Energy Management Strategy for Hybrid Energy Storage Systems in Electric Vehicle –A Review

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***Abstract*—On board energy management system for Electric Vehicle (EV) defines the fuel economy and all electric range. Charging and discharging of energy storage devices take place during running as well as stand-still conditions. Battery-alone EV suffers from range anxiety, current drain during peak power demand and less battery life. It depends on the grid for charging and thus the increasing popularity of EV is increasing burden on the grid. Different energy storage devices are available which could be used on board to form a hybrid energy storage system. Batteries, Ultra-capacitors and fuel cells are some of them. Such a system will act as a stress reduction factor and increase the battery life. In this paper, a detail literature review of various energy storage devices that can be used in EV is presented. A comparative study of various topologies available for this purpose is also presented. Finally, a detailed review of Energy Management Strategy (EMS) is presented with current trends and research gaps i.e., challenges.**

***Index Terms*—Battery technology, electric vehicle, fuel cell electric vehicle, hybrid energy storage system, ultracapacitor, topology, energy management strategy**

Abbreviations-

WHO	World health organization	PEMFC	Proton exchange membrane fuel cell
COVID-19	Corona virus disease 2019	MCFC	Molten carbonate fuel cell
CO_2	Carbon dioxide	DMFC	Direct methanol fuel cell
IC	Internal combustion	SOFC	Solid oxide fuel cell
UC	Ultra-capacitor	BLDC	Brushless direct current
FC	Fuel cell	EDLC	Electric double layer capacitor
FW	Flywheel	AFC	Alkaline fuel cell
EV	Electric vehicle	PAFC	Phosphoric acid fuel cell
Li-ion	Lithium ion	PV	Photo voltaic
Ni-MH	Nickel metal hydride	HESS	Hybrid energy storage system
Ni-Cd	Nickel cadmium	PWM	Pulse width modulation
Li-air	Lithium air	ANN	Artificial neural network
$LiFePO_4$	Lithium iron phosphate	RBS	Regenerative braking system
Zn-air	Zinc air	EMS	Energy management strategy

I. Introduction

Increasing pollution and population are a greatest threat to life on earth. Although it has been delayed but a strong step towards saving of earth is being taken globally. According to global state of air index 2019, India has 7 most polluted cities amongst top ten in the world [1]. As per the mortality is concerned, air pollution is the 5th leading factor worldwide. Death due to air pollution is more as compared to known factors like accidents, malaria etc. More than 90% people are living in such areas where WHO's guidelines do not meet for healthy air. Even more than half of population is living in such area where least requirement as prescribed by WHO is not satisfied. Air quality and increasing population are inversely proportional to each other. Less developed countries are suffering more from the danger of air pollution. According to a report, the rise in greenhouse gases has reached to a new record during 2015-2019 [2]. CO_2 has increased nearly by 20% in last five years. With this succession, global warming will be of 3°C by 2100 and it will continue further. United Nation reports recommends that we must restrict the global warming to 1.5°C by the end of this century. To achieve this, the CO_2 emission must decline by 45% till 2030 and 0% by 2050 [2]. As per the current situation across the world (due to lockdown amid of COVID-19 Pandemic), air quality index has improved drastically. But what after lockdown? Definitely it is required to develop a pollution free transportation system.

Major factor behind generation of greenhouse gases is the abundant use of fossil fuels in many respects. Air pollution due to vehicular emission is one of the key components. To counter this impact, major focus is being given towards electric vehicle and renewable energy sources globally. Due to several advantages of electric mobility like zero emission, less noise, low cost of operation etc., many countries are opting for electric vehicle as main mode of transportation. Every company is planning to bounce back with electric mobility concept and this is going to be one of the solutions. A comparative study of fuel saving per kilometer powered by different energy sources is presented in Fig. 1. With this comparative study, it is clear that cost of operation for electric vehicle is less.

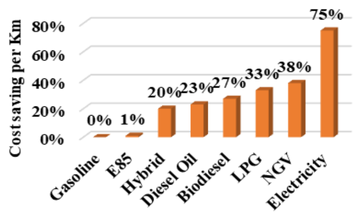

Fig. 1. Comparative representation of fuel cost saving by vehicles powered by Gasoline, Ethanol(E85), Hybrid source, diesel oil, biodiesel, liquid petroleum gas (LPG), natural gas vehicles (NGV) and electricity [3].

Manuscript received July 14, 2021; revised September 18, 2021; accepted September 30, 2021.

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doi: 10.18178/ijeetc.11.2.88-101

In present scenario, electric vehicle is powered by battery only. For certain advantages like, fast charging ability, less space requirement and low maintenance, the use of lithium batteries is dominating in luxurious vehicles [4]. Due to high cost of these batteries, lead-acid batteries are still in use in passenger vehicles like rickshaw etc. Chances of reduction in the cost of lithium ion battery are large in future because several countries are coming with cost effective technologies [5]–[7]. However, low mileage per charge and other battery related limitations are some of the constraints which need to be addressed.

As we know that battery is high energy density device, so during steady state operating condition when the vehicle is moving on a levelled surface, the torque requirement of the motor is not appreciable and hence the power extracted from the battery is normal [8]. However, during dynamic conditions like starting conditions, acceleration or the condition when the vehicle is moving uphill or is overloaded etc., the torque requirement is high and therefore battery is forced to deliver high amount of electric current which is dangerous for the battery life [9]. Therefore, appropriate technology is needed to be explored which could safeguard the battery during such conditions [10]. A concept of hybrid energy storage system appears to be feasible in such cases wherein modern energy storage devices like UC, FC, FW etc. could be used for the power sharing with the battery during dynamic conditions [11]–[14]. Also, energy can be extracted during regenerative braking and by the use of feasible non – conventional energy sources [15]. Altogether any technology developed of this kind will lead to extended battery life as well as extended running mileage of the vehicle.

In present conditions, the converter used for the energy transaction between the source and the drive motor can be made more sophisticated by adopting modern control methods with objectives to minimize the losses, lower the cost, extend the battery life and extend the mileage of overall vehicle drive system [16]–[18].

This paper reviews various energy storage devices which can be used to support the vehicle battery and also different topologies for integrating the storage devices, load and converters. Section II gives information about the battery technology, development, types and analysis based on deciding factors and application. Section III deals with ultra-capacitor, reason for using it in EV and classification based on energy storage mechanism and electrode deals with ultra-capacitor, reason for using it in EV and classification based on energy storage mechanism and electrode materials. The zero-emission fuel cell technology is covered in section IV. Section V presents a detailed review study of HESS topologies consisting of battery and UC as energy centers. Section VI gives the detail review of energy management strategy (EMS). The focus of Section V and Section VI is on the circuit topologies and EMS in general and hence as an example, only battery and UC are considered. Selection of topology and cost analysis is discussed in section VII. Future trends and challenges are discussed in section VIII. In this section issues in the development of EV are also presented. Section IX concludes the paper.

