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Review

Battery-Supercapacitor Energy Storage Systems for Electrical Vehicles: A Review

Diana Lemian and Florin Bode *

Faculty of Automotive, Mechatronics and Mechanics, Technical University of Cluj-Napoca, B-dul Muncii Nr. 103-105, 400641 Cluj-Napoca, Romania
* Correspondence: florin.bode@termo.utcluj.ro

Abstract: The current worldwide energy directives are oriented toward reducing energy consumption and lowering greenhouse gas emissions. The exponential increase in the production of electrified vehicles in the last decade are an important part of meeting global goals on the climate change. However, while no greenhouse gas emissions directly come from the operations of the electrical vehicles, the electrical vehicle production process results in much higher energy consumption and greenhouse gas emissions than in the case of a classical internal combustion vehicle; thus, to reduce the environment impact of electrified vehicles, they should be used for as long as possible. Using only batteries for electric vehicles can lead to a shorter battery life for certain applications, such as in the case of those with many stops and starts but not only in these cases. To increase the lifespan of the batteries, couplings between the batteries and the supercapacitors for the new electrical vehicles in the form of the hybrid energy storage systems seems to be the most appropriate way. For this, there are four different types of converters, including rectifiers, inverters, AC-AC converters, and DC-DC converters. For a hybrid energy storage system to operate consistently, effectively, and safely, an appropriate realistic controller technique must be used; at the moment, a few techniques are being used on the market.

Keywords: vehicle batteries; supercapacitors; electrical vehicles; hybrid energy storage systems; electrified vehicle energy management

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1. Introduction

Globally, energy consumption has increased significantly, as has people's level of well-being all over the globe and, consequently, the number of vehicles. According to data now available, there are approximately 1.5 billion automobiles on the planet, and it is anticipated that by 2030, this number will exceed 2.5 billion [1]. To meet the world's energy needs, global energy directives urge us to transition to sustainable, renewable energy sources instead of fossil fuels. Their use in the commercial, industrial, and residential sectors has been pointed out in [2]. The rapid development of power electronics, which enables the total control of renewable energy sources constrained by stochastic environmental circumstances, is another factor supporting this direction [3].

Now, at the beginning of the 21st century, sustainability is an important aspect of our lives. Our society is transforming and changing at a faster pace than in the past. Finding new ways of increasing the sustainability of the used solutions is a priority nowadays [4].

Electrical vehicles (EVs) are gaining major popularity because soaring greenhouse emissions imply some serious health problems for the population and severe climate changes, inevitably leading to the necessity of solving these issues [5]. The transportation industry is to blame for almost a third of the total emissions of carbon dioxide, whilst over 70% of emissions in the transport industry are ascribed to vehicle transportation [6]. Compared to internal combustion engine (ICE) vehicles, EVs are the most suitable solution in the transport sector for the zero-emissions objective (while they are used) to comply with modern world pollution demands [7]. Although EVs have significant energy storage-related challenges, such as driving distance, battery expense, charging period, volume, and weight [6]. These are some of the reasons that have led to the adoption of hybrid energy storage systems (HESSs) that incorporate batteries and supercapacitors (SCs) for EVs and other electric propulsion (transport) applications.

Some of the most wide-spread objectives of HESSs are regenerative-breaking recovery and to meet the acceleration performance and the capability requirements of driving cycles [8,9], as well as energy loss, battery life, system efficiency, and dynamic performance, while overall weight, volume, and price are taken into consideration when choosing to develop an optimal energy management strategy in HESSs for EVs [10]. An electric car's production process leads to significantly increased energy demand and greenhouse gas emissions than in the case of an internal combustion (IC) vehicle, although it has a significantly lower overall environmental impact during operation. The process used to make battery packs is primarily to blame. Therefore, EVs should be used for as long as possible to minimize the harmful effects of the production process on the environment [11]. Other energy storage systems (ESSs) are incapable of delivering all the features required by EVs to perform at the highest standards. To optimize features, such as power density, energy density, discharge rate, life cycle, and cost, HESSs combine two ESSs that have complementary characteristics, as a result, assuring the best possible performance of ESSs [12].

