energies

Review

A Comprehensive Study of Key Electric Vehicle (EV) Components, Technologies, Challenges, Impacts, and Future Direction of Development

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Abstract: Electric vehicles (EV), including Battery Electric Vehicle (BEV), Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV), Fuel Cell Electric Vehicle (FCEV), are becoming more commonplace in the transportation sector in recent times. As the present trend suggests, this mode of transport is likely to replace internal combustion engine (ICE) vehicles in the near future. Each of the main EV components has a number of technologies that are currently in use or can become prominent in the future. EVs can cause significant impacts on the environment, power system, and other related sectors. The present power system could face huge instabilities with enough EV penetration, but with proper management and coordination, EVs can be turned into a major contributor to the successful implementation of the smart grid concept. There are possibilities of immense environmental benefits as well, as the EVs can extensively reduce the greenhouse gas emissions produced by the transportation sector. However, there are some major obstacles for EVs to overcome before totally replacing ICE vehicles. This paper is focused on reviewing all the useful data available on EV configurations, battery energy sources, electrical machines, charging techniques, optimization techniques, impacts, trends, and possible directions of future developments. Its objective is to provide an overall picture of the current EV technology and ways of future development to assist in future researches in this sector.

Keywords: electric vehicle; energy sources; motors; charging technologies; effects of EVs; limitations of EVs; energy management; control algorithms; global EV sales; trends and future developments

1. Introduction

In recent times, electric vehicles (EV) are gaining popularity, and the reasons behind this are many. The most eminent one is their contribution in reducing greenhouse gas (GHG) emissions. In 2009, the transportation sector emitted 25% of the GHGs produced by energy related sectors [1]. EVs, with enough penetration in the transportation sector, are expected to reduce that figure, but this is not the only reason bringing this century old and once dead concept back to life, this time as a commercially viable and available product. As a vehicle, an EV is quiet, easy to operate, and does not have the fuel costs associated with conventional vehicles. As an urban transport mode, it is highly useful. It does not use any stored energy or cause any emission while idling, is capable of frequent start-stop driving, provides the total torque from the startup, and does not require trips to the gas station. It does not contribute either to any of the smog making the city air highly polluted. The instant torque makes it highly preferable for motor sports. The quietness and low infrared signature makes it useful in military use as well. The power sector is going through a changing phase where renewable sources are gaining momentum. The next generation power grid, called 'smart grid' is also being developed. EVs are being considered a major contributor to this new power system comprised of renewable generating facilities and advanced grid systems [2,3]. All these have led to a renewed interest and development in this mode of transport.

The idea to employ electric motors to drive a vehicle surfaced after the innovation of the motor itself. From 1897 to 1900, EVs became 28% of the total vehicles and were preferred over the internal combustion engine (ICE) ones [1]. But the ICE types gained momentum afterwards, and with very low oil prices, they soon conquered the market, became much more mature and advanced, and EVs got lost into oblivion. A chance of resurrection appeared in the form of the EV1 concept from General Motors, which was launched in 1996, and quickly became very popular. Other leading carmakers, including Ford, Toyota, and Honda brought out their own EVs as well. Toyota's highly successful Prius, the first commercial hybrid electric vehicle (HEV), was launched in Japan in 1997, with 18,000 units sold in the first year of production [1]. Today, almost none of those twentieth century EVs exist; an exception can be Toyota Prius, still going strong in a better and evolved form. Now the market is dominated by Nissan Leaf, Chevrolet Volt, and Tesla Model S; whereas the Chinese market is in the grip of BYD Auto Co., Ltd (Xi'an National Hi-tech Industrial Development Zone, Xi'an, China).

EVs can be considered as a combination of different subsystems. Each of these systems interact with each other to make the EV work, and there are multiple technologies that can be employed to operate the subsystems. In Figure 1, key parts of these subsystems and their contribution to the total system is demonstrated. Some of these parts have to work extensively with some of the others, whereas some have to interact very less. Whatever the case may be, it is the combined work of all these systems that make an EV operate.

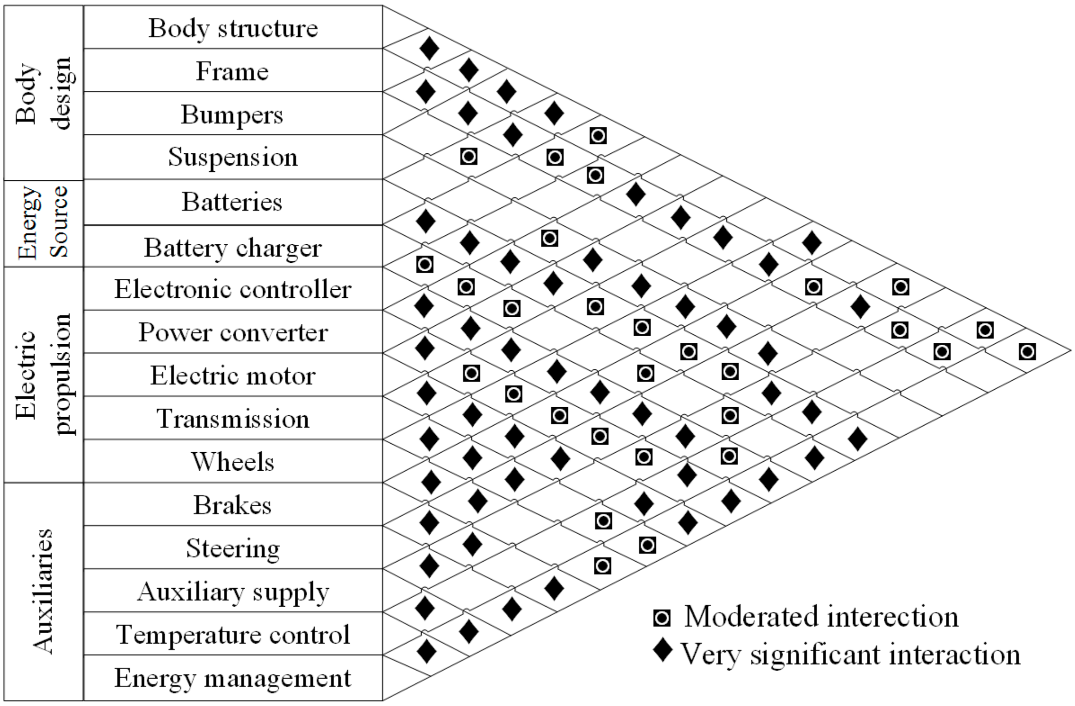


Figure 1. Major EV subsystems and their interactions. Some of the subsystems are very closely related while some others have moderated interactions. Data from [4].

