A review: Energy storage system and balancing circuits for electric vehicle application

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Abstract
The prominent electric vehicle technology, energy storage system, and voltage balancing circuits are most important in the automation industry for the global environment and economic issues. The energy storage system has a great demand for their high specific energy and power, high-temperature tolerance, and long lifetime in the electric vehicle market. For reducing the individual battery or super capacitor cell-damaging change, capacitive loss over the charging or discharging time and prolong the lifetime on the string, the cell balancing is compulsory. The electric vehicles drive train architecture, overall applicable energy storage system, and the balancing circuit categories as cell-to-heat, cell-to-cell, cell-to-pack, pack-to-cell, and cell-to-pack-to-cell are reviewed. The comparative study has shown the different key factors of market available electric vehicles, different types of energy storage systems, and voltage balancing circuits. The study will help the researcher improve the high efficient energy storage system and balancing circuit that is highly applicable to the electric vehicle.

1 INTRODUCTION

Nowadays, the energy storage system (ESS) is becoming very popular in electric vehicle (EV), micro grid, and renewable energy applications. Last few decades, EV became popular and considered a suitable alternative for an internal combustion engine (ICE). ICE vehicles, trains, cargos, including aircraft, are consumed one-third of fossil fuel. In the transportation sector, 1% used electricity, 2% used bio-fuel, 3% used natural gas, and 94% of vehicle used oil [1]. It is proved that ICE and industries are the significant sources of carbon dioxide (CO₂), carbon mono oxide (CO), sulphur dioxide (SO₂), nitrogen oxides (NO). These gases have polluted the environment and the reason for greenhouse effects. In the EV system, ESS is supplied the electric power to drive the motor and other functions such as air-condition, navigation light and so forth. On the driving time, EV does not make eminent the CO₂, CO, SO₂, and NO gas that will help solve the fossil fuel and environment issues for this EV called zero-carbon emission vehicle [2, 3].

Whole over the world, there are more than 5 million EVs have been marked (energy revolution). EVs sales market reached 2% in the USA, 3% in Portugal, 5% in China, 7% in Ireland, 8% in the Netherland, and 2019 more than 50% of new EV soled in Norway. In 2015, the number of passenger EV was 450,000 after that the demand for EVs were rapidly increased and the number of passenger EV is 2.1 million in 2019 [4, 5]. Day by day, the demand for EV is increased rapidly in China and Europe. Furthermore, the whole over the world takes the challenge to reduce global warming and greenhouse gas by increasing the use of EV to substitute ICE vehicles. Many states and countries make policies to adopt the EV and inspire their peoples. These approaches are fetching more

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anticipate and pervasive promote the deployment and growth of EV. Nowadays, EVs are considered as a possible distributed ESS on the grid/micro-grid system via synchronized charging efforts that will relief in balancing the discernments of irregular solar and wind generation. As EVs ESS contains huge power that will vary from 17 to 100 kWh. For that in the demand side management, EVs offer the potential power supply through the pick load period. This way opens a great path to install vehicle to grid (V2G) and grid to vehicle (G2V) system as well as a grid-connected renewable electric system.

In ESS, different types of energy storage devices (ESD) that is, battery, super capacitor (SC), or fuel cell are used in EV application. The battery is stored in the energy in electrochemical and delivers electric energy. Where SC has stored energy in the form of static electric charge and mainly hydrogen (H₂) is used in the fuel cell. Individually ESD cells have 1.5–5.5 V and they are series and parallel connected in the ESD pack to meet the EV demand required voltage. As the ESD are the electrochemical vessel and chemical reaction occurred over the charging and discharging time. Also, performance depends on the chemical reaction and, ESD capacity diminishes by chemical degradation on the whole cyclic life. However, due to manufacturing defects, overcharge and over-discharge, self-discharging rate, internal resistance, and thermal variation have mismatched the cell in the ESD pack. The cell voltage variation occurred in the ESD pack that reduces the capacity and lifetime, also explosion can be occurred during the charging and discharging time [1, 6–8].