Mostly, batteries are distinguished by a relatively high specific energy, whereas SCs have a relatively lower specific energy and substantially high-power density [13]. The batteries lose their performances over time due to peak usage; thus, when EVs require unexpected energy use while accelerating, the battery pack alone cannot perform this requirement. Furthermore, high currents are generated during regenerative breaking which can also shorten the batteries' lifespans [8]. Due to the different values of operating voltage between the batteries and the SCs and to take advantage of the two, the connection is established using a bidirectional DC-DC converter within an HESS [14].

HESSs can be configurated according to passive, semi-active, and active topologies, based on the energy demand and the configuration of the DC-DC converters. In the passive configuration, the energy storage systems (ESS) are linked to the load in parallel with no power control circuits involved, while for the semi-active hybrid, a single DC-DC converter is employed. In active hybrids, two DC-DC converters are used for the circuitry configuration [15]. In addition, regarding the energy management system (EMS), there are two types of strategies [16]. The "on-line" strategy (the rule-based control strategy, the fuzzy logic control strategy, the model predictive strategy, and the filtration-based strategy), also known as the "all or nothing" control strategy, is simple to implement in real-world application. Since these online approaches are frequently developed empirically, they are unable to reach global optimization performances or the "off-line" strategy (the Pontryagin's minimum principle, the dynamic programming approach) that can accomplish globally optimal performances, although due to their high-computing costs, these technologies are challenging to use in practical applications [17].

In this study, the most recent developments in terms of energy storage, power converters, energy management techniques, and control algorithms used in automobiles are pointed out. All the current and most widely used EV-related technologies will be covered. Additionally, the purpose of this study is to present the actual state of the art of a niched domain, namely battery-supercapacitor energy storage systems for electrical vehicles. The reason is that during the discharge of the battery, non-monotonic power consumption emerges, which is accompanied by frequent changes. This can be extremely harmful to the battery's electrochemical process, and a viable solution is to combine the battery with a supercapacitor, which is essentially an electrochemical cell with a similar architecture but with higher speed capability and better cyclability. The study begins with the state of the art of the batteries for electrified vehicles, followed by the state of the art for the supercapacitors for electrified vehicles. Then, the hybrid energy storage systems are presented together with battery-SC HESS topologies and the energy management necessary for these systems.

2. Batteries for Electrified Vehicles

Batteries used for EVs are the most known and commonly used application for power systems due to their ability to transform a chemical energy source into electrical energy and the other way around [18–24]. The batteries are appraised for their energy and power capacities; therefore, the most important characteristics that should be considered when designing an HESS are battery capacity measured in ampere-hours (Ah) with values between 0.02–40 depending on the BEV type [21], the amount of energy packed in a battery measured in watt-hours (Wh) with specific energy ranging between 30–180 Wh/kg [22,24], and the useable state-of-charge (SOC) of the battery which indicates the percentage of energy currently contained within the battery [21].

On the market, there are numerous battery varieties depending on their chemical structure. Currently, lead-acid batteries, nickel-metal hydride (Ni-MH), and lithium-ion batteries are the three the most common rechargeable battery types used in EVs [18–20,22–27]. Table 1 provides some of their characteristic values.

Table 1. Characteristic comparisons of the primary types of batteries used in EVs [21–24,28].

Energy Storage Type	Specific Power (W/kg)	Specific Energy (Wh/kg)	Life (Years)	Cycle	Efficiency (%)	Cost ($/kWh)
Lead-acid battery	50–180	30–50	3–15	500–4500	70–90	50–200
Ni-based battery	50–1000	30–70	15–20	100–40,000	50–90	150–2400
Li-based battery	250–400	90–190	~15	500–18,000	80–95	100–2000

2.1. Lead-Acid Batteries

Lead-acid batteries are rechargeable electrochemical products which have been employed in both domestic and industrial settings. Lead-acid batteries provide several advantages, including low capital costs, high-energy efficiency (>80% [21,24]), quick response times, and minimal rates of self-discharge of only 2% of rated capacity per month (at 25 °C). However, lead-acid batteries have a poor specific energy density 30–50 Wh/kg [21] and a short cycle life of maximum 1500 [18]. The use of lead-acid batteries has been rising, which is why the disposal of the parts are increasing. Lead is dangerous and has negative environmental impacts [22,23,29].