There are quite a few configurations and options to build an EV with. EVs can be solely driven with stored electrical power, some can generate this energy from an ICE, and there are also some vehicles that employ both the ICE and the electrical motors together. The general classification is discussed in Section 2, whereas different configurations are described in Section 3. EVs use different types of energy storage to store their power. Though batteries are the most used ones, ultracapacitors, flywheels and fuel cells are also up and coming as potential energy storage systems (ESS). Section 4 is dedicated to these energy sources. The types of motors that have been used in EVs and can be used in future are discussed in Section 5. Different charging voltages and charger configurations can be used in charging the vehicles. Wireless charging is also being examined and experimented with to increase convenience. These charger standards, configurations and power conversion systems are demonstrated in Sections 6–8 discusses the effects EVs create in different sectors. Being a developing technology, EVs still have many limitations that have to be overcome to enable them to penetrate deeper into the market. These limitations are pointed out in Section 9 along with probable solutions. Section 10 summed up some strategies used in EVs to enable proper use of the available power. Section 11 presented different types of control algorithms used for better driving assistance, energy management, and charging. The current state of the global EV market is briefly presented in Section 12, followed by Section 13 containing the trends and sectors that may get developed in the future. Finally, the ultimate outcomes of this paper is presented in Section 14. The topics covered in this paper have been discussed in different literatures. Over the years, a number of publications have been made discussing different aspects of EV technology. This paper was created as an effort to sum up all these works to demonstrate the state-of-the art of the system and to position different technologies side by side to find out their merits and demerits, and in some cases, which one of them can make its way to the future EVs.

2. EV Types

EVs can run solely on electric propulsion or they can have an ICE working alongside it. Having only batteries as energy source constitutes the basic kind of EV, but there are kinds that can employ other energy source modes. These can be called hybrid EVs (HEVs). The International Electrotechnical Commission’s Technical Committee 69 (Electric Road Vehicles) proposed that vehicles using two or more types of energy source, storage or converters can be called as an HEV as long as at least one of those provide electrical energy [4]. This definition makes a lot of combinations possible for HEVs like ICE and battery, battery and flywheel, battery and capacitor, battery and fuel cell, etc. Therefore, the common population and specialists both started calling vehicles with an ICE and electric motor combination HEVs, battery and capacitor ones as ultra-capacitor-assisted EVs, and the ones with battery and fuel cell FCEVs [2–4]. These terminologies have become widely accepted and according to this norm, EVs can be categorized as follows:

(1) Battery Electric Vehicle (BEV)
(2) Hybrid Electric Vehicle (HEV)
(3) Plug-in Hybrid Electric Vehicle (PHEV)
(4) Fuel Cell Electric Vehicle (FCEV)

2.1. Battery Electric Vehicle (BEV)

EVs with only batteries to provide power to the drive train are known as BEVs. BEVs have to rely solely on the energy stored in their battery packs; therefore the range of such vehicles depends directly on the battery capacity. Typically they can cover 100 km–250 km on one charge [5], whereas the top-tier models can go a lot further, from 300 km to 500 km [5]. These ranges depend on driving condition and style, vehicle configurations, road conditions, climate, battery type and age. Once depleted, charging the battery pack takes quite a lot of time compared to refueling a conventional ICE vehicle. It can take as long as 36 h completely replenish the batteries [6,7], there are far less time consuming ones as well, but none is comparable to the little time required to refill a fuel tank.

Charging time depends on the charger configuration, its infrastructure and operating power level. Advantages of BEVs are their simple construction, operation and convenience. These do not produce any greenhouse gas (GHG), do not create any noise and therefore beneficial to the environment. Electric propulsion provides instant and high torques, even at low speeds. These advantages, coupled with their limitation of range, makes them the perfect vehicle to use in urban areas; as depicted in Figure 2, urban driving requires running at slow or medium speeds, and these ranges demand a lot of torque. Nissan Leaf and Teslas are some high-selling BEVs these days, along with some Chinese vehicles. Figure 3 shows basic configuration for BEVs: the wheels are driven by electric motor(s) which is run by batteries through a power converter circuit.

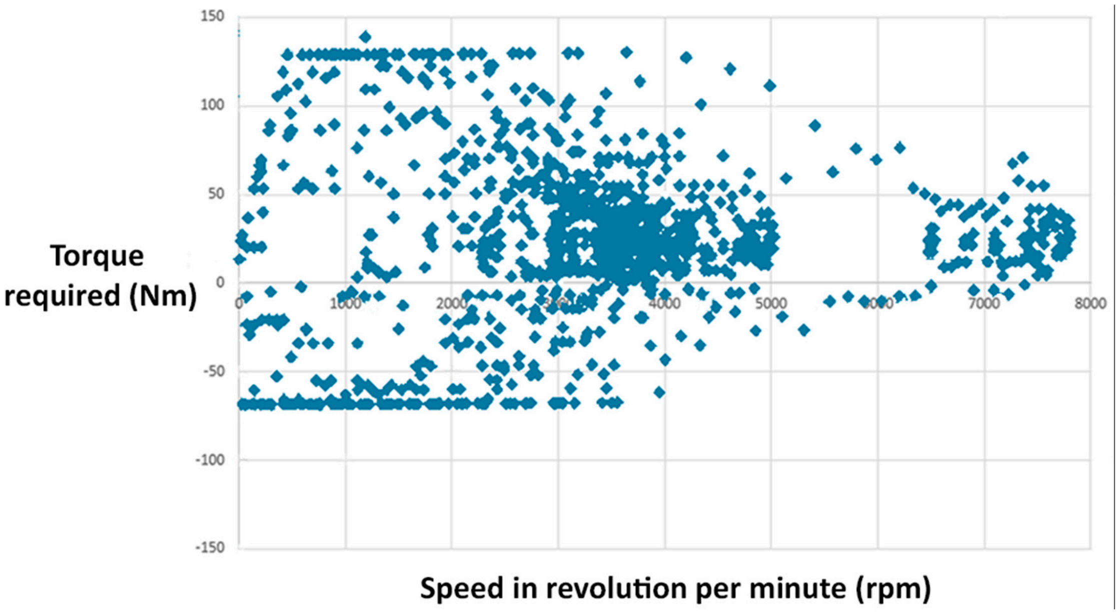


Figure 2. Federal Urban Driving Schedule torque-speed requirements. Most of the driving is done in the 2200 to 4800 rpm range with significant amount of torque. Lower rpms require torques as high as 125 Nm; urban vehicles have to operate in this region regularly as they face frequent start-stops. Data from [4].

