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Supercapacitor management system: A comprehensive review of modeling, estimation, balancing, and protection techniques

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A R T I C L E I N F O

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A B S T R A C T

Recent advances in energy storage systems have speeded up the development of new technologies such as electric vehicles and renewable energy systems. In this respect, supercapacitors have gained interest due to their unique features such as high power density, long lifespan, and wide operating range. To achieve the high-voltage levels required for vehicular or utility applications, a supercapacitor pack should contain hundreds of high-capacity series-parallel cells. The internal states of these cells cannot be obtained by direct measurements and these states are usually affected by operating conditions such as temperature and noise. In addition, due to the uncertainty in the manufacturing processes, the characteristics between different batches or even the same batch of supercapacitor cells will be unavoidably different, which will impose significant challenges in terms of uniformity, functional safety, and durability of the system. Therefore, the supercapacitor pack will require a management system to effectively monitor, control, and protect the cells along all performance boundaries. Based on a comprehensive review of the latest articles and achievements in the field, as well as some useful previous experiences of the authors, this paper provides an overview of the key technologies, functionalities, and requirements for Supercapacitor Management Systems (SMSs). To the best of the author's knowledge, this is the first survey that provides an inclusive collection of key requirements for the SMS, including issues related to the modeling, estimation, control, and protection of the supercapacitors. The supercapacitor is a relatively new technology and no international standard about SMSs and their functional requirements are available up to date. The present survey will perfectly fill these gaps. In the survey, the key SMS requirements are broadly divided into the software and hardware functions, and several key issues including modeling and state estimation functions, control and balancing circuits, etc. Are covered. A comprehensive review of the supercapacitor/SMS vehicular applications is also provided in this paper.

1. Introduction

With the advancement of Energy Storage Systems (ESSs), Electric Vehicle (EV) industry has witnessed significant growth in recent years [1]. Investments are very strong in this sector and it is anticipated that the global market demand of the EVs will exceed 1200 billion dollars by 2027 [2]. Despite the magnificent investments and achievements in the ESS field and electric car industry, there are still some unresolved challenges regarding the lifetime, efficiency, and cost of the ESSs in EVs [3]. An effective way to address these challenges is the hybridization of ESSs and batteries-supercapacitors have gained a particular interest in this regard [4]. Along with the advancements in supercapacitor technologies, it is also critical to develop complementary technologies with enhanced performance to allow industrialization and wider market penetration. In this regard, Supercapacitor Management System (SMS) is of particular importance due to its critical role in the safe and reliable operation of the system. Therefore, review of the functional requirements for SMSs is critical and this is the key issue that this review paper will address.

Different ESS technologies have been used in EVs including batteries, supercapacitors, fuel cells, and flywheels. Among these, batteries have been the dominant ESS technology due to their high energy density and relatively lower cost. Fuel cells are behind batteries due to the lower energy efficiency and higher costs associated with the initial investment

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and hydrogen production. Nonetheless, batteries have relatively low power density, which limits their capability in producing or capturing high current pulses during the EV acceleration or regenerative braking conditions [4]. Besides, batteries have a limited lifetime and strong evidence shows that high charge/discharge rates will speed up their aging process [5,6]. A qualitative comparison between different ESS technologies is shown in Fig. 1. The comparison reveals that, unlike batteries, supercapacitors and flywheels achieve substantially higher power density. However, the energy density of these ESSs is limited and thus, they cannot be used as the sole ESS in EVs. Instead, they can be used along the main battery ESS to act as a power buffer during peak power conditions. This will shift the transients from battery toward supercapacitor or flywheel, which not only reduces the battery degradation but also yields better transient performance such as improved EV acceleration or higher energy efficiency during braking [7,8]. This concept is sometimes referred to as Hybrid ESS (HESS) which combines two or more ESSs to benefit from their complementary characteristics [9–11]. Supercapacitors and flywheels offer similar capabilities as shown in Fig. 1. Flywheel excels the supercapacitor in terms of operating temperature window as well as due to its long no-maintenance life. However, compared to the supercapacitor, it has more complexity and unfavorable dimensions, which makes it useful in applications where there is enough room to place it such as railway transportation applications. Flywheel is a newer technology and more difficult to quantify in terms of cost, given the few commercial competitors available in the market. However, flywheels usually involve multiple expensive components which besides the flywheel materials will cause higher capital expenses compared to supercapacitors [12]. A detailed comparison of the ESSs can be found in Ref. [12].

Supercapacitors, also known as ultracapacitors, have several unique features such as high power density, wide operating temperature range, high efficiency, and long cycle life [13,14]. The effectiveness of the supercapacitor-based HESSs has been demonstrated in a large number of research works, showing improved performance in terms of acceleration of the EV [15], energy efficiency during regenerative braking [9], driving range of the EV [9,16], and the lifetime of battery [17–19]. Remarkably, several commercial EV prototypes available today are using this technology in their drivetrain, e.g. AFS Trinity Power Corporation patented an electric drivetrain concept called "Extreme Hybrid™", which actively combines the battery and supercapacitor technologies [20]. Lamborghini Sian hybrid hypercar also uses supercapacitors to deliver an extra 34 horsepower bridging the gaps in power delivery that occurs during gear shift in the mechanical transmission system [21]. In addition to the HESS applications, the supercapacitors have been used individually in electric buses, known as Capacitor Bus or Capabus [22]. The application of large supercapacitor packs to reduce the DC-link voltage fluctuations in DC networks of railway systems has also been widely studied in the literature [23]. To show the industrial importance of the supercapacitors and SMSs, commercialized supercapacitor-based vehicles are reviewed in Figs. 2 and 3 [22,24–46].

To achieve the desired voltage/energy/power levels, hundreds of supercapacitor cells should be cascaded in series and parallel to form a supercapacitor pack [47,48]. The existence of a large number of cells in the supercapacitor pack imposes high risks in terms of functional safety and reliability. The main reason for this is that the characteristics of the supercapacitors cells such as their capacitance, equivalent series resistance (ESR), self-discharge, etc. Are often inconsistent due to the inaccuracies of the manufacturing equipment, material differences, and uncertainties in the cell manufacturing process. At the pack level, these inconsistencies have negative impacts on the lifetime and performance of the system such as its power and energy availability or inhomogeneous distribution of temperature across the pack, which will accelerate the degradation of the cells. Additionally, the performance of the supercapacitor pack crucially depends on the cells' state variables, which should be estimated since they cannot be directly measured through any physical sensors. What's more, these state variables depend on the operating conditions such as temperature, charge/discharge current, etc. which makes their prediction more challenging. Upsizing of the supercapacitor pack will reduce the predictability and representativeness of these state variables, which further complicates the estimation process. Implementation of effective SMSs will mitigate these problems by enabling accurate estimation of the internal states as well as effective management and protection of the supercapacitor cells in different operating conditions [49]. This will improve the performance, safety, and lifetime of the supercapacitor pack.

By reviewing the state-of-the-art and latest achievements in the field, this article provides a detailed review of the hardware and software functions of vehicular SMSs. Although some review works have been published regarding some specific aspects of the SMSs such as merely modeling or estimation topics, no comprehensive work regarding the

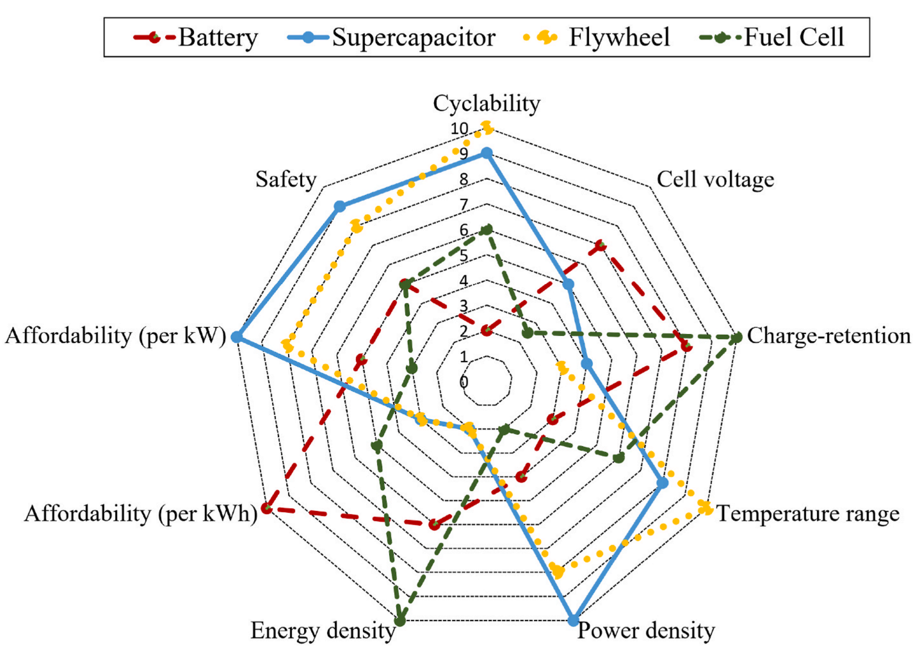

Fig. 1. Qualitative comparison between different ESSs. Quality of each feature is relatively scored on a 0–10 basis [9].

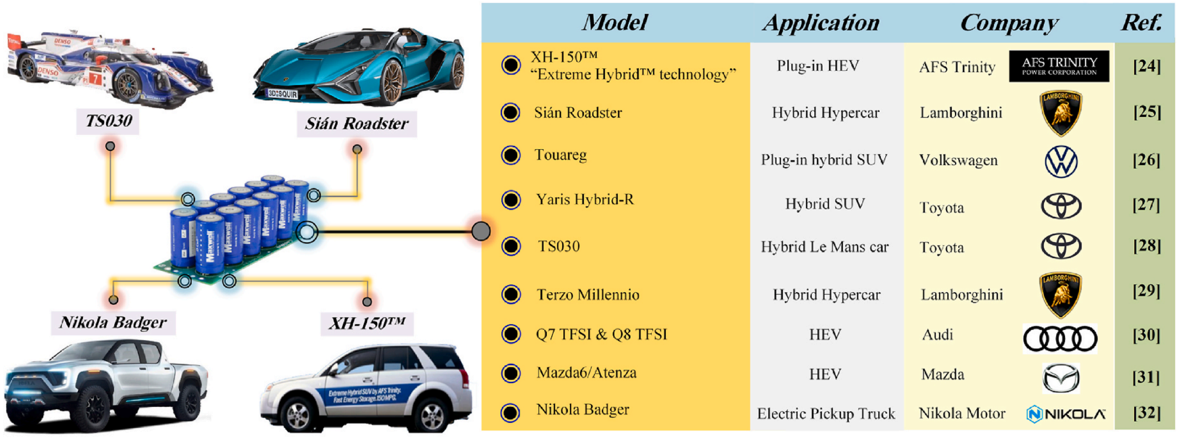

Fig. 2. Review of the industrial applications of the supercapacitors in light EVs and hybrid EVs.