II. Battery Technology for Electric Vehicle Application

Due to favorable characteristics of battery like high energy density, compact size and reliability, it is used in vehicles for different purposes [19]. First rechargeable battery is the lead acid battery and it is popularly used since last more than 100 years [9]. So far, lots of research is carried out to improve the performance of the battery and accordingly many types of batteries are available commercially. Each of these batteries has different characteristics, different specific energy and specific power. This is shown in Fig. 2. For selection of suitable batteries, the specific energy, specific power, cycle life, cost and safety are taken in account. Safety is the utmost important parameter. Cost of the battery should be low and life cycle should be high [9]. Depending upon material used, batteries can be classified as lead acid battery, nickel-based battery, sodium nickel chloride battery and lithium-based battery. Mechanical batteries such as zinc air and lithium air make use of atmospheric air and qualify as a favourable solution for EV.

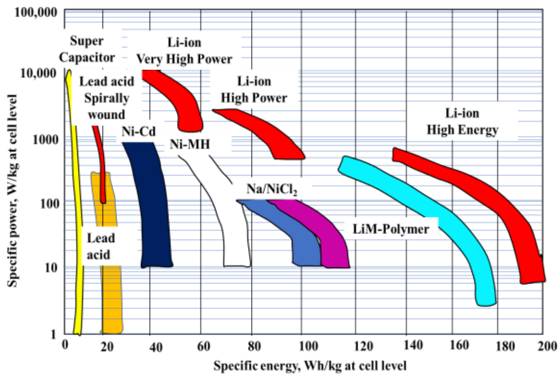

Fig. 2. Characteristics wise representation of batteries [9].

A. Lead Acid Battery Technology

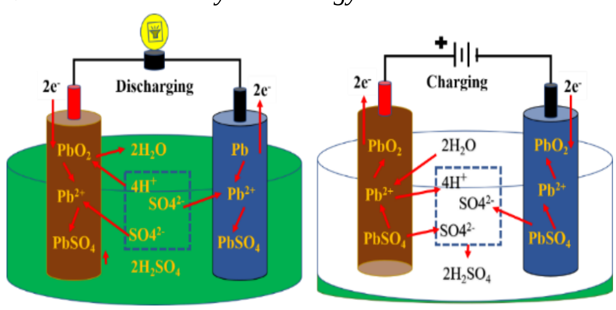

Fig. 3. Lead acid battery chemistry during discharging and charging [5].

Lead acid battery consists of lead dioxide (PbO_2) as negative electrode, metallic lead (Pb) as positive electrode and ulphuric acid (H_2SO_4) as electrolyte. This is represented in Fig. 3. In small EV application generally valve regulated lead acid battery is preferred because of maintenance free, less self-discharge rate and high specific power as compared with other batteries in lead acid module [20].

Lead acid battery suffers from low specific energy (typically between 20Wh/kg to 40Wh/kg) and low specific power (approximately 180W/kg) and hence its weight and size increases for a specific range as compared with other batteries technologies [9]. Its nominal voltage of each cell is 2V. Due to less power and energy density, high charging time, and shorter life cycle (500-1000), it is not preferred to use in luxurious EV [21]. Low production cost and availability, makes it suitable for low power applications. Valve regulated lead acid battery is the most common for small EV applications due to low cost and less maintenance [22].

B. Nickel Based Battery Technology

1) Nickel metal hydride (NiMH) battery technology

NiMH is a rechargeable battery with metal hydride as negative electrode, nickel oxyhydroxide [$NiO(OH)_2$] as positive electrode and potassium hydroxide (KOH) as electrolyte. NiMH batteries have common specifications like cell voltage of 1.2V, energy density of 140Wh/l to 300Wh/l, self-discharge rate of 30% per month, specific energy 60Wh/l to 120Wh/kg, charge discharge efficiency of 66%, specific power of 50W/kg to 1000W/kg and cycle durability of 500-1000 cycles [12], [23], [24].

As compared with lead acid battery it has advantageous properties like higher energy density and better life cycle but its production cost is also high. Due to low cell voltage, its application is usually in small electronics goods. However an improved design of NiMH battery is proposed in literature which can be used in EV [25]. Prakasit *et al.* has presented a paper in which they have simulated NiMH battery and UC for electric vehicle [26]. Major use of NiMH batteries is in hybrid cars. As of 2017, 85% of listed hybrid vehicles were based on NiMH [27]. In the past, NiMH based BEV were General Motor's 'EV1', Honda's 'EV Plus', and Ford's 'Ranger EV' but hybrid electric vehicle up to 1kWh NiMH batteries were used in Toyota's 'Prius', Honda's 'Insights', Ford's 'Escape Hybrid', Chevrolet's 'Malibu Hybrid', and Honda's 'Civic Hybrid' [28].

2) Nickel Cadmium Battery (NiCd)

A NiCd is a rechargeable battery in which nickel hydroxide [$Ni(OH)_2$] is a positive electrode, and cadmium (Cd) is negative electrode. Potassium hydroxide [KOH] which is alkaline in nature is used as electrolyte. NiCd battery has better self-discharge rate but its production cost is high and suffers from memory effect [21], [29]. Discharging and charging behavior of the nickel-based battery in shown in Fig. 4. KOH solution used is highly toxic and due to legal ban on cadmium, NiCd batteries have disappeared from the market. NiMH battery is superior over lead acid and NiCd battery and hence NiMH were preferred [29].

Nickel based battery suffers from poor charge and discharge efficiency, poor performance in cold weather and memory effect.

This has reduced its applicability is reduced for EV application [12].

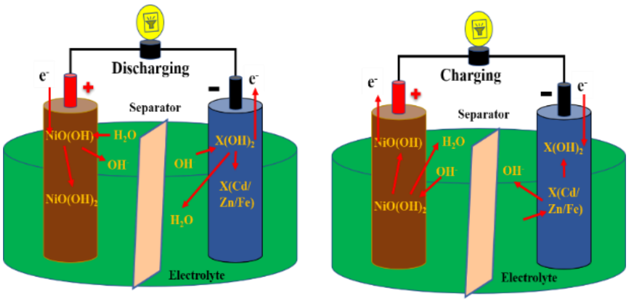

Fig. 4. Discharging and charging schematic of nickel based battery [5], [21], [24].