In the EV system, the storage energy drives the motor, lighting system, other driving systems, and accessories [9]. The rechargeable electrochemical ESD such as lead-acid, Ni-Cd, Ni-MH, ZEBRA, Zn/Air, Na/S, lithium-ion, super-capacitor and so forth are used in EVs. With the development of ESD technology, the demand for ESD is dramatically increasing in portable electric components especially EVs application. Though lead-acid batteries have a big market in the field of renewable ESS over the world currently, lithium-ion has been a promising market in the EV sector. For the EV application, using an ESD some specifications are considered, special entire EV systems efficiently [10–12]. Many requirements have been considered for the selection of the ESD in EV application, especially, safety issues and higher energy storage. At hence, for application in EVs power storage system consider the overloading and overheating, short circuit current which has to be minimized and controlled. Due to the undercharge, overcharge, and temperature profile, the ESD cell voltage charge imbalanced occurs [13]. To reduce the imbalance and temperature effects then ESD cell voltage life-time will be prolonged.

The Battery management system (BMS) is an essential part of EV. BMS ensures that ESD will be protected from inspected damage, reliable facilitates, prolong the lifetime, and uninterrupted power supply on EV driving time [14]. BMS is a vast platform that deeds on numerous platforms that is, voltage balancing, current measurement, state of charge (SOC), state of art is including the fundamentals, structures, and overall performance evaluations of different types of batteries, state of health, charging and discharging procedure, data acquisition, heat management, power management, remaining useful life, cell protection, thermal management, cell monitoring, and battery protection [15–18]. Figure 1 shows an overview of BMS. As ESD is the electrochemical vessel and voltage imbalance occurs during charging or discharging time. The voltage balancing system is one of the major fields of BMS and many researchers work on BMS to monitoring cell status, voltage balancing system, protect the cell from the explosion, and increase the lifetime [18, 19].

This paper contributes to a comprehensive study about the features and drive train architecture of the EV system and the literature by reviewing the ESS technology for EV application. Moreover, this paper presents the charge/voltage balancing circuits for BMS in EV applications. In this paper, remark some issues, advantages and disadvantages of the EV applicable ESD, and balancing circuits that will ensure the sustainable global economy, environment, and recommendations for future research.

## 2 OVERVIEW OF ELECTRIC VEHICLE

EV’s are commonly included road, rail, air, and sea-based vehicle that are partially run by electricity. Recently advance energy storage (ES) technology-led road vehicles such as a personal car or public buses. EV demand is increased (Figure 2) based on the battery and vehicle cost development, sustainable value and chain supply of the battery materials, taxation for government revenue, electric mobility and easy implication on the power system, and the interplay between automated mobility, shared and electric option [20].

Mainly, two types of EV, one is entirely battery electric vehicle (BEV), and another is the hybrid electric vehicle (HEV) that is consists of electronic and other energy sources [21]. HEVs have an intrinsic benefit, and it can be given the fuel economy advance by combining the ICE and battery. It is frequently drive in an urban or rural area, the battery can fully support when it
operates in the downtown area, and it can easily switch in engine outside of the city. Plug-in hybrid electric vehicle (PHEV) and fuel cell electric vehicle (FCEV) are the two subdivided form of HEV [21–23].

BEVs are entirely operated by electricity. This electricity comes from the battery pack. This vehicle is required to charge the battery pack from the charging station to recover the braking energy, and this system is called regenerate braking [24]. BEV driving range depends on the battery capacity. Battery pack capacity continually improved, BEV can be driving range from 100 to 400 km in a single charge [25, 26]. Typically, a motor is intergraded with the fixes, gearing distinctly or differentially, two motor intergrade with fixes gearing beside, the driveshaft. This is to control the different speed levels. Currently, BEV driven system has been introduced the in-wheel system where traction motor is combined inside the wheel; also it required high acceleration torque. Though the in-wheel system is more complicated, it is suitable for the BEV system in city driving [22, 27–29]. The traction motor design technology has been extended so that BEV can be flexible range drive in short or long distance. Moreover, it reduces the energy loss due to mechanical parts utilisation such as the differential, clutch, gearbox, and increased overall efficiency [28–30].

HEV combines with the electric power source and other power sources. Commonly, driving a motor with a battery pack is combined with ICE and fuel tank. Based on the motor and ICE arrangement in the driving system, the HEV system can be classified in series, parallel, series-parallel, and complex HEV [4, 21]. Considering the fossil fuel-saving and low-cost design, commercial HEV are available in the automation market branded by Honda, Nissan, Toyota, and so forth. The driving range of HEV is higher than BEV and easy to handle in any situation. PHEV is another form of HEV where battery pack is charged by external power sources instead of the ICE system. Though HEV battery pack charged by ICE and regenerative braking. HEV and PHEV contain battery packs like BEV intergraded with conventional ICE and the capacity of the PHEV battery pack is around 11 KWh [4, 31].