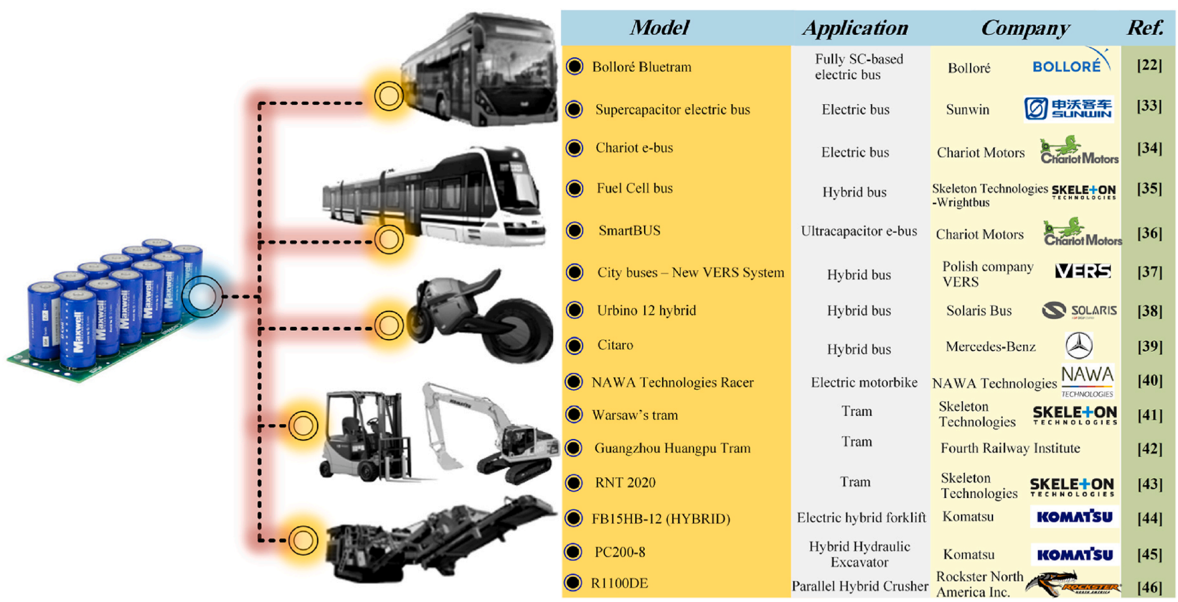

Fig. 3. Supercapacitor applications in electric motorbikes, electric buses, and other heavy-duty vehicles.

SMSs including all necessary functionalities has been published in the past. Likewise, no international standard has been established on this topic. In Table 1, the published review works on the supercapacitor topic and their respective focus area are listed. The review of supercapacitor models and some state estimation functions are provided in Ref. [50]. However, this review paper is old and it does not cover the advancements achieved in the last few years. Likewise, the SMS architecture, balancing function, and some state estimation requirements are not covered in Ref. [50]. This review paper suitably fills the foregoing gaps.

Table 1
Review articles in the area of supercapacitors.

Reference	Subject	Year
[51]	Characterization and modeling	2014
[52]	Supercapacitor active materials	2016
[53]	Supercapacitor material and structure	2016
[54]	Supercapacitor active materials	2016
[50]	Modeling and state estimation	2018
[55]	Supercapacitor electrical circuit models	2018
[56]	Fractional order modeling of supercapacitors	2018
[57]	Electrochemical modeling of supercapacitors	2019
[58]	Supercapacitor reliability issues	2020

The rest of this paper is organized as follows: A preliminary review of the supercapacitor and SMS fundamentals is fulfilled in Section 2. In Section 3, different supercapacitor modeling approaches are reviewed. Section 4 provides a review of different estimation strategies for SMSs. The hardware and software aspects for cell balancing are discussed in Section 5. In Section 6, the challenges and opportunities are explained. Finally, the summary and conclusions of the paper are provided in Section 7.

2. Preliminary review of the supercapacitor and SMS structure

The supercapacitor is a type of capacitor that has capacitance values extremely higher than the conventional electrolyte capacitors. However, from the construction and operation points of view, the supercapacitor and electrolyte capacitor differ, significantly. The structure of the supercapacitor is shown in Fig. 4(a). It consists of positive and negative electrodes (current collectors), a separator, and the electrolyte. The construction of the supercapacitor is more like the electrochemical batteries in which both of the electrodes are immersed in the electrolyte solution and are separated using the so-called separator layer [53]. The separator is a membrane that insulates the electrodes and guarantees only the mobility of ions rather than the electric connection between

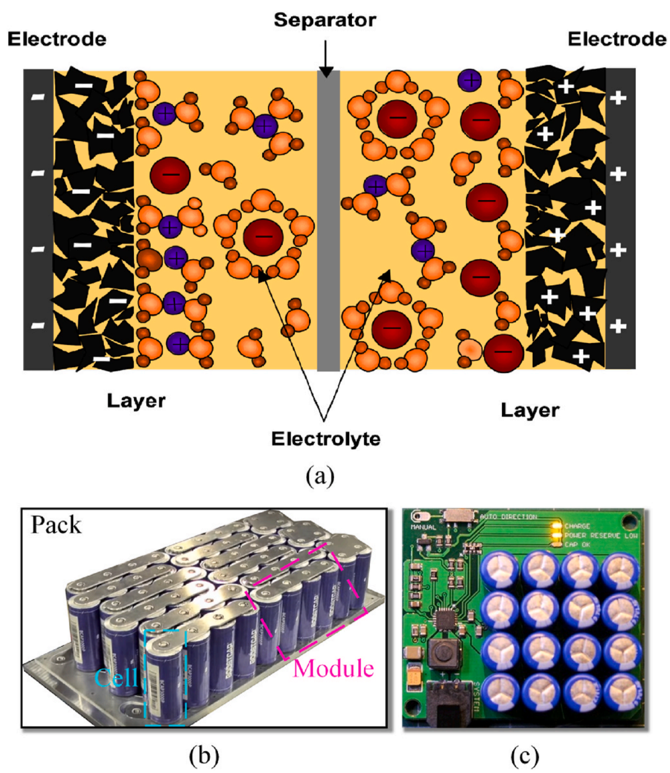

Fig. 4. (a) Structure of the supercapacitor (b) A typical supercapacitor pack (c) A typical SMS integrated with the supercapacitor module [62,63].

them. The energy will be stored through the construction of the so-called double-layer structure (also known as the Helmholtz layer) between the electrolyte and the electrode interfaces [59]. The cations and the anions of the electrolyte solution will be respectively attracted by the negative and positive electrodes forming thin double layers without the need to charge transfer. Therefore, the storage of energy involves no electrochemical phase or composition changes making the whole process extremely reversible so the charge/discharge process can be fulfilled frequently and ideally without any limitation [59]. This is why supercapacitors can achieve extremely higher life cycles than electrochemical batteries [60]. The high capacitance value is achieved by reducing the thickness of the membrane separator and through the high specific surface area of the electrodes, which are constructed using advanced carbon-based material, known as carbon nanotubes (CNTs), with high conductivity and physically porous structure. Supercapacitors can be broadly categorized into three different groups: 1-double layer capacitors, 2-pseudocapacitors, and 3- hybrid capacitors. The hybrid capacitors are also known as Li-ion capacitors, which are a combination of the Li-ion batteries (anode) and supercapacitors (cathode). More information about the physics of the supercapacitor can be found in Refs. [2,59]. In large-scale applications, the supercapacitor pack consists of hundreds of cells [61]. Effective management of these cells is critical to meet the performance, safety, and reliability requirements.

SMS is a new concept with no standardization so far. However, similar to a battery management system (BMS), SMS can be defined as a system that manages the supercapacitor pack [49]. Such a system could include electronic and control systems for measurement, acquisition, and processing of the key variables, mechanical systems such as contactors/fuses to limit the charge/discharge current in normal/abnormal conditions, and any other possible software/hardware technology or apparatus [64,65]. The inputs to the SMS mostly include the sensory circuitry (sensors, supply and pull-up circuitry, interface electronics such as voltage dividers, analog to digital converters, etc.) to measure the current of the main circuit and several voltage sensors to measure cell voltages. Likewise, temperature sensors (NTC, PTC, and/or thermocouple) are used to measure the cells' temperatures, temperature across the pack, and the temperature of the inlet and outlet cooling liquids for thermal management. Other inputs include the signals received from acceleration and braking pedals, general-purpose inputs such as the system ON/OFF commands, signals from interlocks to distinguish the charging conditions, etc.

The SMS processes these signals and generates appropriate commands to control the electric fans or heaters in case the pack is equipped with an active thermal management system or to control the balancing circuit [66]. The SMS also communicates with the electronic control unit (ECU) and the BMS to collaboratively define the charge/discharge power limits in different operating conditions [50]. Likewise, the SMS controls the operation of the contactors to restrain the inrush current caused by the start-up or when the current is extremely high due to abnormal or abusive usage. Additionally, the SMS generates alarms to indicate abnormal conditions and information signals to show the temperature, State-of-Charge (SoC), etc. Fig. 4(b) and (c) show a typical supercapacitor pack and a typical SMS board, respectively.

The management of the cells can be fulfilled in a centralized, distributed, or modular manner, as briefly explained below [67]:

- Centralized SMS: All the supercapacitor cells inside the pack will be supervised and controlled using a single controller, which can be connected to the cells through a multitude of wires. The centralized SMS is cheap but is not expandable. Also, excessive wiring will increase the complexity.
- Distributed SMS: A single SMS board will be installed for each supercapacitor cell and the cell information will be communicated to the main controller through a single data cable. The distributed SMS is very expensive because an SMS board is required for each cell. However, implementation of this structure is relatively easy.
- Modular SMS: This SMS structure follows a master/slave topology, in which each slave SMS board implements primary measurement, estimation, and protection functions for some supercapacitor cells (typically 5 to 10 cells depending on the technology) and the slave SMSs subsequently transmit the data to the master controller for upper-level control and supervision. The modular SMS offers a trade-off between the features of the centralized and distributed SMSs.

Fig. 5 shows different functionalities of the SMS. Likewise, the functional diagram of the SMS is shown in Fig. 6. Different hardware/software functionalities are discussed in the following subsections.

A. Performance Management

The performance management function receives the measured variables of the cells (current, voltage, and temperature) and subsequently processes this data to estimate the state variables such as the SoC. The total voltage of the supercapacitor pack can also be monitored in the SMS. The auxiliary variables that can be measured and monitored in the SMS include, for example, smoke sensors, leakage current to monitor the insulation resistance between the high-voltage pack and chassis of the EV, analog/digital signals from collision detector sensors, etc. The key variables that should be estimated in the SMS include the SoC, internal resistance, and State-of-Power (SoP). The SMS communicates this information to ECU for adaptive control of the charge/discharge currents during regenerative braking or acceleration. The performance management unit is also responsible to control the balancing of the cells. Supercapacitors do not often require a thermal management system due to the wide operating temperature range [68,69]. However, in case cooling systems are contrived, the performance management unit will generate and send appropriate signals to control the operation of the cooling system.