C. Sodium-Nickel Chloride Battery (Zeolite Battery Research Africa-Zebra battery)

In In the same period when Ni-MH battery was being developed, a new type of battery called as Zebra battery was proposed [30]. This technology uses liquid sodium as negative electrode, nickel chloride as positive electrode and beta alumina ceramic as electrolyte [31]. Common specifications of the ZEBRA battery are – nominal voltage of 2.6V, energy density of 90Wh/kg to 120 Wh/kg, specific power of 155W/kg, life cycle greater than 1200 and very low self-discharge rate [32], [33]. As its operating temperature is in the range of 245°C to 350°C, the thermal management is difficult. A prototype models of this type of battery are reported in [12], [34]. Configuration of Zebra cell at high temperature is shown in Fig. 5.

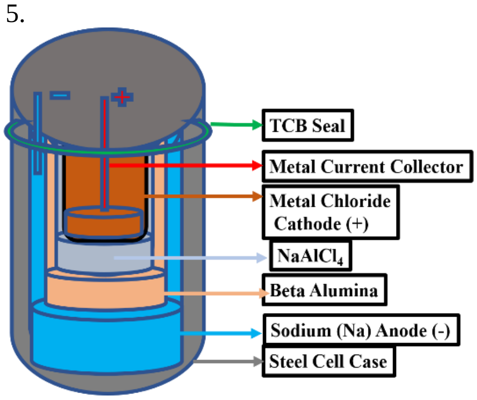

Fig. 5. Configuration of the ZEBRA cell [5], [31], [35].

D. Lithium Based Battery

Due to high energy density, the lithium-based batteries are the first choice for all EVs however, due to high cost; they are used in luxurious vehicles. Researchers are optimizing the cost and size for wide applicability.

There are four primary components of lithium-ion battery cathode, anode, electrolyte and separator. During charging, Li-ions leave the cathode and enter the anode. During discharging, Li-ions enter the cathode and leave the anode. Cathode is made of lithium metal oxide powder. Anode is made of graphitic carbon powder [7], [9]. Cathode and anode structures are organized in Aluminium and copper current collectors respectively and is shown in Fig. 6 (a) and Fig. 6 (b).

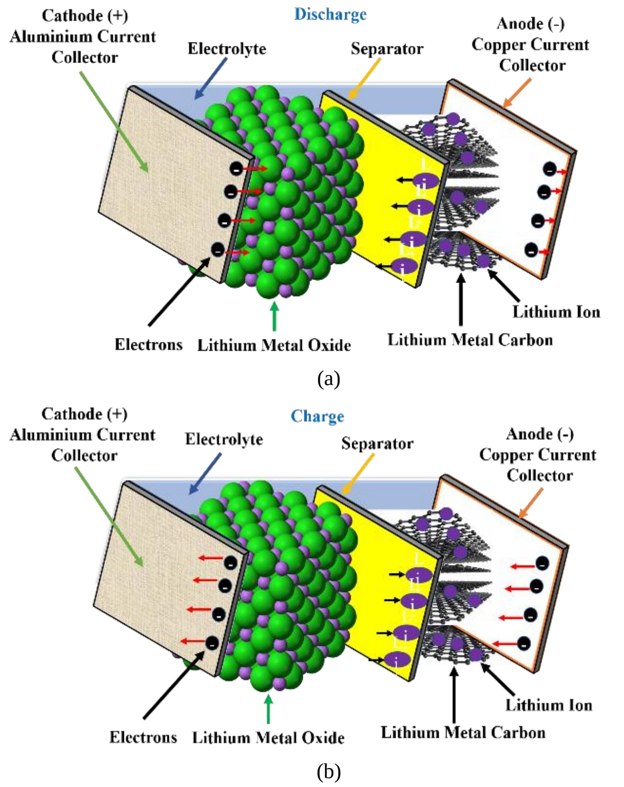

Fig. 6. Charging and discharging behavior of lithium ion battery [23]: (a) Charging and (b) discharging.

The electrolyte is composed of lithium salt and organic solvents. Transfer of lithium ion takes place through this electrolyte only. Electron flow follows the outer circuit. Separator is a micro porous membrane used to prevent the battery from short circuit between anode and cathode while it provides a path to Li-ion [7].

Li-ion battery has good charging and discharging behavior and is presented in Fig. 7 (a) and Fig. 7 (b). During charging it follows the constant current profile and battery voltage increases gradually to nominal values. After that the charging current starts reducing exponentially. [7], [23], [36].

Variation in positive electrode material presents different types of lithium-ion batteries such as lithium cobalt oxide ($LiCoO_2$), lithium manganese oxide ($LiMn_2O_4$), lithium nickel manganese cobalt oxide ($LiNiMnCoO_2$), lithium iron phosphate ($LiFePO_4$), lithium nickel cobalt Aluminium oxide ($LiNiCoAlO_2$) and lithium titanate ($Li_4Ti_5O_{12}$) [37]–[39]. In place of liquid electrolyte as in case of lithium ion, solid electrolytes are preferred in lithium polymer battery.

Lithium cobalt oxide battery's voltage level varies from 3V to 4.2V [40]. This is the mostly preferred technology in the automotive industry. This technology is most researched and used in EV application. Common specification of this battery is – nominal voltage of 3.6V, energy density of 118Wh/kg to 250Wh/kg, power density of 200Wh/kg to 430W/Kg, life cycle of 2000 and self-discharge rate is less than 5% per month [3], [6].

Recent research and development has claimed that cut-off voltage of this battery technology is improved to 4.45V [41], [42].

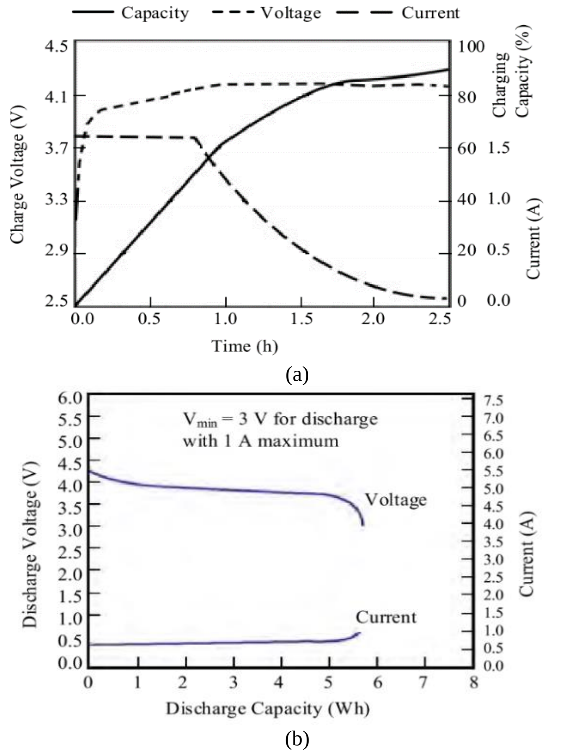

Fig. 7. Charging and discharging characteristics of Li-ion battery [7]: (a) Charging and (b) discharging.

