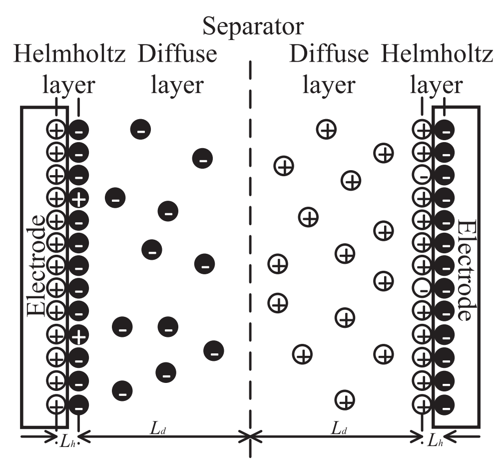

Fig. 3. The Gouy-Chapman-Stern model.

valid for low ion concentration and low electrical potential [33,34]. Bikerman [35] reformulated the Poission-Boltzmann model by incorporating the influence of finite ion size under equilibrium conditions, where the anions and cations in the electrolyte had different sizes with identical valence. Verbrugge and Liu [36] proposed a one-dimensional one-domain mathematical model based on the dilute-solution theory and porous electrode analysis, where the SC was regarded as a continuum entity with homogeneous and isotropic physical properties. Allu et al. [37] further expanded it to a three-domain model based on the uniform formulation of electrode-electrolyte system. This illustrated the benefits of capturing the irregular geometric configuration, charge transport, and related performance in higher dimensions, and introducing spatio-temporal variations, anisotropic physical properties, and upstream parameters into simulations. Wang and Pilon [38] developed a three dimensional (3D) model for SCs that considers 3D electrode morphology, finite ion size, and field-dependent electrolyte dialectic permittivity. In particular, a general set of boundary conditions was derived to describe the Stern layer behavior without simulating it in the computational domain.

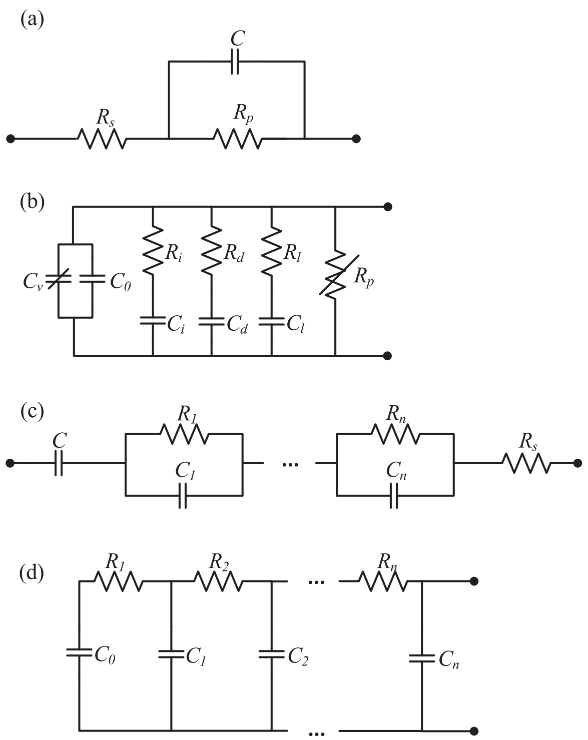

Fig. 4. Equivalent circuit models.

