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Electric vehicles: a review of their components and technologies

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ABSTRACT

The number of electrical vehicles (EVs) on the road has increased in recent years, including battery-electric vehicles (BEV), hybrid-electric vehicles (HEV), plug-in hybrid-electric vehicles (PHEVs), and fuel-cell electric vehicles (FCEV). This mode of transportation is expected to eventually replace internal combustion engine (ICE) vehicles, based on current trends. Each key EV component integrates several technologies that are either currently in use or have the potential to become prominent in the future. Environmental, power systems, and other industries may be adversely affected by electric vehicles (EVs). With sufficient EV penetration, the current power system could be subjected to severe instabilities; nevertheless, with proper management and coordination, EVs can significantly contribute to the success of the smart grid concept. Moreover, EVs have the potential to significantly cut transportation-related emissions of greenhouse gases. However, there are still considerable barriers that EVs must overcome before they can completely replace ICEs. The purpose of this study is to review all the relevant information available on EV architectures, battery energy sources, charging processes, and control approaches. Its goal is to provide a comprehensive overview of current EV technology.

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1. INTRODUCTION

Recently, there are increase in the demand of electric vehicles (EV), which is due to a number of factors. The most prominent role is to lower the greenhouse gas (GHG) emission. In 2009, it has been realized that; transportation accounted 25% of all GHG emissions from energy-related industries [1]. As EVs become more widely used in the transportation sector, this figure is expected to fall; although this is not the only reason for reviving this century-old and once-dead idea as a financially viable and readily available product. Conventional autos require a lot of gas money, but a quiet, easy-to-use electric vehicle (EV) does not. It is quite beneficial as a form of urban transportation. In idle mode, it uses no stored energy or emits any emissions, it can start and stop quickly, and offers the full torque from the start. It also doesn't require gas station excursions. It does not add to any of the haze that contributes to the city's highly filthy air. It's ideal for motorsports because of the instant torque. Because of its low infrared signature and low noise level, it is also beneficial in military applications. The power sector is undergoing a transition, with renewable energy sources gaining traction. Also being created is the next generation electrical grid, which is referred to as the "smart grid." EVs are seen as a key component of this new power system, which includes renewable energy sources and improved grid systems [2]–[4]. All of this has rekindled interest in and development of this mode of transportation.

Using electric motors (EMs) in vehicles was first thought of soon after the motor was invented. In the late 1890s, 28% of all vehicles consisted of EVs, and they were often preferred over conventional internal combustion engine ICE vehicles [1]. However, with meager oil prices, ICE vehicles soon gained colossal momentum, conquering the market, and becoming much more advanced. Though EVs were forgotten, a chance for resurrection appeared: in 1996, General Motors launched a concept named EV1. Soon after, other leading car brands launched their own EVs, including Ford, Toyota, and Honda. Toyota's Prius was the first commercially successful HEV. It was released in Japan in 1997 [1]. Today, these EVs have almost completely disappeared, except for Toyota Prius, which continues to go strong in an evolved form. Currently, Chevrolet Volt, Nissan Leaf, and Tesla Model S are the most widely used EV on the market. BYD Auto has a stranglehold on the Chinese market.

EVs may be thought of as a collection of interconnected subsystems that work via a variety of technologies. Although their combined work is necessary for an EV to use, these parts have varying interactions [5]. EVs can be built with quite a few configurations and options. Section 2 will discuss the general classification for EVs, and section 3 will describe the various configurations. EVs store their power as different types of energy. Batteries are used the most, though some upcoming potential energy storage systems (ESS) include ultracapacitors, flywheels, and fuel cells. Part 4 is dedicated to these energy sources. These vehicles can be charged at different voltages and configurations, discussed in section 5. The controlling algorithms also play a crucial part in EVs, and they will be discussed in section 6. Finally, part 7 will present the outcomes of this paper. The above topics have been discussed before in the relevant literature from different aspects. This study attempts to summarize relevant knowledge and illustrate the system's current state-of-the-art, while also investigating the benefits and drawbacks of competing technologies and their potential for future EVs.

2. TYPES OF EVS

The primary type of EV can run solely on electric propulsion, using only batteries as the energy source. Alternately, they may collaborate with an ICE agent. However, they can utilize alternative energy sources. These are known as hybrid EVs (HEVs). Technical committee 69 electric road vehicles (ERV) of the International Electrotechnical Commission defines a HEV as a vehicle with numerous types of energy sources, storage, or converters, at least one of which is electrical energy [6]. This definition allows many combinations for HEVs. Hence, both experts and the general population have had specific names for each type of combination: vehicles with a battery and a capacitor are called ultra-capacitor (UC) assisted EVs. Those with a battery and a fuel cell are called FCEVs [2], [3], [6]. Based on these distinctions, EVs are categorized into four groups.

2.1. Battery-electric vehicle

BEVs deliver power to the drivetrain exclusively via batteries, relying completely on stored energy. Therefore, range is dependent on battery capacity. Normal range per charge is 100-250 kilometers [7]. In fact, various variables including as driving style, road conditions, climate, vehicle layouts, battery type, and vehicle age have historically been implicated. Once the energy is gone, charging the battery can take up to 36 hours [8], [9], which is significantly longer than refueling a normal ICE car. There are various types that require far less time, however none can compare to refueling a vehicle.

BEVs offer certain advantages: they have simple construction, easy to operate, and are convenient. They do not produce GHGs and are noiseless, and beneficial for the environment. Electric propulsion can give high torques instantly, even at low speeds. Considering these advantages and the limited range, BEVs are perfect for urban transportation. Currently, Nissan Leaf and Tesla Model S are high-selling BEVs, and some Chinese vehicles such as BYD. Figure 1 shows the configuration of BEVs: batteries power the EMs via a power converter circuit, and the engines run the wheels.

2.2. Hybrid-electric vehicle

HEVs are propelled by a combination of an ICE and an electrical power train (PT). This combination can be in different forms, which will be discussed hereafter. HEVs use the electric propulsion system in case of low power demand. This is a great advantage for such conditions as urban transportation, reducing fuel consumption when idling (e.g., during a traffic jam) and reducing GHG emissions. The vehicle turns to the ICE if a higher speed is required. These two drive trains can also collaborate for improved performance. Turbocharged cars like the Acura NSX extensively use hybrid power systems to reduce turbo lag. This set-up bridges the gap between gear changes and enhances acceleration, resulting in improved performance. The batteries can be charged using either the ICE or regenerative braking. Consequently, HEVs are ICE-powered automobiles with an electrical propulsion system for improved fuel economy. Automobile manufacturers have broadly authorized HEV layouts for these benefits. Figure 2 depicts the energy fluxes of a fundamental HEV. Figures 2(a) and 2(b), show that during vehicle beginning, the ICE may employ the motor as a generator to produce and store electricity in the battery. Since both the ICE and the electric motor (EM) operate the PT during passing, it is required to enhance the vehicle's speed. To recharge the battery via regenerative braking, the PT uses the motor as a generator while in motion. To cruise, the ICE acts as a generator, generating electricity to power the motor and charging the batteries. Upon coming to a complete stop, the vehicle's electrical system comes to a complete halt. The energy management mechanisms of HEVs are illustrated in Figure 3. Based on driver inputs, vehicle speed, battery state of charge (SOC), and fuel economy, it distributes power between ICE and EM.