FCEV system likes as BEV system which drives by solely ES pack like a battery or fuel cell. Its working principle similar to HEV, and it charged the battery by regenerative braking. In FCEV, electricity generates by an electrochemical reaction like a battery, but here, typically hydrogen fuel electrochemically converted and produces the power and water, leading to zero tailpipe emissions [4, 21]. FCEV is expensive due to the production cost of H₂ (hydrogen) and several components required to reduce the price for competitive with BEV. The polymer electrolyte membrane is the conventional useable fuel in FCEV [32, 33]. Table 1 and Figure 3 (see Appendix 1 for Figure 3) illustrates the features and drive the EV system [21–33]. The development of EV technologies is enchanting for driving long-distance range, increasing the control system’s flexibility and overall efficiency, reducing the size and total cost. However, EVs required higher capacitive, higher power and energy density, long lifecycle ESS. Therefore many researchers and development companies are working on forthcoming EV development.

3 | ELECTRIC VEHICLE ENERGY STORAGE SYSTEM

Based on the EV application, ESS can be classified into four groups: Namely, electrochemical battery system, chemical storage, electromagnetic storage system, and hybrid ESS as shown in Figure 4.

Every ESS has encompassed different properties. Based on these properties, different applications should be accountable. An ESS not only stores the energy for a longer time but also save the consumer money. Many researchers work on ESS and give their effort so that they can improve efficiency and achieving a cost-effective storage device [34, 35].
### TABLE 1  Representative characteristics of the electric vehicle system

| EV types | Energy source and driving system | Feature | Drawback |
|----------|----------------------------------|---------|---------|
| BEV      | Energy come from battery/SC pack and it drives by the electric motor | Zero carbon emission, Integrating with fixed gearing and differential, crude oil independent, maintain the speed at a different level | Battery capacity, short driving range, requires traction motor for high-speed acceleration, charging facilities. |
| HEV      | Energy come from fossil fuel and battery/SC pack and drive-by ICE and electric motor | Low emissions, complex structure of drivetrains, oil-dependent, can drive in highway and city, good efficiency, reliable and flexible for maintenance. | Battery sizing, Management of energy sources |
| FCEV     | Energy come from liquid hydrogen and drive-by electric motor | Ultra-low emission, crude oil independent, maintain the speed at a different level, high energy efficiency | Lack of fueling systems, high fuel cost, under development |

![Energy Storage System](image1)

**FIGURE 3**  Overview of electric vehicle energy storage system

![Cell voltage balancing topologies](image2)

**FIGURE 4**  Cell voltage balancing topologies
| Brand                  | Battery         | Battery capacity (KWh) | Travel range (mile) | Efficiency (KWh/mile) |
|-----------------------|-----------------|------------------------|---------------------|-----------------------|
| Tesla model S-75      | Lithium-ion     | 75.0                   | 249                 | 0.33                  |
| VW e-Golf             | Lithium-ion     | 35.0                   | 120                 | 0.26                  |
| Renault Zoe           | Lithium-ion     | 41.0                   | 250                 | 0.26                  |
| Kia Soul EV           | Lithium-polymer | 30.5                   | 111                 | 0.27                  |
| Hyundai Ioniq Electric| Lithium-polymer | 28.0                   | 124                 | 0.23                  |
| Nissan Leaf           | Lithium-ion     | 30.0                   | 107                 | 0.28                  |
| Jaguar i-Pace         | Lithium-ion     | 90.0                   | 234                 | 0.36                  |
| BMW i3                | Lithium-ion     | 33.0                   | 114                 | 0.27                  |
| Smart Fortwo Electric Drive | Lithium-ion | 17.6                   | 65                  | 0.25                  |

3.1 | Battery

The battery is an electrochemical device that stores energy in a chemical form and delivers electric energy—two types of battery. One is called the primary battery, and another is a secondary battery. Mainly, secondary electrochemical cells are used in EV [36]. The battery technology development has dramatically impacted the EV industry because batteries are used as an energy source to drive the EV propulsion system [37]. When the lead-acid battery is developed, then it applies to the EV system. After that researcher is developed many other EV applicable batteries, and EV batteries market is increased [38]. Though the researcher is continuously developed the battery chemistry, the EV battery requirement is not significantly changed. EV requires high energy density, power density, higher specific energy and power, temperature tolerance, long lifecycle, and efficiency [37–39]. Many researchers’ able batteries are used in the EV system, such as lead-acid batteries, nickel-based batteries, silver batteries, sodium-sulphur battery, and Li-ion batteries [36, 40, 41]. Nowadays, many EV’s are available in the market, and the most popular EV batteries capacity is presented in Table 2 [42, 43].