3.2. Equivalent circuit models

Equivalent circuit models employ parameterized RC (capacitor-resistor) networks to mimic the electrical behavior of SCs. They have simplicity and ease of implementation due to use of ordinary differential equations (ODEs) in model formulations [39]. Different models exhibit varied accuracy depending on electric circuit configuration and element number, where increasing circuit sophistication is always conducive to elevating model accuracy. The most common equivalent circuit models of SCs in the literature are illustrated in Fig. 4. The simplest equivalent circuit model is an equivalent resistor connected with a capacitor in series as presented in [40]. The capacitor accounts for the canonical capacitance effect of SCs, while the series resistor represents the overall resistance. Spyker and Nelms [41] added another parallel resistor that accounts for the self-discharge phenomenon to form the classical equivalent circuit model as shown in Fig. 4(a). Still, this model can only adequately represent SC dynamics over a time scope of several seconds, which significantly limits its realistic applicability. Zubieta and Boner [42] targeted power electronic applications and developed a model comprising three RC branches, i.e., immediate branch, delayed branch, and long-term branch. Each branch captures the SC characteristics on a distinct time-scale. A nonlinear capacitance was incorporated into the immediate branch as a voltage-dependent capacitor connected with a constant capacitor in parallel. The parameters of the three branches were subsequently extracted through observation of the terminal voltage evolution during a high constant current charging process. For this model, Rajani et al. [43] presented a novel average point method to extract the model parameters. Analogous model representations were devised by other researchers with different characterization methods [44–47]. Particularly, Liu et al. [48] quantitatively investigated the temperature impact on the model parameters, and synthesized a temperature-dependent three-branch model. Zhang and Yang [49] exploited a variable resistor to further characterize the self-discharge process in the three-branch model as shown in Fig. 4(b). Buller et al. [50] proposed a dynamic model using electrochemical impedance spectroscopy (EIS) in the frequency domain. The model was composed of a series resistor, a bulk capacitor, and two parallel RC networks as shown in Fig. 4(c). Our research employed the extended Kalman filter to extract the model parameters under dynamic driving cycles [51]. Aiming at describing the full-frequency-range behavior of an SC, Musolino et al. [52] used a dynamic model to replace the immediate branch of the three branch model, and introduced a parallel leakage resistor to form a combined SC model. Gualous et al. [53] conducted an experimental study of SC serial resistance and capacitance variations, and synthesized an equivalent circuit model with temperature-dependent parameters. Rafika et al. [54] also presented an equivalent circuit model with 14 RCL elements whose values are functions of voltage and/or temperature estimated through EIS methodology. In order to simulate the distributed capacitance and electrolyte resistance determined by the porous electrodes, transmission line models were introduced, taking transient and long-term behavior into consideration, as shown in Fig. 4(d). The model complexity relies usually on the number of the employed RC networks [55,56]. Each RC network is assigned to delineate capacitance and resistance of each pore distribution in electrodes. Generally, increasing RC networks are often beneficial to model fidelity at the expense of computational efficiency. Rizoug et al. [57] employed a hybrid method composed of a frequency approach and a temporal approach to characterize the transmission line model. Dougal et al. [58] used a numerical method to realize automatic model order selection of the transmission model based on the simulation time step, thereby engendering better modeling flexibility and computational efficiency. Our research compared three categories of equivalent circuit models for SCs, in terms of model complexity, precision, and robustness, concluding that the dynamic model displays the best overall performance [59]. Parvini et al. [60] presented a computationally efficient electrical and thermal model to account for their coupling effect for a cylindrical SC cell. The model parameters are dependent on SOC, current direction and magnitude, and operating temperature. The coupled electrothermal model was validated through driving-cycle-based tests. It is worth noted that the transmission model and the dynamic model in Table 1 are with the same model order. However, the model discretion is much easier for the latter one, which makes it more applicable for online implementation. State-space representations of classic, dynamic, and transmission models are given in Table 1.

3.3. Intelligent models

Intelligent modeling techniques, such as artificial neural network (ANN) and fuzzy logic, have been successfully utilized to predict the performance of energy storage systems including batteries and SCs [61,62]. Fig. 5 illustrates an example neuron body which processes the input signals and returns the result. Intelligence-based methods typically have the capability of depicting the complex nonlinear relationship between the performance and its influencing factors, without a detailed understanding of underlying mechanisms [63]. A large amount of high-quality training data is indispensible to ensure model accuracy and generality. These unique features have led to widespread use of intelligent methods for both SC design and performance prediction. For instance, Farsi and Gobal [64] constructed an artificial neural network model to examine the impacts of several intrinsic characteristics on the SC performance, in terms of utilization, energy density, and power density. The model inputs were crystal size, surface lattice length, exchange current density of the active material, and cell current. These parameters are critical for SC prototype design. Wu et al. [65] presented a model for SC behavior simulation, in which the model parameters were predicted through an established ANN model. The inputs of the ANN model were terminal voltage and temperature, and the outputs were two influencing factors put into the model parameter calculation. Eddahech et al. [66] built a one-layer feed-forward artificial neural network to represent the SC behavior as a complex function of current rate, temperature, chemistry, and history. The model fidelity was validated through power cycling with the

Table 1
State-space representations of some equivalent circuit models.