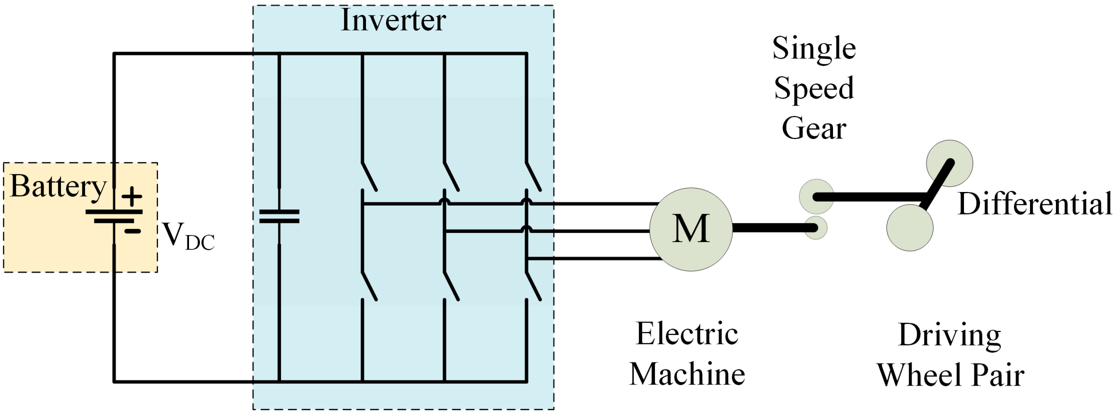
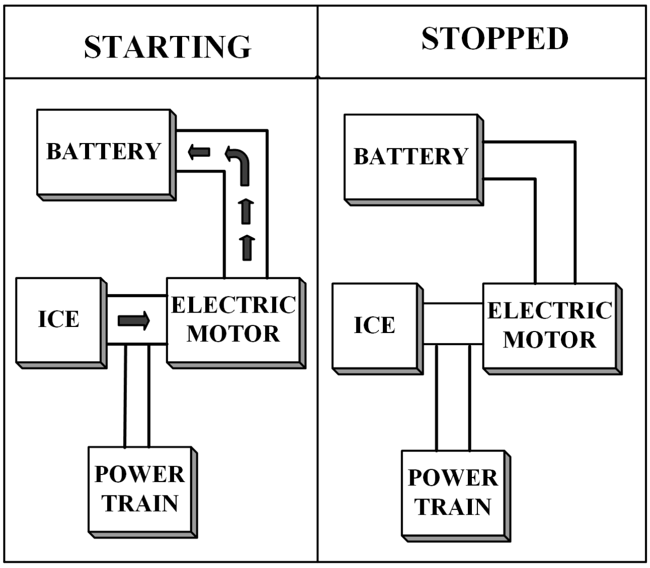


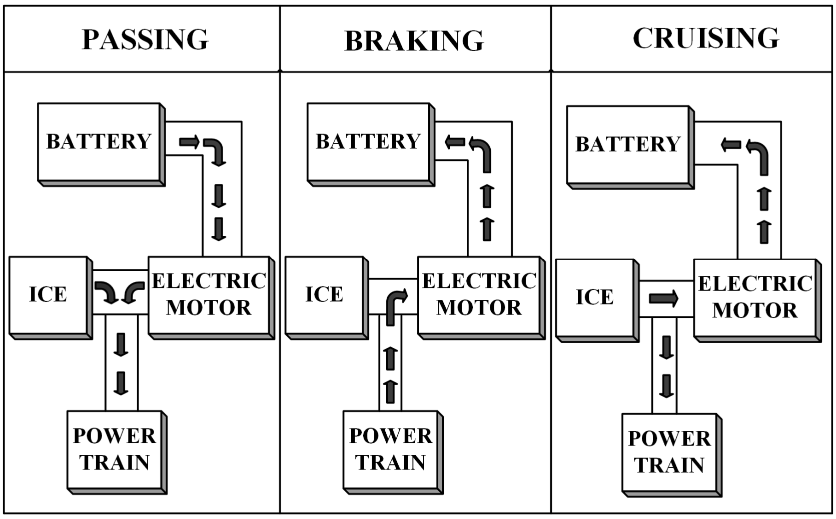
Figure 3. BEV configuration. The battery's DC power is converted to AC by the inverter to run the motor. Adapted from [5].

2.2. Hybrid Electric Vehicle (HEV)

HEVs employ both an ICE and an electrical power train to power the vehicle. The combination of these two can come in different forms which are discussed later. An HEV uses the electric propulsion system when the power demand is low. It is a great advantage in low speed conditions like urban areas; it also reduces the fuel consumption as the engine stays totally off during idling periods, for example, traffic jams. This feature also reduces the GHG emission. When higher speed is needed, the HEV switches to the ICE. The two drive trains can also work together to improve the performance. Hybrid power systems are used extensively to reduce or to completely remove turbo lag in turbocharged cars, like the Acura NSX. It also enhances performance by filling the gaps between gear shifts and providing speed boosts when required. The ICE can charge up the batteries, HEVs can also retrieve energy by means of regenerative braking. Therefore, HEVs are primarily ICE driven cars that use an electrical drive train to improve mileage or for performance enhancement. To attain these features, HEV configurations are being widely adopted by car manufacturers. Figure 4 shows the energy flows in a basic HEV. While starting the vehicle, the ICE may run the motor as a generator to produce some power and store it in the battery. Passing needs a boost in speed, therefore the ICE and the motor both drives the power train. During braking the power train runs the motor as generator to charge the battery by regenerative braking. While cruising, ICE runs the both the vehicle and the motor as generator, which charges the battery. The power flow is stopped once the vehicle stops. Figure 5 shows an example of energy management systems used in HEVs. The one demonstrated here splits power between the ICE and the electric motor (EM) by considering the vehicle speed, driver's input, state of charge (SOC) of battery, and the motor speed to attain maximum fuel efficiency.