2.2. Nickel-Based Batteries

There are four different types of nickel-based batteries: nickel-iron, nickel-cadmium (NiCd), nickel-metal hydride (NiMH), and nickel-zinc (NiZn) [18]. All three varieties utilize nickel hydroxide as the positive electrode and a potassium hydroxide aqueous solution mixed with the electrolyte being primarily lithium hydroxide. The NiCd type employs cadmium hydroxide as the negative electrode, the NiMH type uses a metal alloy, and the NiZn type uses zinc hydroxide [24]. The maximum energy densities for alkaline batteries are often higher than those for lead-acid batteries, and their specific energy densities vary from 50 Wh/kg to 95 Wh/kg. With up to up to 10,000 cycles [18,21,24], NiCd batteries have more extended average operating and cycle lives than lead-acid batteries.

2.3. Lithium Batteries

Lithium batteries (LiBs) are the most appropriate energy storage system for automotive use because of their low mass, high specific energy, high specific power up to 4000 W/kg, and high energy density up to 250 Wh/kg [9,21,22,24,26,27]. Additionally, LiBs have no memory effect and contain no toxic elements, such as lead, mercury, or cadmium [21]. To achieve the desired capacity and voltage for automotive applications, LiBs are made up of numerous electrochemical lithium-ion cells that are incorporated into modules before being added to a battery pack [28]. The main disadvantage of LiBs is their price compared to other types of batteries. LiBs are made up of interconnected cells that vary in length, width, and height, as well as shape (pouch, prismatic, and cylindrical, as shown in Figure 1) depending on the manufacturer [30].

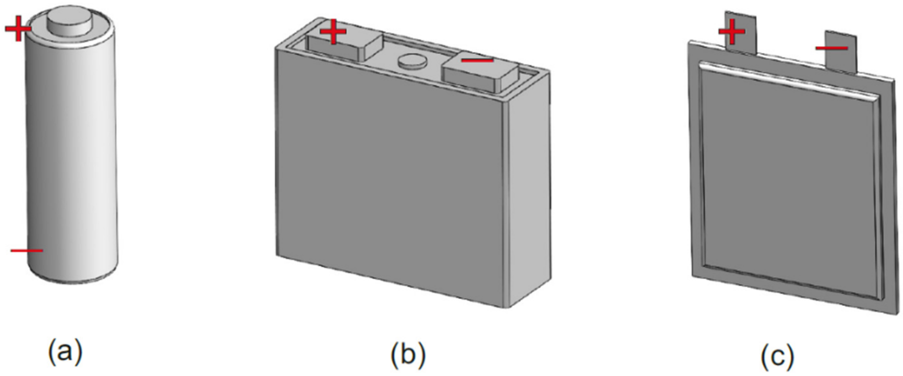

Figure 1. Various battery cell shapes: (**a**) cylindrical, (**b**) prismatic, (**c**) pouch.

The health of LiBs is directly impacted by the parameters of their operation. Degradation arises during charging and discharging, according to the aging process and while being, stored according to the calendar aging [31]. In electric vehicles, battery deterioration causes capacity fade, which limits the vehicle's practical range, and impedance rise, which reduces the battery's usable power output [26,28]. Due to chemical, electrochemical, and mechanical aging of LIBs cells, a steady decline in driving range is projected over the life of a battery pack (up to 25% after around eight years or around 140,000 km) [32].

The number of battery cycles considered practical in the literature ranges between 1000 and 3000 cycles, whichshould assure a long battery life. The lower value of the range (1000 cycles) for an EV with an electrical driving range of 200 km is easily achieved by manufacturers nowadays, and the car would still be able to be driven 200,000 km before the battery's life was up [30]. People in Europe expect a driving range of approximate 300 km, which is not easily achieved by using batteries alone [32]. The EV driving range is one of the major barriers for limiting consumers' choices for adopting sustainable road transport [33]. Thus, adopting the hybrid energy storage by combining the batteries and SCs for better performances could overcome this problem and more, and more people would choose to buy EVs.

Developments to the battery packs' engineering and chemical elements will be essential. The proportion of inactive components in the cell, module, or pack's overall weight and volume should be minimized, and the effectiveness of cell production should be as high as possible. To transcend the existing storage limits of the LIB packs, significant improvements in the chemistry/formulation of the electrolyte and electrodes are required [34]. The difficulty for battery research in the coming years will be to develop greater electrochemical/thermal stability electrolytes. To assure a sustainable future for BEVs, a protracted change to battery chemistries, such as Li-S and metal-air, appears unavoidable, as evidenced by life-cycle assessments [32]. To advance further, new cell chemistry and technology will be required as battery performance limits are predicted to be reached by 2030 [30]. Although, as shown in Figure 2, we can observe a major improvement in recent years regarding the energy density for batteries, especially for Li-Ion batteries.