3.2 | Super capacitor

SC is the electromagnetic ESD which is also formed by electrode and electrolyte. The energy storage capacity depends on the available electrode and electrolyte function, the size of the ions, and the decomposition voltage level of electrolyte. Ultra-capacitor (UC) is another name of SC. In an SC, activated carbon is used for an electrode that provides higher surface area and energy density. On the electrodes, high conducting current collectors are pledge the edge between the electrodes and the contacts in an SC. The electrode works like a medium that conducts and supplies the ions from one to another electrode. The membrane is used as a separator between two electrodes, which consents the mobility of ions charge and prohibits no electronic contact [44–47]. In the last few years, the demand for SC has increased because the battery is replaced by SC due to the first charging, specific power, lightweight, and lifetimes of SC [34, 48]. Based on the energy storage procedure, SC can be classified into three categories (i) electrochemical double layer SC (EDLS) (ii) pseudo-SC (PS) (iii) hybrid SC (HS). EDLS can be classified into three groups, that is, activated carbon, carbon nanotubes, and carbon aerogels. PS can be classified into two categories, that is, metal oxides and conducting polymers. HS can be classified three categories, that is, battery type hybrid, asymmetric hybrid, and composite hybrid [49, 50].

3.3 | Fuel cell

In recent years, the demand for fossil fuel increased gradually with the population over the world but fossil fuel is not sustainable for the future energy system. So, it is necessary to suitable alternative energy sources that are not harmful to the environment [51, 52]. Fossil fuel-based vehicles are one of the main sources for fuel consumption, unsustainable fuel market, and create an environmental problem. Fossil fuel-based vehicles are one of the sources of greenhouse gas. Still, fossil fuel consumption is proportionally high, and it will cover ≈75% of the energy market in the future 2050 [51, 53, 54]. In the FCEV system, energy comes from fuel cell (FC) where electricity directly produces and drives the vehicle with the eco-friendly environmental process. Hydrogen is used as a fuel of the FC. It will overcome the BEV problems and will be future fuel for the transportation system [51, 55–57].

3.4 | Hybrid storage system

This hybrid storage system (HSS) is consists of two EES, that is, battery, SC, or FC. Which one has a high energy density, specific power, high power density, high efficiency, another has a long lifetime, fast response time, and low discharge rate [58]. The most common HSS is battery and SC. Also, cell-FC, SC-FC, or battery-SC-FC combination is formed. The main benefits of the HSS are cost reduction, huge storage capacity, long lifetime, and rise in system efficiency. In the EV system, battery-SC and battery-FC hybrid is applied for performance [34, 59]. Different ESS power ratings, typical discharge time, energy density, power density, lifetime, and efficiency are given in Table A.1 [60, 61]; see Appendix.
For the EV powering, battery, SC, or FC are used. Based on the EV characteristic and demand, lead-acid batteries, nickel-based batteries, silver batteries, sodium-sulphur batteries, Li-ion batteries, SC are used. Researcher and development companies are working on future EV ESS development for high energy storage, economy, and safety issues. For sustainable EVs, ESS is affirmed by perfect balancing and management systems.

4 | BALANCING TOPOLOGY

Different types of voltage/charge balancing circuits have been proposed to effectively use the energy in the ESD pack [19, 40, 62], [70-71]. These balancing circuits are divided into two groups. One is energy dissipative or passive balancing, and another is non-dissipative or active balancing. In the dissipative balancing excess power is converted into heat by the parallel resistor where the high-capacity cell is used to remain consistent battery pack power. Also, this balancing system is a call-to-heat (C2H) balancing system. These balancing circuits are simple, small size and easy to control, but produce heat that required temperature control. A non-dissipative balancing system used passive component, that is, capacitor, inductor, transformer to transfer the energy from higher cell to lower cell on the string or pack. In this balancing system, the balancing efficiency improved which added the advantage of consistency of the ESD string pack [63–65]. In non-dissipated balancing, the energy conversion system is divided into two groups. One is capacitor, inductor, or transfer and converter-based balancing. Another is cell-to-cell (C2C), cell-to-pack (C2P), pack-to-pack (P2P), and cell-to-pack-to-cell (C2P2P) balancing. All balancing topology is present in Figure 4. C2H, C2C, C2P, P2P, and C2P2C balancing procedures are discussed in this paper.

