Battery Energy Storage and Management in Electric Vehicles

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Electric vehicle (EV) technology has received massive attention worldwide due to its improved performance efficiency and significant contributions to addressing carbon emission problems. In line with that, EVs could play a vital role in achieving sustainable development goals (SDGs). EVs have a substantial influence on various goals of sustainable development, such as affordable and clean energy, sustainable cities and communities, industry, economic growth, and climate actions.

battery storage battery management electric vehicles

1. Introduction

Global warming is one of the most concerning issues to scientists and researchers at present, and the main reason behind this vital issue is the greater emission of carbon. Approximately 3 billion metric tons of carbon dioxide emissions will be produced by only passenger cars worldwide in 2021 [1]. According to the statistics, 41% of the carbon dioxide is emitted from the transportation sector globally [2]. In the USA, a total of 29% of the carbon emissions were produced by passenger cars in the year 2020, according to USA Environment Protection Authorities [3]. However, some issues should be investigated further, such as selecting appropriate battery energy storage, fast charging approaches, power electronic devices, conversion capability, and hybridization of algorithms or methods [4][5]. Hence, further investigation is required to improve EV technology to achieve sustainable development goals (SDGs) [6][7].

Unlike traditional vehicle technology, EVs fully depend on batteries in the case of supplying power, and that is why batteries are considered as the heart of EV technology [8]. Many battery technologies have been introduced by researchers that can easily replace the traditional methods of supplying cars, such as the lead–acid, nickel–cadmium, lithium-ion, lithium-ion polymer, and sodium–nickel chloride batteries [9]. Lead–acid battery technology was introduced at the beginning of the journey of battery technology. Although it has a short life cycle, it can provide 20–40 Wh/kg at the stage of 100% charge [10][11]. To solve the life cycle problem, inventors introduced a new technology called the nickel–cadmium battery that has a long-life cycle. However, the fast charging and deep discharging can cause damage to battery health and performance [12]. Removing all the drawbacks of the battery technology, a new technology known as the lithium-ion battery was introduced, which has greater efficiency, longer life cycle, high energy density, and performance at high temperatures. All of these characteristics make this technology most suitable for EV applications [9]. Lithium-ion technology has risen to the peak because of its unique feature such as high energy density, performance at a high temperature, fast charging, and long lifespan. Nonetheless, the performance of lithium-ion batteries varies with the combination of different materials such as cobalt, manganese, iron, nickel, aluminum, and titanate [13][14][15]. Furthermore, the unavailability of the materials is the drawback that makes lithium-ion technology a little bit dull [12]. Although the battery technology has advanced to significant development, each of these batteries has some downsides. Recently, fuel cell and supercapacitor-based EVs have made a significant stride toward the advancement of energy storage in the EV market.

The management system of the battery storage system plays a crucial role in the EV system [16]. For proper supervision of energy storage devices for safe and healthy operation, various techniques and control operations such as cell monitoring, voltage, and current monitoring, data acquisition, charge–discharge control, power management control, temperature control, fault diagnosis, and network and communication network should work spontaneously [17][18][19]. In order to perform all the operations efficiently, a set of highly efficient power electronic devices are needed. DC/DC converters play a vital role in EV technology. The most widely used DC/DC converters are isolated and non-isolated. A non-isolated DC/DC converter such as Ćuk, switched capacitor, coupled inductor, and quasi Z-source converters are used for converting voltage up or down in a relatively low ratio [20][21]. Due to low cost, high efficiency, and lower ripples, DC/DC converters are famous in EV technology. However, present switching control techniques are not reliable enough for EVs. An isolated DC/DC converter is used when the ratio of output and input voltage is high. The buck–boost converter, push–pull converter (PPC), DC/DC resonant converter (RC), zero-voltage switching converter (ZVSC), and full-bridge boost DC/DC converter (FBC) are widely used converters in EV technology, with each having individual drawbacks.

2. Battery Energy Storage and Management in EVs

2.1. Battery Storage Technology

2.1.1. Lead–Acid (Pb–Acid)

The lead–acid battery is considered as one of the oldest battery technologies to be used globally. Lead–acid batteries display a specific energy of 20–40 Wh/kg at 100% of the state of charge (SOC) of a lead–acid battery. It contributes a small cycle life due to the shedding of active material compared to other types of batteries such as nickel metal hydride. The low energy-to-weight ratio and low energy-to-volume ratio are considerable limitations. Furthermore, the lead–acid battery is not an environmentally sound technology due to the presence of lead and acid. Despite several drawbacks, the low manufacturing cost of around 100 USD/kWh makes it suitable for small-scale, light-performance vehicles [10][11].

2.1.2. Nickel–Cadmium (NiCd) Battery

Nickel–cadmium (NC) battery technology was employed in the 1990s, presenting high energy density. The NC battery technology was employed in applications such as power quality and energy reserves for telecommunication and portable services [22]. NC batteries provide a long lifecycle span of 1500 cycles compared with NiMH battery.

However, the NC battery may cause damage due to deep discharge and a faster charging time. NiMH batteries possess a memory loss effect, which occurs due to the battery's frequent charging process before complete discharge. One of the major drawbacks of NC is the adoption of toxic metals such as cadmium during the manufacturing process. Cadmium causes adverse effects on the environment and human health. Equation (1) shows the electrochemical cell reaction of an NC battery, where Cd is used as an anode and NiO(OH) is used as a cathode [12].

$$Cd + 2NiO\,(OH) + 2H_2O \leftrightarrows 2NiO\,(OH)_2 + Cd\,(OH)_2. \quad (1)$$

2.1.3. Lithium-Ion Battery

The lithium-ion battery is considered as one of the leading battery technologies used in EVs. The high energy density, greater efficiency, longer life cycle, and better performance at high temperatures are the well-known features of Li-ion batteries. Lithium maintains the lowest redox potential, which is around (−3.05 V), and the largest electrochemical equivalence of (3.86 Ah·g^{-1}) [22]. It is still recognized as suitable for battery-driven EVs. Moreover, lithium alone has the smallest reduction potential capacity of any element, which enables this battery to hold the topmost cell potential. The most important advantage of this battery relates to the recycling ability of the various components used. However, the material's unavailability and high cost per kWh (135 USD /kWh) represent significant drawbacks [12]. Generally, the performance of the lithium-ion battery relies upon various internal material properties. The selection of materials is crucial, specifically the positive electrode, which controls the battery characteristics such as power, safety, cost, and lifespan [23][24][25][26]. The positive electrode material can be classified into lithium cobalt oxide, lithium manganese oxide, lithium iron phosphate, lithium nickel manganese cobalt oxide, lithium nickel cobalt aluminum oxide, and lithium titanate, which are discussed below [13][14][15].