Wang *et al*. presented a novel development in the lithium cobalt battery technology by implementing, modification in material properties and performing doping, coating processes. As claimed by the author, it has raised the maximum rated voltage to 4.5V. This is presented in Fig. 8 [41].

Another development in the lithium-based technology is the Lithium manganese oxide battery which has a good thermal stability and safety due to its spinal structure. This battery has more specific energy than cobalt and can provide 50% more energy than nickel-based battery [37], [42]. It offers high specific power, high energy density and high-power density.

Lithium nickel manganese cobalt oxide battery provides high specific energy and minimum self-heating rate. Nickel and manganese provide good performance due to low internal resistance of manganese and high specific energy of nickel. Cathode is composed of 33% nickel, 33% manganese and 34% cobalt [42], [43]. The overall performance aspect of this battery is good.

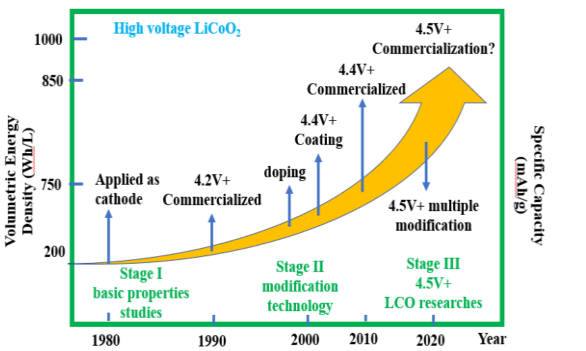

Fig. 8. Historical development of the lithium cobalt oxide battery [41].

Lithium iron phosphate battery has longer life cycle (>2000), high value of c-rating and high value of specific power (2000W/kg to 4500W/kg) hence its applicability increases in EV application. However, its size is large as compared with other type of Li-ion battery. This battery has a capability to operate from –45°C to 70°C temperature. The voltage rating of this battery is less as compared with Li-ion and Li- metal polymer [32], [38].

The lithium nickel cobalt aluminum oxide battery technology is finding more interest amongst researchers due to comparatively high specific energy and high-power density. This feature makes it more suitable for application in EVs [38].

Lithium titanate anodes are used in lithium titanate battery. Its nominal voltage is 2.4V. the unique characteristics of this battery is having c-rate and its life cycle is largest among all lithium-based battery [44], [45].

Lithium polymer battery has its unique characteristics due to its gel/solid type electrolyte. It can be customized to any size. Its specifications are – nominal voltage of 3.7 V, energy density of 130Wh/kg to 225Wh/kg, specific power of 260W/kg to 450W/kg, and self-discharge rate is less. Its life cycle is less as compared with lithium-ion battery [46], [47]. Performance indices for lithium-based batteries are tabulated in Table I.

E. Mechanical Battery

Mechanical batteries like zinc air and lithium air are less preferred for the EV application. Problem with mechanical battery is that, after every cycle, the electrolyte has to be replaced. Mechanical batteries have high energy density but less life cycle as compared with other batteries [36], [48]. Selection of battery for an EV depends on its performance parameters like voltage, energy density, cycle life, etc. Comparison of various batteries on the basis of these deciding factors is presented in Table II.

Improved battery powered electric vehicles are being developed worldwide. Research and development in battery technology is boosting the vehicle performance in terms of range. Recent development of Tesla model-S 85D is capable of covering 270 miles in a single charge [49]. A comparative study of different models of electric three wheelers manufactured by Mahindra & Mahindra Limited known as Mahindra-Treo shows that battery technology is being developed to its maturity level with the development in power density and energy density [50].

Tesla Roaster (200kWh) has battery capacity of 200kWh, Ford Mustang Mach-E(99kWh), Volkswage ID.3(77kWh), Peugeot e-208(50kWh), Mercedes EQC (93kWh), etc. are some of the luxurious EV which are using lithium based battery pack [3].

TABLE I: PERFORMANCE INDICES FOR LITHIUM-BASED BATTERIES [44], [51]

Types of Li-ion batteries	Cell voltage (V)	Energy density (Wh/Kg)	Advantages	Disadvantages	Application
LiCoO2	3.7-3.9	140	High Specific Energy	Short life span and limited load capacity and safety	EVs, cell phones, laptops and digital cameras
LiMn2O4	4	120	high specific power, safety and life span	Moderate in overall performance	EVs, HEVs, medical
LiFePO4	2.3-2.5	100	Good thermal stability, tolerant to abuse, high current rating, excellent safety and long-life span	Moderate specific energy, lower voltage than other lithium-based batteries, cold temperature reduces performance	EVs, power tools and portable devices
LiNiMnCoO2	3.8-4	170	Good overall performance and excels on specific energy	High cost	Power tools, EVs and energy storage
LiNiCoAlO2	3.65	130	High energy and power density, good life span	High cost and marginal safety	EVs and power trains
Li4Ti5O12	2.4	110	Recharge efficiency 98%, life cycle 3000-7000, high safety and stability, quicker to charge, temperature range (-300C to 550C)	small voltage 2.4V per cell, low energy density, difficult to manufacture	Advanced nanotechnology application

TABLE II: DECIDING PARAMETERS OF BATTERIES USED IN EV [9], [12], [52].

Battery type	Nominal voltage (V)	Energy density (Wh/Kg)	Volumetric energy density (Wh/L)	Specific power(W/Kg)	Cycle life	Self-discharge (%per month)	Operating temperature (°C)	Production cost ($/kWhr)
Lead acid	2.0	35	100	180	1000	<5	-15 to +50	60
Ni-Cd	1.2	50-80	300	200	2000	10	-20 tot +50	250-300
Ni-MH	1.2	70-95	180-200	200-300	<3000	20	-20 to +60	200-250
ZEBRA	2.6	90-120	160	155	>1200	<5	+245 to +350	230-345
Li-ion	3.6	118-250	200-400	200-430	2000	<5	-20 to +60	150
Li-metal polymer	3.7	130-225	200-250	260-450	>1200	<5	-20 to +60	150
$LiFePO_4$	3.2	120	220	2000-4500	>2000	<5	-45 to +70	350
Zn-air	1.65	460	1400	80-140	200	<5	-10 to +55	90-120
Li-air	2.9	1300-2000	1520-2000	.	100	<5	-10 to +70	-

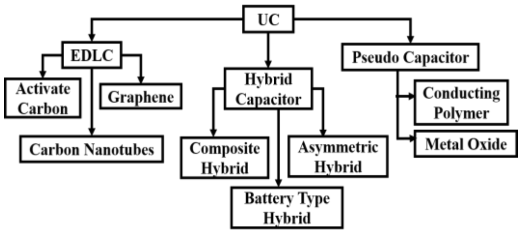

Fig. 9. UCs classification based on energy storage and type of electrode material

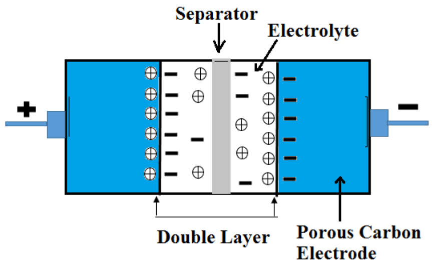

Fig. 10. Formation of double layer in EDLC

III. ULTRACAPACIOTR

Ultracapacitor also called as supercapacitor is an energy storage device which can provide hundreds to thousands of times more power than other storage devices [53]. Though it has poor energy density, the ability of fast charging and discharging has found its application in capacitor vehicles such as Capa bus (capacitor bus). These passenger buses have to stop frequently at the known points where the charging facilities are provided.