4.1 | Cell-to-heat

This passive balancing or cell-to-heat balancing system is very simple. Here, excessive energy of the higher capacitive cell is diminishing by resistor or a transistor with that work on the whole battery lifetime. In this method energy has been not distribute to the other cells in the battery string, pack, or module science wasted by heat from [66–69].

In these methods, produce lots of heat in the air render through the resistor and low efficiency. However, these methods have low cost, simple control, and easy to apply [62-64].

They are fixed shunt balancing, switches shunt balancing, and analog shunt balancing circuit. All C2H balancing circuit is shown in Figure 5. All circuit structure is very simple, reliable, and a simple control circuit required to control these, but it can apply in a small number of cells and reduce the battery lifetime.

4.2 | Cell-to-cell

In the cell-to-cell balancing topology, the excessive energy from the higher cell is transferred to the lower cell by the capacitor, inductor, and converter in the battery cell string. This balancing can be achieved by the energy storage components. Some balancing circuits required closed-loop control, and some are required an open-loop control system. Though the balancing circuit structure is simple, fast balancing process, and good efficiency some of the circuits are complex control systems as well as accurate SOC or voltage sensing. Besides, this balancing circuit has been strong scalability, but it required a large number of switches, balancing components. C2C balancing topology can be divided into two groups: Adjacent cell balancing and direct cell-to-cell balancing [19, 40, 72–86].

4.2.1 | Adjacent cell balancing

In this balancing topology, energy transfer from higher cell to lower cell between two adjacent cells in the ESD string. When the imbalance occurred in the cell string then the control circuit executes the balancing system and energy transfer through of capacitor, inductor, or converter. This balancing
circuit works on charging or discharging mode. This balancing circuits are switched capacitor [72, 73], buck-boost [74, 75], cuk [40, 76], ramp [40, 77], resonant [19, 78], and full-bridge [34, 73] converter. Figure 6 shows the all adjacent cell balancing circuit. Ramp converter worked on unidirectional and other converter work on bidirectional. These balancing circuits have been fast balancing speed, low voltage and low current stress, and good efficiency. However, these balancing circuits required a complex control system, large size, and costly.

4.2.2 | Any cell to cell balancing

In this balancing topology, energy transfer from any cell to any cell on the ESD string. An algorithm is used to find higher cells and lower cell or overcharge and undercharge cells by the cell statues monitoring circuit. When the imbalance occurred in the cell string then the control circuit executes the balancing system and energy transfer through of capacitor, inductor, or converter. This balancing topologies are single capacitor [80, 81], double-tiered switched capacitor [19, 82], single inductor [19, 83], multi inductor [40, 84], single winding transformer [40, 85], single resonant converter [64, 86] based balancing circuit that shown in Figure 7. All of the circuits are bidirectional and work on charging and discharging mode. These balancing circuits are comparatively of low voltage and current stress and good efficiency. However, they have required a complex control system, face ripple current, and take long balancing time.

4.3 | Cell-to-pack

In this balancing topology energy from higher capacitance cell in the ESD pack id transfer over the pack through of capacitor, inductor, and transformer. A cell monitoring circuit continuously monitors the cells in the pack. When a single cell voltage is higher than the average cell voltage on the pack then it executes the balancing process. When the energy transfers through transformer, then the excessive energy stored in the primary winding side and secondary side, transmit this energy in the pack. This balancing circuit has few components and simple structures. This balancing topology faces some switching trouble during transferring the energy. In this balancing topology, only higher energy capacitive cell transfers the energy but lower cell on the string remain hampered so that overall medium
efficiency. C2P balancing circuits are single inductor, single winding transformer, multi winding transformer, multiple winding transformer [40, 87, 88], buck-boost converter, and flyback converter [19, 40, 89–91].