B. Diagnostics

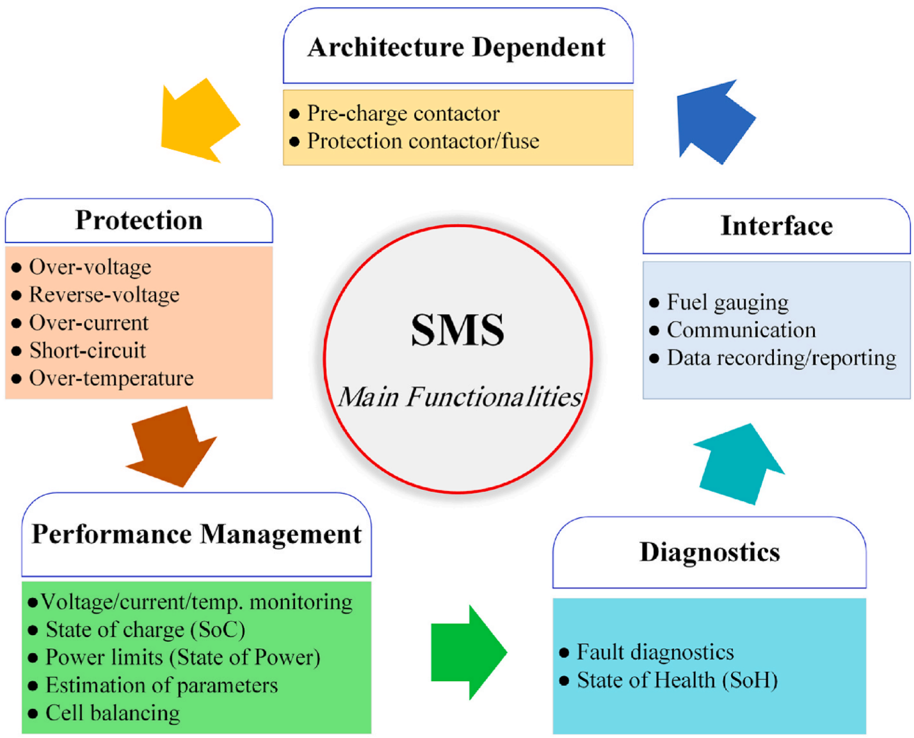

Fig. 5. Key functionalities of the SMS.

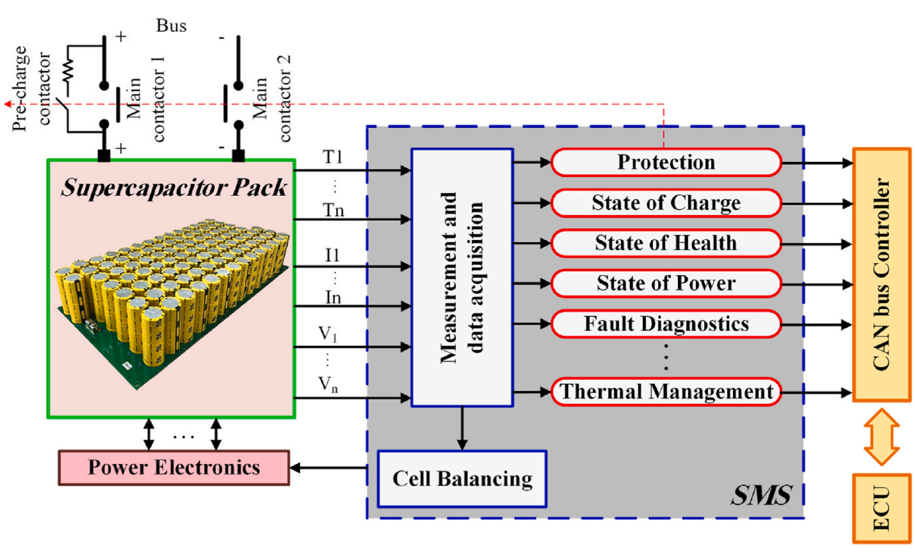

Fig. 6. Block diagram of the SMS.

The diagnostics function is responsible to monitor the supercapacitor aging through continuous estimation of the State-of-Health (SoH). The most important indicators of aging are the capacitance and internal resistance of the cells. The knowledge of SoH will be used to adjust the model parameters in the performance management unit to maintain the accuracy of other functions such as SoC or SoP estimation algorithms. Instantaneous monitoring of the aging variables also enables detecting the unusual reduction of the capacitance or the increment of the internal resistance, which can occur as a result of failures or aggressive operating conditions such as high temperatures.

C. Interface

This unit is responsible for the information exchange through internal/external communications with the Controller Area Network (CAN). For example, sending data to the ECU or BMS, sending the SoC status to the Graphical User Interface (GUI), and storing important data for the guarantee and warranty purposes such as report generation in case of fault conditions, recording periodically the charge/discharge history, etc. [70].

D. Architecture-dependent

Based on the measured variables, processed data, and the data coming from the ECU, the SMS will send necessary commands to the external contactors. For example, if the supercapacitor SoC is low, the pre-charge contactor will be activated by the SMS to avoid inrush currents at the start of the charging process, which can melt down the connectors. Also, the SMS can send a signal to the protection contactor to open it, e.g. in overload conditions, internal/external short-circuit conditions, etc.

E. Protection

Generic types of protection include over-voltage, under-voltage (discharge should be allowed only to a specific limit due to safety reasons), over-current, short-circuit (internal or external), over-temperature, and reverse-voltage protection. For the implementation of these protection functions, some dedicated cell protection ICs are available. For example, BD14000EFV-C from ROHM Semiconductor© and LTC3625 from Analog Devices© are supercapacitor cell balancer ICs, which have integrated cell over-voltage protection features. BQ33100 IC from Texas Instruments© (TI) offers active cell balancing with integrated over-voltage, under-voltage, over-current, short-circuit, and over-temperature protection for up to 5 series-connected supercapacitor cells. GreenPack™ IC from Dialog Semiconductor offers all supercapacitor protection features, as well. TI's BQ77216 and BQ24640 ICs can also be used to protect supercapacitor cells against over-voltage and over-temperature conditions. The protection ICs can be integrated with the main SMS circuitry.

When series-connected supercapacitor cells get discharged very fast, the voltage across the low-capacitance value cells can become negative, which will undesirably affect their lifetime. Thus, the cells need reverse-voltage protection to solve this problem. This can be simply realized by adding a diode in parallel with each cell such that the diode is always reverse-biased in normal operating conditions. To enhance the protection, a Zener diode can be used instead of a standard diode to also protect the cell against the over-voltage condition. LTC3625 features reverse-voltage protection as default.

The protection function should also be able to monitor and detect excessive supercapacitor leakage currents. TI's BQ33100 has an integrated protection unit for the detection of excessive leakage. While the reviewed methods emphasize protection on the cell level, a more systematic online protection approach for supercapacitor arrays has been proposed in Ref. [71]. In this work, the short-circuit and open-circuit faults are detected in the first step. Once the faulty cell is detected, an efficient reconfiguration algorithm is applied to bypass the faulty cell thereby achieving a fault-tolerant operation. Detection of the short-circuit and open-circuit faults in supercapacitor packs have also been discussed in Ref. [72], in which an algorithmic approach based on the recursive extended least-squares (RELS) is utilized to fulfill the fault detection.

The aforementioned units can interactively communicate data with each other or externally with the BMS or ECU of the EV. The block diagram of Fig. 6 shows how these units interact with each other. As seen, usually two contactors at negative and positive terminals are implemented, which allow isolating the supercapacitor pack in special cases, e.g. to isolate the chassis from the supercapacitor pack in case of a repair or to isolate it in case of an accident.

3. Modeling of the supercapacitor

Modeling of the supercapacitor is a critical step to fulfill different objectives including 1- characterization of the electrical/thermal performances, 2- condition monitoring and diagnostics, 2- estimation of SoC, SoP, and SoH, and 4- synthesis of the control mechanisms. The appropriate supercapacitor model should be selected considering accuracy and complexity standpoints. As shown in Fig. 7, the supercapacitor models can be broadly categorized into five major groups: 1- electrochemical models, 2- Equivalent Circuit Models (ECMs), 3- Fractional-Order Models (FOMs), 4- Data-Driven Models (DDMs), and 5- thermal models [73]. The foregoing modeling categories are reviewed in the following.

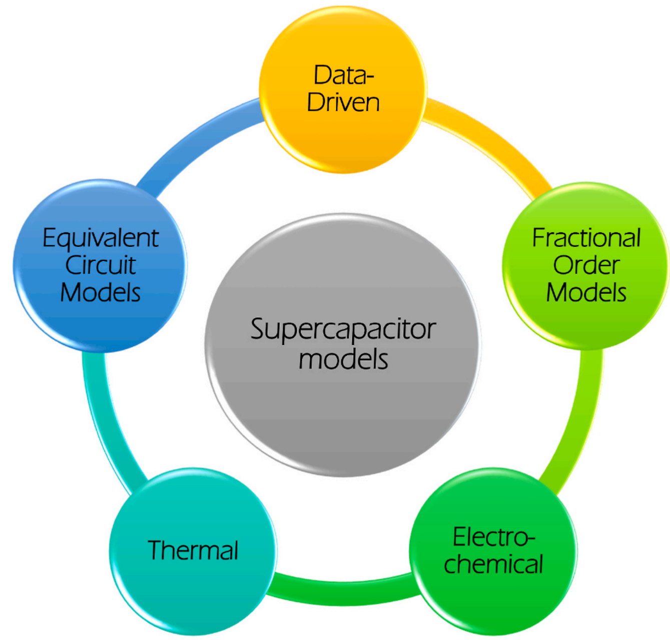

Fig. 7. Classification of different types of supercapacitor models.

A. Electrochemical models

Electrochemical models precisely represent the reaction processes that occur inside the supercapacitor cell (e.g. double layer effect, mobility of the ions and diffusion, etc.), which can be fulfilled using some partial differential equations (PDEs). As previously discussed, supercapacitor works based on the double layer phenomenon or the so-called Helmholtz effect, which is named after the German physicist Hermann von Helmholtz who first discovered the double layer effect, as reported in Ref. [74] for the first time. He found that when an electrode is submerged in an electrolyte solution, the charges will be absorbed in the surface of the electrode. Helmholtz developed a model similar to the traditional electrolyte capacitors to represent this behavior. However, the shortcoming of the Helmholtz model is that the voltage dependency of the capacity cannot be captured with this model. The Helmholtz model was subsequently enhanced in Refs. [75,76], where the double layer phenomenon is modeled considering the mobility of ions in the electrolyte solution. To show the relationship between the electrical potential caused by the diffusion process and the ionic concentration, the Boltzmann distribution equation was proposed in these works. The drawback of this model is that the predicted capacity is higher than the real capacity because in this model the ions are approximated as point charges. With this assumption, the model remains valid only for low electric potentials [77,78]. Later, in Ref. [79], the aforementioned models were combined dividing the electric double layer into two separate layers, i.e. the Helmholtz layer [74] and diffuse layer [75,80]. The series connection of the capacitances related to the Helmholtz and diffuse layers constitute the total capacitance of the double layer. The latter three electrochemical models are depicted in Fig. 8 [81].