Lithium Cobalt Oxide—$LiCoO_2$

Goodenough announced the existence of layered transition metal oxides in 1980 [22]. They are considered among the most commonly implemented positive electrodes. Initially, Sony marketed lithium cobalt oxide (LCO) in 1991 and used cobalt oxide as a cathode which was the most commonly used material in lithium-ion battery technology. The theoretical capacity of LCO is approximately 274 mAh·g^{-1} with a high volumetric capacity of 1363 mAh·cm^{-3}. It constitutes high energy density, offers a moderate lifespan, and has considerable safety applicable for several electronic gadgets such as cameras, notebooks, and tablets [9][12][13]. Nevertheless, the LCO shows unsatisfactory behavior during its operating condition at the rate of high current of charge–discharge. Consequently, proper protections are required due to excessive heating and stress. In addition, the cost of cobalt is high due to its limited availability [27]. Hence, an alternative to cobalt cathode materials is preferred to raise the appropriateness of LCO in EVs.

Lithium Manganese Oxide—$LiMn_2O_4$

Lithium manganese oxide (LMO) is one of the most reviewed cathode materials for lithium-ion battery technology due to its easy accessibility to raw materials and low cost [28][29]. The Bellcore lab developed the LMO battery technology in 1994. The 3D spinel architecture of LMO helps to reduce the internal resistance and simultaneously increases the charge/discharge current flow. It exhibits decent specific power and energy density and can carry >50% more energy than nickel-based batteries. The theoretical capacity of LMO is about 148 mAh·g^{-1}. Pristine LMO ensures 95% delivery of its capacity, which is not possible in the case of LCO [30]. However, it has negative effects on its life cycle and performance. Moreover, LMO has extensive manganese breakdown in the electrolyte at high temperatures, which results in a high capacity loss. The capacity of LMO is approximately 33% lower than that of cobalt-based batteries [31][32][33]. Presently, the application of LMO is carried out in Nissan Leaf EV technology [14].

Lithium Iron Phosphate—$LiFePO_4$

The University of Texas investigated the application of phosphate as a cathode material and concluded that phosphate demonstrates better performance than LCO or LMO batteries at high temperatures and in overcharged states. Phosphates exhibit good thermal stability, operating in the temperature range of −30 °C to 60 °C [34][35]. Lithium iron phosphate (LFP) can contribute with a nominal voltage of approximately 3.2 V and moderate power and energy density. In addition, the LFP battery has low cost, a long lifespan, an enhanced safety system, and high load-handling capability. The major drawbacks of LFP relate to poor lithium diffusion, poor electronic conductivity, and lower specific energy of 160 mAh/g compared to LCO and LMO battery technology. Furthermore, it requires a small particle size and carbon coating to enable performance at high current rates, resulting in a high processing cost [36].

Lithium Nickel Manganese Cobalt Oxide—$Li(Ni, Mn, Co)O_2$

Lithium nickel manganese cobalt oxide (LNMC) battery technology was first commodified in the year 2004. At present, battery industries are focusing on improving the cathode material by developing composite nickel–manganese–cobalt (NMC). These NMC electrode sheets are available in four different compositions, namely, NANOMYTE® BE-50E (NMC111), BE-52E (NMC532), BE-54E (NMC622), and BE-56E (NMC811). These different compositions possess unique outcomes. In terms of minimum capacity, BE-50E (NMC111), BE-52E (NMC532), BE-54E (NMC622), and BE-56E (NMC811) reveal 150 mAh/g, 155 mAh/g, 166 mAh/g, and 190 mAh/g, respectively, while the experimental outcomes were ≥155 mAh/g (2.7–4.3 V @ 0.1 C), ≥165 mAh/g (2.7–4.3 V @ 0.1 C), ≥175 mAh/g (3–4.3 V @ 0.1 C), and ≥200 mAh/g (3–4.3 V @ 0.1 C), respectively [37]. The cathode material of LNMC is developed by utilizing 33% nickel, 33% manganese, and 34% cobalt. The hybrid mixture of NMC draws out the low internal resistance effect of manganese and the high specific energy of nickel. Moreover, LNMC offers high power and energy density with improved lifespan and performance. At present, LNMC has high demand in EV applications for its low self-heating rate and long lifespan (1000–2000 cycles) [38][39][40]. It is suggested that LMNC battery characteristics could be altered by varying the combination of nickel, manganese, and cobalt for certain applications. The increment in manganese percentage leads to an enhancement of specific power, while the increment in nickel leads to an enhancement of specific energy. Presently, the BMW i3 is run by NMC-based lithium-ion batteries [13].

Lithium Nickel Cobalt Aluminum Oxide—$Li(Ni, Co, Al)O_2$

The nickel cobalt aluminum oxide (NCA) battery was commercially presented in 1999. The maximum utilization of nickel as a cathode material reduces the dependency of cobalt in LCO. It provides increased specific power, excellent specific energy of 200–250 Wh/kg, and a durable life cycle. In recent years, lithium nickel cobalt aluminum oxide (LNCA) battery technology has gained increasing attention in EV applications. Due to its high power and energy densities, automobile companies are concentrating on LNCA battery application in EV technology. However, further advancement is needed to improve its safety mechanism [34][41][42]. The automobile giant Tesla is currently utilizing LNCA battery technology to develop EVs [13].

Lithium Titanate—$Li_4Ti_5O_{12}$

Lithium titanate (LTO) has a spinel architecture and is configured using LMO, LNCA as a cathode material, and titanate as an anode material. The spinel configuration delivers a few advantages, such as structural firmness due to the zero strain effect and considerable reversibility [43]. LTO delivers high performance and a long lifespan. Furthermore, LTO operates safely at cold temperatures [44][45][46]. However, the power and energy density of LTO are lower compared to NMC- and NCA-based lithium-ion battery technology. The LTO recommends a constant active potential of around 1.55 V, but the electronic structure depicts insulating behavior with a bandgap of 2–3 eV [47]. The main obstacles that appear in LTO batteries are gas evolution, which leads to battery swelling, and low performance during charge/discharge due to low electrical conductivity [48]. Thus, further explorations are focused on improving these areas, including specific energy and cost reduction.

The figure clearly presents that LMO, LNMC, and LNCA batteries are the best depending upon the voltage, power, and energy categories. On the other hand, LFP and LTO batteries can be used when high lifecycle and safety are major concerns. Moreover, LTO is economically excellent and capable of delivering high performance.