(**a**) Direction of power flow during starting and when stopped.



(**b**) Direction of power flow during passing, braking and cruising.

Figure 4. Power flow among the basic building blocks of an HEV during various stages of a drive cycle. Adapted from [8].

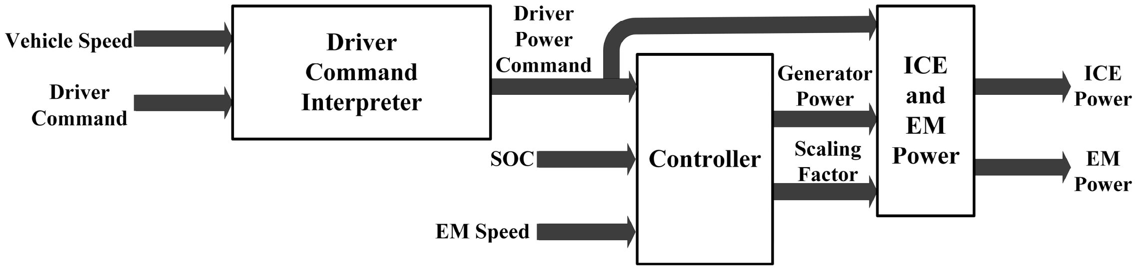


Figure 5. Example of energy management strategy used in HEV. The controller splits power between the ICE and the motor by considering different input parameters. Adapted from [8].

2.3. Plug-In Hybrid Electric Vehicle (PHEV)

The PHEV concept arose to extend the all-electric range of HEVs [9–14]. It uses both an ICE and an electrical power train, like a HEV, but the difference between them is that the PHEV uses electric propulsion as the main driving force, so these vehicles require a bigger battery capacity than HEVs. PHEVs start in 'all electric' mode, runs on electricity and when the batteries are low in charge, it calls on the ICE to provide a boost or to charge up the battery pack. The ICE is used here to extend the range. PHEVs can charge their batteries directly from the grid (which HEVs cannot); they also have the facility to utilize regenerative braking. PHEVs' ability to run solely on electricity for most of the time makes its carbon footprint smaller than the HEVs. They consume less fuel as well and thus reduce the associated cost. The vehicle market is now quite populated with these, Chevrolet Volt and Toyota Prius sales show their popularity as well.

2.4. Fuel Cell Electric Vehicle (FCEV)

FCEVs also go by the name Fuel Cell Vehicle (FCV). They got the name because the heart of such vehicles is fuel cells that use chemical reactions to produce electricity [15]. Hydrogen is the fuel of choice for FCVs to carry out this reaction, so they are often called 'hydrogen fuel cell vehicles'. FCVs carry the hydrogen in special high pressure tanks, another ingredient for the power generating process is oxygen, which it acquires from the air sucked in from the environment. Electricity generated from the fuel cells goes to an electric motor which drives the wheels. Excess energy is stored in storage systems like batteries or supercapacitors [2,3,16–18]. Commercially available FCVs like the Toyota Mirai or Honda Clarity use batteries for this purpose. FCVs only produce water as a byproduct of its power generating process which is ejected out of the car through the tailpipes. The configuration of an FCV is shown in Figure 6. An advantage of such vehicles is they can produce their own electricity which emits no carbon, enabling it to reduce its carbon footprint further than any other EV. Another major advantage of these are, and maybe the most important one right now, refilling these vehicles takes the same amount of time required to fill a conventional vehicle at a gas pump. This makes adoption of these vehicles more likely in the near future [2–4,19]. A major current obstacle in adopting this technology is the scarcity of hydrogen fuel stations, but then again, BEV or PHEV charging stations were not a common scenario even a few years back. A report to the U.S. Department of Energy (DOE) pointed to another disadvantage which is the high cost of fuel cells, that cost more than \$200 per kW, which is far greater than ICE (less than \$50 per kW) [20,21]. There are also concerns regarding safety in case of flammable hydrogen leaking out of the tanks. If these obstacles were eliminated, FCVs could really represent the future of cars. The possibilities of using this technology in supercars is shown by Pininfarina's H2 Speed (Figure 7). Reference [22] compared BEVs and FCEVs in different aspects, where FCEVs appeared to be better than BEVs in many ways; this comparison is shown in Figure 8. In this figure, different costs and cost associated issues of BEV and FCEV: weight, required storage volume, initial GHG emission, required natural gas energy, required wind energy, incremental costs, fueling infrastructure cost per car, fuel cost per kilometer, and incremental life cycle cost are all compared for 320 km (colored blue) and 480 km (colored green) ranges. The horizontal axis shows the attribute ratio of BEV to FCEV. As having a less value in these attributes indicates an advantage, any value higher than one in the horizontal axis will declare FCEVs superior to BEVs in that attribute. That being said, BEVs only appear better in the fields of required wind energy and fuel cost per kilometer. Fuel cost still appears to be one of the major drawbacks of FCEVs, as a cheap, sustainable and environment-friendly way of producing hydrogen is still lacking, and the refueling infrastructure lags behind that of BEVs; but these problems may no longer prevail in the near future.

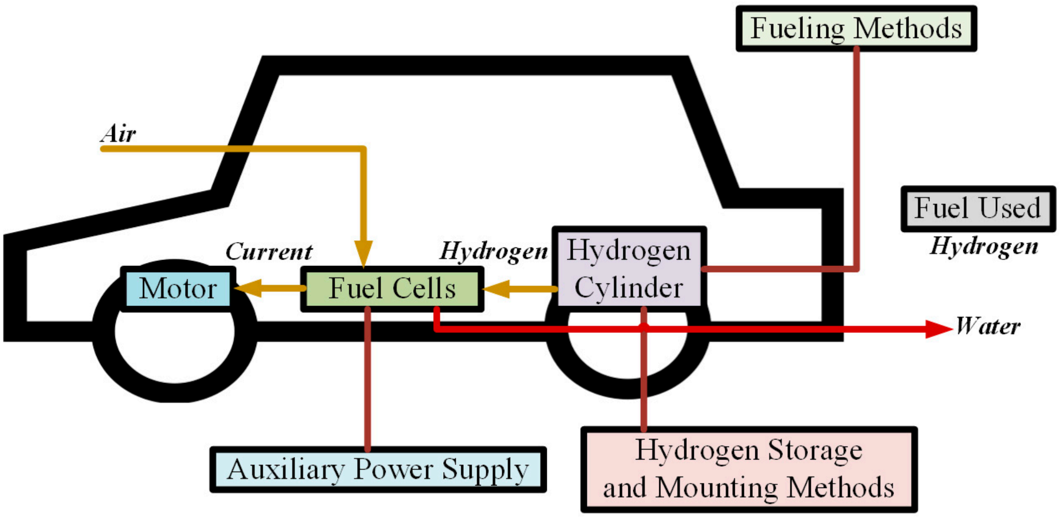


Figure 6. FCEV configuration. Oxygen from air and hydrogen from the cylinders react in fuel cells to produce electricity that runs the motor. Only water is produced as by-product which is released in the environment.