The influence of the different ion sizes was later incorporated in Ref. [82]. A one-dimensional single-domain analytical model has also been proposed in Ref. [83], in which the supercapacitor was considered as a continuum body having uniform and isotropic features. This model was subsequently enhanced in Ref. [84], where a uniform formulation for the electrolyte and electrodes was established as a three-domain model. In a more recent work [85], a conceptual model has been empirically established to explain a universal mechanism based on different carbon materials including microporous, mesoporous, and graphene structures. A lattice model has also been proposed in Ref. [86] to predict the physical, dynamical, and capacitive behavior of

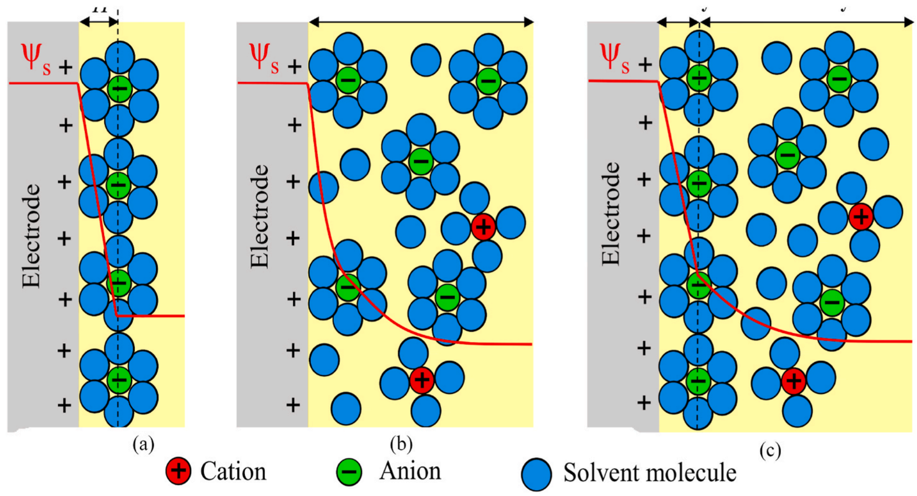

Fig. 8. Schematic of three basic electrochemical models of the supercapacitor [81] (a) Helmholtz model (b) Chapman model (c) Combined model (permission to reuse granted by Rightslink®).

supercapacitors. The model uses molecular-level inputs such as the free energy profiles to represent the ion adsorption, capacitance, and energy barriers for movements between the lattice sites. In a recent study [87], a multi-scale electrochemical model has been established to assess the porous electrodes in terms of the charge transfer capacity and ion-transfer rates. This model can capture the influences of the inter-particle pore and the porous electrode.

Despite the relatively high accuracy, the electrochemical models have low computational efficiency, which hampers their implementation in the SMSs.

B. Equivalent circuit models

The ECMs use electrical circuit parameters to represent merely the supercapacitor electrical behavior rather than the detailed physics and electrochemical effects of the cell. The ECMs are based on ordinary differential equations (ODEs). The most dominant effects that are typically incorporated in the ECMs include the capacitance and its dependency with bias voltage, voltage drop and power loss caused by the internal resistance, self-discharge and leakage current effects, and electric dynamic behavior resulting from the diffusion of the ions. A slight inductive behavior attributed to the supercapacitor metallic shields (parasitic inductance) could also be observed at very high frequencies. In Figs. 9 and 10, different ECMs of the supercapacitor are shown.

The simplest form of the ECM is shown in Fig. 9(a) which consists of an ideal capacitor representing the canonical capacitance and a series-connected resistor representing the internal voltage drop [50]. The main advantage of this model is its simplicity. However, this model neglects some important phenomena such as the self-discharge and voltage-dependency of the capacitance. This model was enhanced in Ref. [78] in which a parallel resistance is added to account for the

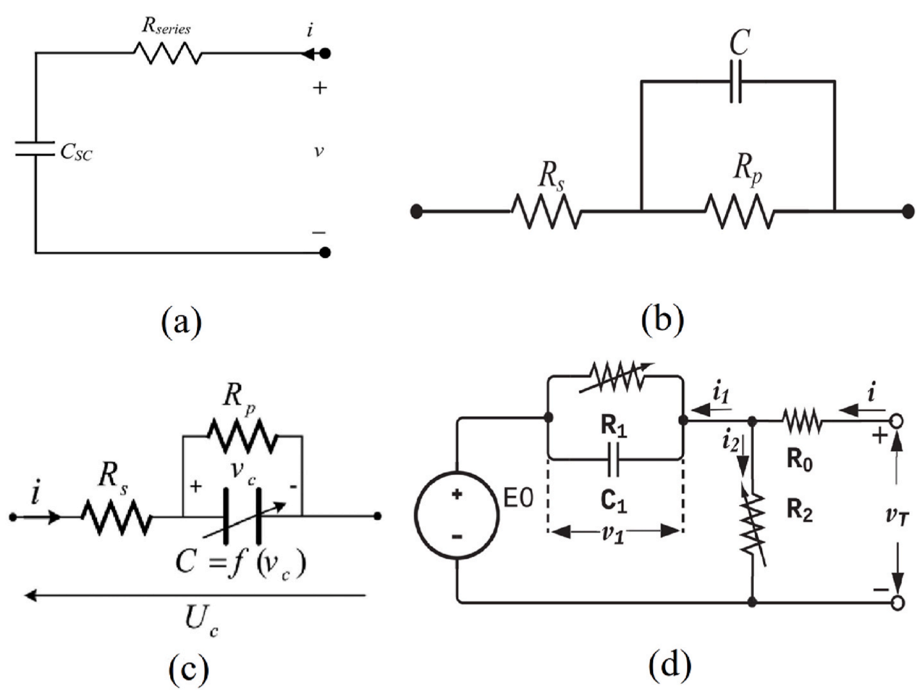

Fig. 9. Different ECMs of the supercapacitor with one RC network (a) Simple RC model (b) Simple RC with self-discharge effect (c) RC model with self-discharge and voltage-dependency effects (d) Model with diffusion-controlled charge distribution (figures collected from Refs. [50,78,88,89]).

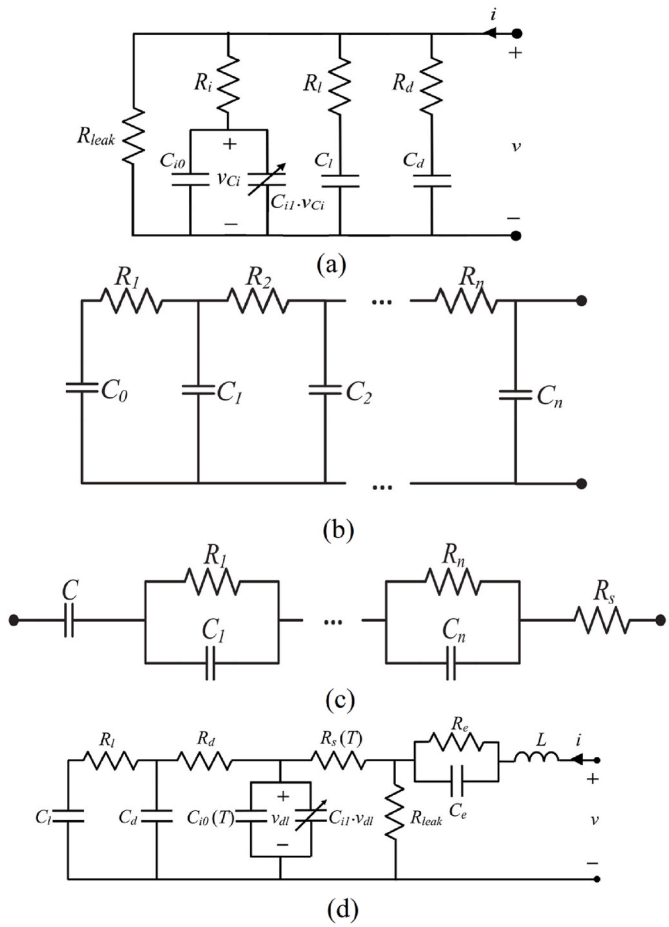

Fig. 10. Different ECMs of the supercapacitor with multiple RC networks (a) Multi-branch model (b) Transmission line model (c) Dynamic model based on RC network (d) High-frequency model considering the temperature-dependency (figures collected from Refs. [50,78,88]).

leakage current effect, as shown in Fig. 9(b). Likewise, the model proposed in Ref. [88] reinforces the previous models by incorporating the voltage-dependency effect, as shown in Fig. 9(c). The dependency of the capacitance on the bias voltage is modeled as follows:

$$C = C_1 + C_2 tanh(\frac{v}{U_x} - U_x) \tag{1}$$

where v denotes the terminal voltage, C_1 and C_2 denote constant parameters that should be obtained by optimization, and U_x denotes the voltage at the inflection point of the hyperbolic tangent function. To simplify the modeling, a linear equation can be used to represent the voltage-dependency of voltage as follows:

$$C = C_1 + C_2 v \tag{2}$$

In a recent study [89], the single RC model is improved as shown in Fig. 9(d). In this model, the resistor R_2 denotes the variable self-discharge effect. The foregoing models cannot suitably capture the diffusion behavior in the mid-frequency range. The multi-branch ECM shown in Fig. 10(a) consists of several RC networks connected in parallel to model the diffusion of the ions through the porous electrodes [90–92]. Different RC networks have different time constants which correspondingly represent specific dynamic behaviors of the supercapacitor. In some research works, the multi-branch model with two parallel RC networks and time-varying resistance for the self-discharge effect has been considered [93,94]. An efficient ladder ECM based on the controlled current source has been proposed in Ref. [95]. This model can accurately represent the dynamic self-discharge effect. Another ECM with a current source and considering different control conditions has been proposed in Ref. [96]. The multi-branch models achieve the highest accuracy in the prediction of the available energy (SoC) and self-discharge of the supercapacitor.

To take into account the distributed nature of the capacitance and resistance of the electrolyte, the transmission line model (TLM) has been proposed [97,98], which is depicted in Fig. 10(b). The number of RC networks determines the fidelity and complexity of the model and a trade-off is usually required to establish the right model for a given application. Each RC network emulates the electrical behavior of the capacitance and resistance formed at each pore distribution in the electrodes. A truncated version of the standard TLM has also been proposed in Ref. [99].

The model of Fig. 10(c) consists of a series resistance representing the instantaneous voltage drop, a bulk capacitor representing the primary capacitance of the supercapacitor, and a definite number of RC networks. These models are suitable to capture high-frequency dynamics, for example, during fast charge/discharge cycles or high-level fluctuating power pulses. In Ref. [100], a dynamic model with 14 RLC elements has been proposed. The model describes the supercapacitor behavior as a function of the bias voltage, temperature, and frequency. In Ref. [101], an efficient dynamic ECM has been established, which inherently allows the continuous distribution of the time constants in the time and frequency domains. This model can consistently explain most of the important phenomena including the time-dependent charging rate and self-discharge effect in the time domain and distribution of the relaxation times in the frequency domain.

More accurate supercapacitor models can be achieved by combining the advantageous characteristics of the aforementioned modeling techniques. For instance, in Ref. [102], an accurate model has been proposed which can represent the supercapacitor behavior up to 1 kHz while being able to capture important phenomena including the self-discharge, charge redistribution, and thermal effects, as shown in Fig. 10(d).