Although there have been substantial improvements in battery performance over the past few years, peak utilization is still the main issue. In EVs, this problem persists since several factors, including driving technique, the road, etc., produce abrupt variations in the power usage [8]. *To overcome this problem HESSs represent an optimal solution by combining two ESSs with complementary qualities (batteries and supercapacitors) to enhance the performances of EVs.*

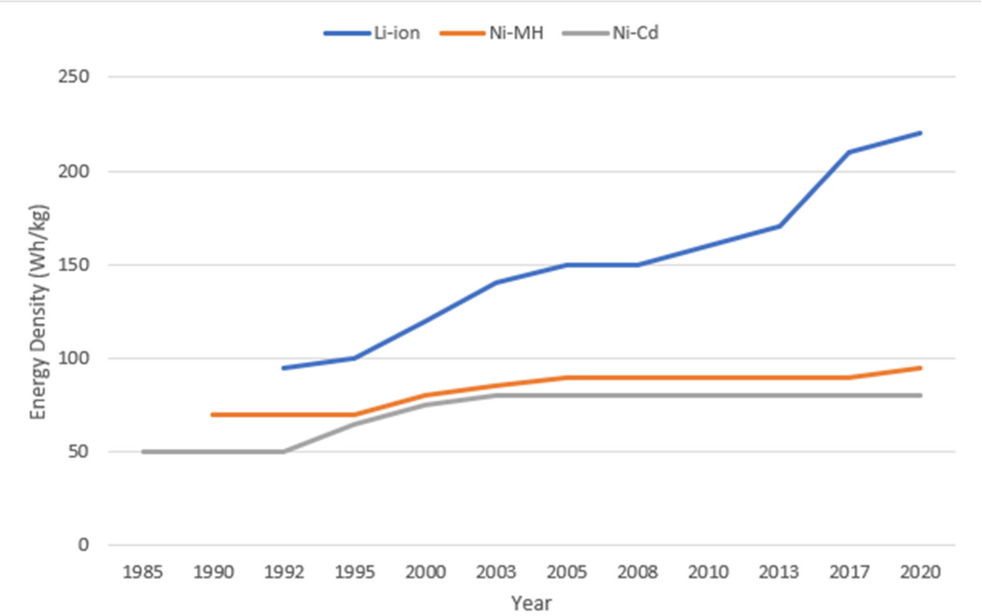

Figure 2. Evolution of energy density in the last decades in batteries with various cell chemistries.

3. Supercapacitors for Electrified Vehicles

The terms "supercapacitors", "ultracapacitors" and "electrochemical double-layer capacitors" (EDLCs) are frequently used to refer to a group of electrochemical energy storage technologies that are suitable for energy quick release and storage [35–37]. Similar in structure to the normal capacitors, the supercapacitors (SCs) store energy by layering two solid conductors with an electrolyte solution. Due to the SCs' significantly higher capacitance compared to traditional capacitors, they have energy storage capacities that can be up to 20 times higher [18,21,22]. The SCs offer great power density, a quick charging–discharging time, and almost infinite cycle lives [7,38]. In industrial and transportation applications, supercapacitors are being utilized more frequently as high-power buffers, either alone or in conjunction with different electrochemical batteries [38,39]. In contrast to batteries, supercapacitors can handle higher power rates and can deliver the same volume with 100 to 1000 times more power; however, they cannot hold the same volume of energy as batteries, which is typically three to thirty times less. Because of this, supercapacitors can be used in applications where power bursts are needed but large amounts of energy storage are not [35,37,39]. Traditional capacitors don not perform well for future applications because of their inflexible and heavy structures. For multifunctional consumer electronics, slimmer, lighter, more flexible, transparent SCs with a variety of unique features and functions are needed [40].

Currently, electric double-layer capacitors (EDLC), pseudocapacitors, and hybrid capacitors are the three types of SC technologies employed in electric vehicles [18,21]. The benefits and drawbacks of capacitor energy storage are listed, and some of these are compared in Table 2.