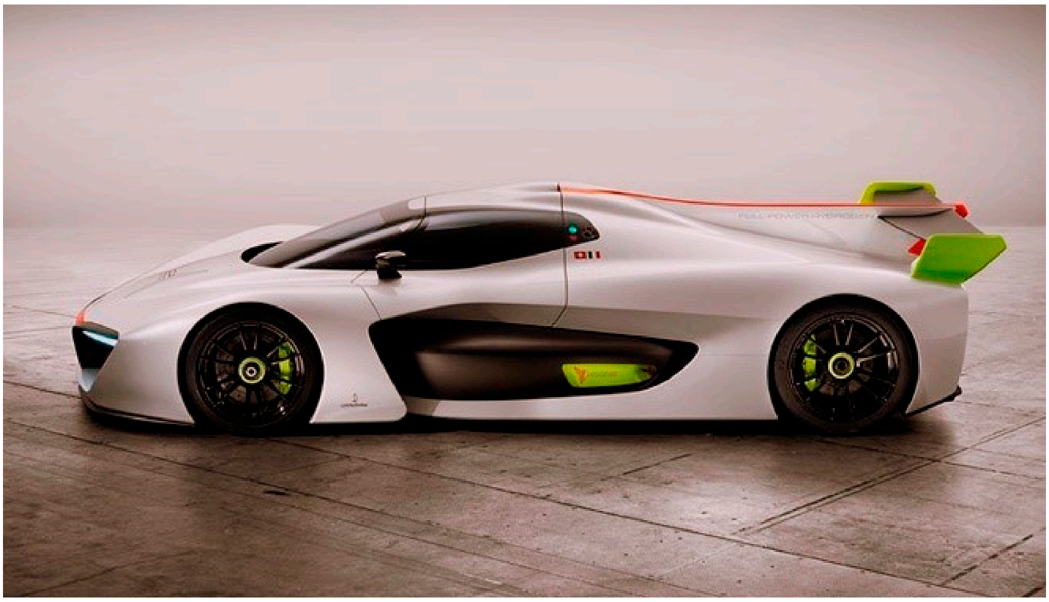


Figure 7. Pininfarina H2 Speed, a supercar employing hydrogen fuel cells.

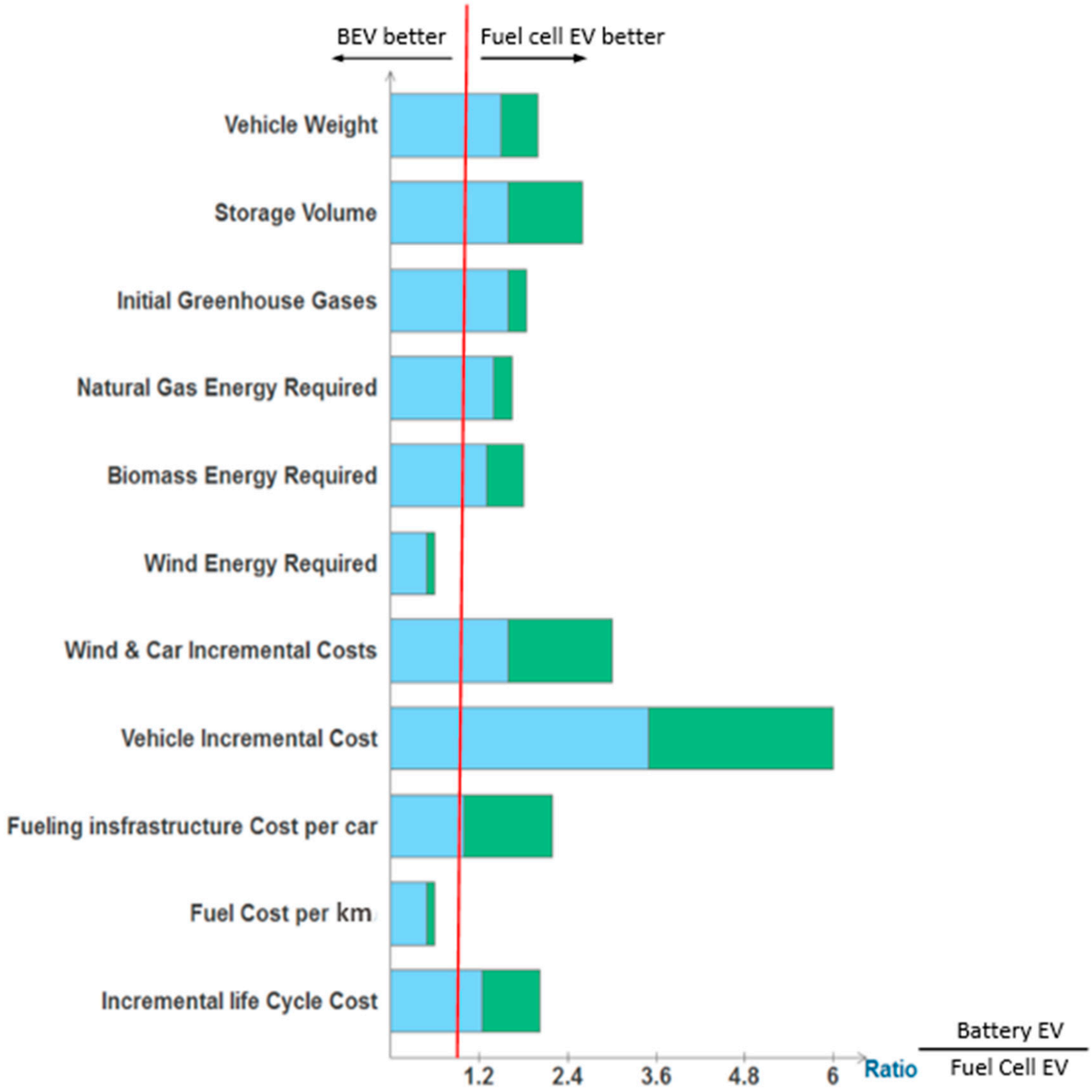


Figure 8. Advanced battery EV attribute and fuel cell EV attribute ratio for 320 km (colored blue) and 480 km (colored green) ranges, with assumptions of average US grid mix in 2010–2020 time-range and all hydrogen made from natural gas (values greater than one indicate a fuel cell EV advantage over the battery EV). Data from [22].