Specific power of the UC can be reached up to 3 kW/kg whereas the Li-ion batteries have the specific power in the range of 200W/kg to 340W/kg [54]. Efficiency of A comparison between UC, electrostatic capacitor, and battery technology of different performance indices is as presented in Table III. Based on the energy storage mechanism and electrode materials used, UCs are classified as shown in Fig. 9 [55], [56]. Electrode materials, electrolyte, separator and voltage rating decides the performance of UCs. If both the electrodes are of same material than that UC is known as symmetrical UC (Sym.) otherwise it is termed as asymmetrical UC (Asym.) Based on the energy storage mechanism, UCs are classified in three categories: EDLC, pseudo capacitor and hybrid capacitor [57]. As shown in Fig. 10, EDLCs have two carbon based electrodes immersed in liquid electrolyte and a separator [58]. Recent developments in electrode material from porous active carbon to grapheme and carbon nanotubes have advanced the UC in terms of energy and power density [55]. Double layer is formed due to accumulation of charge at porous electrodes and the separator as shown in Fig. 10.

TABLE III: COMPARISON OF ELECTROCHEMICAL ENERGY STORAGE DEVICES [59], [60]

Characteristics	Electrolytic Capacitor	UC	Battery
Specific energy (Whr/Kg)	<0.1	1-10	10-100
Specific power (W/kg)	>10,000	500-10,000	<1000
Discharge time	10^{-6} to 10^{-3} s	Sec. to min.	0.3 - 3 hr.
Charge time	10^{-6} to 10^{-3} s	Sec. to min.	1 – 5 hr.
Efficiency (%)	About 100	85-98	70-85
Cycle life	Almost infinite	>500000	About 1000

Due to porosity of activated carbon, surface area increases from 10000 to 100000 times [61], [62]. No faradic action takes place during accumulation of charge and this mechanism allows fast energy storage, delivery and better performance. Power density of the EDLC is higher than the other types but specific energy is low (5-7Wh/Kg) with high self-discharge and high cost [55], [63]. In pseudo capacitor, the faradic action (reduction and oxidation just like in case of battery) takes place which increases the energy density and specific capacitance as compared to EDLC [55], [64].

Hybrid capacitor offers the combined characteristics of EDLC (high cyclic stability and better power performances) and pseudo capacitor (greater specific capacitance and energy density) [63]. Pseudo capacitor and hybrid capacitor gives better performance due to their energy and power density [65].

UCs are widely used where high pulse of current is required. Manufacturers and different characteristics of UCs are tabulated in Table IV.

TABLE IV: UC CHARACTERISTICS OFFERED BY COMMERCIAL MANUFACTURERS [66]

Company	Type	Device	Capacitance (F)	Rated voltage (V)	Sp. Energy (Wh/kg)	Sp. Power (kW/kg)	Operating T (°C)	Application
Maxwell U.S.A.	Sym.	Cell Module	1-3400 5.8-500	2.3-2.85 16-160	0.7-7.4 2.3-4	2.4-14 3.6-6.8	-40/65 -40/65	Transport, energy, storage
LS Mtron Rep. Korea	Sym.	Cell Module	100-3400 2.5-500	2.7-3 16-381	3.3-7.5 2.3-5	0.9-2.4 0.3-0.6	-40/65 -40/65	Industry, electronics, transport
Nesscap Co., Ltd, Canada	Asym. Sym.	Cell Cell Module	50-300 3-5000 1.5-500	2.3 2.3-2.7 5-125	4.8-8.8 2-5.7 1-3.7	4.9-6.2 6-17 2.5-6.8	-25/60 -40/85 -40/85	Heavy Vehicle, pitch Control
Panasonic Corp, Japan	Sym.	Cell Coin	3.3-100 0.1-1.5	2.3-2.7 3.6-5.5	1.4-4.1 0.13-1.5	0.29-3.65 10^{-3}	-40/70 -40/85	Electronic Devices
Vinatech Rep. Korea	Hybrid Sym.	Cell Cell Module	10-800 1-3000 2.5-60	2.3 2.5-3 16-144	4-12 0.7-6.5 1.7-5.6	0.4-0.8 1-11.3 0.4-4	-25/60 -40/70 -40/70	Transport, ups, wind turbine
Yunasko Ukraine	Hybrid Sym.	Cell Cell Module	1.3 400-3000 13-500	2.7 2.7 16-90	37 4.7-6.2 3.9-2.1	4 7.1-41 3.3-11.3	-40/60 -40/60 -40/60	Transport, Industry, Electronics
Ioxus Inc U.S.A.	Sym.	Cell Module	1250-3150 21-500	2.7 16-162	4.5-6.3 2.2-3.8	23-34 0.2-0.4	-40/85 -40/85	Transport, Renewable Energy, backup
SPS Cap China	Sym.	Cell Module	1-5000 0.5-500	2.5-2.7 16-2300	0.9-6.5 1.4-3.6	0.5-8 0.3-0.7	-40/60 -40/60	Transport, wind turbine, microgrid

Though China and other countries are developing CAPA vehicles (capacitor-based vehicles), the applicability of UCs in transportation system is still in development stage. CAPA vehicles are traction vehicles that uses UC bank [66].

Application of the UCs in railways is on the rise because after application of UCs, catenary free operations are achieved and energy is saved. A combination of the 400V battery system along with 640 UCs of 1800 F each is implemented to reduce the peak power demand and catenary free operation in Mannheim, Germany [67]. In Paris and Rotterdam also, for energy saving and catenary free operation, UCs are used but it can be charged from overhead lines in about 20 seconds [67]. Apart from the electric rail and buses, use of UCs in passenger vehicle is on rise. A commercial fuel vehicle MAZDA i-ELOOP is utilizing UCs for regenerative braking along with the IC engine and claiming 10% of fuel saving [68]. Lamborghini's Sian Roadster is using UCs [69]. Due to the advantages of UC, its usage in commercial vehicles is on the rise but again cost is high and control becomes complex.