Lithium-Ion Polymer

At the beginning of the 21st century, lithium-ion battery technology started to shift the paradigm from liquid electrolyte cells with metal housing to plastic casings. The battery technology was generally named as a lithium-ion polymer (LPO) battery [49]. The LPO battery technology is a secondary battery that consists of a polymer electrolyte in the liquid electrolyte utilized in usual lithium-ion batteries [50]. All Li-ion cells expand at high levels of state of charge (SOC) or overcharge due to slight vaporization of the electrolyte. This may result in delamination and bad contact of the internal layers of the cell, which in turn brings diminished reliability and overall cycle life of the cell. Lithium-ion polymer batteries have delivered satisfactory outcomes and have taken over nickel–metal hydride (NiMH) batteries for moveable electronic devices such as smartphones and laptops. They provide excellent high energy density (400 $Wh{\cdot}L^{-1}$) compared to other types of batteries. The high power and energy density make them qualified candidates for EV and HEV applications [51]. They also contribute toward the extended cycle life of ordinary Li-ion batteries. The temperature should be kept at less than 50 °C to ensure the available cell capacity and utilize the full life span. However, functional instability materializes during limited battery discharge and overload conditions.

Lithium-Ion Silicon

The initial work with lithium-ion silicon (LS) technology was initiated by Sharma and Seefurth in 1976 [52]. The preliminary research in LS battery technology was conducted by Dahn et al., as well as other teams from the year 1990 to 2000. At the same time, extensive research work was conducted between 2011 and 2015 [53]. The LS battery shows great potential due to its high capacity and long cycle life. However, some concerns related to LS battery technology need to be overcome, such as low Coulombic efficiency, lower real mass loading density, and high cost. Silicon anodes are among the most promising anode materials for lithium-ion batteries due to their various advantageous features, including the highest known capacity and relatively low working potential. However, the problem of extremely large volumetric change must be addressed before silicon anodes can be utilized in practical lithium batteries.

2.1.4. Sodium–Nickel Chloride (Na/NiCl$_2$)

The high-temperature sodium–nickel chloride (SNC) battery, also known as the ZEBRA (zero-emission battery research activity) battery, is manufactured from diluted sodium and nickel chloride. The solid ceramic simultaneously acts as an electrolyte and a separator at an optimal operating temperature of 270–350 °C. The specific energy of SNC is reported to be 125 Wh/kg with an energy efficiency of 92%, which is better than Pb–acid, NCd, and nickel–metal hydride (NMH) battery technologies [54]. The major concern of SNC is its operational safety due to the high operating temperature of 300 °C and its storage for longer periods. Furthermore, the high internal resistance and faster self-discharge cause low power capability for SNC batteries [55].

2.1.5. Fuel Cell

A fuel cell is an electrochemical device that uses two redox processes to transform the chemical energy of a fuel (typically hydrogen) and an oxidizing agent into electrical energy. Fuel cells require a constant supply of fuel and oxygen (often from the air) to sustain the chemical reaction, and they can constantly create electricity as long as fuel and oxygen are available. Sir William Grove created the first fuel cells in 1838. One century later, Francis Thomas Bacon created the hydrogen–oxygen fuel cell in 1932 [56]. Song et al. [57] examined the temperature effects on the performance of fuel cell-based hybrid EVs. Quan et al. [58] evaluated the fuel cell EV energy management strategies using model predictive control considering performance degradation in real time. Fuel cells offer a much more silent and a smoother alternative to conventional energy production that can greatly reduce CO_2 and harmful pollutant emissions. However, the fuel cell is expensive to manufacture due to the high cost of catalysts (platinum).

2.1.6. Supercapacitor

A supercapacitor (SC), sometimes known as an ultracapacitor, is a high-capacity capacitor that bridges the gap between electrolytic capacitors and rechargeable batteries. It has a capacitance value that is significantly higher than ordinary capacitors but with lower voltage restrictions. In comparison to electrolytic capacitors, it typically stores 10 to 100 times more energy per unit volume or mass, accepts and delivers charge considerably more quickly, and can withstand many more charge and discharge cycles than rechargeable batteries. Nguyen et al. [59]

used the SC for energy storage in EV applications. Although the SC exhibits long life, it has some drawbacks, such as the generally lower amount of energy stored per unit weight compared to an electrochemical battery.

2.2. Battery Management System in EVs

The battery management system (BMS) can be defined as a system that assists in managing the battery operation via electronic, mechanical, and advanced technological systems [60]. The basic aims of BMS are cell/battery protection from being damaged and ensuring optimum operating conditions. The BMS ensures the proper supervision of the battery storage systems through control and continuous monitoring via various control techniques such as charge–discharge control, temperature control, cell potential, current, and voltage monitoring, thus enhancing the safety and lifetime of the energy management system (EMS) [61][62][63]. Nonetheless, the deep charge and discharge of the battery during long-distance traveling in EV are fundamental issues [64], potentially causing the failure of the battery or shock hazards due to the high discharge and thermal effect [65]. The BMS becomes effective in minimizing these difficulties by controlling the charge and discharge profile, as well as managing the thermal behavior of the battery packs. The state of charge (SOC), state of health (SOH), and remaining useful life (RUL) are the key parameters in the BMS for understanding the status of the battery. The BMS also protects the battery pack from high-voltage stress and short-circuit current by integrating controllers, actuators, and sensors [14]. The key components and operation of BMS applications in EV technology are explained below.

2.2.1. Battery Cell Monitoring

The information on battery charging/discharging, health, temperature, and fault diagnosis is the foundation for completing the BMS duties [66][67]. Generally, a pack of battery cells is used in EVs [68]. The battery cell may react differently during the battery charging/discharging operation. As a result, continual battery cell monitoring is required to investigate the different states and performance indices [69]. The findings of the battery cell monitoring can help the system function better by managing, protecting, balancing, and controlling operations [70].

2.2.2. Voltage and Current Measurement

The battery cells are connected in series and parallel to the battery bank to acquire a sufficient amount of voltage and current. Hundreds of cells are linked in series in battery packs of electric automobiles, resulting in a large number of voltage measurement channels. When the cell voltage is measured, there is accumulated potential, and the combined potential of one cell differs from another. Hence, a suitable charge equalization must be provided in order to enhance EV autonomy [71]. An accurate battery cell measurement is required for the estimation of SOC and other battery states. One of the common voltage monitoring methods is the voltage divider technique which consists of a resistor and precise temperature-corrected voltage reference used to monitor the cell voltage. The other available methods are the optical coupling relay, optical coupling isolation amplifier, discrete transistor, and distributed measurement [60]. High-voltage current sensors are used to monitor the current of the battery module, which is later converted to a digital signal via analog to digital conversion (ADC). Finally, the voltage and current data are utilized to appropriately estimate the SOC, SOH, and RUL [72].