C. Fractional order models

The FOMs are based on the fractional calculus, which was first developed by Leibniz and L'Hospital in 1695 [103]. Compared to the ECMs with integer-order differential equations, the FOMs are composed of non-integer-order differential equations, which strengthens their capability to represent dynamic behaviors. The FOMs can achieve an acceptable accuracy level with a relatively lower number of modeling parameters compared with the ECMs. However, the FOMs are prone to inaccuracies because the model parameters will change with the variations of the voltage, current, and frequency. A typical supercapacitor FOM is shown in Fig. 11, which is composed of one series and one parallel resistor, a constant phase element (CPE), and the so-called Walburg-like element [104]. A half-order FOM has been proposed in Ref. [105]. In Refs. [106,107], Freeborn established a simple FOM based on the series connection of a resistor and a CPE. A similar FOM has been considered in Refs. [108,109], where the parameter extraction is fulfilled using the step response data. In another work, Freeborn studied the effect of artifacts caused by the optimization algorithms in the parameter extraction of the FOMs [110]. A pioneer work has been fulfilled in Ref. [111], in which a two-step least-squares fitting algorithm is proposed for online estimation of the FOM parameters. A simple FOM similar to Refs. [107,108] has been considered and the parameter

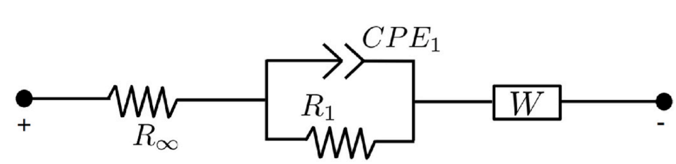

Fig. 11. A typical FOM of the supercapacitor [104].

estimation task is fulfilled by estimating the derivative order and subsequently estimating the resistance and capacitance from the current and voltage measurements. The Laplace transform and the convolution theorem have been used to extract the FOM parameters in Ref. [112]. In Ref. [113], based on the porous electrode theory, a fractional linear model has been established around the operating voltage. Based on this model, a set of fractional linear models is then used to represent the supercapacitor behavior at different operating conditions. The models are then augmented yielding a nonlinear supercapacitor model, which is updated in an online manner using the mean least squares (MLS) algorithm. In Ref. [114], the self-discharge effect of the supercapacitor is incorporated into the FOM by adding a resistor across the CPE. Identification of the FOM using constant-resistance charge/discharge experiment, constant current charge/discharge test, and the EIS has been investigated in Ref. [115]. In Ref. [116], a FOM consisting of a series resistor, a series CPE, and two parallel resistor-CPE networks has been proposed. The model is then transformed to the state-space form for estimation of the supercapacitor SoC. Some good review works about the fractional-order modeling of the supercapacitors have been fulfilled in Refs. [104,108,117].

D. Data-driven models

DDMs rely on obtaining extensive data in various operating conditions. The datasets can then be applied to intelligent models such as artificial neural networks (ANNs) or fuzzy logic (FL), which can learn from the data to represent the dynamic behavior of the supercapacitor. The schematic of a typical ANN is shown in Fig. 12. The ANN is composed of three layers, namely the input, hidden, and output layers. Generally, the DDMs have a strong potential in capturing the supercapacitor dynamic behavior. However, obtaining large data in all operating conditions of the supercapacitor is a difficult, time-consuming, and costly process. One of the early works on data-driven modeling of supercapacitor has been fulfilled in Ref. [118], in which the supercapacitor is treated as a black-box system and the modeling is fulfilled using the ANN. The supercapacitor current and temperature are considered as the input and the voltage is considered as the output. Another data-driven method for supercapacitor modeling based on radial basis function (RBF) ANN and extreme learning machine has been proposed in Ref. [119]. In Ref. [120], the feedforward ANN trained with the back-propagation algorithm has been proposed for the supercapacitor modeling. The inputs of the model are considered to be the supercapacitor temperature and the percentage of the aged carbon material and the capacitance is considered as the model output. The feedforward ANN has also been used in Refs. [121,122]. The temperature, current, and voltage of the supercapacitor are considered as the input and the voltage is considered as the output. A discrete-time fractional-order neural network has been proposed in Ref. [123], in which the supercapacitor current and voltage at current and previous sample points are considered as the input and output of the model, respectively. In Ref. [124], a recurrent ANN has been used for supercapacitor modeling with temperature, current, and voltage considered as the input and the terminal voltage considered as the model output.

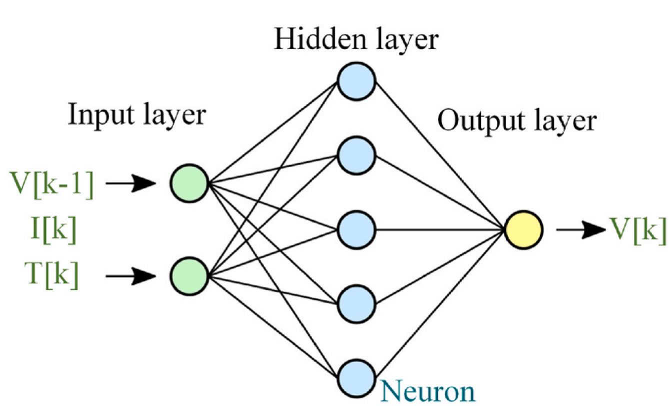

Fig. 12. Supercapacitor model based on ANN [104].

E. Thermal models

The previously reviewed models are not able to predict the internal temperature of the supercapacitor T_{SC}. However, in vehicular applications, a significant amount of heat will be generated as a result of harsh charge/discharge currents. It is important to monitor the internal temperature to realize effective thermal management. Additionally, some key parameters of the supercapacitor models such as the internal resistance and capacitance depend on the temperature. The experimental studies in Ref. [125] have shown that the increment of the temperature increases the supercapacitor capacitance but reduces the ESR. Likewise, some studies have shown that higher temperatures will speed up the self-discharge process of the supercapacitor [78]. Higher values of T_{SC} will also accelerate the side reactions inside the cells such as the oxidation processes, which will speed up the degradation process [126]. It is important to characterize the thermal effects to predict the behavior of the supercapacitor with higher accuracy.

The thermal model of the supercapacitor is mainly composed of two different segments: 1-heat generation and 2-heat transmission. One source that generates heat during the normal operation of the supercapacitor is the ohmic losses caused by the internal resistance. Likewise, reversible heat can be generated as the result of entropy change in the double layer. The heat transmission segment of the thermal model represents the characteristics with which the generated heat will be transmitted away through natural cooling, forced-air cooling, liquid cooling, etc. The thermal model presented in Ref. [127] is shown in Fig. 13(a). In the model, the heat generation is modeled as a current source, which is a function of the supercapacitor current, C_{th} represents the thermal capacity of the supercapacitor, R_{th} denotes the equivalent thermal resistance of the supercapacitor, and T_a denotes the surrounding air temperature. A similar thermal model has been established in Refs. [102,128], in which the effects of heat transmission through convection and conduction processes are separately included in the model through two series-connected resistors $R_{convection}$ and $R_{conduction}$, as shown in Fig. 13(b).

An efficient electrothermal model which combines a two-state ECM with a linear two-state one-dimensional thermal model has been pre-

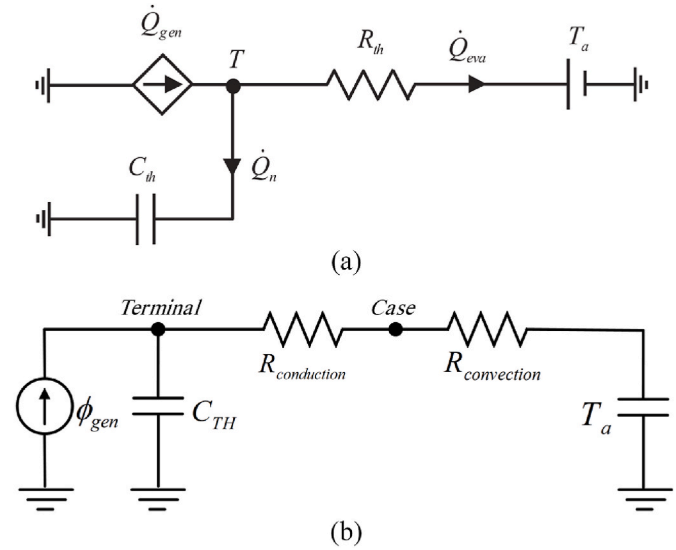

Fig. 13. Supercapacitor thermal models (a) Model presented in Ref. [127] (b) Model presented in [128].

sented in Ref. [129]. The combination of the electrical and thermal models provides a good accuracy while the model also allows the temperature-dependent parameters to be updated in real-time. The model can achieve RMSE of about 90 mV and 0.21°C in predicting the supercapacitor terminal voltage and temperature, respectively. In Ref. [130], a three-dimensional finite element thermal model is presented for the supercapacitor to investigate the internal temperature distribution of the cell. In Refs. [131,132], four thermocouples were installed inside the supercapacitor cells and the thermal investigations on the generated reversible and irreversible heats were fulfilled. A thermal model is subsequently established, which allows the determination of the internal and surface temperature distribution of the cells in both space and time.

4. State and parameter estimation in the SMS

The performance of the supercapacitor significantly depends on its internal state variables including the SoC, SoH, and SoP. To achieve effective monitoring, control, and protection of the supercapacitor, it is critical to obtain online estimations of these parameters in the SMS. The SMS uses this information, for example, to estimate the available energy, regulate the charge/discharge current rates, determine the health status of the pack, etc. Remarkably, these state variables are interconnected, which complicates the estimation process. For example, the SoC estimation process depends on the knowledge of the capacitance, which should come from the SoH estimation. Likewise, for SoP estimation, both the supercapacitor SoC and SoH must be known. In the following subsections, the estimation techniques regarding the SoC, SoH, and SoP are respectively reviewed.

A. Estimation of the state-of-charge

The SoC of the supercapacitor is an indicator of the remaining charge in the cell [133,134]. The simplest way to measure the remaining energy is based on the terminal voltage and the capacitor energy formula, i.e. $E = \frac{1}{2}CV^2$ with E being the stored energy in Joules, C the capacitance of the supercapacitor in Farad, and V the terminal voltage in Volts. However, this approach is inaccurate because the terminal voltage does not completely comprehend the underlying physical phenomena, especially when the operating range of the power consumption is wide causing some internal unobservable charges that cannot be understood only by reading the terminal voltage [135]. The existing techniques for SoC estimation can be classified into four different groups: 1- observer-based techniques, 2- filtering-based techniques, 3- data-driven methods, and 4- hybrid methods.

The observer-based methods use the supercapacitor model to estimate the SoC. The SoC estimation by the Luenberger Style Observer (LSO) has been proposed in Ref. [136]. The LSO is used to predict the terminal voltage and based on the difference between the predicted and the measured voltage, a feedback loop is incorporated in the estimation process to rectify the errors. The application of the Sliding Mode Observer (SMO) for SoC estimation has been discussed in Ref. [137]. In this work, the two-branch ECM of the supercapacitor is considered. However, the effect of the self-discharge is neglected when the ECM is transformed to the state-space form. In Refs. [138,139], the generalized extended state observer (GESO) has been proposed for SoC estimation, in which the nonlinear three-branch ECM of the supercapacitor is considered. The considered model is similar to the ECM shown in Fig. 10 (a) except that in Refs. [138,139] the effect of the leakage current is ignored in the model. The observer-based methods achieve higher accuracy than the conventional methods. They also have good computational efficiency, which makes them suitable for embedded implementation in SMSs. However, the observers cannot effectively handle the stochastic nature of the measurement noises [140–142].

The SoC estimation algorithms based on filtering can perfectly handle the negative effects of the measurement noises and the modeling uncertainties [143–146]. In Refs. [135,147], the extended Kalman filter (EKF) has been used together with the nonlinear three-branch ECM to estimate the SoC. The EKF provides good robustness against the measurement noises/errors and the mis-modeling. In Ref. [148], the dual EKF (DEKF) algorithm has been applied for SoC and parameter estimation in the SMS. In this work, one EKF is considered to estimate the SoC and a second EKF algorithm is used to update the model parameters. The EKF algorithm linearizes the supercapacitor nonlinear model at each iteration, which could lead to sub-optimal results or even divergence of the filter. Likewise, the EKF involves the calculation of a heavy Jacobian matrix, which can result in computational inefficiency. To address these problems, a joint SoC and parameter estimation algorithm based on the Unscented Kalman filter (UKF) has been proposed in Ref. [88]. The ECM shown in Fig. 9(c) is considered as the supercapacitor model and the parameters of the model, i.e. the resistances and capacitances, are introduced to the estimation framework as some new state variables. Therefore, the SoC and the parameters are simultaneously co-estimated by the UKF algorithm. The flowchart of the co-estimation algorithm is shown in Fig. 14.