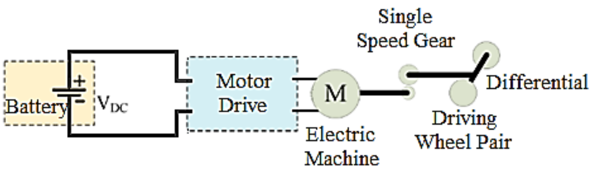

Figure 1. Structure of a BEV, the inverter changes DC electricity to AC power [7]

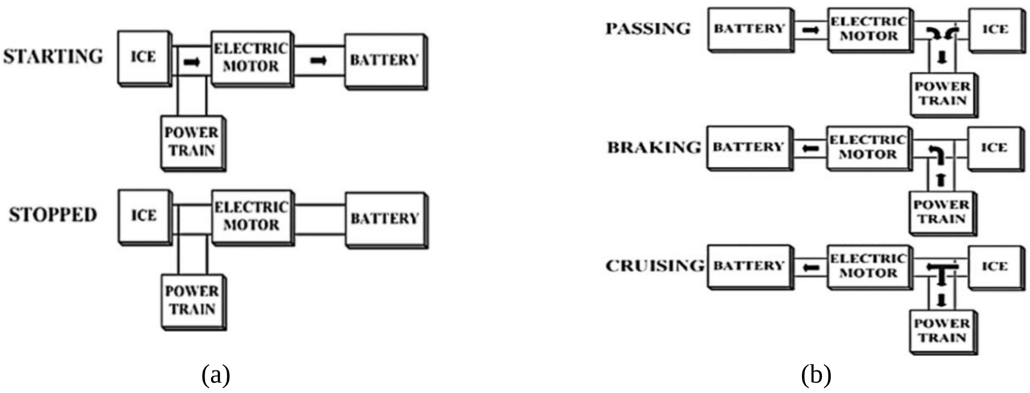

Figure 2. Power flow of HEVs (a) power flow during startup and stop and (b) power transfer during acceleration, braking, and cruising [10]

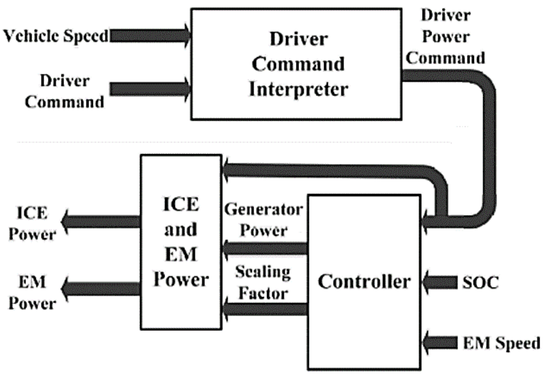

Figure 3. HEV's energy management system [10]

2.3. Plug-in hybrid-electric vehicle

The PHEV concept emerged to extend HEV all-electric range [11]–[16]. Again, the ICE and electrical PT are used, but with PHEVs, the electric motor is the main drive, necessitating a larger battery. PHEVs run on electricity and only use ICE when the batteries are low. The ICE boosts or charges up the battery, extending the vehicle's range. Unlike HEVs, PHEVs can charge directly from the grid and benefit from regenerative braking. Since, they can mostly run by electricity, PHEVs have less carbon footprint. They also consume less fuel, which reduces costs. Currently, Chevrolet Volt and Toyota Prius are two examples of hybrid vehicles that are now available on the market.

2.4. Fuel-cell electric vehicle

FCEV can also be called fuel cell vehicle, these EVs are run by fuel cells that produce electricity through chemical reactions [17]. FCEVs are used hydrogen fuel cell vehicles because hydrogen is the most fuel widely used in this industry. The hydrogen is carried in special high-pressure tanks. Oxygen is also required for power generation and is obtained from ambient air. The energy supplied by the fuel cells is transferred to the EM, which drives the wheels. The extra energy is stored in a battery or supercapacitor [2], [3], [18]–[20]. Batteries are used in several commercially marketed FCEVs, such as the Toyota Mirai and the Honda Clarity. FCEVs produce water during power generation, and the vehicle ejects this water from the tailpipes. Figure 4 shows the configuration of an FCEV. These vehicles have the advantage of producing their electricity without emitting carbon compared to any other type of EV. Besides, refilling an FCEV takes no more time than filling a conventional vehicle at a gas pump. So, these vehicles may be recommended much more widely soon [2], [3], [6], [21]. However, the shortage of hydrogen fuel stations is a key obstacle to the widespread use of this technology. However, even a few years ago, charging stations for BEVs or plug-in hybrids were not commonplace. The U.S department of energy (DOE) highlights another drawback: fuel cells cost over $200/kW, far more than an ICE, which costs less than $50/kW [22], [23]. Another concern is safety regarding flammable hydrogen that could potentially leak out of the tanks. If all these obstacles were eliminated, FCEVs would represent the future of vehicle transportation. Because, considering their advantages, FCEVs appear to be better than BEVs in numerous aspects [24]. Figure 5 illustrates this comparison. As a result, the figure compares two ranges (320 versus 480 km), taking into consideration a variety of criteria such as weight, beginning GHG emissions, and necessary storage volume, in addition to other parameters. The horizontal axis stands for the attribute ratio of BEV to FCEV. All these features are indicated so that higher ratios mean a disadvantage. Based on the figure, BEVs are only better in fuel cost per kilometer and require wind energy. The former is still a significant drawback for FCEVs, as there has yet to be a way for producing hydrogen in an environment-friendly, cheap, and sustainable way. Also, the refueling infrastructure seems to fall behind. Still, these problems may all be solved soon. Table 1 presents a comparison between various types of vehicles for driving components, energy sources, and limitations.

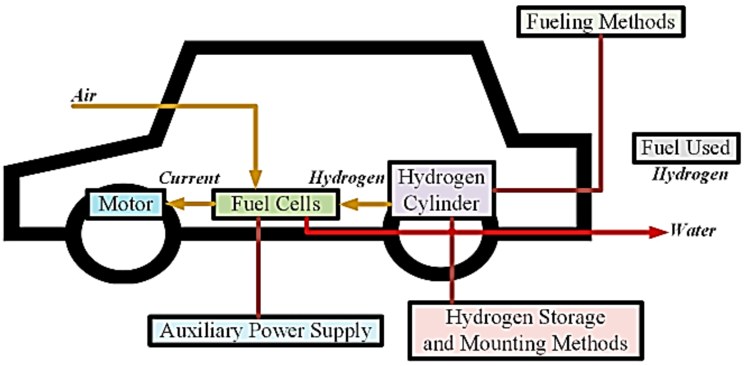

Figure 4. FCEV's configuration

Table 1. Comparative analysis of several vehicle types [6]

Type	Driving component	Energy Source	Features	Drawbacks
BEV	EM	Battery, and UC	There are no emissions; the system is not reliant on oil; the range is mostly determined by the battery type, and the system is commercially available.	The capacity of the battery; range; recharging time; the accessibility of charging stations; and elevated pricing.
HEV	EM, and ICE	Battery, UC, and ICE	Low emissions; long range; complicated construction with electrical and mechanical driving trains; and commercially available.	Controlling power sources and optimizing the size of batteries and engines.
FCEV	EM	Fuel cell (FC)	Little emissions; high efficiency; independence from electric power; and commercial availability.	Affordability of a fuel cell; a feasible method of producing fuel; and the availability of fueling stations.

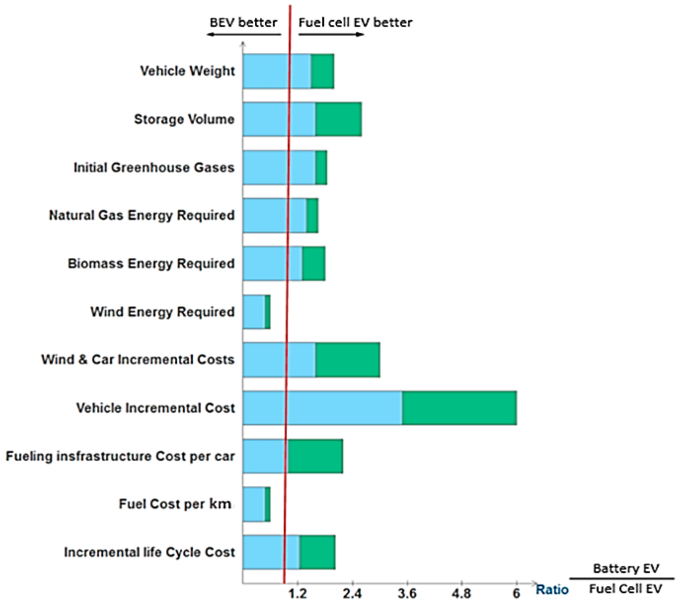

Figure 5. Advanced characteristics ratio between BEV and FCEV for 320-km (blue) versus 480-km (green), presuming a standard grid mix in the US from 2010 to 2020, and that all hydrogen is delivered from natural gas (amounts above 1 indicate an advantage for FCEVs over BEVs) [24]

3. EV CONFIGURATIONS

EV are quite flexible because they do not have the intricate mechanical arrangements needed to run a conventional vehicle [6]. EVs have only one moving part, which is the motor. The power supply that the motor needs can be from a wide range of sources. The motor and the power supply can be placed in different vehicle parts if connected through electrical wires. Besides, as mentioned, EVs can either run exclusively on electricity or use both an EM and an ICE in conjunction. This flexibility in the configuration of ECs has paved the way for various configurations according to the type of vehicle.