IV. Fuel Cell Technology

The fuel cell technology is gaining more attention due to its zero-emission process. In 1838, Swiss scientist C.F. Schonbein presented the concept of fuel cell but first fuel cell was only developed in 1839 by Sir William Robert Grove [70]. In mid-1960, more research was carried out for the advanced application of fuel cell and the Government of USA, Japan and Canada started funding the research work on this technology [71]. The Electrical energy is generated using chemical energy of the fuel and that is fuel cell technology. This device takes fuel and air as input and through chemical reaction electricity and water are produced as output [72]. Fuel cell technology is similar to IC engine in terms of its use of fuel and also similar to that of a battery as it produces electricity. Characteristic of fuel cell is similar to battery under load condition [71]. Input reactants are fed into the cell and in the presence of electrolyte, reaction occurs and as an outcome, electricity is produced. The fuel cell operational diagram is as shown in Fig. 11 [36], [70].

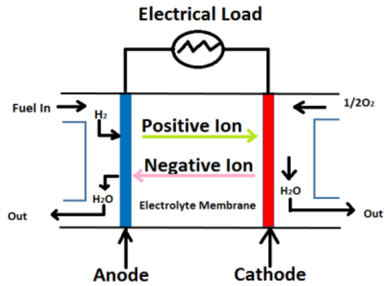

Fig. 11. Fuel cell operational diagram

Types of fuels used in the fuel cells classify its types. Inside a fuel cell, hydrogen from fuel reacts with oxygen from air and produces water plus electricity as output. This reaction can be understood by equation (1) [73].

$$2H_2+O_2 \rightarrow 2H_2O+Energ \qquad (1)$$

Chemical reactions at anode and cathode are given by (2) and (3), respectively [73]

$$2H_2 \rightarrow 2H^+ + 2e^- \qquad (2)$$

$$\frac{1}{2}O_2+2H^+ + 2e^- \rightarrow H_2O \qquad (3)$$

Based on the chemical properties, operating temperature, power generation capability and applicability, fuel cells are classified into different groups. This is tabulated in Table V. The chemical reaction for each of them are presented in Table VI. Transportation system needs high power, high efficiency, negligible emission and controllable operating temperature so PEMFC fits in this criterion. It is capable of producing electric power in the range of 1kW to 250 kW. Operating temperature range is 50OC to 100OC and efficiency range between 53% to 58% [70]. For transportation application, commercially available FC based vehicle is presented in Table VII.

TABLE V: Classification of Fuel Cell Based on Operating Characteristics [70], [74], [75]

Types	Electrolyte	Fuel	Cell voltage (V)	Operating temperature (°C)	Electrical η (%)	Applications
AFC	KOH solution	Pure H_2	1.0	90-100	60	Space, military
PAFC	Liquid H_3PO_4	Pure H_2	1.1	150-200	>40	Distributed generation
SOFC	Partially stabilized zirconia	H_2, CO, CH_4	0.8-1.0	600-1000	35-43	Electric utility, large distributed generation
MCFC	Solution of Li, Na, K carbonates	H_2, CO, CH_4	0.7-1.0	600-700	45-47	Electric utility, large distributed generation
PEMFC	Solid organic polymer Polyperfluorosulphonic acid	Pure H_2	1.1	50-100	53-58	Backup power, portable power, transportation
DMFC	Solid polymer membrane	CH_3OH	0.2-0.4	60-200	40	Mobiles, computers and another portable device

TABLE VI: Chemical Reactions for Different Fuel Cell [76]

Fuel cell type	Reaction at anode	Mobile ion	Reaction at cathode
AFC	$2H_2+4OH^- \rightarrow 4H_2O+4e^-$	OH^-	$2H_2O+4e^-+O_2 \rightarrow 4OH^-$
PAFC	$H_2 \rightarrow 2H^+ + 2e^-$	H^+	$(1/2)O_2+2H^+ + 2e^- \rightarrow H_2O$
SOFC	$H_2+O^{2-} \rightarrow H_2O+2e^-$	O^{2-}	$(1/2)O_2+2e^- \rightarrow O^{2-}$
MCFC	$H_2O+ CO_3^{2-} \rightarrow H_2O+CO_2+2e^-$	CO_3^{2-}	$(1/2)O_2+ CO_2+2e^- \rightarrow CO_3^{2-}$
PEMFC	$H_2 \rightarrow 2H^+ + 2e^-$	H^+	$(1/2)O_2+2H^+ + 2e^- \rightarrow H_2O$
DMFC	$CH_3OH+H_2O \rightarrow 6H^+ + 6e^- + CO_2$	H^+	$6H^+ + 6e^- + (3/2)O_2 \rightarrow 3H_2O$

TABLE VII: COMMERCIALLY AVAILABLE FC BASED ELECTRIC VEHICLE (FCEV) AND HYBRID ELECTRIC VEHICLE (FCHEV)

Vehicle model	Power rating	Battery	Type	Energy Source	Range (mile)
Hyundai Xcient FCEV 2020 [77]	350 kW, 3400 Nm of Max torque	73.2 kWh	FCHEV	Hydrogen	249
Mercedes-Benz GLC F-Cell 2019 [78]	155 kW Asynchronous motor 365 Nm Torque	13.5 kWh Li-ion	FCEV	Hydrogen	310
Hyundai Nexo 2018 [79]	120 kW PMSM, 395 Nm Max torque	40kW output power	FCEV 95kW	Hydrogen	380
Honda FCX clarity 2014[80]	100 kW PMSM, 256 Nm Max torque	288 V Li ion	PEMFC 100 kW	Hydrogen	231
Honda clarity fuel cell 2017[81]	130kW PMSM 300Nm max torque	346 V Li-ion	103kW FCHEV	Hydrogen	434
Toyota Mirai 2016[82]	113 kW PMSM 335 Mn max torque	-	114 kW FCEV	Hydrogen	312
Hyundai Tucson FC 2016 [83]	100kW	24 kW Li-polymer	PEMFC 100 kW	Hydrogen	265
Hyundai ix 35 2013[84]	122 kW and 205 Nm max torque	-	FCHEV	Hydrogen	369
Toyota FCHV-adv[85]	90 kW PMSM 260 Nm max torque	21 kW Ni-MH	90 kW FCHEV	Hydrogen	400-500

V. HYBRID ENERGY STORAGE SYSTEMS (HESS) FOR EV

In battery electric vehicle, main source of energy is battery only. This battery has to sustain many dynamic operating conditions and road terrains which results into poor performance, reduced cycle life, rapid discharge etc. [86]. In order to provide a good assistance to battery, UCs can be used along with the battery. High power density of UCs will be utilized during starting and acceleration of the vehicle which reduces the peak power demand from battery resulting into improved performance, better cycle life and efficiency along with the range of travel [10], [87]. As discussed earlier, Table III, presents a detailed characteristic of the battery and UC.