The advantage of this method is its high accuracy, which is achieved by incorporating the correlation between the supercapacitor states and parameters in the estimation process. The UKF has also been used in Refs. [89,149], in which more complicated battery models are used to further increase the estimation accuracy. Also, in Ref. [150], a comparison between the EKF-based and UKF-based SoC estimation mechanisms is fulfilled, where it is concluded that the UKF excels the EKF in terms of accuracy and convergence time.

The data-driven SoC estimation methods are based on ANNs which are trained using the supercapacitor measurements in different operating conditions. In Ref. [151], an ANN composed of one input layer with 3 neurons, one hidden layer with 50 neurons, and one output layer with a single neuron is used to estimate the SoC. The current, voltage, and temperature are considered as the input to the network and the SoC is considered to be the ANN output. The ANN has also been used in Ref. [152] to estimate the SoC in a combined battery/supercapacitor ESS.

The hybrid SoC estimation methods combine the algorithms from the previously reviewed groups. For example, in Ref. [153], the back-propagation ANN is combined with the KF algorithm to predict the

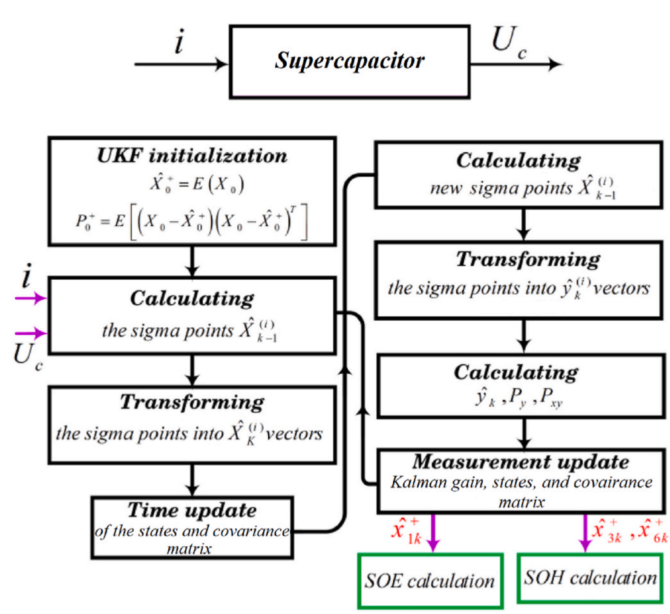

Fig. 14. Co-estimation of the supercapacitor SoC and the parameters with UKF algorithm [88] (Permission to reuse granted by RightsLink®).

supercapacitor SoC. The accuracy of this method is reported to be between 94% and 99% depending on the size of the training data.

B. Estimation Methods for State-of-Health

In automotive applications, high charge/discharge current levels, high-temperature conditions, overvoltage conditions, etc. will initiate side reactions that will cause the aging of the supercapacitor. These side reactions can generate some unwanted solid or gas particles in the electrolyte, which will have mainly two negative effects: 1-the solid particles fill the porous networks, which will reduce the effective surface area across the electrodes. Thus, the capacitance of the supercapacitor will be dropped. 2- The generated gas particles increase the inner pressure of the supercapacitor, which can create some cracks on the electrode and current collector. This not only further reduces the capacitance but also will increase the ESR limiting the supercapacitor deliverable power. Even if the supercapacitor pack remains unused, its performance can still deteriorate due to the so-called calendar aging [154,155]. The capacitance and the internal resistance can be considered as two key signatures to indicate the SoH. Various methods have been proposed for the estimation of the supercapacitor SoH. The existing methods are reviewed in the following.

The basic approach for determining the aging parameters is EIS [156–160]. The EIS is based on perturbation of the supercapacitor using sinusoidal excitation signals at different frequencies, which can accurately characterize the supercapacitor in the frequency domain. This method is very accurate however, it is an inherently offline approach and it cannot be applied for vehicular applications, in which the SoH parameters should be estimated in real-time. Likewise, the EIS requires advanced test devices that are complex and expensive. The standard method for calculation of the ESR and the capacitance is described in IEC 62576:2018, which is based on the constant current charging up to the U_R, constant voltage charging at U_R for 300s, and constant current discharging down to $0.4U_R$, with U_R being the rated voltage of the supercapacitor. The test procedure is shown in Fig. 15. The capacitance of the supercapacitor can be calculated as follows:

$$C = \frac{2W}{(0.9U_R)^2 - (0.7U_R)^2} \tag{3}$$

where C denotes the capacitance, W is the discharged energy between the start and end voltages, and U_R is the rated voltage of the supercapacitor. Also, the internal resistance can be calculated using the following formula:

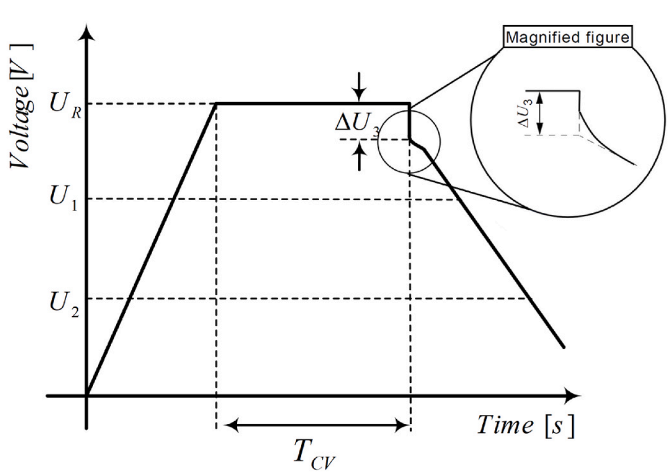

Fig. 15. Voltage waveform during the constant-current constant-voltage charging/discharging procedure specified in IEC 62576:2018 for supercapacitor characterization.

$$R = \frac{\Delta U_3}{I_d} \tag{4}$$

where R is the internal resistance, I_d is the discharge current, and ΔU_3 is the amount of voltage drop. It is recommended to use straight-line approximation using the least-squares method to obtain ΔU_3 as shown in the zoomed area in Fig. 15.

The IEC method requires taking the supercapacitor out of service to carry out offline laboratory charge-discharge experiments. Therefore, similar to the EIS, it is not well-suited for automotive applications, which require online and onboard estimation of the SoH. More advanced SoH estimation methods are based on the RLS algorithm [72,161–164], state observers [165–167], Kalman filters [88,165,168], Particle filter [169,170], ANN and deep neural networks [171–173], etc. [159, 174–177]. Different algorithms for supercapacitor SoH estimation are listed and compared in Table 2.

C. State-of-Power

The SoP knowledge is critical to determine the instantaneous available power of the supercapacitor pack in the acceleration, regenerative braking, and gradient climbing conditions. The original approach for

Table 2
Review of the supercapacitor SoH estimation algorithms.

Reference	Method	Average error	Inputs	Online/ offline
[161]	RLS	Unspecified	Voltage and current of the supercapacitor	Online
[72]	Extended RLS	$\leq \pm 0.6\%$	Voltage and current of the supercapacitor	Online
[162]	RLS with time-varying forgetting factor	$\leq \pm 3.0\%$	Voltage, current, and temperature	Online
[163]	LS	Unspecified	Voltage and current of the supercapacitor	Offline
[164]	RLS	$\leq 1.7\%$	Voltage and current of the supercapacitor	Online
[165]	Sliding mode observer	$\leq 1.4\%$	Voltage and current of the supercapacitor	Online
[166]	Interconnected observers	Unspecified	Voltage and current of the supercapacitor	Online
[167]	Adaptive observer	$\leq 2\%$	Voltage and current of the supercapacitor	Online
[168]	EKF	$\leq 4.62\%$	Voltage and current of the supercapacitor	Online
[88]	UKF	$\leq 0.5\%$	Voltage and current of the supercapacitor	Online
[169]	PF	$\leq 8.37\%$	Voltage, current, and temperature	Online
[170]	PF	$\leq 6.5\%$	Voltage, current, and temperature	Online
[172]	Deep Belief network	2.2%	Cycle number	Offline
[171]	Neo-Fuzzy Neural Approach	$\leq 4.4\%$	Impedances at four different frequency conditions	Online
[173]	long short-term memory neural network	$\leq 3.4\%$	Cycle number	Offline
[176]	Based on balancing circuit	$\leq 7.0\%$	Voltage and current ripples	Online
[177]	Lyapunov-based adaptation law	$\leq 2.0\%$	Voltage and current	Online

estimation of the maximum available power is described in IEC 62576–2018, which is known as the matched impedance power method. The following formula can be used to obtain the maximum power density:

$$P_{dm} = \frac{0.25 \times U_R^2}{R \times M} \quad (5)$$

where P_{dm} denotes the maximum power density of the supercapacitor in W/kg, U_m is the rated voltage in V, R is the internal resistance or ESR, and M is the mass of the supercapacitor. This power estimation is optimistic and does not take into account the variations of the internal voltage and the ESR as a function of the temperature, aging, and SoC level. Besides, this approach is offline and cannot be used for real-time estimation of the SoP in the SMS. To include these effects in the process of the supercapacitor SoP estimation, the method proposed by Prof. Plett [178,179] can be reused. In this method, the SoP can be estimated considering the voltage limits of the supercapacitor. Accordingly, taking the ECM of Fig. 9(c) as an example, the maximum available charge power can be estimated as follows:

$$P_{charge}^{max} = I_{charge}^{max} \times (v_c + R_s \times I_{charge}^{max}) \quad (6)$$

where P_{charge}^{max} is the maximum achievable charge power, v_c is the internal voltage, R_s is the internal resistance, and I_{charge}^{max} is the maximum available charge current obtained as follows:

$$I_{charge,es}^{max} = \frac{U_c^{max} - v_c}{R_s} \quad (7)$$

$$I_{charge}^{max} = min\{I_{charge,es}^{max}, I_{charge}^{limit}\} \quad (8)$$

where U_c^{max} is the upper voltage limit and I_{charge}^{limit} is the charge current limit. Similarly, the maximum achievable discharge power can be obtained as follows:

$$P_{discharge}^{max} = I_{discharge}^{max} \times (v_c - R_s \times I_{discharge}^{max}) \quad (9)$$

where $I_{discharge}^{max}$ is the maximum available discharge current obtained as follows:

$$I_{discharge,es}^{max} = \frac{v_c - U_c^{min}}{R_s} \quad (10)$$

$$I_{discharge}^{max} = min\{I_{discharge,es}^{max}, I_{discharge}^{limit}\} \quad (11)$$

where U_c^{min} is the lower voltage limit and $I_{discharge}^{limit}$ is the discharge current limit. Some other methods for estimation of power capability in combined battery/supercapacitor systems are based on the EKF algorithm [180] and Fisher information matrix and Cramer-Rao bound analysis [181]. In Ref. [180], the model of the supercapacitor is first developed and identified using the RLS algorithm. The model is then used together with the EKF algorithm to estimate the SoC. Finally, based on the static limits for the current, charge/discharge cut-off voltages, and SoC constraints, the power availability is estimated. The method in Ref. [181] is similar to Ref. [180] except that the model parameters are identified based on the Fisher information matrix and Cramer-Rao bound analysis. The power prediction is fulfilled based on 1 s and 30 s horizons.