2.2.3. Data Acquisition

The data acquisition system (DAS) is used for measuring and estimating the parameters of the battery pack, such as current, voltage, temperature, and SOC [73][74]. This facilitates diagnosing the battery's health and identifying defective cells. It also investigates battery changes that would assist in delivering the status of battery aging, climate, and other factors. The DAS is an integral part of the BMS, which consists of a hardware device (microcontroller unit) and software. The DAS uses the ADC module for data conversion. A controlled area network (CAN) bus and serial communication interface (SCI) module are used to exchange information and communicate with the BMS [75][76][77].

2.2.4. Battery State Estimation

The battery state estimation is critical for estimating battery charge and health. The SOC, SOH, RUL, state of function (SOF), state of power (SOP), state of energy (SOE), and state of safety (SOS) are some of the common battery states [78].

State of Charge

SOC can be defined as the proportion of currently available capacity to maximal battery capacity [79]. It is not directly measurable from terminals; hence, a method must be created to predict the state from measured data [80]. The appropriate assessment of SOC is not only needed for battery protection from degradation but also for the highest level of energy management [81]. Several methods are available to estimate the SOC, such as the discharge test method, sliding mode observer method, neural network method, fuzzy logic method, impedance method, and internal resistance method, as well as Kalman filter (KF), machine learning, and deep learning approaches [69]. The Ampere-hour (Ah) and open-circuit voltage methods are also common methods to calculate the SOC [82][83]. The Ah technique becomes a simple choice for SOC calculation since charging or discharging current may be easily monitored. However, the accuracy of SOC estimation is not error-free, and the firmness of the initial state is complex. Furthermore, the estimation accuracy is improved in the open-circuit voltage (OCV) method, but the long resting time limits the rapid application of this method in EVs [84]. KF-based SOC estimation achieves accurate results but has complex mathematical computation and functional relationships [85]. Recently, machine learning and deep learning methods for SOC estimation have received wide attention due to their high accuracy, improved learning capability, better generalization performance, and convergence speed [86].

State of Health

The SOH of the battery can be defined as the available maximum capacity left by the cycling effect of charge–discharge [87]. The following equation can be used to estimate the SOH:

$$SOH\ (\%) = (Q_{actual} Q_{rated}) \times 100, \quad (2)$$

where Q_{actual} is the actual capacity of the battery, and Q_{rated} is the rated capacity [88].

The SOH can be easily estimated from an understanding of capacity degradation and the internal resistance of the battery. A variety of methods have been developed to estimate battery SOH, which can be divided into three categories: model-free, model-based, and data-driven methods [88]. Electrochemical impedance spectroscopy (EIS) analysis is much more convenient compared with direct methods for capacity and internal resistance estimation in a model-free method [89]. On the other hand, model-based methods follow the equivalent circuit model and electrochemical model to estimate the capacity and internal resistance during battery operation. Similarly, the data-driven method uses the support vector machine (SVM) mechanism to estimate SOH by measuring the terminal voltage, current, and temperature [90].

Remaining Useful Life

Accurate and robust EV performance is subjected to the battery's remaining useful life (RUL). The battery's continuous charging and discharging process results in capacity degradation, which can deliver unacceptable outcomes such as major breakdown, economic loss, and safety issues [5][91]. Therefore, it is crucial to estimate the RUL of the battery toward the achievement of safe, accurate, robust, and reliable operation of EV technology [92]. When the battery is charged and discharged continuously, and its capacity remains 70% or 80% of the initial capacity, the battery needs replacement. Therefore, several model-based and data-driven-based techniques have been explored to predict the RUL of the battery. The model-based techniques rely on a mathematical model and detailed experiments; however, the technique requires a huge volume of data to estimate the battery degradation pattern. On the other hand, data-driven methods depend on battery historical data, which comprise various parameters such as voltage, current, impedance, capacity, and temperature. Data-driven methods predict the RUL by considering battery data and do not require complex mathematical models [91].

State of Function

The SOF is described as the capability of a battery that can finish a specific task. It narrates the performance of the battery in terms of meeting the power demand [93]. It can also be determined from the ratio of available useable energy to the maximum stored energy of the battery [94]. The SOF is estimated with the help of SOC, SOH, and temperature [60]. The SOF can be calculated from a few approaches, such as (adaptive) characteristic maps and equivalent circuit models, including the fuzzy logic control method [95]. The SOC, power pulse duration, power, voltage, and temperature are the characteristics needed in (adaptive) characteristic maps [93]. Additionally, KF and artificial neural network (ANN) algorithms are adopted in model-based methods for the accurate estimation of SOF. The parameters related to SOC, SOH, and C-rate of the battery are also employed in the fuzzy logic algorithm to estimate the battery SOF [60].

2.2.5. Battery Protection Strategies

Battery protection is one of the major tasks of BMS. Due to alterations in physical and chemical characteristics of the battery and frequent charge–discharge, voltage and charge deviance may occur in battery cells [96]. The overall battery performance and lifetime may be reduced because of the deviation of voltage and charge. Moreover, the deep discharge below the minimum SOC limit and overcharge of the battery beyond the C-rating may cause a critical situation for the battery [97]. Thus, a suitable protection system for the battery in EV applications is important. The proper maintenance of operating temperature is also a significant parameter for ensuring safety. The BMS provides temperature safety limits which stand between 0 °C and 60 °C for charge and between −20 °C and 60 °C for discharge [98]. It also provides deep discharge protection, overcharge protection, high-temperature protection, uplifted voltage protection, and power cutoff safety. However, BMS safety protocols should comply with the automobile International Organization for Standardization (ISO) 26262 [99].

2.2.6. Battery Equalizer Control

The BMS can protect the battery from abnormalities that are caused by the under/overcharging of the battery through individual cell monitoring and charge equalization control [100][101]. The undercharging of the battery can deteriorate the lifetime, and overcharging of the battery can damage it completely. To enhance and maintain the constant performance of the battery, the equalization of voltage and charge of battery cells is critical [102]. Battery equalizer control can be broadly categorized into active and passive charge equalization controllers [103].