Table 2. Advantages and disadvantages of electric double-layer capacitors, pseudocapacitors, and hybrid capacitors [21,40–42].

Electric Double-Layer Capacitor	Pseudocapacitor	Hybrid Capacitor
High voltage and high power operation	Low-voltage functioning is restricted by electrochemistry and the solvent's solvent decomposition voltage.	Increased cell voltage
Electrode's substance of choice is carbon.	Materials utilized as electrodes are metal oxides and conducting polymers.	Consisting of materials containing either conducting polymers or metal oxides in the carbon

Table 2. *Cont.*

Electric Double-Layer Capacitor	Pseudocapacitor	Hybrid Capacitor
The creation of an electrochemical double layer serves as a charge storage mechanism, non-Faradaic process.	Redox reactions, faradaic process allow the charge to be stored.	Both faradaic and non-faradaic processes store the charge.

3.1. Electric Double-Layer Capacitors

The two charged layers that develop at the electrode/electrolyte interfaces are referred to as electric double layers (EDL), and the ensuing potential-dependent charge storage capability is related to electric double-layer capacitance [40,43,44]. Therefore, these SCs are known as electric double-layer capacitors (EDLCs). Compared to electrostatic capacitors, EDLCs have a much higher capacitance because they use nanoporous materials with high specific surfaces as active electrode materials [37,42].

3.2. Pseudocapacitors

Pseudocapacitors improve energy density and specific capacitance more than EDLCs because they store the charge by electrosorption, oxidation–reduction reactions, and intercalation mechanisms, which are known as faradaic processes [37,42,44]. The ability of electrodes to produce the pseudocapacitance effect is influenced by the electrode pores' sizes and shapes, as well as the materials' chemical affinities to the ions adsorbed on the electrode surface. The provided voltage increases the charge storage linearly [40,42].

3.3. Hybrid Capacitors

In recent years, hybrid supercapacitor systems with greater voltages and improved energy density have been created by combining some battery-type electrodes with supercapacitor-type electrodes. According to some researchers, "hybrid" supercapacitor systems are technically "asymmetric" supercapacitor systems since they are built on two separate supercapacitor-type electrodes [40,44].

The electric double-layer capacitor and the pseudocapacitor are two mechanisms that many of the currently available SCs use [8]. It has been noted in a number of publications [18,39,43] that SCs can operate longer than any other ESSs. High power and high energy supply systems for EVs cannot be achieved simultaneously by ultracapacitors. As a result, the ultracapacitors handle short-term power requirements, while the batteries supply the vehicle's long-term autonomy [21]. An active HESS enables ultracapacitors and batteries to operate at their full capacity to satisfy the dynamic EV demand. Due to the active HESS configuration's use of the energy from the ultracapacitors, there is improved fuel efficiency and increased energy security [7].

4. Hybrid Energy Storage Systems

The dual-source HESS can overcome the drawbacks of using a solitary source of energy by combining two energy sources in the vehicle electric propulsion system [18]. HESS adoption presents several benefits, such as lengthening of system and storage life, cost and volume savings compared to using a single storage system, and an improvement in overall system effectiveness [45]. These often integrate high-energy and high-power storage components with an overall improvement in power density and energy density being the main benefit of such hybrid systems [45,46]. In addition, there are numerous additional potentials energy storage configurations based on SMES, CAES, or flywheel [45] managing solar and wind energy on a large scale [39,47] and microgrids systems where local loads are powered by distributed power supplies, storage devices, controllable loads, and power-conditioning equipment [48,49]. In the literature, there are several dual source combinations, including battery and SC, battery and magnetic energy storage, battery and flywheel, battery and hydraulic accumulators, battery and fuel cell, SC and fuel cell, compressed air energy storage and battery, compressed air energy storage and fuel cell, etc. [50]. More research is being done on the combined usage of battery and SC storage to improve the HESS's overall performances, even if other configurations also offer certain distinctive advantages [47]. Hence, the battery–SC combination can make use of each other's complementing qualities. Due to its similar operating concept, wide availability, and affordable initial cost, this combination has gained popularity [25,49]. Four varieties of converters are available, including rectifiers, inverters, AC-AC converters, and DC-DC converters.