Model	State-space representation
Classic model [41]	$\begin{cases} \frac{du_c}{dt} = -\frac{1}{CR_p}u_c + \frac{1}{C}i \\ V_c = u_c + iR_s \end{cases}$ where V_c denotes the output voltage of the model, R_s is the internal resistance which includes the electrolyte resistance and contact resistance, R_p is used to simulate the self-discharge phenomenon, u_c denotes the voltage across the capacitor and i is the charging current.
Dynamic model [50]	$\begin{bmatrix} \frac{du_1}{dt} \\ \frac{du_2}{dt} \\ \frac{du_3}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{1}{R_1C_1} & 0 \\ 0 & 0 & \frac{1}{R_2C_2} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \begin{bmatrix} \frac{1}{C} \\ \frac{1}{C_1} \\ \frac{1}{C_2} \end{bmatrix} i$ where u_0 represents the bulk capacitance, u_1 and u_2 denote the voltages of the two RC networks, V is the output $V = u_0 + u_1 + u_2 + R_Si$ voltage, and R_s represents the series resistance.
Transmission model [54]	$\begin{bmatrix} \frac{du_1}{dt} \\ \frac{du_2}{dt} \\ \frac{du_3}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{R_2C_1} & \frac{1}{R_2C_1} & 0 \\ \frac{1}{R_2C_2} & -\frac{R_2+R_3}{R_3R_2C_2} & \frac{1}{R_3C_2} \\ 0 & \frac{1}{R_3C_3} & -\frac{1}{R_3C_3} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \begin{bmatrix} \frac{1}{C_1} \\ 0 \\ 0 \end{bmatrix} i$ where u_1, u_2 and u_3 denote the voltages across the capacitors C_1, C_2 and C_3, and V is the output voltage. $V = u_1 + R_1i$

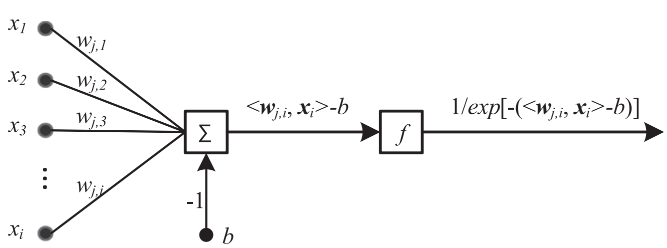

Fig. 5. Example neuron body with multiple inputs and single output.

resulting model further used for voltage control purposes. Weigert et al. [67] established a SOC estimator using artificial neural network for a battery-ultracapacitor hybrid energy storage device. Marie-Francoise et al. [68] also used an ANN model to track the output voltage subject to current, temperature, and voltage variations. The ANN network was claimed to provide useful information on the transient behavior of an SC, taking thermal influences into account.

3.4. Fractional-order models

In order to further improve modeling accuracy, fractional-order calculus has been introduced for SC modeling applications [69,70]. The consequent fractional-order models consist in non-integer order differential equations and often have a stronger capability of capturing the SC dynamics, compared with integer-order equivalent circuit models. Fig. 6 illustrates an example of fractional-order model, which consists of a series resistor, a parallel resistor, a CPE (constant-phase element), and a Walburg-like element. Regarding fractional-order models, Riu et al. [71] has done a pioneering work by introducing a half-order model for SCs capable of representing the SC behavior with high credibility, while reducing computational burden. However, the fractional differentiation order was fixated in model parameterization process, and this inevitably restricted the potential of improving modeling accuracy. Martynyuk and Ortigueira [72] proposed a fractional-order model for SCs, whose parameters were identified based on

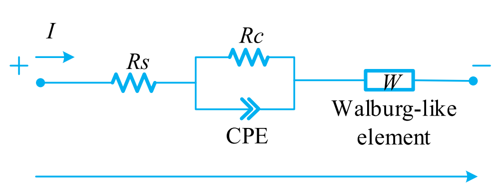

Fig. 6. Example of SC fractional-order model.

the impedance data. Also, Bertrand et al. [73] derived a non-linear fractional-order model through frequency analysis. Similarly, Martín et al. [74] presented a Havriliak–Negami based function model that achieved excellent fitting to the whole frequency range. These attempts invariably applied frequency-based impedance data to model identification. Nevertheless, the accuracy of the parameterized model is highly dependent on the precision and availability of the impedance spectra of SCs, which is only attainable in a laboratory environment. A considerable model mismatch may occur when these laboratory-calibrated models were used at practical conditions. On the contrary, Dzieliński et al. [75] proposed a fractional-order model whose parameters were identified based on time-domain data collected through constant-current charging test. Likewise, Freeborn et al. [76] estimated the impedance parameters of a fractional-order SC model by step voltage response rather than direct impedance measurement. Nonetheless, the model precision may be severely compromised, when exposed to varying loading conditions in non-laboratory conditions, since the model parameters can be highly sensitive to variable conditions. Gabano et al. [77] introduced a fractional continuous LPV (linear-parameter-varying) model, which was synthesized from a set of locally identified LTI fractional impedance models through a cubic spine interpolation technique. The operating voltage-dependent nonlinear behavior of SCs was considered, attaining higher accuracy and robustness.