The active charge equalization controller (CEC) works on the principle of transferring energy from cell to cell, cell to battery pack, or battery pack to cell [104]. The excess energy is collected from overcharged cell and delivered to the undercharged cell to equalize the charge and voltage. The active CEC can also be categorized into three types, namely, capacitor-based, inductor/transformer-based, and converter based. The energy transfer from cell to heat via a shunting resistor is the basic hypothesis of passive CEC, which can be distinguished into fixed shunting, switched shunting, and analog shunting. A fixed resistor is used in the fixed shunting method to bypass the current flows and control the voltage. Similarly, a controllable switch (relay) bypasses the release path from the overcharged battery in the switched shunting method. The most effective method among the three is the analog shunting method which uses a transistor instead of a resistor to complete the task of the current bypass from high-energy cells [103].

2.2.7. Charge and Discharge Control

The battery charging/discharging determines the protection, performance, and durability. Incorrect charging drastically accelerates the battery’s deterioration. Nonetheless, enhancing battery efficiency, reducing overheating, and prolonging the life cycle depends on controlled and quality charge and discharge. There are a few conventional but widely used charging techniques for resolving battery charging issues with a variety of aims and termination circumstances. The charging techniques can be classified into four types: constant-current (CC) charging, constant-voltage (CV) charging, constant-current/constant-voltage (CC-CV) charging, and multistage constant-current (MCC) charging [105]. A constant current rate is the main approach adopted by the CC technique to charge the battery. During the CC technique, a low current rate can lower the charging speed, which is not suitable for EV applications. The CV charging method works on the basis of a predefined constant voltage to charge the battery, eliminating the risk of overcharge and enhancing the battery cycle life. The charging speed and temperature variation are new modifications that have been added to this technique. The hybrid charging technique is CC-CV which works on interconnecting the principle of predefined current, a voltage of CC, and CV. In the beginning, the battery is charged with constant current (CC), and then the voltage is increased to a safe limit. In the end, the battery starts working in the CV phase and remains as such until the target capacity is obtained. Constant multistage series current is injected into the battery during the whole process of charging in the MCC charging technique. This highlights the basic difference between CC-CV and MCC. The speed of MCC charging is quite slow compared to the CC-CV technique. However, fuzzy logic technology has been incorporated with MCC to improve performance [90][106].

EV performance depends not only on energy storage but also on power and energy intelligent control strategies. In order to regulate power/energy flow efficiently in electric vehicles, the energy storage control system must be capable of dealing with high peak power when accelerating or decelerating [107]. Two basic types of common strategies are adopted for power and energy management (PEM) control [108]. A low-level component control strategy enhances the PEM performance and flexibility via a power transfer train mechanism that connects ESS, auxiliary ES, ICE, and generators altogether. A high-level supervisory control system works on the time-based data extraction process and balances the operations of different components. Various types of efficient PEMC systems have also been reported in several research for HEV; among them, two major types are rule-based and optimization-based. The rule-based strategy can be classified into two types: deterministic rule-based and fuzzy logic. The real-time optimization and global optimization PEMC systems are types of optimization-based PEMC systems [109][110][111].

2.2.9. Operating Temperature Control

The battery temperature significantly impacts several aspects of battery performance, including longevity, energy conversion efficiency, and safety [112]. The rapid charge–discharge cycle of the battery was identified as the main cause of the rising operating temperature of the battery, which reduces the battery performance [113]. A low operating temperature affects the electrolyte performance, and a high operating temperature causes thermal runway and safety issues. Temperatures of more than 40 °C and less than −10 °C cause capacity losses and performance degradation of the battery. Hence, the thermal management of a battery pack in an EV is a crucial aspect [114]. To ensure the operation at optimal operating temperature, a BTMS should perform crucial tasks such as heat removal from the battery by cooling, increasing heat when the temperature is too low, and providing suitable ventilation for exhaust gases. According to the heat transfer medium, the BTMS can be classified into air, liquid, and phase-change material (PCM) types [115]. The internal temperature estimation of a battery is another important issue that can prevent the battery from aging and explosion risk. The internal temperature estimation can be performed using micro-temperature sensors, EIS measurement, and a lumped-parameter battery thermal model [90][115]. In contrast to battery-based EV applications, fuel cell vehicles (FCVs) have shown huge potential toward decarbonization. They are more efficient than conventional internal combustion engine vehicles and produce no tailpipe emissions since they only emit water vapor and warm air. However, thermal management in FCV should be considered an important research area to be explored [56]. Accordingly, Hu et al. [116] developed an operating temperature tracking control framework to decouple the operating temperature from the complicated driving conditions of the FCV.

2.2.10. Fault Diagnosis

The unbalance, undercharge, overcharge, overcurrent, and extremely low or high temperatures are some critical issues suffered by battery storage systems [117]. Moreover, other types of faults related to data acquisition, networking, programming, etc. are experienced by BMSs in EV technology. The International Electrotechnical Commission (IEC) developed a BMS standard in 1995 that stipulates that BMSs for EVs must have battery fault diagnosis functions that can provide early warnings of battery aging and risk [60]. Analytical model-based, signal processing, knowledge-based, and data-driven methods are frequently used for fault diagnosis in EV applications [118]. The model-based method detects the faulty parameters with the help of a residual signal that is compared with a threshold to determine the fault. However, the diagnosis results can be affected by measurement and process noise. Time-domain analysis is a key tool to collect the test data for fault analysis in the signal processing-based method. Wavelet transform is a widely used technique in signal processing methods to carry out multiscale fault analysis for battery systems [119]. In addition, machine learning and expert systems are the methods used in a knowledge-based method for fault diagnosis, which can also be utilized to identify the battery lifetime. Moreover, the information entropy, local outlier factor, and correlation coefficient are the key tools to detect faulty data in the data-driven method for fault diagnosis [118][120].

2.2.11. Communication and Networking

BMS communication with the EV and its external system is essential to protect the battery storage unit. The communication system can be established through wires or data links [121]. A simple BMS consists of a microcontroller unit, debugger, CAN bus, and host computer. For battery status monitoring, a monitoring IC such as AS8505 is used to communicate with the microcontroller through I/O lines via a CAN bus, which controls the cell data and monitors the balancing process [122]. The battery parameters such as voltage, current, and cell temperature are utilized to estimate the SOC, SOH, DOD, etc. in BMSs, which can also be used in IoT-based wireless communication systems with EVs to monitor battery health. The wireless communication technologies that can be employed to monitor battery comprise ZigBee communication, Wi-Fi communication, GSM communication, Bluetooth communication, GPRS communication, and GPS [123][124]. Furthermore, parameter identifier (PID) codes can also be used to collect critical parameters such as voltage, temperature, energy, power, SOC, SOH, DOD, and resistance. Additionally, PIDs use the CAN bus for data processing. Therefore data-driven personalized battery management schemes based on the platform of big data and cloud computing were introduced by Wang et al., [122].