4.1. Battery–SC HESS Topologies

The distribution of power among diverse power sources is coordinated using appropriate energy management systems (EMSs) and topologies for HESSs. Additionally, by properly distributing output power throughout the system, these methods improve system economy and efficiency while extending the lifespan of HESSs [51]. The HESS can either be linked to the DC bus or the AC bus using a separate DC-AC converter. To utilize both and minimize their drawbacks, HESS is typically developed by connecting the supercapacitor and battery through a bidirectional DC-DC converter [14]. There are three types of interconnection topologies: passive, semi-active, and active [7,8,13,15,38,39,49,51–54]; their structure is shown in Figure 3. Based on the system requirements and the functions of the energy management system, a wide range of topologies can be chosen.

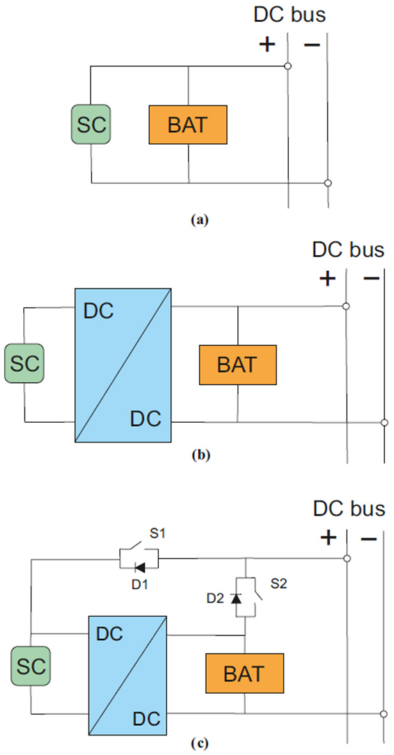

Figure 3. Topologies for HESS: (**a**) passive, (**b**) semi-active, (**c**) active configuration.

In active HESS topologies, two bidirectional DC-DC power converters are used to connect the ESS elements to the DC bus and actively manage the flow of their power [7,8,38,51,53,54]. The energy storage devices' voltage can be distinctive from the DC bus voltage due to DC-DC converters [52]. In EV applications, DC bus voltages must remain constant during the driving duration; therefore, a fully active topology is the primary option for these kinds of applications [51]. A fully operational HESS can be used to implement the optimal control. However, this design compromises the efficiency, cost, and component size of the HESS. The design is also more complex than a passive design [8].

There are two types of active topologies: parallel and series [15,49]. By inserting a DC-DC converter between the supercapacitor and the load, parallel topology eliminates the drawbacks of ultracapacitor voltage fluctuations and matching, making it by far the best active hybrid. By putting a DC-DC converter between the battery and the DC link, it is possible to achieve both virtually the battery's steady current flow and the load's and the battery's voltage differences [15]. High power storage and high energy storage are cascaded in the series architecture along with a power converter to isolate it from the DC bus. Since this topology requires the power converter to meet the HESS's overall power rating, it is frequently disregarded [55].

For passive topologies the ESS devices' electrical characteristics only influence the power-sharing mechanism and responsiveness for the terminals that are directly linked to the DC bus [7,15,38,39,51,53,54]. The impedance ratio determines how the load is divided in the passive architecture, which is similar to synchronous generators running in parallel. The load is distributed similarly based on the ESS's output characteristics and internal resistance. Temperature and the current state of charge have significant impacts on resistance in this situation [39,49,52].

Due to its limitations, such as lack of controllability and variable power sharing dependent on source impedance, and due to their direct connection to the system, ESSs are susceptible to cascading failure during emergencies, and the DC bus voltage or load voltage should exactly match the voltage of the ESS [15,38,51,52].

One energy storage unit connects straight to the DC connection, while the other is connected via a DC-DC converter in a semi-active HESS setup [7,51], which compared to fully active and passive HESSs, is a decent trade-off between system price and efficiency. Additionally, the semi-active topology can be used to execute the majority of control techniques [16,17]. Semi-active structures with regulated SCs and batteries have been examined in the literature [16].

In the supercapacitor semi-active topology, the battery is directly coupled to the DC bus while the SC is coupled in series with a bidirectional DC-DC converter to take use of its wide voltage range [8,38,54]. Because the battery is linked directly, the voltage of the DC bus is stable. Therefore, choosing and designing a converter that can handle strong currents and significant voltage variations adds to the price [39].

