Smart Storage Systems for Electric Vehicles – A Review
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ABSTRACT
Electric vehicles (EVs) have been recently developed in advance levels and in particular the battery technologies have also been developed. Although the development in battery technology has been advanced, the usage does not entirely accompany the power consumption. There are harmful electrochemical processes in battery technology. But there is a solution by changing its architecture to couple the battery with a supercapacitor to have a high rate battery cycle and a better capability. A supercapacitor gives more energy to battery in case more energy is needed. In this designing and architecture, supercapacitor and battery are considered to be different units and in electrical engineering point of view it is considered to be a hybrid system. This manuscript is devoted to review recent works on applications of battery and supercapacitor of EVs.

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1. Introduction
The California air resource board was the first board that tried to reduce pollutions from electric vehicles. The first look of the board was on the obstacles against high battery capacity, high cycling capacity, and good rechargeable capacity with quick response in batteries. So, the board directly worked by having a team for development of electric vehicles to improve power as well as energy density in electric vehicles [1,2]. Predominance loses occurred in their performance due to some reason associate with their properties of chemical stability and electro active materials. The selection procedure of the compatible electrolyte deals with redox activity, overcharging, and morphology of electrodes of electric vehicles batteries.

The high level advancement are made for the improvement of the battery conductivity nature, in the peak significant advancement time there was a problem associated with the peak usage of batteries. The usage of battery prevails all over the world, and the demands occurred even for small electronic devices. Thus, it causes rapid changes in power consumption of all small devices such as mobile phones and laptops apart from electric vehicles. The newly developed batteries performed monotonically with corresponding electrochemical reactions during discharge cycles but electric vehicles need more power during acceleration, and the power consumption of battery cannot be authorized well at quick discharge cycle. This also applies to high charge cycle of batteries in electric vehicle braking. When the acceleration and braking repeat the fluctuation flow, it shortens the life cycle of battery.
Various types of hybrid rechargeable batteries are used in electric vehicles [3–6], but the most commonly used type of battery was lithium ion batteries, which are the most promising energy storage devices among many devices even for small-scale electronic devices like mobile phone and laptop. The lithium ion battery having different requirements in energy consumption for electric vehicles when that is compared along with their applications of small electronic devices. Therefore, novel lithium ion batteries should be designed and developed in favor of high cell-voltage, electrode materials, and high cycles as well as demand sacrificing ability [7]. For the sudden power consumption, LiFePO$_4$ are employed as cathode materials for electric vehicle applications. It has high performance quality and excellent cyclability in electric vehicles [8].

The batteries and supercapacitors are energy and charge storage devices but the major differences are on having good capacity and fast ability of discharging and charging factor, yet, supercapacitors cannot be used as power sources for electric vehicles because supercapacitors have lower energy density than batteries. Nevertheless, supercapacitors will be a good option to get more power within a short period of time. In some scenario, battery need more power than energy density and in that case we can couple supercapacitors with batteries for electric vehicles. The way of coupling is similar to the coupling of classic capacitors with electronic devices; but for instantaneous power supply.

The electrical response between capacitors and supercapacitors is different due to the commercial utilization of double-layered capacitors as first generation supercapacitors. The scientific context refers to the system of works, based on pseudo capacitive behavior. The redox of a pseudo-capacitor is depends on the electrochemical systems. The electrochemical redox provides an opportunity for high specific capacitance and cyclability in pseudo capacitors. However, many of the published literature highlighted that the mechanism of the supercapacitors [9–14] can able work long than other storage devices.

The batteries with supercapacitors designing is said to be a hybrid energy storage system. The combinations of the batteries and supercapacitors have more advanced properties like reduced fluctuation time and prolonged operation time. Figure 1 illustrates recent advancements in hybrid energy storage system.

The next-generation hybrid energy storage system may be increased with the efficiency of electric vehicles. The hybrid energy storage system is designed with braking energy storage in both supercapacitors and batteries. This incorporated design is used back to enhance the energy storage in batteries. For example, a theoretical approach of a lithium ion battery with supercapacitor design gives a high performance in hybrid energy storage system [16] and considerable light weighted active materials of electrochemical capacitors with values of power density and the power management can have major impact on overall performance of electric vehicles [17,18]. The usage of the hybrid energy storage systems is most economical due to the power management [15, 18].