3. Key Technological Progress of EVs

3.1. Power Electronics Technology

Power converter structures need to be dependable and lightweight for automotive applications with minimal electromagnetic interference and low current/voltage ripples to meet the automotive industry standards for high reliability and efficiency [125][126]. A proper interface between energy storage systems (ESSs) and power electronics converters is required for effective EV operation. There are numerous varieties of ESSs that are coupled to different types of power electronic converters in electric vehicles. AC/DC converters are typically used to charge

ESSs through charging stations or grids. To accelerate the vehicle, ESSs transmit the necessary energy from a battery to the motor. However, the energy provided by ESSs is unreliable and suffers from significant voltage dropouts. As a result, DC/DC converters are crucial in transforming uncontrolled power flow into controlled/regulated power flow to support various electrical loads and auxiliary power supply in EVs [5].

3.1.1. DC/DC Converter: Non-Isolated

When voltage needs to be stepped up or down by a relatively small ratio, non-isolated converters are typically utilized. These types of converters are applicable where the presence of dielectric isolation is not a major issue [127][128]. The mid- and high-range vehicular types are more appropriate for utilizing non-isolated DC/DC converters [129]. A conventional boost DC/DC converter is usually employed where low DC voltage gain is required (<4%). There are five major types of commonly used DC/DC converters: multi-device interleaved, Ćuk, switched capacitor, coupled inductor, and quasi Z-source converters [5][130].

Because of their simple construction, low cost, high efficiency, lower ripples, and easy-to-use control method, multidevice interleaved (MDI) bidirectional DC/DC converters are frequently utilized in BEV and PHEV powertrains. They can maintain the constant magnitude of input current and output voltage ripple without including additional devices such as an inductor or capacitor. Some advantageous features of interleaved converters make them highly suitable for EV applications, such as enhanced heat dispersal, high energy density, reduced current stress, high efficiency, small size filter, and inherent ability to eliminate current ripples [131]. The interleaved topology suggested in [132] is structurally simple and has high modularity, resulting in reduced current stress on the switches and enhanced heat distribution. However, the current configuration of this converter can only be used for a low-power EV that can carry a maximum of two passengers. For high-power EVs, the structure needs to be extended using supercapacitors, making it structurally complex, bulky, and expensive. A two-phase bidirectional interleaved converter was proposed in [133] for EVs. This converter can be operated in both buck and boost mode with fast and low overshoot switching performance. A major drawback of this converter is that its operation is highly reliant on the switching control technique. In order to achieve the optimized performance from this converter, a highly complex control technique named optimal Bézier curve is required. The dynamic response of this converter with direct switching control is poor and may not be suitable for EVs. A two-phase hybrid mode interleaved converter was developed by [134] for EV fuel cells. This converter has the ability to simultaneously operate in continuous conduction mode and discontinuous conduction mode. With regard to load conditions and duty cycles, the boundaries between the two conducting modes are distinguished. Although this converter showed high-performance efficiency with low output voltage and current ripple, the dynamic performance of this converter has not been verified. Since the modes are distinguished on the basis of load conditions, transient conditions can greatly hamper the performance of this converter.

The Ćuk converter (CC) delivers flexibility toward regulating the output power as compared with input power. The Ćuk converter is developed by utilizing a single magnetic core and delivers important features such as low ripples/harmonics and high efficiency. The Ćuk converter also delivers high-performance efficiency compared with the DC/DC boost converter by controlling the current ripple through the L−C filter. A modified Ćuk converter for

Toyota Prius was proposed in [135] with a basic proportional–integral (PI) controller for tuning and filtering. Since the conventional PI controller has various performance deficiencies such as sluggish transient response, high overshoot, manual tuning, and poor filtration, the real-time execution of this converter is questionable. Furthermore, a bridgeless modified Ćuk converter was developed in [136] to improve the power quality of the EV charger. The proposed converter's operation was verified under transient voltage conditions, and it successfully followed the IEC 6100-3-2 standard for reduced current harmonics. The only downside of this proposed topology is that it utilizes an additional flyback converter for current harmonic reduction, which is connected through a transformer. Thus, the implementation of this converter will be significantly expensive, and it will also have increased weight.

Additionally, In EVs, the switched-capacitor bidirectional converter (SCBC) uses synchronous rectification to conduct turn-on and turn-off actions. By utilizing switched capacitors, the SCBC can deliver stable voltage and current without magnetic coupling. Additionally, with the employment of power switches in SCBC, the application of additional components is minimized to improve the power conversion efficiency [137]. Some of the recently proposed SCBCs for EV applications can be found in [137][138][139]. Nonetheless, the SCBC suffers from various factors such as high harmonics and low efficiency at widespread input to output voltages. Zhang et al. [137] designed a switched capacitor-based converter for EV applications without the magnetic coupling that can deliver continuous inductor current and a stable switched-capacitor voltage through the switched capacitors. The performance of the proposed configuration was investigated using a 300 W prototype considering a wide voltage-gain range and variable low-voltage side (40 V to 100 V). The results demonstrated a maximum efficiency of the converter of 94.39% in step-up mode and 94.45% in step-down mode. Zhang et al. [140] developed a hybrid bidirectional DC/DC converter with switched capacitor-based converter for hybrid energy source-based EVs. According to the experimental outcome obtained from a 400 W prototype, the researchers validated the characteristics and theoretical analysis of the proposed converter.

On the other hand, the coupled inductor bidirectional converter (CIBC) demonstrates improved performance efficiency due to high voltage gain and low voltage stress compared to SCBC [141]. A reduced-component CIBC was proposed in [142] for EV charging applications. This topology can provide a wide range of voltage conversion by operating in both buck and boost mode. It also showed a high performance efficiency greater than 95%. Another CIBC for EVs was proposed in [143], and the operation was verified under transient conditions using simulation and experimental results. However, both of these CIBC topologies have inherent weaknesses due to the application of leakage inductance, resulting in resonance and voltage spikes [144]. This drawback can cause serious consequences in EV applications; therefore, the implementation of CIBC for EVs is still limited in the industry. Wu et al. [145] developed a couple inductor-based converter for EVs to enhance the voltage gain and decrease the switching voltage stress. An experimental model of the converter rated as 1 kW, 40–60 V to 400 V, was designed to validate its performance.