5. Control and balancing of the supercapacitor packs

The root causes, modes, and effects of the supercapacitor pack unbalance are reviewed in Fig. 16. The original cause of unbalance is related to the cell inconsistencies resulting from the material differences, equipment inaccuracies, and uncertainties in the manufacturing process. In practice, even if the supercapacitor cells are produced from the same manufacturing line or batch process, their internal characteristics such as the ESR, capacitance, and self-discharge rate can be different. Such differences are problematic when a large number of cells are put together in a pack.

For example, the cells with lower capacitance tend to charge/discharge faster, which can cause voltage and SoC unbalance in the supercapacitor pack. Inconsistent ESR values will lead to different internal and terminal voltage drops, which complicates the management of cells. For instance, a cell with higher ESR will hit the discharge cut-off voltage before the other cells, which will reduce the useable energy of the pack. The unbalance problem restricts the deliverable power and

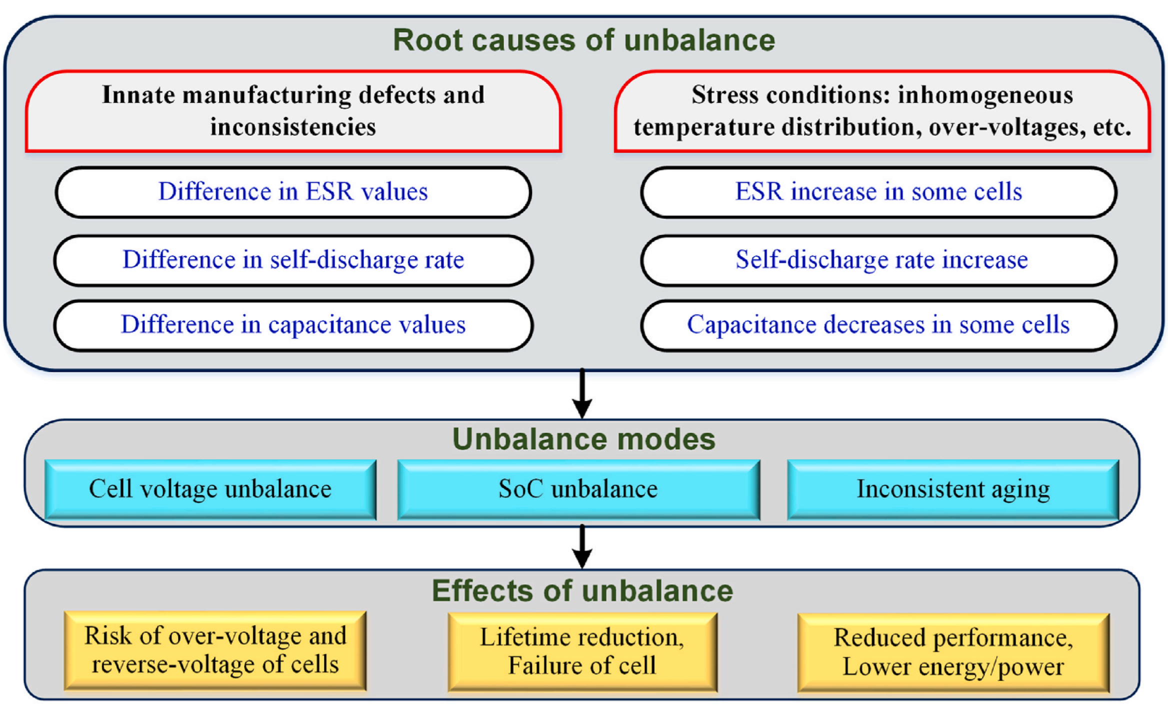

Fig. 16. Root causes, modes, and effects of unbalance in supercapacitor packs.

energy of the pack hindering the EV performance. Also, it might cause cell over-voltage, which will result in faster degradation. The cell unbalance can also cause uneven temperature distribution across different cells, which can aggravate the mentioned problems even further. It is therefore essential to use effective balancing approaches to mitigate the aging of the cells and to improve the pack's performance. Fig. 17 shows the categorization of different balancing techniques used for supercapacitors.

As seen, the balancing topologies can be broadly classified as passive and active. The basic idea behind passive balancing is to dissipate energy in the cells with higher SoC levels. To this end, some resistances (fixed/switched) are used in parallel with each cell. Fig. 18(a) shows a typical passive balancing method consisting of a switch and a resistor across each supercapacitor cell. When the voltage of a cell is too high, the switch is turned on and the extra charge is consumed by the corresponding resistor. Passive balancing is very simple and low-cost but the efficiency of this method is low. Likewise, the balancing process is very slow with the passive techniques.

The basic idea behind active balancing is to transfer energy (using capacitors, transformers, or DC-DC converters) from high-SoC cells to low-SoC cells. The switched-capacitor active balancing technique is shown in Fig. 18(b). Considering a case in which SC_1 has a higher voltage than SC_2 (SCs being the supercapacitor cells), one can set S_0 and S_1 to the up-state, which causes the extra charge flow into C_1. Then, S_0 and S_1 will be both switched to the down-state forcing the stored energy to charge SC_2. A similar procedure should be fulfilled for the rest of the supercapacitor cells. The balancing time in this topology is long (a transfer of energy from SC_1 to SC_n takes place by transmitting from SC_1 to SC_2, then SC_2 to SC_3, all the way to the SC_n). Other configurations of the capacitor-based active balancing have also been proposed to provide switching of the capacitors in various combinations to improve flexibility and reduce the balancing time. These configurations include single-capacitor, double-tiered capacitor, and multiple-layer capacitor. Another active balancing scheme is based on using DC-DC converters, as shown in Fig. 18(c). Several isolated/nonisolated DC-DC converters such as buck-boost converters, flyback converters, multi-winding transformer topology (MWTT), etc. have been used to achieve an active balancing of supercapacitor cells. The active balancing methods offer relatively higher efficiency and balancing speed. However, active balancing has higher complexity and cost since they require several inductors, capacitors, switches/transistors, etc. A comprehensive comparison between different balancing schemes in terms of balancing time, complexity, efficiency, etc. is fulfilled and provided in Table 3 [182].

Besides the topological standpoint, the balancing methods can also be classified based on the equalization variable. The equalization variable depends on the balancing target, i.e. balancing the voltage, SoC [203,204], or SoH [205]. Balancing based on voltage is the simplest form of balancing since the voltages of the cells are easily measurable. Balancing the SoC and SoH (capacitance) requires real-time estimation of these states for all the supercapacitor cells. Thus, these methods have lower computational efficiency compared with the voltage-based balancing approach. Nonetheless, the balancing based on SoC and SoH offers better performance increasing the energy and power availability of the pack [206] The advantages and disadvantages of different balancing strategies are reviewed in Fig. 19.

Concerning the equalization control approach, there are several

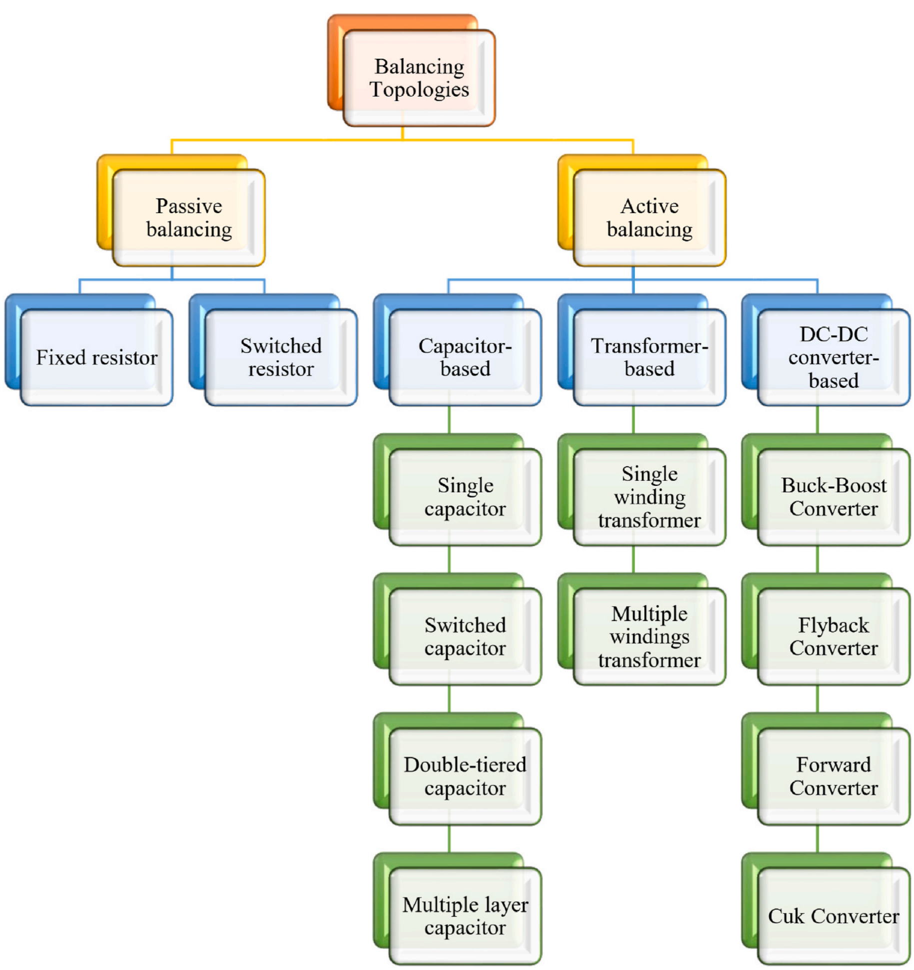

Fig. 17. Categorization of different topologies for balancing the supercapacitors.

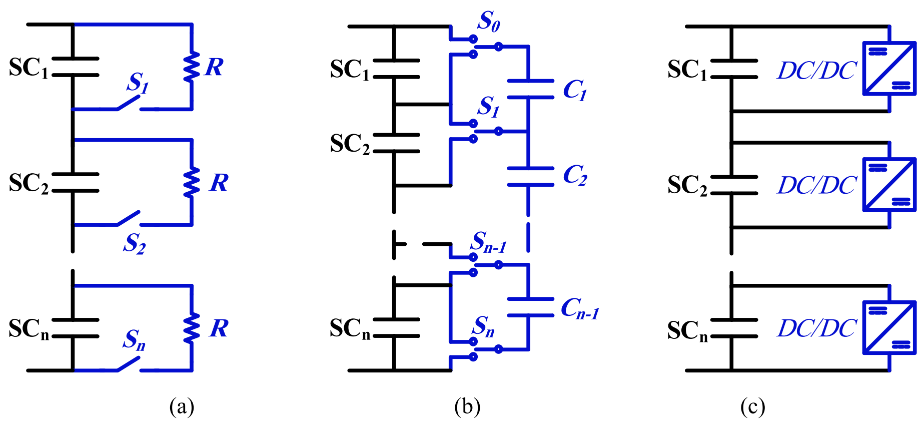

Fig. 18. (a) Passive balancing by switched resistors. (b) Active balancing with switched capacitors. (c) Active balancing with DC-DC converters.