4.4 | Pack-to-cell

The battery pack transfers its energy to the weaker cell on the cell string through the peripheral balancing circuit. A cell monitoring circuit continuously monitors the cells in the package. When a single cell voltage is lower than the average cell voltage on the pack, then it executes the balancing process. When this balancing process is executed through the transformer, the battery pack is connected with the secondary winding and primary winding individually connected with the cell. These balancing circuits are bidirectional and work on charging or discharging mode, voltage/charge balancing variance is comparatively high, and overall efficiency is slightly improved. The C2P balancing circuits are single winding transformer, multi winding transformer, multiple winding transformer, and flyback converter.

4.5 | Cell-to-pack-to-cell

C2P2C is a compacted and complex balancing circuit. In this balancing process, energy transfer into C2P, P2C, or pack to pack (P2P) through the capacitor, inductor, and transformer. C2P2C balancing systems are single switches capacitor, single inductor, single winding transformer, multi-winding transformer, multiple transformers, and flyback converter-based balancing circuit (shown in Figure 8). A single switch capacitor or single indicator is used to transfer the energy from one pack to another pack. In this balancing system, battery pack size has become enormous, and balancing circuit size is comparatively small but takes a long balancing time. Also, coaxial and double layer multi-winding transformer is used to transfer the energy from C2P and P2C [89]. When a cell has excess energy over the battery pack, it passes through the transformer's energy to the lower cell on the battery pack. For the double layer transformer, the energy comes from the cell that mutually transfers the package’s two groups. This balancing process is simple, and balancing speed is fast, but, in this process, excess energy is supplied in a group, but weak cells on the group directly cannot get this energy. A coaxial multi-winding transformer balancing system can distribute the energy in two or more cells at a time, and this balancing can be transferred to the energy with high-speed. However, the manufacturing process of this balancing system is very complicated.

5 | COMPARATIVE ANALYSIS OF THE BALANCING TOPOLOGY

Several key points of voltage/charge balancing topology are compared, that is, balancing time, no of the elements for balancing circuit, control complicity, voltage and current stress, efficiency, size, and cost. Some of the circuits are work on charging and discharging time, bidirectional, cheap, and suitable for higher energy storage battery pack. Passive or C2H balancing circuits are small in size, inexpensive, and easy to control. However, they are produced heat that reduces the overall efficiency and has changes for the explosion. Active balancing circuit efficiency is overall better than a passive balancing circuit. C2C balancing circuits have comparably small in size to C2P, P2C, or C2P2C.

In the balancing topology, the passive balancing circuit is used in a small energy application system; a simple control system, however, takes a long balancing time. An inactive balancing system single inductor, capacitor, or transformer-based balancing circuits are required sensible monitoring and smart control system. Multiple inductors, capacitors, or transformer-based balancing circuits are faster than single inductors, capacitors, or transformer-based balancing circuits. In Section 4, several balancing circuits are present. Based on Section 4, Tables A.2, A.3 (see Appendices) illustrates the several critical points shown where existing research worked on several balancing circuit, and they have adopted the characteristic on emulation and comparison in different power applications.
In the case of energy conversion, balancing circuits are selected depend on charging and discharging working function. Based on the excellent feature, C2C balancing circuits are suitable for EV applications. Among all of the balancing circuits, buck-boost balancing circuits are first-rate features but required smart monitoring and intelligent control system. Single and multiple inductors and transformer-based balancing circuits are faced magnetising loss and implication cost is high but comparatively low efficient. Single and multiple capacitor-based balancing circuits are low cost but take a long balancing time. The flyback converter is viable to use in EV application but it faces magnetising loss and costly. On the other hand, the resonant converter is suitable and high efficient to EV applicable. However, EV required overcharge protection, wide range applicable, easy to control, and high efficient balancing circuit.

6 | ISSUES, CHALLENGES, AND RECOMMENDATIONS

In recent years, the demand for EV is dramatically increased and now EV technology is satisfactory. Moreover, the EV system reduces oil consumption, CO₂, and greenhouse gas emission. ESSs in EV is a continuous process where the technology continuously changes and improve a suitable and more reliable EESs for EV applications. Though EV technology is satisfactory there are some issues and challenges are summarized.

EV required a suitable driving motor which has lower power density and efficiency [92, 93].

- EV driving range depends on the battery capacity that is shown in Table A.2, but the efficiency on the driving range is low that is near 25%–36% [42, 43].
- The raw material and supply are challenging issues to produce higher density EESs [37, 94, 95].
- EV system required sensitive energy management system [40, 94, 96, 97].
- Power electronics interface is the more challenging for EV because of ESSs, motor drive, and system efficiency are optimized [40, 94, 98].
- EV faces the fire explosion during the operating period [95, 99].
- EV charging interface [41].
- ESSs of EV are the costly and bulky size [17, 36, 37, 40, 41].
- ESD is the electrochemical vessel, so during the manufacturing and recycling period environmental pollution occurred [17, 40].