The four types of models emulating the electrical behavior of SCs are straightforwardly summarized and contrasted in Table 2 for convenient reference and evaluation.

3.5. Self-discharge

SC self-discharge is an important aspect to consider during the process of a system design, particularly for long-term static power supply applications [78]. Since charged SCs have higher Gibbs free energy in comparison with discharged ones, a pseudo-driving force exists to drive open-circuit voltage (OCV) decay. This is called "self-discharge" phenomenon, and the OCV may drop up to 60% over several weeks and thus significantly limits SCs' power-delivery capability. Self-discharge mechanisms have been investigated with the aim of developing suitable models of the phenomenon. Ricketts and Ton-That [79] pointed out that SC self-discharge is caused by two different mechanisms, i.e., ion diffusion and leakage current. Ion diffusion that certainly results in charge redistribution originates from the temporary inaccessibility of the deeper and smaller pore size of the porous electrodes during charging/discharging process [80]. Black and Andreas [81] investigated the effect of charge redistribution on self-discharge and

Table 2
Summary of model types for SC electrical behavior simulation.

Category	Subclass	Upside	Downside	Examples
Electrical behavior	1). Electrochemical models	Description of inside physical-chemical reactions; High possible accuracy	Heavy computation; Immeasurability of some parameters	[27-38]
	2). Equivalent circuit models	Moderate accuracy; relatively easy implementation and model identification	Absence of physical meanings; susceptible to aging process	[39-60]
	3). Intelligent models	Good modeling capability; disclosure of the influencing factors to desirable model output	Sensitive to training data quality and quantity; poor robustness	[61-68]
	4). Fractional-order models	Better capability to fitting experimental data; few model parameters	Heavy computation;	[69-77]

examined self-charge that purely comes from the redistribution. Niu et al. [82] showed that the potential decay of the charged SC exhibited an exponential relationship with time, and was strongly affected by initial potential. This evidenced the charge redistribution effect on self-discharge, since the charge redistribution is believed to highly depend on the polarization potential. Yang and Zhang [83] synthesized self-discharge as a variable leakage resistance in a SC equivalent circuit model, and modeled it as a function of voltage rather than time. This formulation enabled the SC model suitable for practical utilization in an environmentally powered wireless sensor node. Kaus et al. [84] experimentally investigated the major factors influencing self-discharge, e.g., charge duration, charge history, working voltage, and temperature. Kowal et al. [85] further presented a detailed analysis of potential impacting factors on self-discharge and described their relationship using exponential functions. Diab et al. [86] leveraged a parameterized equivalent circuit model to characterize self-discharge of a SC, with a detailed focus on the leakage current and diffusion of ion at the electrode-electrolyte surfaces. The effect of temperature and initial voltage on the model parameters were examined in detail.

3.6. Thermal modeling

Even though SCs have low internal resistance, a great amount of heat may be generated inside SCs, as they are often operated under high-rate cycling, leading to considerable temperature variations [87]. This may have significant implications to the performance and lifetime of SCs that are strongly sensitive to temperature [88]. An accurate prediction of SC thermal condition is essential for designing cooling management at a stack level, tuning of temperature dependent parameters of electrical circuit models, and assessing aging level [46]. Schiffer et al. [89] experimentally assessed the thermal behavior of a SC, and concluded that heat generation arises from an irreversible Joule heat generation and an irreversible heat generation evoked by a change of entropy from the ion movement between discharged and charged conditions. Dandeville et al. [90] further acquired time-dependent heat profiles of a SC through the calorimetric technique and verified the Schiffer's conclusion. Diverse models have been attempted to predict SCs temperature performance, which can be generally grouped into two categories, i.e., first principle models and comprehensive models. The first principle models center on the use of partial differential equations to represent the thermal dynamics of SCs, which are usually solved by numerical discretization methods. For example, Gualous et al. [91] developed a SC heat equation and solved it using the finite difference method to determine the temperature distribution as a function of the time and position. Similarly, Wang et al. [92] put forward a three dimensional finite element thermal model of a stackable SC and analyzed its inner temperature field through a constant current charge-discharge test. Again, on the basis of the first principles, d'Entremont [93] derived a governing energy equation combined with the modified Poisson-Nernst-Plank equation to emulate electrodiffusion in the binary electrolyte. In particular, the influence of ion diffusion, steric effect, and entropy changes on the reversible and irreversible heat generation was incorporated into the model formulation.