Rajashekara predicted a slightly different future for FCVs in [23]. He showed a plug-in fuel cell vehicle (PFCV) with a larger battery and smaller fuel cell, which makes it battery-dominant car. According to [23], if hydrogen for such vehicles can be made from renewable sources to run the fuel cells and the energy to charge the batteries comes from green sources as well, these PFCVs will be the future of vehicles. The FCVs we see today will not have much appeal other than some niche markets. Figure 9 shows a basic PFCV configuration. Table 1 compares the different vehicle types in terms of driving component, energy source, features, and limitations.

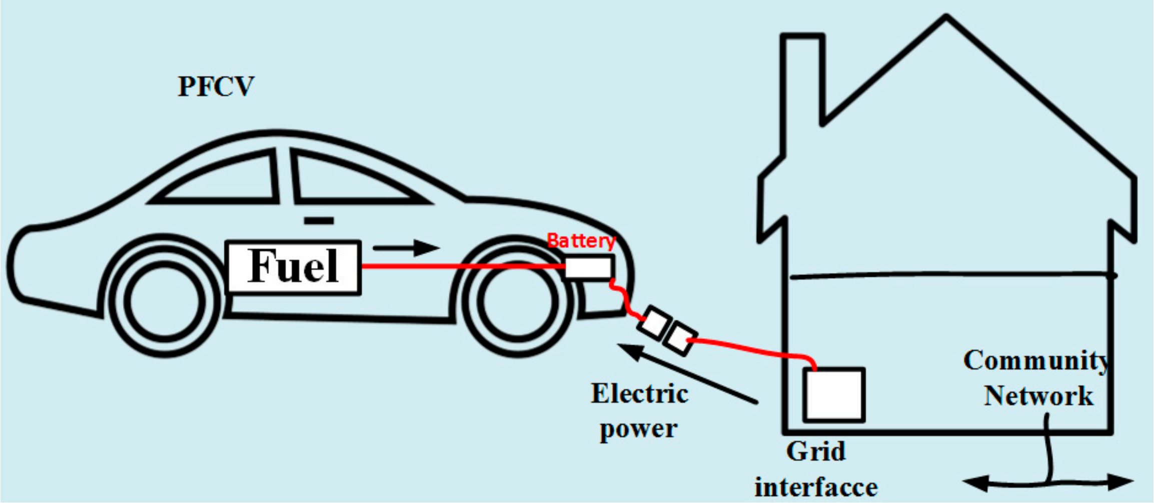


Figure 9. PFCV configuration. In addition to the fuel cells, this arrangement can directly charge the battery from a power outlet.

Table 1. Comparison of different vehicle types. Adapted from [4].

EV Type	Driving Component	Energy Source	Features	Problems
BEV	• Electric motor	• Battery • Ultracapacitor	• No emission • Not dependent on oil • Range depends largely on the type of battery used • Available commercially	• Battery price and capacity • Range • Charging time • Availability of charging stations • High price
HEV	• Electric motor • ICE	• Battery • Ultracapacitor • ICE	• Very little emission • Long range • Can get power from both electric supply and fuel • Complex structure having both electrical and mechanical drivetrains • Available commercially	• Management of the energy sources • Battery and engine size optimization
FCEV	• Electric motor	• Fuel cell	• Very little or no emission • High efficiency • Not dependent on supply of electricity • High price • Available commercially	• Cost of fuel cell • Feasible way to produce fuel • Availability of fueling facilities

3. EV Configurations

An electric vehicle, unlike its ICE counterparts, is quite flexible [4]. This is because of the absence of intricate mechanical arrangements that are required to run a conventional vehicle. In an EV, there is only one moving part, the motor. It can be controlled by different control arrangements and techniques. The motor needs a power supply to run which can be from an array of sources. These two components can be placed at different locations on the vehicle and as long as they are connected through electrical wires, the vehicle will work. Then again, an EV can run solely on electricity, but an ICE and electric motor can also work in conjunction to turn the wheels. Because of such flexibility, different configurations emerged which are adopted according to the type of vehicle. An EV can be considered as a system incorporating three different subsystems [4]: energy source, propulsion and auxiliary. The energy source subsystem includes the source, its refueling system and energy management system. The propulsion subsystem has the electric motor, power converter, controller, transmission and the driving wheels as its components. The auxiliary subsystem is comprised of auxiliary power supply, temperature control system and the power steering unit. These subsystems are shown in Figure 10.