The supercapacitor was first (1990) introduced in electrical vehicles by Panasonic Company with 2.3V; when the supercapacitor unit consisted of $2\times40$ has been installed on Mazda bongo friendee (Japanese car). The overall performances were investigated for the rapid regenerative energy on braking and sudden acceleration energy [19]. The same case is applicable for the hybridization of the supercapacitor in electrical vehicle batteries [20,21], such as ultra batteries [22], aluminum air

Figure 1. Power density- energy density plot of various rechargeable and commercial electric double layer capacitor (EDLC) type such as battery-supercapacitor hybrid devices (BSH-blue region) and next generation of battery-supercapacitor hybrid devices (violet region) [15].
batteries [23], lithium ion batteries [19], value regulate lead acid [19,21] and ultra battery of PbO2 [22]. Shaohua Yang and Harold Knickle [23] used aluminum air batteries for the first time for electrical vehicles, in which car acceleration and driving power were generated enough through Al/air battery system. However, the hybrid energy storage system was developed to satisfy basic demands and it was achieved by some combinations

- Smaller dimension with light system
- More power supply and increase in vehicle performance
- Stable performance at zero temperature
- Longer life in operation

The high efficient energy storage system has been lately emphasizing usage for electric vehicles applications. Therefore, hybridization of supercapacitor with batteries was explored extensively and motivated. The main objective of the article is to promote the recent advancements in batteries coupled with supercapacitors or hybrid energy storage systems, and an overview of them gives rise to modeling, simulation, and the power management system for electric vehicle applications. The performances and designs of hybrid storage system are discussed in Section 2, overview of the energy managements in hybrid energy storage system and thermal effects has been discussed in Sections 3 and 4, the effect and performance of driving cycle has been discussed in Section 5, the simulation and modeling for electric vehicles have been discussed in Section 6.

2. Designing and Performance

In order to increase the efficiency of hybrid energy storage systems, the configuration and performance should be increased with careful designing in the way to strengthen each and every component with exploited usage and minimum weakness. For this, the high power densities of supercapacitors and high storage capability of batteries must be considered. For both batteries and supercapacitors, the state of charges denotes the usage of the power capacity in both charge and discharge current limit. The voltage range and pulse is identified by Guizhou Ren et al. [5]. He concluded the configurations of hybrid energy storage systems, by means of the following configurations in literature:

(i) Design with no converter
(ii) Bi-directional DC/DC converter in series and parallel

The three types of hybrid energy storage system categories based on the reports in literature are the followings: Battery/supercapacitor (passive), semi active and full active configurations. In the beginning, design of the supercapacitors/ultracapacitors and batteries are coupled to the DC bus [18, 21, 24–32] (Figure 2(a)), and this design is more comfortable but the performance of a supercapacitor cannot be achieved to its full potential and specific control algorithms should be used for this system. Any control algorithm can be induced only in a full active hybrid energy storage system (Figure 2(c)) involved two bidirectional DC/DC converters. However, the size of the design, efficiency, and cost are just compromised. The semi active configuration gives us a good compromise and a better performance with only one involved bidirectional DC/DC converter (Figure 2(b)), which is favored to hybrid energy storage systems [16,32–34].

In addition, there are comparative studies on the performance of these three configurations [5,21,24–36]. For example, Ziyou Song et al. [32] investigated the semi active battery/supercapacitor with repeat power variations in battery (two cases): during acceleration and deceleration, and the performance of hybrid energy storage system is studied in both cases: either the supercapacitor is directly connected with a battery or the supercapacitor is connected with a DC/DC converters. In that case, the beneficial part is the supercapacitor in all over the energy storage system when full potential is involved with power controller. Eckhard Karden et al. [37] investigated a future hybrid energy storage system. Holland et al. [27] investigated a hybrid system of a lithium ion battery with a supercapacitor having beneficial controlling efficiency and ability of pulse loads at power demand. When these two devices are connected in parallel, they share power with respect to a load during an active pulse. During pulse off time the capacitor is recharged by the battery. Here, the study shows that the supercapacitor in the hybrid energy storage system slightly increases the current capacity.