Researchers and development companies are continuously working to solve the issues and challenges. There are some recommendations or suggestions which have been coming from the studies and that will be helpful for future research.

- Using the in-wheel-motor for avoiding the differential and fixed gearing
- In the equalisation circuit use the Zener diode to replace the resistance
- Using wide-bandgap semi-conductors switches
- Integration of the equalisation circuit with EV charger
- Re-configurable batteries
- First charging station with battery swapping facility

7 | CONCLUSION

The ESS and balancing circuits are essential issues for EV applications. The development of ESD and balancing circuits are quite challenging. Many researchers work on EV, ESS, and voltage balancing systems for a better future EV system. However, every ESS and balancing circuit has some limitations. In this paper, some issues, advantages, and disadvantages of the EV applicable ESD and balancing circuits are remarked, that will ensure the sustainable global economy and environment: Different types of EV driving train architectures are depicted.

- Available EVs in the market are presented.
- Different types of ESS that is applicable in the EV system.
- Different types of balancing circuits and features.
- Comparison in several key points among all the balancing circuits.

This paper accumulated these issues and features that will help future research on EV applicable ESS and balancing circuits. The EV system required high specific energy and power, overcharge and undercharge capable, high-temperature tolerance, and long cyclic life storage system. For considering, these issues hybrid ESD can be preferable for the EV system. The passive or energy dissipative balancing circuit is simple in design, control, execution, small, and cheap. However, they produce a lot of heat and less efficiency. Inactive or non-energy dissipative balancing, any C2C circuits short in size and flexible but required a sophisticated control system and take balancing time. Still, adjacent cell balancing is fast balancing speed and functional efficiency. For the fast balancing C2P, P2C, or C2P2C circuits are applicable, but overall efficiency is low compared with C2C balancing circuits. This study suggests that EV system requires smart drive train architecture, high capacity and long lifecycle ESD, and overall highly efficient balancing circuits.

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APPENDICES

**FIGURE A.1** Drive train architecture of the EV system. Hear, C-charger; D-differential; G-generator; I-inverter; M-motor; BP-battery pack; FG-fixed gearing; FT-fuel tank; MD-motor drive; PC-power converter; SCP-supercapacitor pack; BMS-battery management system; DDC-DC-DC converter; ICE-internal combustion engine

**TABLE A.1** Energy storage system properties

| ESS              | Power rating (MW) | Typical discharge time | Energy density (W·h L⁻¹) | Power density (W L⁻¹) | Lifetime (cyclic life) | Efficiency (%) | Advantage                                                                 | Disadvantage                                                   |
|------------------|-------------------|------------------------|--------------------------|-----------------------|------------------------|----------------|--------------------------------------------------------------------------|-----------------------------------------------------------------|
| Lead acid battery| 0–20              | s–h                    | 3–15                     | 90–700                | 250–1500               | 75–90          | Low cost, high power density, and specific power                          | Short lifetime, high maintenance                                |
| NiCd battery     | 0–40              | s–h                    | 5–20                     | 75–700                | 1500–3000              | 60–80          | Better lifetime                                                           | Low specific energy                                            |
| Li-on battery    | 0–0.1 min–h       | 5–100                  | 1300–10,000              | 600–4500              | 65–75                 | High specific energy and power density, Thermal, overcharge, and costly | Thermal, overcharge, and costly                                 |
| NaS battery      | 0.05–8 s–h        | 10–15                  | 120–160                  | 2500–4500             | 70–85                 | High specific power and energy density                                  | Temperature effect, a safety problem, costly                   |
| VRB battery      | 0.03–3 s–10 h     | 5–20                   | 0.5–2                    | > 10,000              | 60–75                 | High density, lifetime                                                   | Low power density                                              |
| ZnBr battery     | 0.05–2 s–10 h     | 5–10                   | 1–25                     | 1000–3650             | 65–75                 | Fast charging ability, lifetime, low cost                               | Low power, large, high temperature                            |
| SC               | 0–0.3 ms–1 h      | 10–20                  | (4–12)*104               | >5*105                | 85–98                 | Lifetime, light weight, applicable in high temperature, efficient       | Low power rating, large size, costly                           |
| Fuel cell        | 0–50 s–24 h       | 600                    | (200 b)                  | 0.2–20                | 103–104               | 34–44          | High power rating and energy density                                      | Low efficiency, costly                                        |
### TABLE A.2  Key characteristics between all balancing circuits