In the battery semi-active topology, the SC is directly connected to the DC bus while the battery is connected in series with a bidirectional DC-DC converter [39,54]. Since the battery is disconnected, the convertor can configure the battery current profiles to be very smooth. High values of current variations during emergency acceleration and deceleration can be absorbed by the ultra-capacitor. However, because of the ultra-direct capacitor's connection, the DC bus voltage will fluctuate [38].

Therefore, the topology most suitable for vehicular applications is the semi-active one which is typically chosen as the ideal topology as a balance between expenses and complexity of control technique [39]. Among the two types of semi-active topologies there are distinctions, such as energy savings where SC/battery semi-active HESS can save more energy compared to the battery/SC design [56].

4.2. Energy Management

A complex system management plan must be created to ensure the greatest possible advantage of each ESS in the HESS [51]. The ESSs must be protected from harsh environments, have robust system operations under all conceivable loading circumstances, and have their usable lifetimes increased [8,54]. Power capacity, timing of controller response, controller cost, reduction of power fluctuation, and hybridization structure are only a few of the factors that affect the choice of an appropriate control strategy for HESS. For the HESS to operate consistently, effectively, and safely, an appropriate realistic controller technique must be used [49].

The EMS can be broadly branched into two levels. The low-level control system adjusts the DC bus voltage and regulates the flow of the current into and out of the ESS components in accordance with the reference signals produced by the high-level control system. The high-level control system carries out a power-allocation approach, SoC monitoring and control, and other innovation and environmental management strategies to accomplish the desired control objectives [49,54].

Simple power allocation methods may not be adequate to efficiently distribute the energy storage system's component energy demand in the HESS due to the complicated and non-linear properties of the battery and supercapacitor during the charging/discharging operation. Advanced EMS supervisory control algorithms have been developed as a result [54]; therefore, rule-based control methods and optimization-based control methods constitute the majority of their classification [10,39].

Rule-based control (RBC) methods directs the power exchange of the HESS using rules derived from mathematical models and practical knowledge. Based on a sequential decision-making procedure involving the control aim, RBC was established [49,54]. The RBC methods primarily consist of the fuzzy logic approach [57], finite state machine [58], sliding mode control [59], and thermostat control strategy [54].

Optimization-based control (OBC) methods utilize modern optimization algorithms, including linear programming, dynamic programming, evolutionary techniques, such as the genetic algorithm, simulated annealing, and particle swarm optimization [54]. Global ("off-line") and real-time ("on-line") optimization are two categories under which the OBC technique can be categorized [10,60]. The "on-line" strategy, also known as the "all-or-nothing" control strategy, is simple to implement in real-world applications. Since these on-line strategies are often empirically built, they are unable to reach global optimization performances. The "off-line" strategy can accomplish globally optimal performances, although due to their high-computing costs, these technologies are challenging to use in practical applications [17]. The OBC techniques mainly include model predictive control [61], dynamic programming [62], stochastic dynamic programming [63], genetic algorithm [64], particle swarm optimization [60], and robust control [65]. A brief classification of these methods is structured in Figure 4.

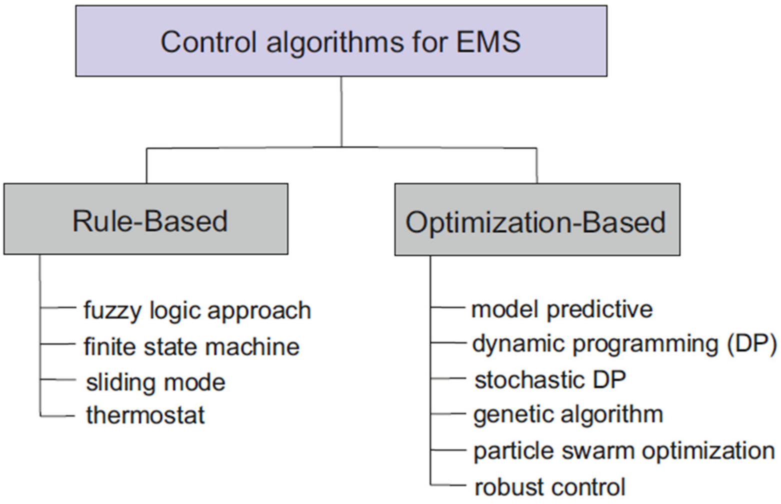

Figure 4. Classification of EMS control strategies [10,17,39,54,60].