The future demands and requirements of batteries in hybrid energy storage system is proposed by Eckhard Karden et al. [38] Similarly, the energy conservation and management-overlap circuit for hybrid electric vehicles was proposed by Hosein-Farzanehfard et al. [39]. This needs a control in voltage of supercapacitors and high voltage in batteries, and such a matching boosts a proper power flow from high voltage batteries to low voltage supercapacitors in the hybrid energy storage systems. A buck converter is needed with a power boost combination to attain bidirectional capability. The 0V transition bucks with power boost
The converter acts as a soft switch interface for supercapacitors. Thus, it reduces the switching control and increases the efficiency of the converter.

The general mechanism of charge and discharge between the electrode of the battery and electrode of the supercapacitor is given in Figure 3(a). Ernst Ferg et al. [40] investigated the efficiency of the hybrid energy storage system with two different configurations. In that scenario, lithium ion battery with Value Regulated Lead Acid (VRLA) having 1Ah capacity is connected with a 2F
supercapacitor. The parallel connections are made in both cases. Figure 2 shows a study on capacity performance at different SOC in a hybrid energy storage system. Figure 3(b) shows the charge acceptance between lithium ion batteries with state of charge of the supercapacitors. Figure 3(c) shows the discharge performance between lithium ion batteries state of charge of the supercapacitors, while Figure 3(d) shows comparison between hybrid systems of VRLA batteries with supercapacitors and the other one without supercapacitors for charge acceptance. The discharge between VRLA batteries with state of the charge of the supercapacitors is shown in the Figure 3(e).

It can be seen that a lead acid battery is coupled with a supercapacitor have considerable advantage over the one without a supercapacitor during charging and discharging.

However, the lithium ion battery with a superconductor gives much more benefits during charge acceptance and discharging than a VRLA battery with a supercapacitor. Thus, lithium ion battery with supercapacitor system has a higher efficiency due to lower Warburg impedance value. The battery management systems importance is also highlighted. The study of batteries management systems is required for current levelling and regenerative braking.

The dynamic programming approach for semi active hybrid energy storage system was proposed by Ziyou Song et al. [31], and they use a converter with lower rating on semi active configuration. Here, the main thought is to minimize the cost and dimensions of a battery with a supercapacitor in the hybrid system; and the thermal degradation is also reduced to regain the capacity. Jain Cao et al. [41] proposed a new hybrid energy storage system and they compared conventional hybrid energy storage system with this new system, when the new design is able to utilize the power of the capacitor without required matching of DC/DC converter. Thus, the power requirement for battery pack can be reduced. A comparative analysis between simulation and experimental results shows that the utilization of ultra capacitor is up to 75%, and an experimental setup was built (Fig. (a)) with some major components (Table 1) to verify the electrical viability (Fig. (b) and (c)) of the new design hybrid energy storage system.

This study results an optimization of battery size and an increase in number of supercapacitors in the hybrid energy storage system. A novel approach on the duality of the battery with energy management for electric vehicles is proposed by Shou Zhang et al. [42]. In that design (Figure 5(a)), the hybrid energy storage system has multiple operating modes such as N-MOSFET, P-MOSFET and DC/DC converter. Two rules based on control power balances in energy management strategies were developed. In hybrid systems, the energy flows from battery to supercapacitor, which is monitored by a DC/DC converter and the battery are protected from Regenerative breaking of direct recharging. The experimental modeling and simulation modeling confirm the validity and performance of multimode operations in hybrid energy storage system. The high efficiency of this system has regards with conventional hybrid energy storage systems. Thus, the every systems efficiency has been
improved by 1.85% for New European Driving Cycle (NEDC) and 0.28% for Urban Dynamometer Driving Schedule (UDDS).