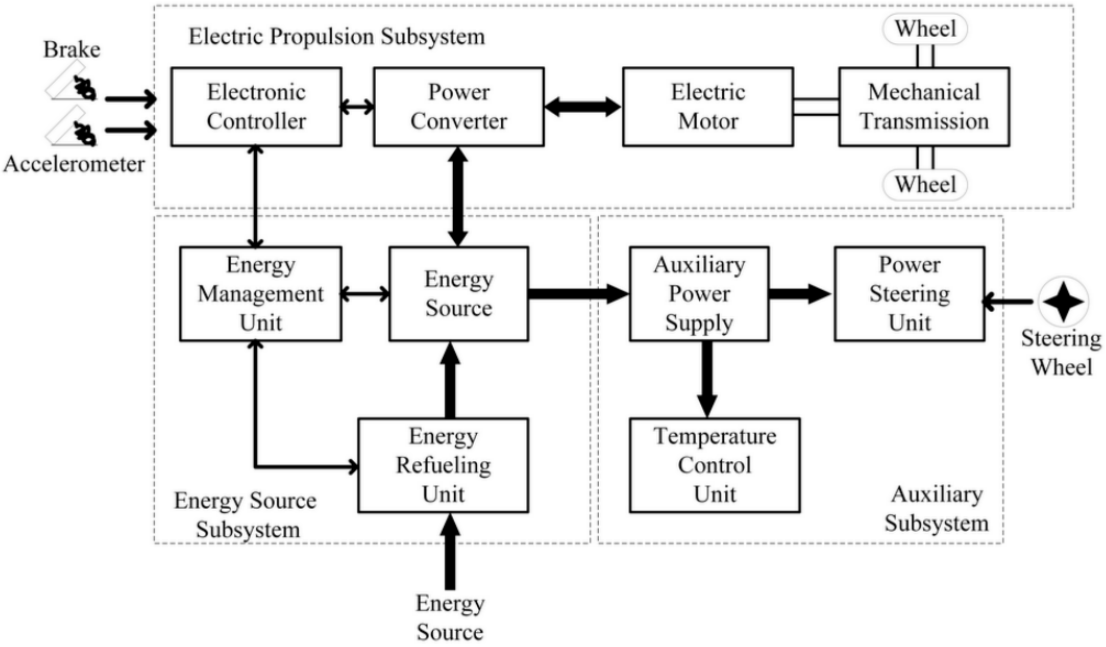


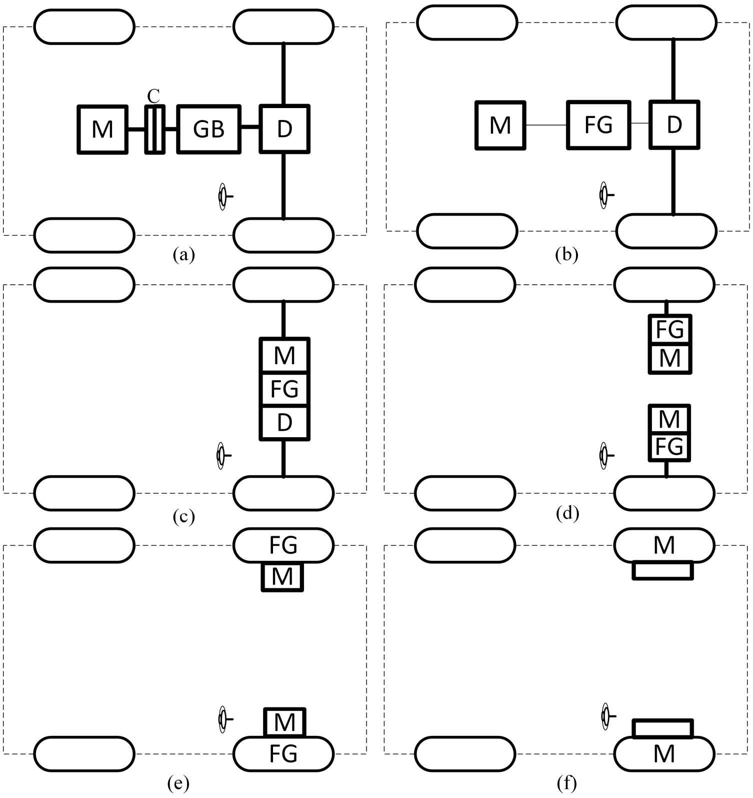
Figure 10. EV subsystems. Adapted from [4].

The arrows indicate the flow of the entities in question. A backward flow of power can be created by regenerative actions like regenerative braking. The energy source has to be receptive to store the energy sent back by regenerative actions. Most of the EV batteries along with capacitors/flywheels (CFs) are compatible with such energy regeneration techniques [4].

3.1. General EV Setup

EVs can have different configurations as shown in [4]. Figure 11a shows a front-engine front-wheel drive vehicle with just the ICE replaced by an electric motor. It has a gearbox and clutch that allows high torque at low speeds and low torque at high speeds. There is a differential as well that allows the wheels to rotate at different speeds. Figure 11b shows a configuration with the clutch omitted. It has a fixed gear in place of the gearbox which removes the chance of getting the desired torque-speed characteristics. The configuration of Figure 11c has the motor, gear and differential as a single unit that drives both the wheels. The Nissan Leaf, as well as the Chevrolet Spark, uses an electric motor mounted at the front to drive the front axle. In Figure 11d,e, configurations to obtain differential action by using two motors for the two wheels are shown. Mechanical interaction can be further reduced by placing the motors inside the wheels to produce an 'in-wheel drive'. A planetary gear system is employed here because advantages like high speed reduction ratio and inline arrangement of input and output shafts. Mechanical gear system is totally removed in the last configuration (Figure 11f) by mounting a low-speed motor with an outer rotor configuration on the wheel rim. Controlling the motor speed thus controls the wheel speed and the vehicle speed.

EVs can be built with rear wheel drive configuration as well. The single motor version of the Tesla Model S uses this configuration (Figure 12). The Nissan Blade Glider is a rear wheel drive EV with in-wheel motor arrangement. The use of in-wheel motors enables it to apply different amount of torques at each of the two rear wheels to allow better cornering.



C: Clutch; **D**: Differential; **FG**: Fixed Gearing; **GB**: Gear Box; **M**: Electric Motor

Figure 11. Different front wheel drive EV configurations. (**a**) Front-wheel drive vehicle with the ICE replaced by an electric motor; (**b**) Vehicle configuration with the clutch omitted; (**c**) Configuration with motor, gear and differential combined as a single unit to drive the front wheels; (**d**) Configuration with individual motors with fixed fearing for the front wheels to obtain differential action; (**e**) Modified configuration of Figure 11d with the fixed gearing arrangement placed within the wheels; (**f**) Configuration with the mechanical gear system removed by mounting a low-speed motor on the wheel rim. Adapted from [4].