In general, EVs are considered systems that incorporate three subsystems: an energy source, the propulsion subsystem, and the auxiliary subsystem [6]. The energy source includes the energy supply, the charging system, the energy management system, and the storage system. EM, power converters, controllers, transmissions, and driving wheels constitute the propulsion system. The auxiliary subsystem is made up of three components: an auxiliary power source, a temperature control system, and a power steering unit. Figure 6 gives a general look at these subsystems.

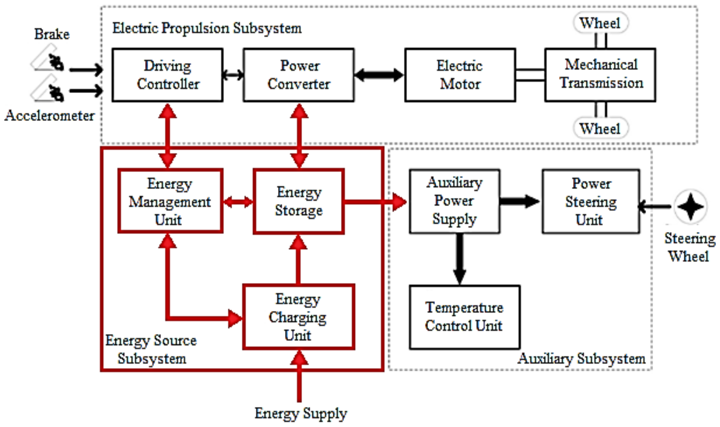

Figure 6. Subsystems of EVs [6]

The arrows point to the flow of these components. Some features like regenerative braking can create a backward power flow. Majority of electric vehicle batteries and ultracapacitors/flywheels

(UCs/FWs) are frequently compatible with these energy regeneration strategies [6]. In-wheel motor arrangements eliminate the requirement for a central motor, transmission, differential, universal joints, and driveshaft, effectively lowering the drive train's weight [25]. Additional features include improved steering and a greater capacity for storing batteries, fuel cells, or luggage. Although, this configuration requires wires that connect the motor to the power and control systems, which may get damaged by the harsh environment, vibration, or acceleration. wireless in-wheel motor system (W-IWM), has been suggested by [26] and has been tested in an experimental car using this architecture. They replaced the wires with two coils that could transfer power between them. Figure 7 shows an in-wheel motor configuration. Figure 8 shows the efficiency of such systems at different stages. For such conditions, the problems associated with misalignments could be overcome through magnetic resonance coupling, which provides wireless power transfer (WPT) [27]. Secondary inverter power can also be applied to a controller that changes with the voltage on the secondary side [28]. When using 2 kW of power, WPT may achieve a transmission efficiency of 90 percent in both directions because to magnetic resonance coupling [29]. As a result, W-IWM is regenerative braking compatible.

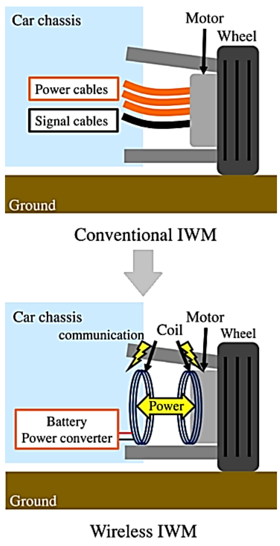

Figure 7. Conventional and wireless IWM [26]

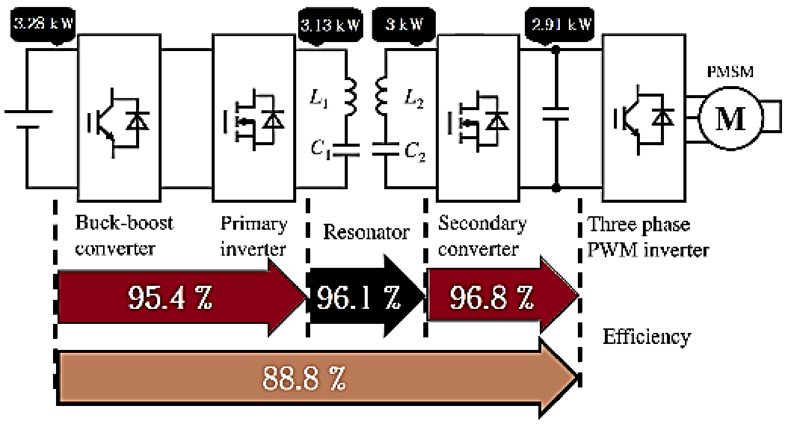

Figure 8. W-IWM configuration demonstrating performance at 100 percent torque reference [26]

3.1. HEV configurations

HEVs have both an ICE and an electric propulsion system. Different configurations are categorized into four groups based on how they are set up [6].

- Series hybrid configuration
- Parallel-hybrid configuration
- Series-parallel-hybrid configuration
- Complex hybrid configuration

3.1.1. Series hybrid configuration

This is the most straightforward configuration for an HEV because the wheels are only connected to the motor. The engine powers a generator that generates electricity. Simply, this may be thought of as an EV with an ICE generator [6]. Figure 9 shows the drive train of a series hybrid configuration. The pros and cons of this configuration are shown in Table 2.

3.1.2. Parallel-hybrid configuration

This arrangement joins the EM and the ICE to the wheels in tandem. Any of them can deliver the power. It is therefore an ICE-powered vehicle with electric aid [6]. In this type of vehicle, the EM can charge the energy storage by the ICE or via regenerative braking. Figure 10 shows the parallel-hybrid drive train configuration. Table 3 displays the pros and cons of the parallel-hybrid structure. A comparison between series hybrid and parallel hybrid systems is given in Table 4.

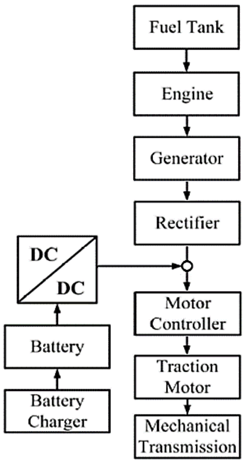

Figure 9. The series hybrid system's drive train [30]

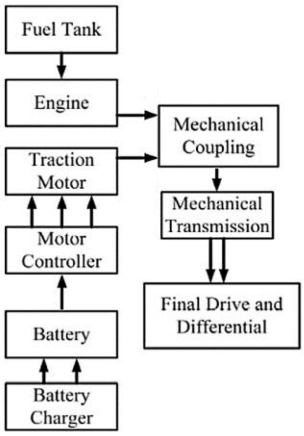

Figure 10. The PHEV system's drive train [30]

Table 2. The pro and cons of a series hybrid EV (SHEV) configuration [10]

No	Pros	Cons
1	Possibilities to build a more efficient and modular power plant.	It is necessary to have a large traction drive system, as well as adequate algorithmic implementation
2	The driveline has been optimized	There are several energy conversions stages
3	There is the chance of a quick "black box" service exchange	
4	It has a long-life and well-stablished technology	
5	It can achieve zero emissions	

Table 3. Shows the pros and cons of a PHEV configuration [30]

No	Pros	Cons
1	Ability to achieve zero emissions	Expensive
2	Economic benefit, and	Complicated control, and
3	Increased adaptability	Requires a high voltage to function properly

Table 4. Comparison of SHEV and PHEV structures [10]

Parameters	PHEV	SHEV
Voltage (V)	14, 42, 144, 300	216, 274, 300, 350, 550, 900
Power (kW)	3.0 – 40.0	> 50.0
Relative gain in fuel economy (%)	5.0 – 40.0	> 75.0

3.1.3. Series-parallel-hybrid configuration

The series-parallel-hybrid EV system (SPHEV) combines the series-hybrid and the parallel hybrid configurations. This approach claims to provide the benefits of both, but it is more difficult and costly. The complications are somewhat due to a planetary gear unit [30]. Figure 11 illustrates the configuration of a planetary gear unit. Here, the sun gear is coupled to the generator, the ring gear is coupled to the output shaft, the planetary carrier is coupled to the internal combustion engine (ICE), and the pinion gears maintain the connection throughout the entire system. The trans-motor is a simpler version in which the engine is connected to the stator and the rotor is connected to the drive train wheel through gears [30]. The configuration of a series-parallel-hybrid drive train with a planetary gear unit is depicted in Figure 12. Figure 13 depicts the replacement trans-motor system.