The power management design for smart storage system for smart electric vehicles was proposed by Yanjun Huang et al. [43]. They had done their research on a comprehensive study of power management strategies in electric vehicles. The hybrid energy storage system is based on an optimizer model, which works on a quadratic programming algorithmic system that includes three steps: (i) The first element of the control policy with the minimum cost, (ii) Use of dynamic model system that helps to predict the future outputs in the optimization region, (iii) Evaluation of the cost function in the future output that is shown in Figure 5 (b). Furthermore, it shows better performance of Zero Emission Battery Research Activity which was investigated by Ottorino Veneri et al. [44].

3. Energy Management System

It is necessary to managing the benefits of energy deriving from and into the smart system. Another significant hybrid energy storage system has been designed in literature [4,42,45–53] for energy management system. In this design the hybrid energy storage system has a multimode...
operating mode with following inputs: batteries with state of charge and outputs, the load voltage, demands in current, accelerations and vehicle speed, health condition of batteries and state of charge of the battery degradation at 0° temperature. In some case of studies, the energy consumption to manage systems was reduced by adding a regenerative braking that gives much efficiency in urban drive test rates which has been investigated in [57]. A new novel approach has been evolved in [42] of Shuo Zhang et al., which allows a good consumptions of the Regenerative Breaking and good accelerations at a time and the article proposes a flow diagram for flowchart controlling bus communications, where power supply works with algorithms based on different modes (Figure 5). Based on the analysis, \( y(\text{min}) \leq y(t) \leq y(\text{max}) \) and \( u(\text{min}) \leq u(t) \leq u(\text{max}) \) give us an energy management system optimizations; here \( t = 0, 1, \ldots, N - 1 \). The minimum power is delivered for the load of the supercapacitor and possible energy is absorbed from regenerative energy. In that case, the new cycle of acceleration is supported. A prototype was developed for electric vehicles of 1,550 Kg to demonstrate the energy management system with the help of algorithms; and utilizing the performance of bidirectional DC/DC converter is directly connected to CAN bus for energy deliver from supercapacitor. The multimode energy storage system also gives the rules based control performance at power distributions between the supercapacitors and batteries [40]; the power balance strategies and the configurations of energy management system in the multimode hybrid energy storage system were validated.

Yanjun Huang et al. [53] proposed a controller designing model and construct an experimental system to be validated. According to their proposed method, the structure and modeling of Regenerative auxiliary power system were discussed with driving cycle; the simulation analysis shows that the usage of fuel saves up to 7%. For the future study on robust model, predictive controller has been designed for electric vehicles without predefined drive cycle. Two control factors was addressed in their work: (a) Having well records on two reference variables, the load voltage and current of the battery; (b) achieving smooth transition during load switch. In this model, the linear matrix inequality constraints with numerically efficient optimization problems were converted by designed problems.

The reinforcement learning of offline algorithm is used in the power management for hybrid energy storage system. In there, the ultracapacitor behaves more actively assist the braking energy during discharge of the battery [58]. Jingyang Fang et al. [59] proposed the different energy storage units for virtual synchronous generator that helps to control the power fluctuation of the battery and they also verified that through experimental results. Later, in the year of 2018 Yi Zhang et al. [60] also try to optimize the power fluctuation.

The hybrid energy storage technology for energy management is investigated with the help of mathematical representations and algorithms to optimize the real time management systems [51,61-64]. The future works depends on the use of bidirectional DC/DC converter to control energy flow and to reduce the

### Table 1. Major components for experimental setup.

| Power supply         | 50A 40V DC Switching type | Ref. [41] |
|----------------------|---------------------------|-----------|
| Electronic Load      | NHR-4750-2 (100 A, 2kW)  | Ref. [41] |
| DC/DC converter      | Bidirectional, 40A 450v Half bridge | Ref. [41] |
| By pass switch       | Tyco Electronics EV200AAANA | Ref. [41] |
| Data Acquisition     | DL2- Race Technology      | Ref. [41] |
| System               | (0-12V 100Hz 16bit)       | Ref. [41] |
| Battery              | PC625 – Odyssey (12V 1Ah) | Ref. [41] |
| Ultra-Capacitor      | Maxwell 310F cell (32.4V 25.8F) | Ref. [41] |

![Figure 5.](image-url) (a) The multimode operations at hybrid energy storage system [42]. The red connection line denotes high voltage circuits and the blue line shows for CAN bus communication. (b) Flow diagram of controlling power supply, works with algorithms for power management [43].
dynamic response of ultracapacitors and also we should develop a method which allows precise selection of the filter parameter and sizing of supercapacitors. The Lyapunov function [63] based voltage controller helps to fully active batteries connection with supercapacitors. Zing Song et al. [65] recommended a set of rules from the dynamic programming result to improve the performance of online controller.