Lastly, due to several significant properties such as simple design, common ground, and wide range of voltage gain, the quasi Z-source bidirectional converter (QZBC) is employed in EV technology. Commonly, the EV application employs a conventional two-level QZBC topology. The QZBC replaces the conventional Z-source DC/DC boost converter by enhancing the output voltage gain, which is suitable for high step-up voltage conversion

[146]. However, the employment of QZBC results in various drawbacks such as uneven input current and capacitance of high-voltage stress [128].

3.1.2. DC/DC Converter: Isolated

Isolated converters are essential where the output is completely separated from the input. In low- and medium-power vehicle applications, isolated DC/DC converters are commonly utilized [5]. Some of the important isolated DC/DC converters employed in BEV and PHEV applications are flyback, push–pull, multiport, resonant, zero-voltage switching (ZVS), dual-active bridge full bridge, ZVS full-bridge, and forward converters.

When a buck–boost converter splits an inductor into transformers, the result is a flyback converter (FBC). This is an isolated DC/DC converter that stores energy during the on state and transfers it to the off state. The application of FBCs can be carried out in low-power applications due to their various characteristics, such as low cost, high output voltage, and electrical isolation [147]. The constructional features of FBCs can obtain high gain and reduce the output current ripple and the leakage inductance [148]. A boosting multioutput FBC was proposed in [149] for EV application. This topology consists of three separate FBCs to provide multioutput voltage. Although this topology has high voltage gain and can be applied in high-power EV because of a parallel connection, it requires a transformer winding technique to decrease leakage inductance, which can drastically increase the cost and weight of this topology. A multiphase bidirectional FBC was developed for hybrid EVs in [150]. Due to its modularity, it is suitable for high-power applications while maintaining structural minimization and features such as high voltage gain, accurate operation during load fluctuations, decreased current ripple, and parallel-battery energy capacity. However, similar to the FBC in [149], it also utilizes a transformer, making it highly expensive and overweight.

The working principle of the push–pull converter (PPC) is based on the transformer operation, which transforms power from primary to secondary. A rectifier diode, bypass capacitor, power switches, and transformer circuit are the basic circuit components of the PPC configuration. The PPC demonstrates simple topology with high efficiency and results in low conduction loss due to low peak current. However, careful attention is required while operating the PPC due to the formation of a low impedance path and high current [151]. Some notable PPC topologies developed particularly for EV applications can be found in [152].

The multiport isolated converter (MPIC) performs the operation while considering several input sources and offers galvanic isolation. The performance efficiency and functionality are improved by feeding back the recovered power obtained during regenerative braking to the input sources [153][154]. A highly energy-efficient T-type MPIC was proposed in [155] for EVs. In order to handle multiple energy generation/storage units, the suggested converter unit has multiple input sources. Because the unit requires fewer switching components, the cost of the power electronics interface for EV implementation is greatly reduced. Although this MPIC has shown promising performance, it requires a complex multipurpose algorithm for accurate energy management in different modes of operation. Furthermore, another novel MPIC with the inherent ability to control multidirectional power flow was suggested in [156]. Unlike [155], this topology offers galvanic isolation by using a common magnetic link among the multiple input sources. It can be stated that MPIC topologies comprise several advantageous features compared to other converter topologies, especially for EV applications. Nonetheless, they are still in the early phase of development for EVs, and further research is required to optimize their cost and weight since they utilize transformers [129].

A DC–DC resonant converter (RC) is made of a resonant tank constructed with a combination of inductors and capacitors. The RC exhibits several benefits, including low switching loss, zero circulating currents, zero-voltage switching, and high efficiency. These features can be essential for EV applications, as demonstrated in [157][158]. However, RC exhibits various limitations in terms of transformer design complexity and high magnetizing current [158], which requires further improvement.

The zero-voltage switching converter (ZVSC) was designed on the basis of the dual half-bridge topology placed on both sides of the main transformer. Due to various strengths such as less circuitry topology, easy control, soft switching, and higher efficiency, the ZVSC is regarded as highly suitable for EV technology [159]. The topology of ZVSC can be adopted for both BEV and PHEV powertrains even though it has a power limitation >10 kW for automobiles [160][161]. The experimental verification of a 53.2 V, 2 kWh low-voltage and high-current lithium-ion battery energy storage system based on a 6 kW single-phase dual-active bridge (full-bridge) achieved efficiency as high as 96.9% [162]. A three-phase dual-active bridge with phase-shift modulation and burst mode switching was evaluated for battery energy storage systems to achieve high power density, high efficiency, and galvanic isolation [163].

The full-bridge boost DC/DC converter (FBC) is the most convenient converter topology that diminishes the voltage and current stresses on diodes and switches. The FBC operates in three stages: initially an inverter (DC/AC), then a high-frequency transformer (HFT), and finally a rectifier (AC/DC). This type of converter contributes higher step-up voltage due to HFT and galvanic isolation between input and load. An improved FBC was developed in [164] for efficient power conversion and distribution in EV charging. It has other valuable characteristics such as the minimized size of the EV charger and switching loss, faster operation, and economical performance. Moreover, another FBC was suggested in [165] with the phase-shift switching control technique. Even though FBCs have some effective characteristics for EV applications, they have a major performance deficiency; their maximum achievable efficiency is only around 91.5% [166].

Lastly, the forward converter (FC) works on the forward balancing technique, which has a fast balancing time and is easy to control. It consists of one magnetic core with one primary winding and multiple secondaries based on the desired application. The energy is transferred to the secondary when the switch is turned on. A few forward converter topologies have recently been developed for EV applications [167][168][169].

3.2. EV Charging Technology

EV charging is a major barrier to sustainable adoption in the global market. Charging entails injecting a suitable amount of electrical power from the grid into the battery. The length of time it takes to charge a battery is determined by the battery’s capacity and the charger’s power level. Three methods are frequently utilized for charging the battery of an electric vehicle (EV), i.e., conductive charging, inductive charging, and battery swapping [170][171].

3.2.1. Conductive Charging

Conductive charging involves EV charging by connecting to the grid through a wire, allowing for a direct connection between the charger and the vehicle. This charging method comprises a rectifier (AC/DC) and converter (DC/DC) with power factor correction (PFC), which is categorized as an onboard and off-board charger. The construction of the rectifier and the DC/DC converter initially determines the topology of an on-board and off-board conductive charger [171][172]. The on-board charger is placed inside the EV, which is frequently utilized for slow charging. However, a fixed location is mandatory for an off-board charger, which is applicable for quick charging. The Nissan Leaf, Tesla Roadster, and Chevy Volt all are suitable EVs having conductive charging [173].