3.1.4. Complex hybrid configuration

Unlike the series-parallel system, the complex hybrid system allows bidirectional power flow. The current terminologies denote this system as a series-parallel configuration. This system suffers from high costs and complexity [6]. In complex hybrid systems, continuously variable transmission (CVT) can facilitate power splitting or source selection for wheel propulsion. Using electric arrangements for these processes is known as an e-CVT, which Toyota Motor Co. introduced. CVTs can be utilized in a variety of ways, including hydraulic CVTs, mechanical CVTs, hydromechanical CVTs, and electromechanical CVTs; they also use one of two methods for power splitting: input splitting and complicated splitting [30]. At the transmission input, a power-splitting mechanism is utilized for input splitting. Certain Toyota and Ford cars make use of this mechanism [32]. Different manufacturers have different modes for both splitting mechanisms [32]. Figures 14 and 15 show some of these mechanisms. These kinds of power splitting HEVs include an engine, wheels, two electric machines, and a planetary gear (PG), with twenty-four ways to combine these. Indeed, using other PGs would result in over one thousand ways. One optimal design has been proposed, incorporating a single PG [31]. The rear wheels in four-wheel drive (4WD) systems do not require a power transfer system because they have their own motor. Thus, they can implement a two-motor hybrid configuration, providing energy reproduction via regenerative braking [33]. Figure 16 shows a 4WD HEV structure. There are also stability enhancement schemes for these configurations by controlling the rear motor [33].

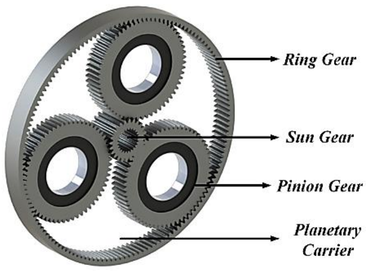

Figure 11. Planetary gear unit [31]

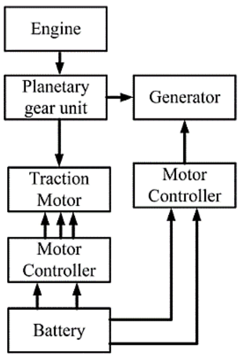

Figure 12. Drive train of a SPHEV system with a planetary gear unit [30]

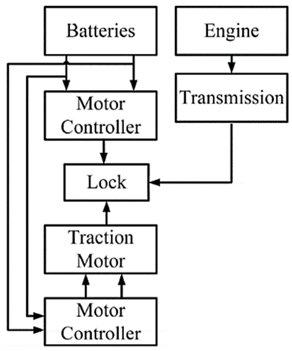

Figure 13. Drive train of a SPHEV system with trans-motor [30]

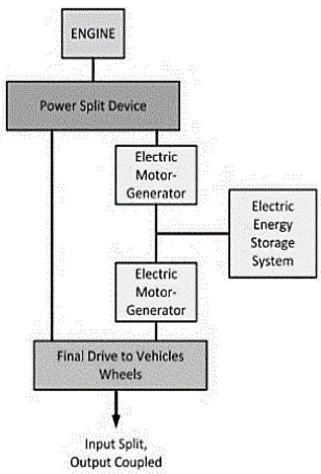

Figure 14. Input split e-CVT system [32]

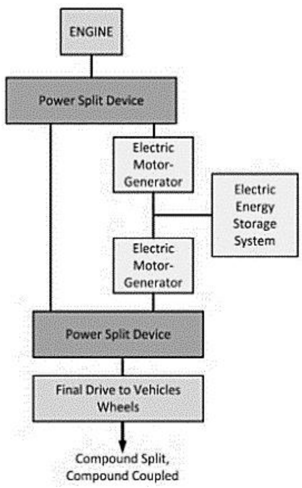

Figure 15. Compound split e-CVT system [32]

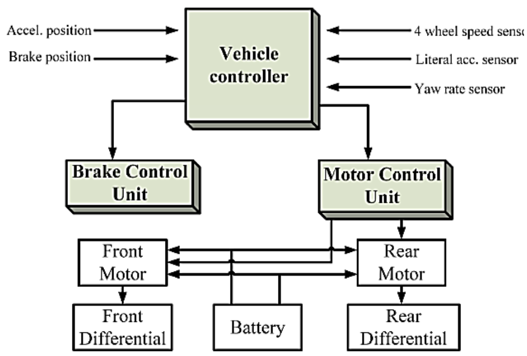

Figure 16. Structure of a 4WD HEV [32]

4. ENERGY SOURCES

EVs can have various sources of energy, with certain criteria [6]. Among these, the two most important are energy density and power density [30]. Indeed, the perfect energy source would require other features as well, including fast charging, long service and cycle life, less cost, and easy maintenance. High specific energy is needed for long-range driving, while high specific power improves acceleration for short-range driving. The ideal source requires diverse features, so lots of energy storage systems (ESS) are discussed, with different combinations to meet various needs [6].

4.1. Battery

For the longest time, batteries were the main energy source for EVs. Indeed, eventually, other technologies were employed. The prominent types of batteries include lead-acid, Ni-Cd, Ni-Zn, Ni-MH, Li-polymer, and Li-ion batteries [34], [35]. The advantages of graphene batteries for EVs, as well as their structural models and implementation [34]. Each type of battery has its own pros and cons. Table 5 shows the key features of some battery types [36]–[46]. Table 6 gives a cross-comparison for common batteries according to their advantages over one another.

Table 5. Typical battery types, their fundamental components, benefits, and drawbacks [36]–[46]

Battery Type	Components	Features	Drawbacks
Lead-acid	– The negative electrode is a pliable lead (NE). – Positive electrode: Lead oxidation (PE). – Electrolyte: Distilled sulfuric acid	– Affordability in terms of manufacturing volume. – Relatively cheap cost. – Mature technology that has been utilized for more than fifty years.	– It is limited to a maximum of 20% of its capacity. – If utilized at a high rate of discharge, it has a short lifespan. – Has a low density of energy and power. – A heavier weight.
Nickel-Metal Hydride (NiMH)	– Alloy of nickel and titanium with vanadium and other metals to form NE. – Nickel hydroxide as a PE. – Alkaline solution as an electrolyte.	– Double the energy density of lead-acid batteries. – Environmentally friendly. – Recyclable. – Operational safety at high voltage. – Capable of storing volumetric power and energy. – Longer cycle life. – Wider operating temperature range. – Resistant to overcharging and over-discharging.	– On high load currents, the battery's lifetime is reduced to roughly 200-300 cycles. – Due to the memory effect, useful power has been reduced.
Lithium-ion	– NE is made of oxidized cobalt; PE is made of carbon. – Lithium salt solution in an organic solvent as an electrolyte.	– NiMH has a doubled energy density. – High-temperature performance. – Recyclable. – Memory effect is minimal. – Extremely high specific power. – Superior specific energy – The battery has a lifespan of roughly 1000 cycles.	– Expensive. – Takes long time for recharge, albeit it is faster than many other battery types.
Nickel-Zinc (Ni-Zn)	– Zinc as a NE. – Nickel oxyhydroxide as a PE.	– High density of energy and power. – Low-priced materials are utilized. – Capability with extended duty cycles – Environmentally sustainable. – It may be used in temperatures ranging from -10 to 50 degrees Celsius.	– Dendrite development is rapid, preventing usage in cars.
Nickel-Cadmium (Ni-Cd)	– Cadmium as a NE. – Nickel hydroxide as a PE.	– Long service life. – Capable of discharging filly without causing damage. – Recyclable	– Cadmium can pollute the environment if it is not appropriately eliminated. – Expensive for vehicular use.