Other studies suggested several comprehensive models to characterize the SC thermal dynamics. For instance, Sakka et al. [94] presented a study of thermal modeling and heat management of a SC pack, where the thermal model was based on a thermal-electric analogy, making the temperature prediction more intuitive. Berrueta et al. [95] coupled an electrical circuit model with a thermal model to delineate the SC behavior considering temperature impacts. The combined electro-thermal model was proven through a series of tests emulating loading conditions in pragmatic applications. Sarwar et al. [96] also proposed an electro-thermal model to predict the electrical and thermal behavior of a SC cell under a wide range of operating conditions. Each element of the model retained physical meaning. The electrical model was strongly coupled with the high-fidelity thermal model which considered material geometries, thermal properties, and air gaps. The heat generation and transfer model was used to predict the temperature variations within a cell for various conditions.

4. SC state estimation

Accurate state estimation with the presence of model uncertainty and noise is critical for ensuring reliant, efficient, and resilient operation of SC systems [97]. The most important tasks include SOC estimation and SOH monitoring. A precise metering of SOC can allow energy management controller to make better use of SCs' power potential without incurring detrimental overcharge/overdischarge or other catastrophic hazards. Different from conventional capacitors, SCs exhibit a nonlinear relationship between the terminal voltage and SOC. Besides, SC systems always endure dramatic and fast SOC variations in high-power delivering scenarios, owing to the intrinsic limit of low energy density. These challenges have invited a rich library of literature. SOH is more concerned with assuring an optimal (or economical) system design for resilience and reliability, since SCs are usually deployed as maintenance-free devices, and often inaccessible in many applications [98]. Thus, it is crucial to precisely assess the health level of SC systems by establishing high-fidelity SOH models.

4.1. SOC estimation

The SC SOC is more directly related to its terminal voltage, compared to rechargeable batteries. This is a result of the unique electrostatic energy storage characteristic. However, the reading of terminal voltage for SOC indication may lead to a considerable bias from true SOC, due to the existence of self-charge (charge redistribution and leakage current) and side-effect reactions (pseudocapacitance) inside SCs. Thus, some examinations have been conducted to explore improved solutions, which mainly hinge on intelligent models or model-based state observers. For example, our previous study established a neural network model for SC residual capacity estimation in electric vehicles, where current, voltage, and temperature are considered as the influencing factors [99]. Nadeau et al. [100], based on the three-branch equivalent circuit model, synthesized a Kalman filter for tracking the SOC of a SC, which was experimentally validated in a solar

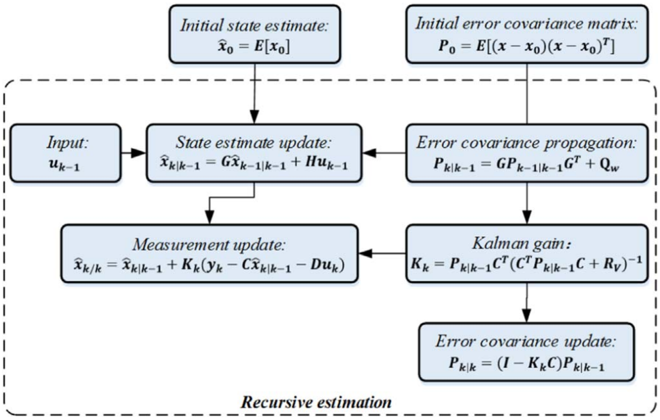

Fig. 7. Flowchart of the extended Kalman filter for the SC SOC estimation.

power application. Chiang et al. [101] applied the extended Kalman filter (EKF) to simultaneously obtain the SOC and temperature estimates using a combined formulation of a voltage-and-thermal-dependent equivalent circuit model and a thermal model. Fig. 7 gives a schematic flowchart of the proposed EKF SOC estimator.