| Methods                      | Time  | Control complexity | Voltage and current stress | Efficiency | Size    | Cost    |
|------------------------------|-------|--------------------|---------------------------|------------|---------|---------|
| Fixed shunt                  | Slow  | Simple             | Zero/Zero                 | Poor       | Small   | Cheap   |
| Switch shunt                 | Slow  | Simple             | High/High                 | Low        | Small   | Cheap   |
| Analog shunt                 | Slow  | Simple             | High/High                 | Low        | Small   | Cheap   |
| Single switch capacitor      | Medium| Complex            | Low/Low                   | Better     | Medium  | Medium  |
| Switch capacitor             | Medium| Medium             | Low/Low                   | Better     | Medium  | Medium  |
| Double-tired switch capacitor| Medium| Complex            | Low/Low                   | Better     | Medium  | Medium  |
| Single inductor              | High  | Complex            | Low/Low                   | High       | Large   | Medium  |
| Multi inductor               | High  | Complex            | Low/Low                   | High       | Large   | Medium  |
| Single winding transformer   | Medium| Complex            | Medium/Low                | Better     | Large   | Costly  |
| Multi-winding transformer    | Medium| Complex            | Low/Low                   | Better     | Large   | Costly  |
| Fly-back converter           | Medium| Medium             | Low/Low                   | Good       | Large   | Costly  |
| Boost converter              | High  | Complex            | Low/Low                   | Better     | Medium  | Medium  |
| Buck-boost converter         | Vary High| Complex          | Low/Low                   | Better     | Medium  | Medium  |
| Ramp converter               | Medium| Complex            | Medium/Low                | Good       | Large   | Costly  |
| Cuk converter                | High  | Complex            | Low/Low                   | Better     | Medium  | Medium  |
| Resonant converter           | High  | Complex            | Low/Low                   | Better     | Medium  | Costly  |
| Full-bridge converter        | Medium| Complex            | High/High                 | Better     | Large   | Costly  |

### TABLE A.3  Advantage and limitation of the balancing circuits

| Balancing technique          | Advantage                                                                 | Limitation                                                                 |
|------------------------------|---------------------------------------------------------------------------|-----------------------------------------------------------------------------|
| Switch shunt                 | Simple, miniature size and low cost, and applicable for HEV                | Low efficiency,                                                            |
| Analog shunt                 | Simple, miniature size, and low cost                                     | Low efficiency                                                             |
| Single switch                | Charge/discharge condition and better efficiency                          | Complex, long equalisation time,                                            |
| Switch capacitor             | Charge/discharge condition and better efficiency                           | Complex switching, and low energy                                          |
| Single inductor              | Bidirectional, low current, and voltage stress                             | Complex switching, complex                                                 |
| Multi inductor               | Bidirectional, low current and voltage stress, high equalisation speed, and efficiency | Complex switching                                                           |
| Multi-winding transformer    | Medium equalisation speed, low current stress and power loss, and suitable for HEV and EV | Complex, only charging mode, costly, high magnetic loss, and large size     |
| Multiple winding             | Bidirectional, medium speed, and suitable for HEV and EV                  | Complex, high magnetic loss, and costly                                    |
| Fly-back converter           | Charging/discharging modes, medium equalisation speed and efficiency, low current, and voltage stress | Complex, costly, and large size                                            |
| Buck-boost converter         | Bidirectional, high equalisation speed, minor power loss, low current, and voltage stress, and charging/discharging modes | Complex, costly                                                             |
| Ramp converter               | Bidirectional, soft switching, and less power loss                         | Complex, costly, and large size                                            |
| Cuk converter                | High equalisation and efficiency, low current and voltage stress, and suitable for HEV and EV | Complex, require voltage sensing                                            |
| Resonant converter           | High equalisation speed and efficiency, minor power loss, low current and voltage stress, and charging/discharging modes | Voltage sensing, complex, and costly                                       |
| Full-bridge converter        | High equalisation speed and efficiency, negligible power loss              | Complex, large size, and costly                                            |