4. Thermal Effects in Hybrid System

Qingsong Wang et al. [54] studied the thermal effects and its runway performance has been review with safety enhancement on lithium ion batteries for future development. They made their research on performance of LiCoO$_2$ batteries, which are subjected to severe degradation and the model fades in a suggested wide temperature range. A new degradation model of LiCoO$_2$ battery that can be evaluated at 155 C using oven test; the heat generated counter and thermal runway have been suggested using three dimensional models (Figure 6). The thermal effects for other battery and supercapacitor are shown in the Table 2. The safety issue relating to the thermal runway is very complicated process involved in material science and engineering. Therefore, Qingsong wang et al. [54] adapted the dynamic degradation model varied with temperature from -20 C to 10 C. The operation of Dynamic Programming technique reduces the cost of the battery and the heats loads on the Smart storage system at completely enveloping air condition is about 75% heating efficiency used in China bus driving cycle (CBDC). The driving range with low cost of battery; high heating efficiency has been simulated through six supercapacitor modulus for hybrid energy storage system is represented in the below Figure 7. The simulation results are carried out between 25 C and 50 C for 30 to 60 driving cycles. Generally, the total cost for short range driving scenario will raise the heating power and it can be considerable decreased with long-range driving scenario.

The stability of supercapacitors and batteries in hybrid energy storage system has been investigated by the state key laboratory of automation, safety, and energy [66]; a consequence is that the surface temperature distribution and durability of the smart system guarantee the thermal stability of supercapacitors [55,67,68, 90]. The thermal performance and electric load were supported by supercapacitor model under harshest environment, and the whole electrical load was supported by ultracapacitors in hybrid energy storage system [55,57]. This approach is replaced by battery power during load distribution between battery and supercapacitor bank; that balances the thermal stability of the electric vehicle with suitable algorithms in the energy management system [69]. As seen in Figure 6, the temperature of the surface distribution of the battery is clearly shown with respect to time and analysis operation in the completely enveloping condition. The unsteady distribution of the temperature of the supercapacitor during 100th cycles is tested by algorithm of finite element method, and the result shows a periodic steady state is attained at 50th test cycle at ambient temperature raising condition. The modeling features and thermal management strategy is worked uniformly with the help of supercapacitor module present inside at appropriate range. The future works may moves on hybrid compressed air battery

![Figure 6](image-url). Three dimensional models are due to thermal effect at (60, 61, 62, 63, 64, 65, and 66 min) [54].
it includes proper amount of heat loss during charge and discharge to quantify the efficiency of thermal effects [71].

5. Hybrid System Performance with Effects in Driving Cycle

The most important criteria to be considered during the performance of hybrid energy storage system are about driving cycles [25,47–49]. Tomaz Katrasnik [48] investigates the performance of the driving cycle and accelerating driving test with wide temperature range. He highlighted the importance of the efficiency on DC/DC controlling supercapacitors incorporated with electric vehicle driving cycle. The strain on the battery was reduced with peak current efficiency modulation. The supercapacitors allowed great extraction in energy from battery. The significant effects were in the supercapacitors, that able to absorb quickly Regenerative Breaking energy [57] and to increases the efficiency of electric vehicles. He suggested using supercapacitors in the city-bus application.