Yang and Zhang [102] tried to use a linear capacitance instead of the rated capacitance for the SC energy estimation based on the SC physics. Dey et al. [103] proposed an online SC SOC estimation scheme using sliding mode methodology for a hybrid energy storage system composed of batteries and SCs. The estimation scheme contained two separate state observers for batteries and SCs, respectively.

The two types of SC SOC estimation methods are summarized in Table 3 for convenient reference.

4.2. SOH monitoring

SOH monitoring or aging evaluation is another fundamental aspect of state estimation to ensure safe and durable operation of SC systems. An increase of equivalent series resistance (ESR) and decrease of capacitance are two main indicators of SC aging. These are often used to define the end-of-life of an SC. The commonly-adopted criteria are an increase of 100% ESR or a reduction of 30% of capacitance [104]. Intensive efforts have been devoted to probing aging mechanisms and establishing credible aging models. It is well acknowledged that voltage and temperature are the two predominant factors that impact on the aging of SCs because elevated voltage and temperature may accelerate the decomposition of the electrolyte and side reactions within electrodes [105]. The electrolyte decomposition products can be easily trapped in the pores of electrodes, leading to decreased pore accessibility [106]. Additionally, the electrolysis of the water traces in the electrodes releases oxygen and hydrogen which further blocks the electrode pores and the separator while increasing the internal pressure [107]. Kötz et al. [108] monitored the aging of a SC in terms of capacitance, internal resistance, and leakage current by tests under constant load conditions at different voltages and temperatures. The testing results revealed that the SC aging was significantly accelerated under increased voltages or elevated temperatures. Bohlen et al. [109,110] quantified the effects of voltage and temperature on SC aging through analysis of different SC models in accelerated aging tests. They proposed a lifetime simulation model for dynamic applications. In addition to voltage and temperature, the cycling condition is expected to be another momentous factor that prominently affects SC aging. Hammer et al. [111] analyzed the cycling impact, in addition to temperature, upon SC aging using a cycling profile of a railway-traction system. Kreczanik et al. [112] compared SC degradation with cycling to that without cycling under identical voltage and temperature, and validated the role of cycling in SC aging acceleration. Furthermore, a novel method was proposed to quantify the acceleration of aging in a cycling phrase. Torregrossa and Paolone [113,114] experimentally studied the current and temperature effects on SC aging, and created a SOH model for age monitoring. SC aging assessment and prediction has been addressed in several different applications with specialized cycling profiles [115–117], with voltage and temperature impacts again being the main focus. Omar et al. [118] proved that the cycling profile had a larger influence on ESR increase than on capacitance reduction. Briat et al. [119] studied the contribution of calendar aging to the SC performance degradation during power cycling by monitoring the parameters of an impedance model. Chaari et al. [120] found out that the SC capacitance does recover after a rest period during an interruption of an accelerated aging test. This is due to charge redistribution, impunity rebalancing and return to the cell thermodynamic steady-state conditions. They accordingly proposed a model to predict the capacitance recovery during rest. Chaoui et al. [121] developed an online system identification method for SC SOH estimation using a Lyapunov-based adaptation law, so that the observer's stability can be guaranteed by the Lyapunov direct method. El Mejdoubi et al. [122] presented an online SOH estimation method using the extended Kalman filter as well.

The SC SOH monitoring methods are categorized in Table 4 for convenient reference.

5. Industrial applications of SCs

SCs have been adopted in multitude industrial applications, and there are a number of research papers that provide technical details for SC-attached systems.

5.1. Uninterruptible power supplies (UPS)

UPS systems are used to provide reliable and uninterruptible power for critical loads by transferring power supply from the utility to backup energy storage when a power disruption occurs. Rechargeable batteries are always the primary choice owing to their comparatively high energy density. However, there are several disadvantages associated with batteries, such as low power density and limited cycle life. The pulsating currents during utility power disruption would increase battery losses and reduce battery cycle life [123]. Instead, Lahyani et al. [124] proposed a combination of rechargeable batteries and SCs for UPS energy storage, where SCs were utilized to suppress the peak power applied to the batteries during backup time and offered full power delivery during short-time grid outages. By maintaining SCs at a suitable charge, SCs would fulfill impulse power demands to subdue the battery current transients, therefore prolonging the service life of the overall energy storage.

Table 3
Summary of all SC SOC estimation methods.