Table 3
Review of different balancing methods for supercapacitors [182,183].

Balancing Approach	Circuit Components						Cost	Efficiency	Speed	Control simplicity	Size	Modularity	Switch voltage stress
	SW	R	L	C	D	T							
Dissipative method [184]	*n*	*n*	*0*	*0*	*0*	*0*	*5*	*1*	*5*	*5*	*5*	*3*	*5*
Switched capacitors [185]	*2n*	*0*	*0*	*n-1*	*0*	*0*	*5*	*3*	*2*	*5*	*5*	*3*	*5*
Switched-capacitors (chain structure) [186]	*2(n + 2 m)*	*0*	*0*	*n + m*	*0*	*0*	*4*	*4*	*3*	*4*	*4*	*2*	*5*
Parallel switched-capacitor [187]	*2n*	*0*	*0*	*N*	*0*	*0*	*2*	*4*	*3*	*4*	*3*	*4*	*5*
Mesh switched-capacitor [188]	*2n*	*0*	*0*	*2n*	*0*	*0*	*2*	*4*	*4*	*4*	*3*	*5*	*5*
Resonant switched-capacitor [189]	*4n*	*0*	*n*	*N*	*0*	*0*	*1*	*5*	*3*	*4*	*2*	*3*	*3*
Switched-inductor-capacitor [190]	*n*	*0*	*0*	*n/2*	*0*	*5 m*	*3*	*5*	*4*	*2*	*3*	*3*	*5*
Multi-mode inductor [191]	*5n-4m*	*0*	*n-m*	*0*	*0*	*0*	*1*	*4*	*3*	*4*	*2*	*4*	*3*
Buck–boost DC-DC converter [192]	*2n*	*0*	*n-1*	*0*	*0*	*0*	*4*	*3*	*2*	*3*	*3*	*5*	*5*
Flyback or forward conversion [193]	*2n*	*0*	*0*	*0*	*0*	*m*	*2*	*3*	*3*	*2*	*3*	*3*	*5*
Flyback conversion [194]	*2(n-m)*	*0*	*0*	*0*	*2(n-m)*	*m*	*3*	*4*	*3*	*2*	*3*	*3*	*2*
Forward conversion [195]	*n*	*0*	*0*	*N*	*0*	*m*	*3*	*5*	*5*	*3*	*4*	*5*	*4*
Forward–Flyback Converter [183]	*n*	*0*	*0*	*0*	*0*	*m*	*4*	*4*	*5*	*5*	*5*	*5*	*5*
Equalizer with wave-trap concept [196]	*2 m*	*0*	*n*	*N*	*n*	*n*	*2*	*3*	*3*	*1*	*2*	*1*	*1*
Single transformer [197]	*2(n + 5 m)*	*0*	*m*	*4 m*	*0*	*m*	*2*	*4*	*3*	*4*	*3*	*1*	*3*
Optimized next-to-next balancing [198]	*4(n-1)*	*0*	*2(n-1)*	*0*	*0*	*0*	*3*	*3*	*2*	*4*	*2*	*4*	*5*
Zero current switching inductor [199]	*4n*	*0*	*m*	*m*	*0*	*0*	*1*	*4*	*4*	*4*	*2*	*2*	*3*
Multiphase interleaved approach [200]	*2(n-1)*	*0*	*n-1*	*0*	*0*	*0*	*4*	*4*	*4*	*4*	*3*	*2*	*3*
Multilayer modular equalizer [201]	*n + m*	*0*	*n-1*	*0*	*0*	*0*	*3*	*4*	*4*	*5*	*3*	*3*	*4*
Modular voltage multiplier [202]	*2 m*	*0*	*2 m*	*n + 2m-1*	*2n*	*0*	*3*	*5*	*4*	*5*	*4*	*2*	*4*

The parameter *n* is the number of cells in the supercapacitor string, *m* denotes the number of supercapacitor modules in the supercapacitor string, SW denotes switch, *R* denotes resistor, *L* denotes the inductors, *C* denotes capacitor, *D* denotes diode, and *T* denotes transformers in the relevant balancing topology. Likewise, the scores 1 to 5 qualitatively rank different topologies with 1 being the worst quality and 5 being the best quality.

methods that can be used. This includes, for example, the simple rule-based and look-up table-based methods or more advanced algorithms such as Fuzzy logic and model predictive controllers. However, existing works for balancing the supercapacitor cells are merely based on simple rule-based control methods. In the future, it would be worthwhile to develop and study the effect of different control methods on the balancing performance of the supercapacitors.

6. Challenges and opportunities

SMS is a technology enabler for supercapacitors in industrial applications. It is important to review their challenges and opportunities to better identify the existing gaps and future trends.

To reduce the overall system cost, SMSs are usually equipped with low-cost microprocessors. The SMS includes several models and algorithms to meet the functional requirements for large supercapacitor packs. However, the implementation of these algorithms for a large number of cells in the supercapacitor pack can challenge the real-time

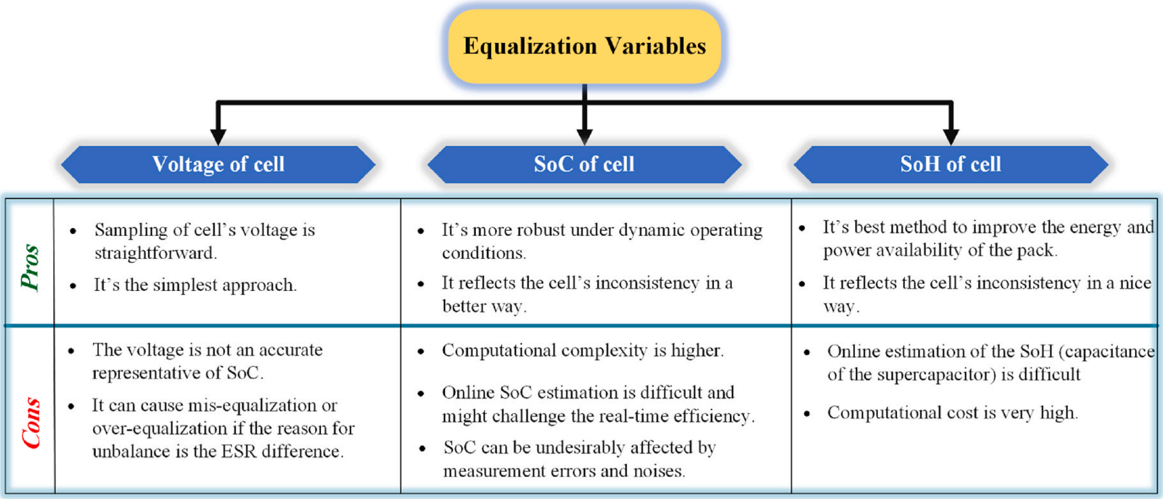

Fig. 19. Comparison of balancing with different equalization variables.

efficiency. The SMS accuracy should thus be compromised by reducing the complexity of these algorithms to maintain the real-time feasibility. Bigger sampling times might have to be adopted to improve the real-time efficiency but this will reduce the SMS responsiveness rate. Nonetheless, processor technologies are continuously advancing and more powerful processors are becoming available at lower costs. This will provide the opportunity to explore more advanced models and algorithms in SMSs, such as cutting-edge techniques based on artificial intelligence and machine learning to enhance safety, performance, and lifetime. Implementation of the SMSs on the cloud space through the Internet-of-Things (IoT) platforms provides a larger computational resource opening room for more complex methods.

The operating voltage and energy density of the supercapacitors are still low. Electric vehicles companies are developing new drivetrain technologies allowing for higher DC-link voltage to improve performance. This means a larger number of cells should be put together, which leads to more challenges in terms of reliability, safety, and cost-effectiveness. However, the technology of supercapacitors is also growing fast. The research toward finding new materials with higher surface areas and new electrolytes continues to build supercapacitors with higher energy density and larger voltage windows. The intelligentization of the manufacturing processes through emerging technologies such as digital twins will allow fabricating cells with higher consistency, which can positively change the requirements for SMS design in the future. While these opportunities might enable us to store more energy and power in supercapacitor cells, it also calls for developing more advanced techniques and algorithms for SMS to control the potential risks.

The ESS technologies are growing very fast but the choice of an ultimate ESS in the vehicles is still an open question. While the search for the best ESS continues, hybridization of the supercapacitors and batteries can provide a very nice trade-off to make the most of the advantageous features of each ESS. Hybridization decouples energy and power in the design and creates more flexibility to build more efficient ESSs for a wide range of vehicles. Concerning hybridization, an open question that leaves room for future work is to define how SMS should interact with the BMS and the vehicle ECU.

Last but not least, a major bottleneck for SMS is that no standard has been established to determine its functional requirements. The requirements for SMS architecture, modeling, SoX estimation, communication, and interfaces should be established to allow SMS industrialization and better market penetration.

7. Summary and conclusions

A comprehensive review of the automotive SMSs and the related topics including the SMS structure and functionalities, supercapacitor modeling and state estimation, control and balancing of the supercapacitors, etc. is presented in this article. Different SMS architectures including the centralized, distributed, and modular SMSs are reviewed. The fundamentals of the supercapacitor are reviewed and based on the system-level requirements for the operation of the supercapacitors, the key hardware/software requirements for the automotive SMSs are detailed and discussed in different sections of the article.

In Section 3, a detailed review of the supercapacitor modeling approaches is provided and different models including the electrochemical models, ECMs, FOMs, DDMs, and thermal models are surveyed in detail. It is argued that from the SMS standpoint, the appropriate model should provide a compromise between the required accuracy level and the computational resources available in the SMS processor. Also, it is sometimes needed to adopt more than one type of supercapacitor model to realize multiple objectives, such as control of the safety electrical and thermal performance boundaries. The ECMs provide the best trade-off among the mentioned decision factors although the type of model should also depend on the type of the application. The necessity for SoX estimation to predict the status of the cells and the pack is discussed in Section 4. The SoC should be continuously estimated in the SMS to control the charge/discharge process, balancing of the cells, and most importantly to predict the remaining energy. The continuous and up-to-date SoH knowledge should be acquired by the SMS to assess the health status of the cells and the pack as a whole. In addition to the prediction of the aging conditions, some of the real-time SoH estimation methods can predict the failures of the supercapacitor, as well. The SoP is also another important state in the SMS that determines the amount of power that can be safely harvested/injected from/to the supercapacitor pack. The review of different control and balancing methods is fulfilled in Section 5. Different passive and active balancing methods are reviewed. It is discussed that the choice of the suitable balancing approach is a trade-off between various factors such as cost, complexity, balancing speed, and efficiency. Many of the manufacturers nowadays are using passive balancing due to its simple structure and low cost. However, active balancing methods might be more interesting in applications where performance is a more critical factor than the cost and complexity, e.g. in racing cars that also involve faster charge/discharge of cells.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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This work was supported by the National Elites Foundation of Iran under project no. 711–3452. The authors appreciate the financial support received for carrying out this research. We acknowledge the permission to reprint Fig. 8 from {Wang, H. and Pilon, L., 2011. Accurate simulations of electric double layer capacitance of ultramicroelectrodes. *The Journal of Physical Chemistry C*, *115*(33), pp.16711-16719} Copyright {2011} American Chemical Society.

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