Chau et al. [18] present the operations of 3 driving-modes of hybrid energy storage system; such as braking/downhill modes, acceleration-or-hill-climbing mode and normal driving mode. They have selected the controlled philosophy in the way of working batteries at the rate of output power level in hybrid energy storage system operation; whereas supercapacitors would receive and deliver a power difference during braking/downhill driving and acceleration/hill climbing driving, respectively. It was noticed that energy management system and efficiency at hybrid electric vehicles via hybrid energy storage system may provides different result for different operating circumstance. For slowly moving vehicles, the energy exchange is also very small, so the storage element absorbs all energy. On the contrary for fast moving vehicles, exchange of energy may be larger. Similarly, if the variation of speed is so large then the exchange of energy will also increase. Here, the most of the energies are being dissipated. Therefore, it is very important to monitoring the state of the charge of the supercapacitor since it may depends on the vehicle speed. If the vehicles speed is low then the state of the charge on supercapacitor remains high and empowering energy boosts at electric vehicle acceleration whereas at high speed vehicles the supercapacitor should stay in state of discharge. A DC/DC converter is mandatory to accommodate the voltage fluctuation at supercapacitor and the motor is optimized the power consumption and conservation with the help of supercapacitors [57].

Ali Castaings et al. [49] evaluate the effect of energy management system under different driving cycle and the deviation at the state of charge of supercapacitor which is correlated with the variation of the electric vehicle speed and the regenerative breaking energy was totally absorbed by the supercapacitor. Under ‘ideal driving cycle,’ the result confirmed that the energy management system was well designed with good performance. In the real driving cycle, three cases could occur here is shown at Table 3.

He Tian et al. [66] investigate on driving cycle in energy management system and presented a novel approach on optimal supercapacitor size in the hybrid energy storage system. Two main characteristics such as maximum discharge and energy demand have been used in simulation and the resultant observes a direct

Table 2. Heat effect.

| Type                  | Heat Generation | References |
|-----------------------|-----------------|------------|
| VRLA + 1250 F of supercapacitor | 25 C–50 C       | [24]       |
| Li-ion + 2300F of supercapacitor | 40 C–50 C       | [35]       |
| NiMH + 1500F of supercapacitor      | 20 C–40 C       | [99]       |

Figure 7. (a) The minimum and maximum temperature for 60 driving cycle, (b) hybrid system of six supercapacitor module, (c) T=25 C & 50 C [99].
influence of intensity factor and online energy management strategy on supercapacitor. This identification of the diving parameter is used for optimization on hybrid energy storage system.

6. Modeling and Simulation for Electric Vehicle

Shuo Zhang et al. [42] give a multimode smart storage system, validation, and energy management strategy. The simulation of NEDC (New European Driving Cycle) and UDDS (Urban Dynamometer Driving Schedule) was based on Advance Vehicle SimulatOR. Then the experimental platform has been constructed for future validation. Most of the researchers are using Matlab-Simlink software to investigate parallel link supercapacitor with battery [28,72]. In that model, the two batteries were connected in series with 4.2V and three supercapacitors were also being placed in series with 2.8V.

For high power automobile application, we need to connect supercapacitor parallel with lead acid batteries; this was studied by Mamadou Baloi Camara et al. [72]. The main use of this model is to improve the life cycle and the performance of smart storage system. The electric vehicles are very complex system containing sub systems. Developing and designing part of the vehicle are based prototype design and then testing this prototype physically to assess the design. The physical testing and prototype are so costly. Therefore, simulation and computer modeling are more flexible. There are lot of literatures to dedicate about supercapacitor, ultracapacitor, battery, pseudocapacitor and smart storage system modeling and simulations [36,49,51,55,56,58–65,67–98]. The first simulation having 8 units comprises with graphical interface of data (I/O) [18]. Those units are considering as energy source, performance, transmission and controller with new driving cycle was achieved by collaboration (Japan, USA, and Europeans). The performance of electric vehicles can be evaluated by climbing capability, fuel economy, speed of the vehicle, etc. The key parameter was considered as optimization of driving and fuel economy. As the simulation showed, the mass ratio of electric vehicle is influenced by optimization. It should be noted that hybridization ratio of gross weight and energy source weight leads to high power on device. Thus, the simulation shows the better performance of smart system in electric vehicles [36,49,62,64,65,94–96].