The dynamic programming (DP) EMS is regarded to be ideal for vehicular applications; as a result, the method with the best optimization efficiency is one that is closest to the DP outcome. For this strategy it is necessary to be aware of the operational conditions in advance [39].

Since most of the topologies and EMSs are simulated using acquired working condition data or by direct measuring data during the functioning of the HESS, it strongly depends on the vehicle type and its operating conditions, for instance, urban buses where HESSs provide a significant amount of quickly delivered power optimal for accelerating, braking, and motor-starting processes for each route stop [66], trams where HESSs must support bursts of energy supply in each substation where they charge in a short period of time [67], and electric cars where customers need better prices and driving ranges [33].

Each type of topology and EMS for HESSs has its advantages and disadvantages. With further research we can overcome these. Cao et al. [53] proposed a new HESS which can fully utilize the power capacities of SC without the need for a matching power DC-DC converter. Son et al. [68] investigated the relationship between driving cycle characteristics and the combined optimization outcomes of HESSs, including both optimization issues for SC size and on-line EMS. The findings demonstrate that for various driving cycles, the ideal SC size and on-line EMS are directly determined by how intensely the driving cycles consume energy from HESSs. Bambang et al. [69] proposed a model predictive control strategy with hysteresis used for tracking the reference current which can maintain the DC bus voltage in accordance with the reference value and limit the slope of the battery and fuel cell currents. Sinha et al. [48] suggested a novel adaptive fuzzy logic control method, which, when compared to the traditional fuzzy logic control algorithm, had successful results in reducing the downsides of over or underutilizing an ESS to maximize the usage of multiple ESSs in HESSs.

5. Conclusions

An extensive review on the most recent developments in terms of energy storage, power converters, energy management strategies, and control algorithms used in vehicles was performed in this study.

Despite significant advancements in battery technology, available batteries at this time do not fully meet the energy requirements of EV electricity consumption. The principal issue is the battery discharge process where the non-monotonic power consumption is accompanied by frequent changes. This is extremely harmful to the battery's electrochemical process, and a viable solution is to combine the battery with a supercapacitor, which is essentially an electrochemical cell with a similar architecture but with higher speed capability and better cyclability.

The study begins with a review of the batteries used in the electrified vehicle industry that points out the fact there have been substantial improvements in battery performance over the past few years, but the peak utilization is still the main issue. In the electrified vehicle case, this problem persists since several factors, including driving technique, the road, etc., produce abrupt variations in the power usage, and this will lead eventually to the irremediable deterioration of the batteries.

Lithium batteries are the most used at this moment but to transcend the existing storage limits of the lithium batteries packs, significant improvements in the chemistry/formulation of the electrolyte and electrodes are required. In this regard, the challenge for battery research in the future years will be to develop greater electrochemical/thermal stability electrolytes.

To assure a sustainable future for batteries for electrical vehicles, a long-term transition to battery chemistries, such as Li-S and metal-air, appears unavoidable, as evidenced by life-cycle assessments. To advance further, new cell chemistry and technology will be required as battery performance limits are predicted to be reached by 2030.

In contrast to batteries, supercapacitors can handle higher power rates and can deliver 100 to 1000 times more power in the same volume, but they cannot hold the same quantity of energy as batteries, which is typically three to thirty times less. The ultracapacitors handle short-term power requirements, while the batteries supply the vehicle's long-term autonomy.

High power and high energy supply systems for electrical vehicles cannot be achieved simultaneously by ultracapacitors. As a result, the ultracapacitors handle short-term power requirements, while the batteries supply the vehicle's long-term autonomy. An active hybrid energy storage system enables ultracapacitors and batteries to operate at their full capacity to satisfy the dynamic electrical vehicle demand. Due to the active hybrid energy storage system configuration's use of the energy from the ultracapacitors, there is improved fuel efficiency and increased energy security.

For the future, to increase the lifespan of the batteries a coupling between the batteries and the supercapacitors for the new electrical vehicles seems to be the most appropriate way, at least for the vehicles destined for more start/stop operations. Given the fact that the process used to produce batteries and supercapacitors is primarily to blame for the higher energy consumption and the greenhouse gas emissions, electrified vehicles should be used for as long as possible to minimize the harmful effects of the producing process on the environment.

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