Figure 17 depicts the multiple battery cells used in EV battery packs. The heat produced by the battery cells is dissipated using cooling tubes. Preventing premature end-of-life (EOL) [47] necessitates that these cells have the same SOC for equal degradation rate and capacity. This can be accomplished with a power electronic control device, also known as a cell voltage equalizer, which ensures that each cell has the same SOC and voltage. These equalizers can have various types of constructions or operating principles. Resistive equalizers burn up the extra power in cells, while capacitive equalizers switch off capacitors to transfer energy between cells with different levels of energy. Another type is inductive capacitors, which again transfer energy between cells with different levels of energy using inductors [47]–[54]. Table 7 shows the advantages and disadvantages of each type. Figure 18(a) shows the configuration of the resistive equalizer, while Figure 18(b) shows a capacitive one. Figures 19(a) and 19(b) show the schematic diagrams for both transformer-based inductive and several transformers-based Inductive. Table 8 shows a comparison between the types of equalizers.

Table 6. Comparative analysis of various types of batteries [46]

Advantages Over	Lead-acid	Ni-Cd	NiMH	Li-Ion Conventional	Li-Ion Polymer
Lead-acid		– Volumetric energy density (VED) – Gravimetric energy density (GED) – Range of operating temperature (ROT) – Rate of self-discharge (RSD)	– VED – GED – RSD	– VED – GED – RSD	– VED – GED – RSD – Design features (DF)
Ni-Cd	– Output voltage (Vo) – Cost – Higher cyclability (HC)	NA	– VED – GED	– VED – GED – RSD – Vo	– VED – GED – RSD – DF
NiMH	– Vo – Cost – HC	– ROT – Cost – HC – RSD	NA	– VED – GED – ROT	– VED – GED – RSD – DF
Li-ion (Conventional)	– Cost – HC – Safety – Re-cyclability	– ROT – Cost – Safety – HC – Re-cyclability	– Cost – Safety – RSD – Re-cyclability	NA	– VED – GED (potential) – Cost – DF – Safety
Li-ion (Polymer)	– Cost – HC	– ROT – Cost – HC	– VED – Cost – HC	– ROT – HC	NA
Absolute advantages	– Cost – HC	– ROT – Cost	– VED	– VED – GED – ROT – RSD – Vo	– VED – GED – ROT – RSD – Vo – DF

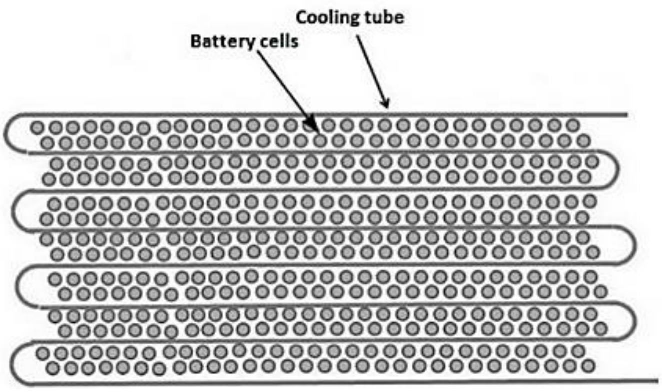

Figure 17. A battery pack's cell configuration

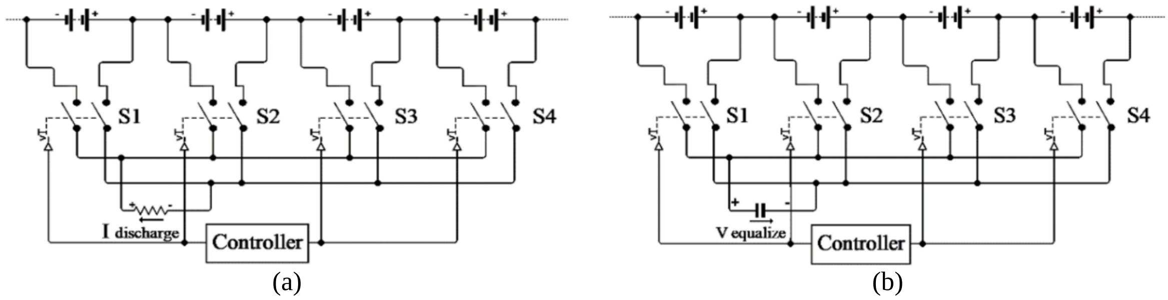

Figure 18. Equalizer structures (a) resistive equalizer and (b) capacitive equalizer [47]

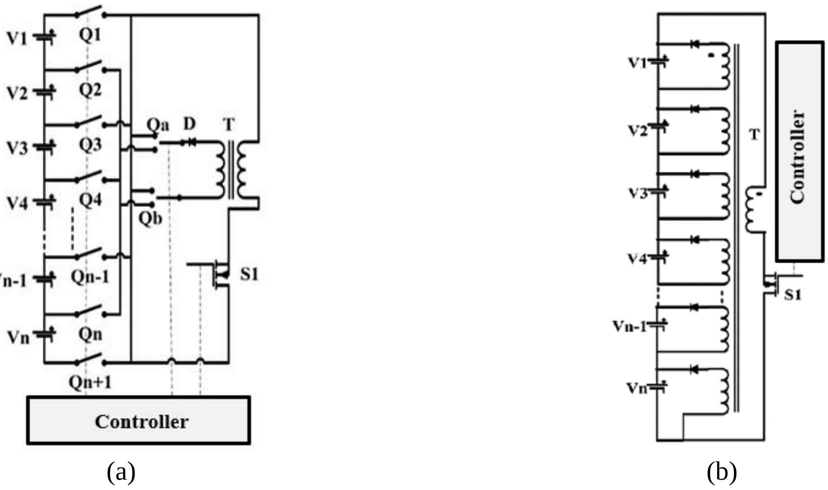

Figure 19. Equalizer structures (a) transformer-based inductive and (b) several transformers-based inductive [49]

Table 7. The benefits and drawbacks of different types of equalizers [47]–[54]

Equalizer Type	Benefits	Drawbacks
Resistive	– Lowest cost, most extensively used for laptop batteries	– Low equalizing current. – Only suitable during the last phases of charge and flotation. – Approximately 0% efficient. – In EV applications, all equalizing current is converted to heat, hence it is not recommended.
Capacitive	– Increased current capability over resistive equalizers. – Elimination of control concerns. – Ease of implementation	– Inability to manage inrush current. – Possibility of dangerous current ripples flowing in the event of large cell voltage discrepancies – Is unable to supply the required voltage differential for equalization of the SOC.
Transformer-based Inductive	– All cells get the right amount of electricity without any extra control or loss of theory.	– A complicated transformer with a lot of secondaries that is hard to make in large quantities. – Not suitable for EV batteries. – Unable to deal with complicated control systems.
Several transformers-based Inductive	– Individual transformers are employed, making mass manufacture easy.	– Unbalanced voltage and current are still difficult to avoid using commercial inductors.

Table 8. Comparison of equalizers; The advantage levels are denoted by the letters (A1 to A3), with A3 being the highest level, and the disadvantage levels are denoted by the letters (D1 to D3) with D3 being the worst level [47]

Type of Equalizer	Current of Equalizer	Distribution Current	Control Current	Ripple Current	Manufacture	Cost	Control
Resistive	D2	NA	A1	A3	A3	A3	A3
Capacitive	D1	A1	D2	D2	A2	A2	A2
Basic Inductive	A2	A1	A1	A2	A1	D1	D1
Cuk	A2	A1	A1	A3	D1	D2	D1
Transformer	A1	A3	D2	D2	D2	D2	A2

4.2. Ultracapacitors (UCs)

Two electrodes are separated by an ion-rich liquid dielectric in UCs. When a potential is supplied, the positive electrode attracts negative ions and the negative electrode attracts positive ions. This way, the charges are physically stored on electrodes, providing a significantly higher power density. UCs often have a long cycle life because there is no chemical reaction on the electrodes. Although, the lack of a chemical reaction means lower energy density [36]. They also have low internal resistance, meaning high efficiency. Nevertheless, if they are charged at exceptionally low SOC, this results in a high output current [55], [56]. Because the terminal voltage of UCs is precisely proportional to the SOC, they can operate across their voltage range [36]. Figure 20 shows the basic construction of a UC cell. Since EVs go through a lot of start/stop conditions, the rate of battery discharge is extremely unpredictable. Despite the low power need in general, accelerating or hill-climbing will require high power rapidly [6], [36]. The power that a high-performance electric vehicle needs is about sixteen times the normal power it requires [6]. UCs stand out in this context because they can deliver tremendous power for short periods of time. They can also swiftly capture regenerative braking energy [2], [36]. Using the battery and UC depicted in Figure 21 as a system, these flaws might be corrected, resulting in a more reliable and efficient power source.