Category	Subclass	Upside	Downside	Examples
SOC estimation	1). Artificial neural networks	Good nonlinear mapping; disclosure of the influences of related factors	Sensitive to training data quality and quantity; poor robustness	[99]
	2). Kalman filter-based and observer-based methods	Online and closed-loop	Relatively heavy computational burden; sensitive to precision and robustness of battery model	[100, 101]

Table 4
Summary of all SC SOH monitoring methods.

Category	Subclass	Upside	Downside	Examples
SOH monitoring	Mechanism analysis based empirical SOH models	Exposure of underlying reasons behind SC aging;	Offline and empirical; Time-consuming for model establishment	[108–117, 120]
	Kalman filter-based and observer-based methods	Online and closed-loop	High computational requirement; susceptible to accuracy and robustness of SC models	[121, 122]

5.2. Power electronics

Power electronics devices are an integral part of many power systems for power-level bridging, AC-DC, or DC-AC transformation. Large back-up storage requires batteries, although DC links usually use DC capacitors for short-term charge storage. SCs can provide an alternative in power electronic converter applications. The high capacitance can reduce the size of energy back-up unit, leading to power rating increase and/or cost reduction. Kankanamge and Kularatna [125] presented a DC-DC converter design with improved end-to-end efficiency based on a SC-assisted low-dropout regulator technique.

In contrast to the switching regulators with bulky inductors, the use of SCs as lossless voltage dividers could effectively alleviate the ratio-frequency interference and electromagnetic interference issues, since the energy reuse only happens at quite low frequency ranges. Ortuzar et al. [126] analyzed a multi-state inverter using three-state converters where a SC was deployed as a DC-link. The high capacity of the SC helped obtain a very stable DC-link and made it possible to keep feeding the contaminated load during a voltage dip.

5.3. Renewables integration

Renewable energy systems have been being intensively developed in recent years. However, there exist considerable frequency and voltage fluctuations when integrating these systems, as a consequence of the intermittent nature of many renewable energy sources. Therefore, an energy storage system is often needed in a renewable system to buffer the electricity generation with consumption. Energy storage plays an important role in load leveling, energy arbitrage (storing energy to use when the price is at a premium), primary frequency regulation, and power peak shaving [127]. Abbey and Joos [128] presented a wind turbine generator with SCs as the energy storage unit to mitigate the impacts of intermittency. The SCs were harnessed to reinforce the DC bus during transients, thus enhancing its low-voltage ride-through capability. Abbey and Joos [129] reported on a three-level inverter for wind energy conversion, where the SC was used to increase the clamping capacitance, and the SC voltage is allowed to vary. A space vector modulation scheme was employed to solve the uneven space vector distribution issue and produce undistorted currents. The efficacy of the proposed system for intermittency attenuation was validated by simulation and experimental studies. Pegueroles-Queralt et al. [130] put forward a simple power smoothing strategy based on SCs for conditioning of renewable energy generation in a distributed network. The strategy focused on managing the SC SOC while generating a power file capable of smoothing the power variations of a renewable energy generation system. Mutoh and Inoue [131] introduced a series-connected SC pack to facilitate the implementation of Maximum Power Point Tracking (MPPT) for photovoltaic generation systems, through fast charging/discharging to better accommodate varying weather conditions.

5.4. Hybrid energy storage

Hybrid energy storage systems combine more than one energy storage devices with complementary characteristics, especially in terms of energy and power, to achieve performance improvement and size reduction in comparison to standalone usage. SCs are an ideal complement to high-energy but slow-response energy storage devices, such as fuel cells and rechargeable batteries, owing to their fast response time and extremely long lifespan. An example hybrid energy storage system is given in Fig. 8. This prompts renewable energy and EV penetration through appropriate electronics and control design. Hybridization with fuel cells or rechargeable batteries or both has been well documented in the literature for various engineering applications [132–134]. In these hybrid systems, SCs are invariably used to meet the dynamic transients while fuel cells or batteries are only responsible for fulfilling the average power demands. For fuel cells, the SC can offset slow cell response. This makes fuel cells applicable for dynamic load leveling applications, such as fuel cell hybrid vehicles [135,136]. For batteries, the dynamic components of load would be handled by SCs, resulting in better retention of battery cycle-life and power enhancement as a whole [136–138]. Bauman and Kazerani [139] conducted a comparative study of discrepant hybrid energy storage configurations including fuel-cell-battery, fuel-cell-SC, and fuel-cell-battery-SC for fuel-cell hybrid vehicle applications. The overall performance of each configuration, in terms of acceleration time, fuel economy, and cost, was systematically examined and compared. Lemofouet and Rufer [140] reported an unusual hybrid energy storage system using compressed air and SCs for a maximum efficiency point tracking.