In a HESS based EV, the power transaction between energy source, storage device and motor are controlled with the help of power electronic converter(s) which follows the control methodology that is designed to achieve the required objective. In addition to the battery and storage device, the regenerated energy from the machine when acting as a generator during braking operation is also available and should be used optimally.

Different topologies for the interface of storage devices and motor with the power electronics controllers are available in the literature. They are passive topology, semiactive topology, active topology, shared bus topology and multiport topology.

In passive topology, there is no converter on the DC side as shown in Fig. 12 (a) and therefore no control can be exercised on this side. Due to equivalent series resistance (ESR) of UC, its self-discharging rate is high as compared with the battery and hence terminal voltage reduces with time. Any small difference in terminal voltage of battery and UC will result in large amount of circulating current and chances of breakdown are obvious. In this configuration, stored energy of UC cannot be fully utilized. Due to these limitations, passive topology is least applied.

The drawback of passive topology is overcome in semi-active topology by introducing a DC/DC controlled converter between the battery and UC as shown in Fig. 12 (b). The voltage across UC is controlled by this converter and it may be operated in buck or boost mode and then it is connected to the battery. This configuration is also termed as battery-UC or UC-battery configuration. Controlling of converter is in such a way that DC bus voltage is maintained constant at desired reference value. Since UC current flows in the converter switches, the converter size should be large.

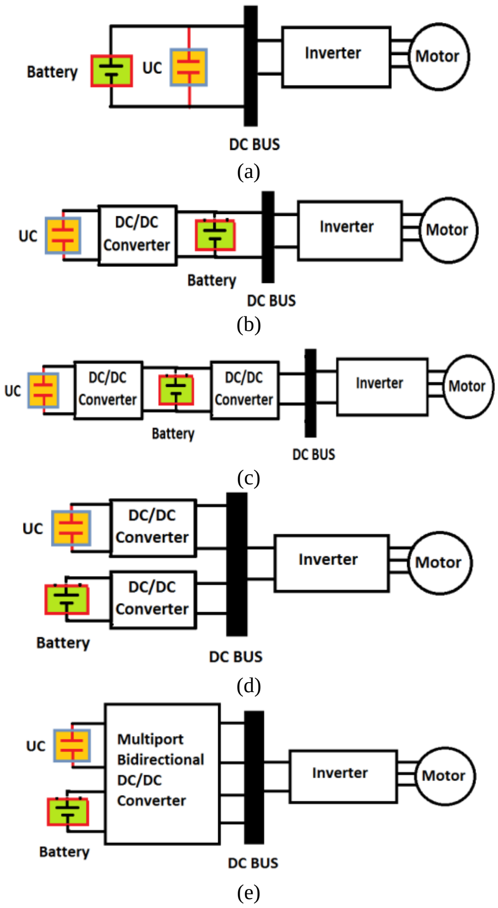

Fig. 12. (a) Passive topology [88], (b) Semi-active topology [89]–[91], (c) Active topology [92], (d) Shared bus topology [93], [94] and (e) Multiport topology [95]–[97].

Active topology as shown in Fig. 12 (c) allows full control of UC and battery. Here two DC/DC converters are used. These converters are operated in either buck mode or boost mode. Due to cascade connection, it's controlling and operation is complicated. In this configuration, frequent charging of the UC is required.

Shared bus topology shown in Fig. 12 (d), is the most preferred one in EV. It provides effective control of battery and UC power. This configuration is useful for capturing the regenerated power also. UC assists the battery during starting, acceleration and during uphill driving which reduces the peak power demand of the battery. For battery, unidirectional DC/DC converter is used and for UC, bidirectional DC/DC converter is used. Due to large number of switches, its cost is high.

In order to reduce the number of switches and the overall cost, multi input bidirectional DC/DC converter can be used which is shown in Fig. 12 (e). To operate these systems, different control methodologies are available in literature.

VI. ENERGY MANAGEMENT STRATEGY (EMS)

For the optimum utilization of energy, power flow needs to be controlled in the HESS taking into consideration, the DC bus voltage, state-of charge of UC & battery, and driving cycle. The energy management strategies reported in literature for the battery-UC HESS can be classified into rule-based strategies and the optimization-based strategies. The former ones also called as Heuristic methods are simple and real-time implementable. A common rule-based approach uses a low pass filter (LPF) to allocate the low frequency component of total power demand to the battery and the high frequency component to the UC. They are usually developed based on heuristics or engineering experience, and cannot guarantee the actual optimal solution. Whereas, the optimization-based strategies aim to achieve the best possible power allocation for a given performance criterion by optimal power-split using the prior or predicted driving cycles over a future horizon [98], [99]. Further, the optimization-based methods are grouped into global optimization-based and real time-based methods. The global optimization-based method considers the energy management problem for a complete and single driving cycle. Real-time methods implement instantaneous optimization problems that only consider the current state of the system [100]. In literature, different control strategies are reported and is presented in Fig. 13. [100], [101] .

Other classical EMSs are also proposed in literature. Azibet *et al*. [102] used the cut-off frequency of proportional-integral controllers to share the required power between different energy sources. Rajabzadeh *et al*. [103] performed the power management of fuel cell-UC using a dynamic modelling that takes into account the regulation of both DC bus voltage and the current sources. In [104], Chowdhary *et al*. proposed a filter-based approach for EMS in Microgrid and divided the total power required by the load into slow transient power and fast transient power by using a low pass filter. The former component is supplied by battery and latter one by UC. The authors in [105] proposed an energy-based UC controller rather than voltage-based control. In [106], a PI controller with priority-based algorithm has been reported.

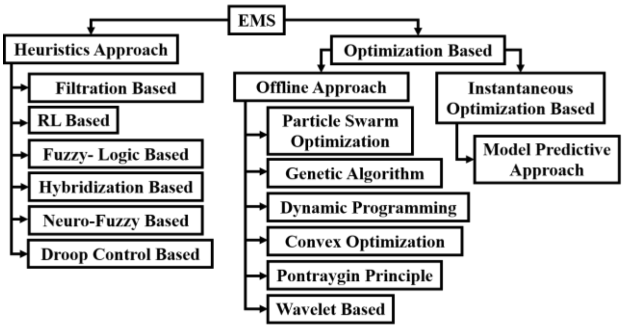

Fig. 13. Classification of EMS

Many authors have popularly preferred Fuzzy logic with other techniques to achieve the desired performance. This is mainly because the Fuzzy logic controller can accommodate the intrinsic non-linear characteristics of UC and battery. Combination of fuzzy logic and neural network are used in [107] and [108] to manage the energy in Microgrid and EV. Mazid *et al*. employed a combination of Flatness control technique and Fuzzy logic to plan the specific trajectory on the system output and manage the energy sharing between battery and UC [109].