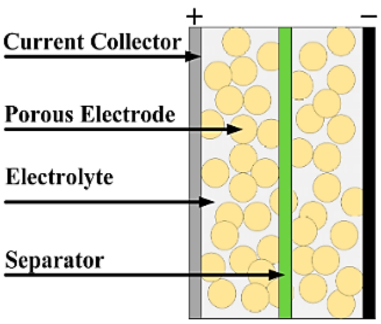

Figure 20. UC cell [57]

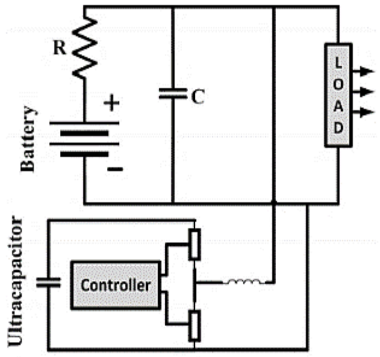

Figure 21. Configuration of battery and UC [58]

5. CHARGING SYSTEMS

EVs can be charged with DC or AC systems, with different configurations that are often called levels. These levels determine the time required for a full charge. Chargers also need to fulfill with certain safety standards [47].

5.1. AC charging

AC charging systems consist of an AC-DC converter that converts the AC feed to DC for charging. The society of automotive engineers (SAE) has determined EV AC charging power levels, these are classified as follows:

- Level 1: 12 A or 16 A current based on circuit ratings, with a maximum voltage of 120 V. Level 1 charging takes up to 12.5 hours for a small EV, so it can be used to charge overnight [7], [47], [59].
- Level 2: This is the most common method for EVs; it requires a direct connection to the grid via an Electric Vehicle Service Equipment (EVSE) with an on-board charger. Maximum voltage is 240 V, maximum current is 60 A, and maximum power is 14.4 kW [47], [59].
- Level 3: This system consists of a permanent, hardwired supply for charging electric vehicles that provides more than 14.4 kW of power. Fast chargers, for instance, are capable of recharging EV batteries in 30 minutes [47], [59]. Table 9 shows the AC charging characteristics as defined by the SAE.

Table 9. SAE AC charging levels [7], [45], [47], [59], [60]

AC Charging level	Supply Voltage (V)	Maximum Current (A)	Circuit Breaker Rating (A)	Output Power Level (kW)
Level 1	120.0 V, single-phase (1-ph)	12.0	15.0	1.08
	120.0 V, 1-ph	16.0	20.0	1.44
Level 2	208.0 to 240.0 V, 1-ph	16.0	20.0	3.3
	208.0 to 240.0 V, 1-ph	32.0	40.0	6.6
	208.0 to 240.0 V, 1-ph	≤ 80.0	Per NEC 635	≤ 14.4
Level 3	208.0 – 480.0 – 600.0 V	150.0 – 400.0	150.0	3.0

5.2. DC charging

DC systems can be mounted at a garage or a charging station. These systems require dedicated wiring and installations, providing more power and faster charge than AC systems. The output is DC, so vehicles with different battery packs require changing the voltage, which modern stations can do automatically [47]. DC systems are classified based on the power levels they supply to the battery [47]:

- Level 1: 450.0 V and 80.0 A, up to 36.0 kW
- Level 2: 450.0 V and 200.0 A, up to 90.0 kW
- Level 3: 600.0 V and 400.0 A, up to 240.0 kW

5.3. Wireless charging

Likewise known as wireless power transfer (WPT), wireless charging has attracted great interest for its convenience [4]. This system requires no plugs or cables and offers a lower risk of sparks in wet environments [4]. Many R&D centers, government organizations, and universities are currently running WPT research. The main suppliers are Witricity, Evatran, LG, Momentum Dynamics, HaloIPT, Conductix-and Wampfler [27]. However, WPT is not yet available for commercial EVs due to some safety concerns. Different organizations in different countries have reported various specifications for standardization: Canadian Safety Code 6 in Canada [61], IEEE C95.1 in the USA [62], ICNIRP in Europe [63], and ARPANSA in Australia [64]. Although, some other technologies are considered to provide the facilities of WPT, with different operating frequencies, efficiency, electromagnetic interference (EMI), etc.

Inductive power transfer (IPT) has been utilized for a while; however it is a contactless technology, not a wireless one. Capacitive power transfer (CPT) provides reduced prices and a smaller size at lower power levels but is incompatible with electric vehicle (EV) charging. Permanent magnet coupling power transfer (PMPT) lacks efficiency and several other problems. Among these alternative technologies, resonant inductive power transfer (RIPT) and on-line inductive power transfer appear to be the most promising (OLPT). However, because of their infrastructural needs, many systems may not be practical. Resonant antennae power transfer (RAPT) is conceptually like RIPT, but its resonant frequency is in the MHz region, which can be harmful to people. This can be lessened or eliminated by shielding; however range and performance will likely suffer, with the added difficulty of generating such high frequencies [65]. Table 10 compares the performance, complexity, cost, power levels, and volume of wireless charging systems. Due of various health risks, misalignment concerns, and range issues, it is improbable that wireless charging will be available in personal vehicles anytime soon. Another idea has been to make roads with embedded WPT systems, charging passing vehicles, although such constructions would suffer heavily in terms of costs [27]. Currently, the only wireless systems available are still in trial. The potential advantages of wireless charging are non-negligible, so this system can yet be integrated in EVs.

Current EV systems use onboard AC systems for low power levels and DC systems for higher power levels. The combined charging system (CCS), the CHArge de Move (CHAdeMO), and the Supercharger are the three current standards for DC systems [18] (for Tesla vehicles). CCS provides 50 kW of power, CHAdeMO provides the same, while Supercharger provides 120 kW of power [66], [67]. CCS and CHAdeMO are also capable of providing fast or dynamic charging and vehicle-to-infrastructure (V2X) facilities [8], [68]. Currently, the majority of EV charging stations offer level 2 AC charging. A Level 3 DC charging network is also available for Tesla vehicles. The majority of stations offer CHAdeMO or CCS by default, thus the car must be compatible with the applicable setup. Japanese manufacturers choose CHAdeMO, but European and American manufacturers prefer CCS. The literature [7] discusses the charging technologies currently utilized in EVs and the time required for a full charge.

Table 10. Comparison of wireless charging systems (WCS), low (L), medium (M) and high (H)

WCS	Performance			Cost	Volume/Size	Complexity	Power level
	Efficiency	EMI	Frequency kHz				
IPT	M	M	10 – 50	M	M	M	M/H
CPT	L	M	100 – 500	L	L	M	L
PMPT	L	H	100 – 500	H	H	H	M/L
RIPT	M	L	1000 – 20000	M	M	M	M/L
OLPT	M	M	10 – 50	H	H	M	H
RAPT	M	M	100 – 500	M	M	M	M/L

6. EV CONTROL SYSTEM

Control systems are essential for the effective operation of EVs and their systems. For EVs to travel smoothly, sophisticated control mechanisms are required. In addition, it is not simple to provide sufficient power when required, estimate the available energy from onboard sources, and optimize the use of this energy for maximum range. Another key factor is charging as quickly as possible without causing aburden on the grid. There are various algorithms to meet all these needs. Still, the EV culture keeps growing, creating a greater need for better algorithms.