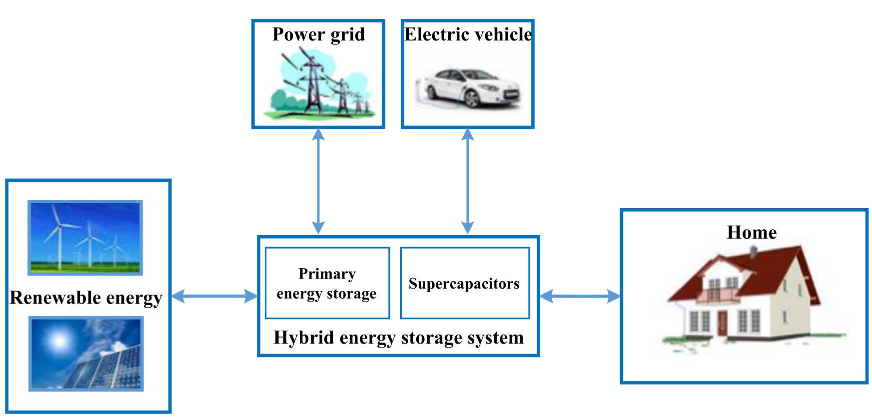

Fig. 8. Hybrid energy storage system for renewable energy and EV applications.

5.5. Other industrial applications

SCs are also a good choice as energy buffer for adjustable variable drives (AVDs) and other industrial applications. AVDs have grown in popularity as the required inverter cost has dropped, and they are efficient and flexible. Nevertheless, they are subject to power fluctuations and interruptions, which may trigger AVD actions such as reset and shut-down that interrupt operation. Durán-Gómez et al. [141] provided a ride-through approach under short-term power interruption with a SC-powered flywheel converter for ASDs. Abdel-baqi et al. [142] used SCs to supplement diesel-powered generators in hydraulic mining shovels, in order to meet the dynamic response, increase the efficiency, and deliver better fuel economy. The SCs were operated when the rate-of-change of the load exceeds a specific limit, so that they could ease the power ramp requirement for the generators, thereby maintaining an optimal engine speed.

6. Summary and conclusions

A comprehensive survey of the recent literature on SC modeling, state estimation, and important industrial applications from a control/management perspective is presented. We briefly introduce the advantageous traits of SCs as a promising energy storage technology for peak power delivery, including high power density, low internal resistance, wide operating temperature range, excellent durability, *etc*. These properties are due to the double-layer capacitor structure, which stores energy through electrostatic charge transfer at the interface of electrolyte and electrodes. Unlike conventional capacitors, the concomitant reversible Faradaic reactions result in nonlinear behavior. Hence there has been much work on developing models to simulate the electrical behavior and self-discharge phenomenon of a SC. Additionally, since SCs are always exploited to meet high-power demands, high-fidelity thermal models are much needed for efficient thermal management design to secure operational safety.

Various models are elaborately discussed, in terms of model structure, complexity, and accuracy for electrical behavior simulation, which are sorted into four groups: electrochemical, equivalent circuit, intelligent, and fractional-order models. For self-discharge simulation, extensive efforts are directed to revealing the related mechanism and developing reliable models, with diffusion and charge redistribution being considered as the main causes behind such a phenomenon. For thermal modeling, both first principle models and comprehensive models are presented for SC temperature prediction, with the former exhibiting better modeling precision at the cost of simplicity and computational speed.

Methods for SC SOC estimation and SOH monitoring are also systematically reviewed. For SOC estimation, the extended Kalman filter is the primary choice in the literature for its characteristics of online, self-corrected implementation. For SOH monitoring, the survey shows that most of methods begin with the analysis of underlying aging mechanism, underscoring the effects of temperature, voltage, and cycling conditions on SC aging. Then, numerous SOH models are accordingly developed, based on aging mechanism analysis.

Finally, important industrial applications for SCs are introduced, such as UPS systems, power electronics, renewable energy systems, and hybrid energy storage systems. In such applications, both high power density and prominent durability of SCs are greatly valued.

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