Chunjie Zhai *et al*. proposed a predictive EMS for the battery/UC HESS based on semi-active topology. They used the pattern sequence-based velocity predictor to predict the future short-term velocity profile. Chaotic particle swarm optimization is opted to solve the power split optimization problem that is formulated by splitting the HESS energy loss and the battery capacity loss [98].

The sliding mode control drive was used in [110]. A non-linear control structure based on passivity and model prediction techniques by incorporating the rate limiting action was proposed for a HESS based DC Microgrid in [111]. Sebastian *et al*. proposed a convex optimization framework for the optimal power allocation for a battery/UC HESS, considering hard power limits on all storage and powertrain components and hard limits on battery and UC storage [99].

Optimization based approaches are potentially more effective but are computationally heavy and more complex than rule-based heuristics. Dynamic programming (DP) methods can be used to determine the globally optimal control input for arbitrary cost functions, system dynamics, and hardware constraints. However, DP are computationally inefficient, and can only be used offline [99]. The global optimization methods due to their high computational time, cannot be implemented in real-time directly. The real-time EMSs yield online capable approaches but they are sensitive to different driving cycles [100].

Most of the work in the field of EMS is limited to the simulation level [100]. A considerable number of works is needed to be done to validate the reliability of methods proposed in literature. Objectives such as minimization of battery health degradation, drivability optimization, electric motor longevity should be included in the overall cost structure [100].

VII. Selection of Converter Topology and Cost Analysis

A shared bus topology is suitable for the independent control of the sources in EMS. It requires one bidirectional dc/dc converter for the UC and one boost dc/dc converter for the control of battery with a total switch count equal to three. The bidirectional converter makes use of two switches whereas the boost converter requires only one switch. If this topology is compared with single converter topologies like semiactive topology and multiport topology (see Fig. 12 (b) and Fig. 12 (e)), it is found that the shared bus topology offers more flexibility, high degree of freedom for independent control of battery power and UC power and cost effectiveness. The semiactive topology which has only one converter can control only one storage device i.e., either the battery or UC. In multiport topology, the number of required switches is five or more. This increases the complexity of multiport topology and makes it more costly though it can be used to control both the UC power and battery power [94]-[96], [112]. Higher number of switches in a multiport topology will require additional supplementary circuits like driver, signal conditioning etc. which will increase the system sensitivity to parameter variation, electromagnetic interference and reliability. Also, the efficiency of single converter multiport topology is low as compared to shared bus topology [96], [112]. Secondly, in the event of malfunction in HESS, the single converter topology will halt the whole system and cost more to replace the faulty converter. Whereas if shared bus topology is employed, only the faulty converter will need replacement and reduce the standby cost.

VIII. Challenges

Development of EV have a potential to safeguard our environment because of its zero-emission capability by utilizing clean energy. Most EV manufacturers prefer Lithium battery but its use increases the vehicle cost. In real-life conditions when running on road, the vehicle dynamics and road terrains affects the battery calendar life, cycle life and efficiency. Over all range anxiety is also a concern [113], [114].

UCs can provide better assistance to the battery as both overcome each other’s limitations. Battery being a high energy density device and UC being a high power density device, alone each of them cannot lead to the satisfactory performance of EV [115], [116]. UC can act as a sink during charging (extract the power during regenerative braking) and can deliver high pulse of current when the motor is loaded beyond battery’s current capacity. However, coordinated power distribution between them using bi-directional DC/DC converter have challenges [117]. Secondly, UC rated voltage is very low (about 2.7V). This requires connecting them in series when used in practical application. Voltage balancing across each of them during charging is very important and needs more attention [66].

Fuel cell technology ensures emission-free operation and offers better driving distance per charge [118]. However, unlike UC, FC do not have a longer lifetime. Study needs to be carried out on hydrogen consumption and oxygen starvation of the FC [119]. Due to high cost and low lifetime, use of fuel cell has not become popular in EV application [9], [120]. EV suffers from dependency on grid for charging purpose. Utilization of the on-board renewable energy sources is limited to research work only. Therefore, for range extension, clean energy, sustainable and cost-effective system, advanced control technology with the interface of power electronic devices is required to be developed for future mobility.

HESS can mitigate the disadvantages associated with EVs but EMS employed is still in development stage and this is the reason that battery and UC based commercialized vehicles are not available in the market. Rule based EMS has ability to give simple and real time solution but as it depends on engineer’s knowledge also includes trial and error hence no standards are available and cannot provide optimal solution. Optimization based EMS can give optimal solution but its real time implementation is difficult. Maximum research works are limited to simulation level only and hence this area possess a huge research scope for advanced and intelligent EMS.

IX. Conclusion

This paper has reviewed the energy storage systems and there use in electric vehicles. Popularly, the batteries preferred in EVs are lead-acid, Li-ion and NiMH batteries. The choice amongst them is based on the cost and sophistication of the vehicle. NiMH batteries have higher ability to store energy as compared to other batteries. However, the cycle life of battery in battery-alone vehicles is limited due to the tough operating conditions on road and therefore an auxiliary energy storage device on board can serve to improve the battery life as well as the mileage. Different types of ESS are discussed which includes battery, ultra-capacitor and fuel cell. Power electronic converters are vital in energy transaction and energy management in vehicular application. Different topologies that integrate the battery, UC and motor are presented and discussed. Finally, challenges in ESS, EMS and future prospects are presented.

The main consideration in the development of EV system is energy storage system, range extension and battery life. Until and unless renewable energy sources are used, it is difficult to develop the EV as range extender. This paper gives a clear indication towards the use of renewable energy sources, range extension, battery life improvement and advanced EMS which may be simple and real time implementable.

Conflict of Interest

The authors declare no conflict of interest

AUTHOR CONTRIBUTIONS

Initially, both authors had rounds of mutual discussion based on their own knowledge and the current state-of-art for the enhancement of battery life and running mileage of electric vehicle. They planned to compile it systematically in the form of a paper and distributed the work amongst themselves. Accordingly, Alok Ranjan conducted the initial review research and drafted the first manuscript. Sanjay Bodkhe reviewed the same for the content, logical flow of information, originality of presentation, technical data, citation etc. Multiple revisions were carried out to incorporate the corrections and tune it as per the requirements of the journal. The submitted manuscript (final version) is approved by both authors.

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