Driving control systems assist drivers in maintaining the vehicles in control, particularly at high speeds or inproblematic circumstances like rain or snow. Some of the mature applications of driving control systems for conventional vehicles include cruise control, traction control, and different driving modes. Implementing these systems in EVs seems more efficient, since the driving forces that EVs require are easier to control, with less mechanical-electrical conversion. When operating a vehicle, a variety of forces act in a variety of directions. A driving control system must perceive these forces perfectly and maintain the desired stability by providing torque to the wheels. Figure 22 shows the forces in different directions, affecting the wheels of a car in a horizontal plane. Lf and Lr are the distances of the front and rear axles from the vehicle's center, while Tr is the distance between the wheels on a single axle [25]. Using a model with separate rear-wheel drive systems, [69] presented a control mechanism for maximum torque without slippage. The authors estimated velocity and wheel slide using a LuGre model of dynamic friction. This information was used by the control algorithm to establish the maximum permissible traction force on the road by regulating the torque of the rear motors. Kang *et al.* [70] utilized a model with two motors for the front and rear shafts and a three-part algorithm for the front and rear shafts for 4WD electric vehicles. This method improved the vehicle's lateral stability and mobility and decreased its tendency to roll over. This mechanism is depicted in Figure 23 on a car model. Driver inputs are considered, and the algorithm calculates, based on the selected control mode, which braking and motor actions will be executed [70].

Figure 24 shows this system, including the inputs, actuators, and controller levels. All-wheel-drive EVs now have access to a new stabilization technology form [25]. Figure 25 gives an illustration of this system. A steering assistance system with differential drive has been shown by [71]. Figure 26 shows this system’s structure. EVs with in-wheel drive can accomplish lateral stability by predicting the sideslip angle and measuring lateral tire forces with sensors [72]. The upper layer comprises the differential drive-assisted steering (DDAS) and direct yaw moment control subsystems. Inputs are processed by the traction control subsystem, while the lower layer carries out the control [71].

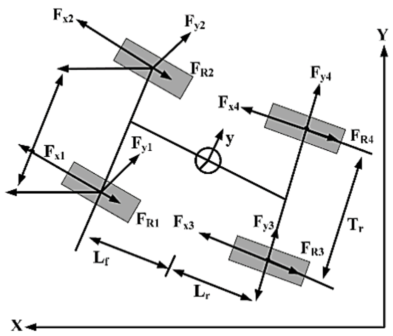

Figure 22. The forces on car wheels [25]

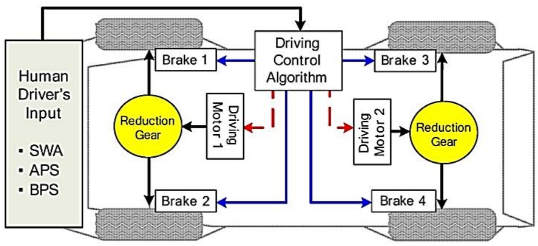

Figure 23. System components for four-wheeled electric vehicles [70]

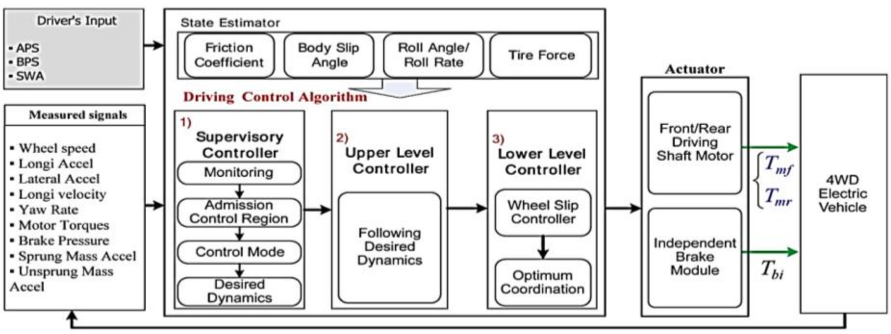

Figure 24. Operating principle of the control system uses driver commands and sensor measurements, driving the actuators in line with a three-level algorithm [70]

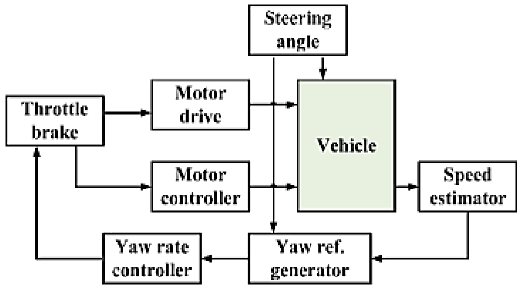

Figure 25. Operating principle of the vehicle stability system. the yaw reference generator uses a neural network [25]

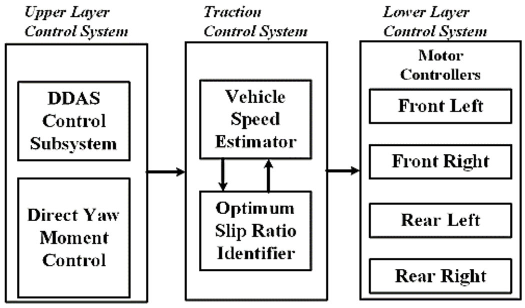

Figure 26. Independent torque control system [71]

Energy management in EVs is crucial for assessing the range and determining which driving style must be used. Multiple-energy-source vehicles, such as HEVs, require efficient energy management algorithms for optimal energy consumption. The SOC of lithium polymer batteries is determined using a particle filter and multi-model data fusion, according to [73]. This algorithm can produce findings in real-time, unaffected by measurement noise. Figure 27 illustrates the system's operating concept. In PHEVs for medium-sized vehicles, researchers [74] have examined methods for distributing the power demand between sources. This strategy incorporated multiple drive cycles as opposed to one, calculating the likelihood of battery depletion and considering the relative costs of fuel and electricity to optimize power management. A novel parallel hybrid vehicle with a hydraulic–electric configuration has been presented by [75] to solve the drawbacks of heavy hybrid cars that only use one energy source. Figure 28 shows the transition among operating modes for this vehicle. It can use one or both hydraulic and electric systems from startup to shut down. The algorithm that the authors prepared aims to adjust some key factors, with a logic threshold technique for optimum performance, stable SOC, and efficient fuel economy. Figure 29 gives the operating principle of this system. Using quadratic programming, [76] came up with an energy management algorithm that can keep the battery's current under control and help save fuel. Li *et al.* [77] have created a new quantity termed battery working state (BWS) using fuzzy logic. According to the results of their simulation, this strategy could maximize the engine's fuel economy while preventing excessive emissions. According to [78], dynamic programming (DP) and the pontryagin minimum principle (PMP) were evaluated for regulating energy in parallel HEVs with automatic manual transmission (AMT) and it was determined that DP-PMP was preferable despite giving comparable results. Bernard *et al.* [79] has presented a real-time control system for FCEVs that will cut hydrogen use. This technology involved the efficient distribution of electricity between the fuel cell assembly and the energy buffer (ultracapacitor/battery). This control system was developed using a non-causal optimization approach based on optimum control theory. The authors then developed the mechanism in a 600 W fuel cell arrangement. Geng *et al.* [80] developed an energy management system for a nonprofit plug-in hybrid vehicle (PHEV) (EMS). With the rising currents in EV penetration, the grid suffers from problems. Reducing the charging time and producing minimum pressure on the grid simultaneously has been hard to accomplish. Still, there is plenty of research on this subject, with numerous charging system algorithms for satisfactory charging.

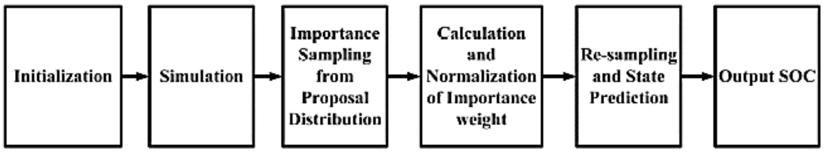

Figure 27. Algorithm for testing SOC performance [73]

In a charging station, the algorithm shown in Figure 30 developed by [81] enables intelligent charging for a fleet of plug-in hybrid electric vehicles (PHEVs). This technique employed distribution estimation (EDA). Considering variations in energy prices, EV owners' preferred time zones, and random EV plug-ins, [82] have developed a load control system. Paying attention to these criteria, the system used an optimization technique called the maximum sensitivities selection (MSS), charging EVs based on the priority time zones and maintaining grid criteria like voltage profile, generation limits, and losses. The authors simulated this system with an IEEE 23 kV distribution system. When they came up with an algorithm for managing energy in EV charging parks with renewable energy, [83] employed a fuzzy controller. This algorithm considered charging/discharging times, sharing power among EVs, and V2G services. The objective here was to reduce charging costs and impact on the grid at the same time. Figure 31 shows the flowchart of this system.