When it comes to charging electric vehicles, several standards are used. These requirements are mostly determined by the location in which the EV technology is embraced and employed. For instance, the charging of EVs in North America and the Pacific is based on SAE-J1772 specifications. Furthermore, the charging of EVs in China is based on GB/t 20234 standards, whereas the charging of EVs in Europe is based on IEC-62196 standards. The standards for North America, the Pacific, and China depend on the application of charging modes. On the other hand, the European standards are solely divided into categories on the basis of charging power, i.e., AC or DC.

According to the survey, the North American SAE-J1772 standard is only compatible with the 120 V recharge mode, in contrast to the IEC-62196 and GB/T-20234 standards, which can operate at a greater voltage even in their lowest charging modes.

Moreover, the GB/T-20234 standard has a lower current intensity (10 A) than the other two standards, which have a current intensity of 16 A. However, the SAE-J1772 only supports a maximum intensity of 200 A in its most powerful modes, compared to 400 A for the IEC-62196 and 250 A for the GB/T-20234. In addition, the North American SAE-J1772 standard provides a reduced power of 1.9 kWh in comparison to the 2.5 kWh of the GB/T-20234 and the 3.8 kWh based on the AC power source. On the other hand, the IEC-62196 standard offers the power of 120 kW at 480 V AC which is much higher than the other two standards.

Moreover, the International Electrotechnical Commission (IEC) established the IEC-62196 standard in 2001 as a global standard for charging an electric vehicle in Europe and China. The general guideline for the charging process and energy transferred pattern was introduced by the IEC-62196 standard, which was deduced from the IEC-61851 standard. The IEC-61851 administers a first classification of the type of charging based on its nominal power and the recharging time [174][175]. The EV users are offered four modes of charging the vehicle, as mentioned below.

- Mode-1 (slow charging). This mode is designed for domestic use purposes, frequently used in client houses. It provides the maximum current intensity of 16 A with a single-phase or three-phase power outlet facility, including neutral and earth conductors.

- Mode-2 (semi-fast charging). A similar charging approach is implemented in this mode with a slight modification in current intensity and user facility. This mode can handle the current intensity of a maximum of 32 A, and it also allows users to utilize the charging in public places.

- Mode-3 (fast charging). This mode contributes to a fast charging process with the help of current intensity from 32 A to 250 A. This model also adopts the specific power supply known as EV supply equipment (EVSE), which is utilized for recharging electric vehicles. This EVSE device accommodates a communication system that provides a communication advantage with the vehicles. Additionally, a control system to regulate energy flow, a monitoring system to observe the charging process, and a protection system are incorporated for protection with the EVSE.

- Mode-4 (ultrafast charging). According to the latest IEC-62196-3 standard, this model has a maximum charging power capacity of up to 400 kW. This standard also defines a direct connection between the EV and the DC supply network, having a maximum voltage of 1000 V and a current intensity of up to 400 A. An external charger is required in this mode, which provides protection, control, and communication between the vehicle and the recharging point [172].

3.2.2. Wireless Charging

Wireless power transfer (WPT) has been around for over two centuries. Nikola Tesla conducted tests at Colorado Springs, USA, in 1899 to see if electrical energy could be transmitted without wires. Wireless charging technology involves transferring electricity from one medium to another without the use of a contact medium. Electromagnetic radiation, electric coupling, and magnetic coupling are the three primary types of WPT systems. Moheamed et al. [176] classified the available WPT technologies into three categories.

WPT works in three stages: initial conversion of power supply, then resonance between coil to transfer power, and final charging of the battery. An input AC power supply is converted to high-frequency AC at the first stage. This high-frequency AC is utilized to generate an alternating magnetic field at the transmitter side (primary); as a result, AC voltage is induced at the receiver (secondary side coil). Finally, the AC voltage at the receiver is converted to DC to charge the battery. A magnetic resonant coupling and DC/DC converter can be incorporated at the secondary to improve the performance of the system. The converter system provides an efficiency of 90% under the frequency variation of 20 to 100 kHz.

WPT is also a convenient source of charging because of its flexibility and comfort. Currently, there exist two wireless recharge modes, namely, capacitive power transfer (CPT) and inductive power transfer (IPT). However, IPT is the most often utilized since it can be applied to a wide range of gap lengths and power levels. In contrast, CPT, despite showing promising results with high power levels in terms of kilowatt-power-level applications, is only suitable for small gap power transfers.

An IPT system is electrically separated, and there is minimal wear and tear on mechanical components because no physical touch is necessary. The design of the magnetic structure is crucial in the IPT system for EV charging due to high-power applications. The magnetic coupling between the primary and secondary pads determines the power transfer capabilities of an IPT system, which is determined by the geometry, size, materials, and relative location of the magnetic couplers [177]. Recently, a 30 kW bus online electric vehicle (OLEV) IPT system was used at a bus stop, maintaining a charging height of 170 mm with an efficiency of 80% [178].

Moreover, the CPT technology is based on the notion of a capacitor's functioning. An air gap (d) between the conducting plates of a capacitor is generally filled with a dielectric substance for insulation. The direction of the electric field is reversed every half-cycle in an AC excitation, and the charge and discharge are alternately repeated. According to this method, the capacitor is thought to be carrying an AC. Power transmission via a metal barrier, system simplicity, minimal eddy current loss, and less electromagnetic interference (EMI) are all advantages of CPT technology [179][180].

Furthermore, depending on the situation, there are three different types of wireless recharges: (a) stationary charging, where the vehicle remains stationary or static during charging. For acceptable misalignment, the owner may just park the car in a location and leave it for charging with a set range, (b) opportunity charging, which occurs when the vehicle is stopped for a short period of time, and (c) dynamic charging, which occurs when the vehicle is moving along a dedicated charging lane. Utilizing this method, the charging of public transport (buses and taxis) is possible at the stops when passengers board and alight [171][181][182].

3.3. Battery Swapping

The battery swapping approach is one of the most time-efficient and hassle-free charging methods. In this method, the EV replaces the drained battery with a completely charged battery at a battery swapping station (BSS). Then, the BSS transfers the empty battery to the battery charging station (BCS) to recharge it. After the complete charge, the BCS transfers it back to the BSS for exchange in EVs. To complete the BSS process, a distribution transformer, AC/DC converters, battery chargers, vehicle batteries, robotic arms, charging racks, a maintenance system, a control system, and other types of equipment are required. One major advantage is that the battery swapping stations may execute bulk bidirectional power transfer with the grid. During peak demand, the fully charged batteries can inject electricity into the grid, while charging occurs during off-peak hours [170].

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