The pulse configurations can be determined by two measures: (i) the duty cycle, and (ii) the energy under pulse; the duty cycle determine the time interval and power distributions are present in the load pattern (Figure 8). For motivation of smart storage system, let us observe that it does not provide as much benefit over an individual device, then the pulse own by recharging capacitor through battery [28]; the relaxation epoch is done between two successive pulses. Wenzhong et al. [80] give a symmetry difference on modeling and simulation tool for hybrid electric vehicles. They presented a different technique in system modeling illustration and power train components. The software for simulations and modeling: (i) Virtual Test (VT), (ii) Advanced Vehicle SimulatOR (AVISOR). The dynamic model (DM) and quasi steady (PSAT) are component presented in modeled through example applications. In addition to control the speed of the vehicle and fuel economy, the backward facing models and forward facing models are proposed by Abbas Fotouhi et al. [76] with driving cycle. He provided a review on three families of battery models they are, (i) electrochemical model, (ii) mathematical model, (iii) equivalent circuit model. The first principle of electrochemical model gives good apprehensiveness and high precision; but it cannot be used for long time period. The second principle of equivalent circuit model acquire from electrochemical impedance spectroscopy test application or from system information method application. The third principle of mathematical model differs in quality and complexity of state of charge. Some models are having variable which determine the state of the function and operating point, which are used in either implementation of polynomial functions or static lookup tables. The opportunity and application on smart system storage depends on the new type of lithium selenium [88] and lithium sulfur [87] batteries.

Song et al. [32] simulated a smart storage system and analyzed the short duration performance with power distribution between its modules during decelerations and accelerations. They investigated the supercapacitor bank on the usage of in and out to the battery in the smart storage system. In minor case, the supercapacitor was directly connected with the battery shunt or the supercapacitor connected directly with DC/DC converter to boost the charging time. Moreover, the prototype models and experimental data help to
observe the unsteady state during deceleration and acceleration and they are recommended for power controller due to complex concern control.

Paul Bentley et al. [24] used a spice electrical simulation package for a parallel supercapacitor with valve regulated lead acid battery to know their performance at hybrid electric vehicle driving condition. The combinational arrangement of parallel-combined supercapacitor decreases the pulse (I) during voltage recharge. The cell takes 5 h to being charged at the rate of 1.53A, the value obtained by means of discharging cell and supercapacitor distinctly at open-circuit volt. The state of charge and discharge value for supercapacitor is calculated as $0.6 \, \text{m} \Omega$ (resistance) and for cell as $4.17 \, \text{m} \Omega$ (resistance). The controlled port Hamiltonian and state space model increases the battery power management and reduce the errors [81]. This model had batteries and supercapacitors with motor as a load to deliver energy in electric vehicles.

Fiorenti et al. [83] give a work on experimental validation and development in dynamic models of smart storage system involving in the lead acid batter parallel to electrochemical double layer capacitor. The parameter of lead acid battery shows the state of charge and current direction; while the parameter of electrochemical double layered capacitor model was identified as diverse temperature. This system model incorporated with four operation scenarios: (i) without start and stop, (ii) with start and stop technology, (iii) hybrid energy storage system, (iv) operation of stand-alone battery.

6.1. Alternative Application

The use of smart storage system in hybrid electric vehicles against the sulfaction of the valve regulated lead acid batteries was investigated by Stieneker et al. [92]. They presented the hybrid system configuration that increases the life time of battery and decreases the sulfaction. The best performance of smart electric bus was presented by Victor Herrera et al. [93]. A novel design was proposed by Xiangyang Xia et al. [98] in which they reduces the ripple of the output current and improved the life of the battery with the help of new bidirectional DC/DC converters and a limited dynamic rules for smart energy storage system.

7. Conclusion

The main objective of this article is to promote the recent advancements in batteries coupled with supercapacitors or hybrid energy storage systems, and an overview of them gives rise to modeling, simulation, and the power management system for electric vehicle applications; where the new design is able to utilize the power of the capacitor without required matching of DC/DC converter. Thus, the power requirement for battery pack can be reduced. A comparative analysis between simulation and
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