To address difficulties at the distribution level, [84] has proposed a charging technique consisting of two steps that shifts the loads on transformers. The first stage used PMP to derive the ideal power for all EVs based on the dynamic aggregator concept. The calculated power was distributed among the EVs in the second stage using fuzzy logic. According to the authors, the system is practicable for practical usage. Richardson *et al.* [85] employed linear programming to find out the greatest charging rate for electric cars and the best route to get power to them when they were looking for the best way to charge electric automobiles in a distribution network. This method can achieve significant EV penetration in residential power systems while requiring little to no upgrading. Algorithms to optimize revenues in a one-way voltage-to-grid (V2G) system have been developed by [86] employing an aggregator.

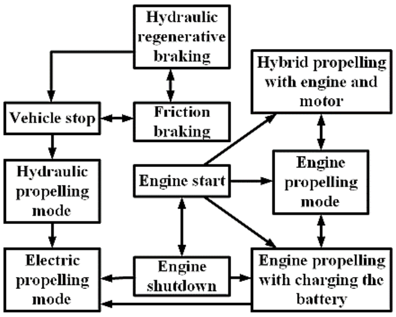

Figure 28. Block diagram for changeover between operational modes [75]

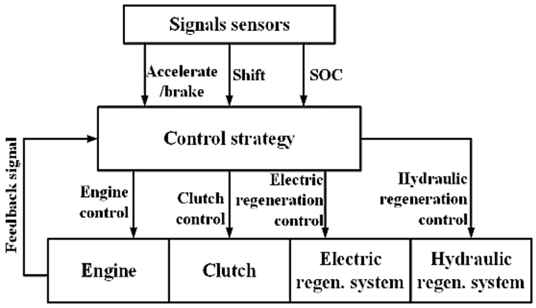

Figure 29. Control system operating concept of parallel hybrid vehicle with hydraulic–electric configuration [75]

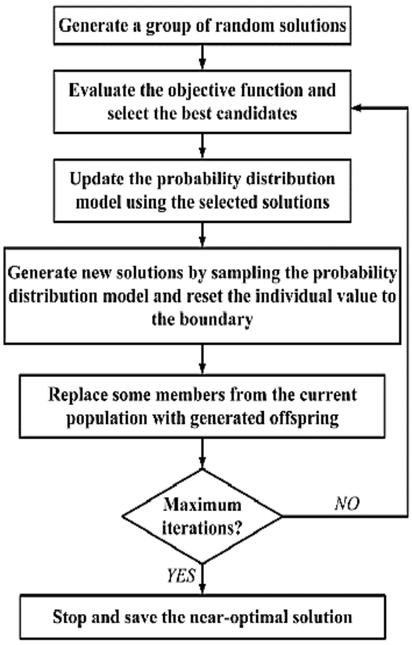

Figure 30. Intelligent charging algorithm proposed for a community charging station [81]

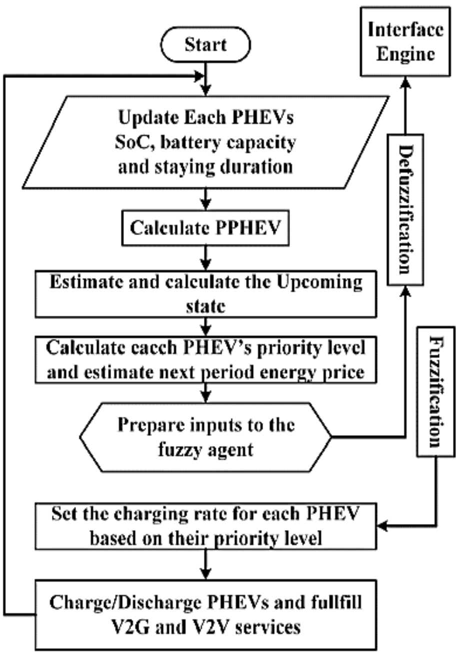

Figure 31. Management system's flowchart [83]

7. OUTCOMES

This paper has reviewed major technologies and future tendencies of different sectors, focusing on the crucial components of EVs. The following points summarize the key findings reached here:

- There are numerous varieties of electric vehicles, with BEVs and PHEVs being the most popular. The major prerequisite for FCEVs to become widespread is the development of low-cost fuel cells, which requires additional research. As important technologies, including as energy storage and charging systems, evolve, BEVs are also projected to dominate the market. FCEVs may potentially be favored by the military or as utility cars, but their widespread adoption seems improbable at present.
- EVs can have front-wheel drive, rear-wheel drive, or all-wheel drive (AWD). Each mode features unique combinations. The motor can alternatively be housed within the wheel, which has numerous advantages. Although not yet economically viable, this arrangement may be practicable following further study.
- Series, parallel, and series-parallel are the most common HEV configurations. Series-parallel systems are commonly used in current automobiles because of their higher efficiency and lower fuel consumption.
- Batteries are currently the main energy source of EVs. The lead-acid and the NiMH technologies have gone out of date, whereas Li-ion batteries are used today, although not able to provide enough energy to eliminate range issues. Research in this area should focus on higher capacity and better power density. Nonetheless, given that ESS costs affect EV prices significantly, low-cost energy sources will continue to be explored.
- Ultracapacitors offer high power and density and therefore are considered auxiliary power sources. When coupled with batteries, they can satisfy some of the prerequisites of a perfect energy source. Flywheels, on the other hand, are compact and can store and discharge power on demand. Furthermore, if FCEVs become more popular in the future, fuel cells may come to the fore.
- EVs can be charged at different voltage levels, with either an AC or DC supply. Higher voltage provides faster charging. DC supplies eliminate the necessity of adjusting from AC, reducing delays and losses. Still, higher voltage will increase the pressure on the grid and can potentially cause voltage imbalances. High voltage charging still has numerous problems and therefore attracts a large body of research.
- CCS and CHAdeMO are the main charger configurations available now, although they are not compatible with each other and are supported by several automakers. A third system called a supercharger has been introduced by Tesla, providing faster charging. Based on the current situation, we cannot tell which one(s) will prevail. So, there is need for further research, either for comparisons or for compatibility.
- All charging systems still suffer from very long charging times. This is a major obstacle for the growth of the EV market. This area warrants extensive research to compete with the short times that conventional ICE vehicles need to refill. Wireless charging theoretically offers a lot of promising advantages but is still far from commercial use.
- Different techniques are utilized to reduce energy losses and to increase efficacy, including weight reduction, rational energy management, and regenerative braking. Research can focus on improving the aerodynamic body designs, using lighter and stronger materials, or restoring lost energy.
- There have been a variety of algorithms for driving assistance, energy management, and charging. A lot of work needs to be done in this area, especially in terms of charging and energy management. A rise in electric vehicle (EV) use is expected to lead to an increase in the demand for more efficient algorithms.

8. CONCLUSION

Electric vehicles (EVs) have a huge potential to become the mode of transportation of the future, while also saving the earth from the impending tragedies caused by global warming. In comparison to conventional vehicles, which are directly reliant on depleting fossil fuel reserves, they represent a feasible option. This article covers a wide range of topics related to electric vehicles, including their many configurations, power sources, charging methods, and modes of control. Each section's important technologies have been explained and their potentials have been provided. Electric vehicles (EVs) have a wide range of implications across a wide range of industries, and the enormous potential they must contribute to a cleaner and greener energy system through collaboration with smart grids and the integration of renewable sources has been highlighted. The limitations of contemporary electric vehicles (EVs) have been identified, as well as potential remedies to these problems. The most up-to-date optimization and control algorithms have been added as well. Finally, the findings of this article consolidate the entire text, offering a clear image of the EV sector as well as the areas that require additional investigation and further research.

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