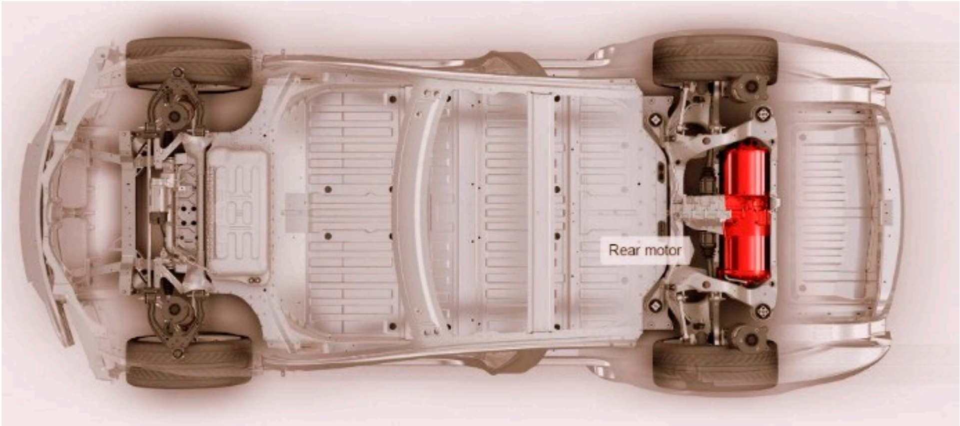


Figure 12. Tesla Model S, rear wheel drive configuration [22,24]. (Reprint with permission [24]; 2017, Tesla.)

For more control and power, all-wheel drive (AWD) configurations can also be used, though it comes with added cost, weight and complexity. In this case, two motors can be used to drive the front and the rear axles. An all-wheel drive configuration is shown in Figure 13. AWD configurations are useful to provide better traction in slippery conditions, they can also use torque vectoring for better cornering performance and handling. AWD configuration can also be realized for in-wheel motor systems. It can prove quite useful for city cars like the Hiriko Fold (Figure 14) which has steering actuator, suspension, brakes and a motor all integrated in each wheel. Such arrangements can provide efficient all wheel driving, all wheel steering along with ease of parking and cornering.

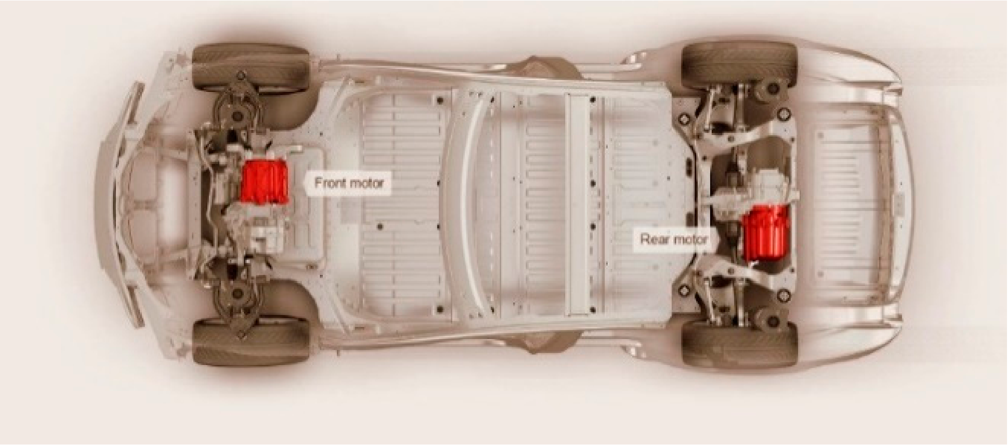


Figure 13. Tesla Model S, all-wheel drive configuration [24]. (Reprint with permission [24]; 2017, Tesla.)

Figure 14. Hiriko Fold—a vehicle employing in-wheel motors.

In-wheel motor configurations are quite convenient in the sense that they reduce the weight of the drive train by removing the central motor, related transmission, differential, universal joints and drive shaft [25]. They also provide more control, better turning capabilities and more space for batteries, fuel cells or cargo, but in this case the motor is connected to the power and control systems through wires that can get damaged because of the harsh environment, vibration and acceleration, thus causing serious trouble. Sato et al., proposed a wireless in-wheel motor system (W-IWM) in [26] which they had implemented in an experimental vehicle (shown in Figure 15). Simply put, the wires are replaced by two coils which are able to transfer power in-between them. Because of vibrations caused by road conditions, the motor and the vehicle can be misaligned and can cause variation in the secondary side voltage. In-wheel motor configurations are shown in Figure 16, whereas the efficiencies at different stages of such a system are shown in Figure 17. In conditions like this, magnetic resonance coupling is preferred for wireless power transfer [27] as it can overcome the problems associated with such misalignments [28]. The use of a hysteresis comparator and applying the secondary inverter power to a controller to counter the change in secondary voltage was also proposed in [28]. Wireless power transfer (WPT) employing magnetic resonance coupling in a series-parallel arrangement can provide a transmitting efficiency of 90% in both directions at 2 kW [29]. Therefore, W-IWM is compliant with regenerative braking as well.

Figure 15. Experimental vehicle with W-IWM system by Sato et al. [26]. (Reprint with permission [26]; 2015, IEEE.)

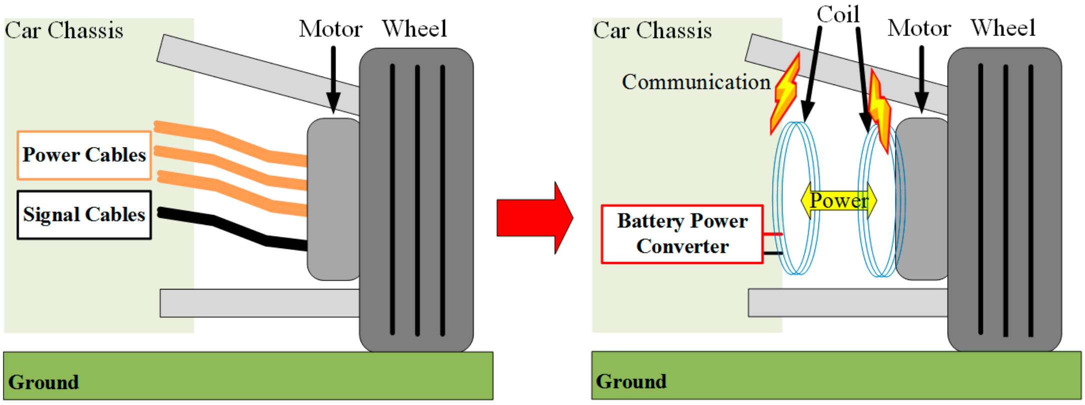


Figure 16. Conventional and wireless IWM. In the wireless setup, coils are used instead of wires to transfer power from battery to the motor. Adapted from [26].

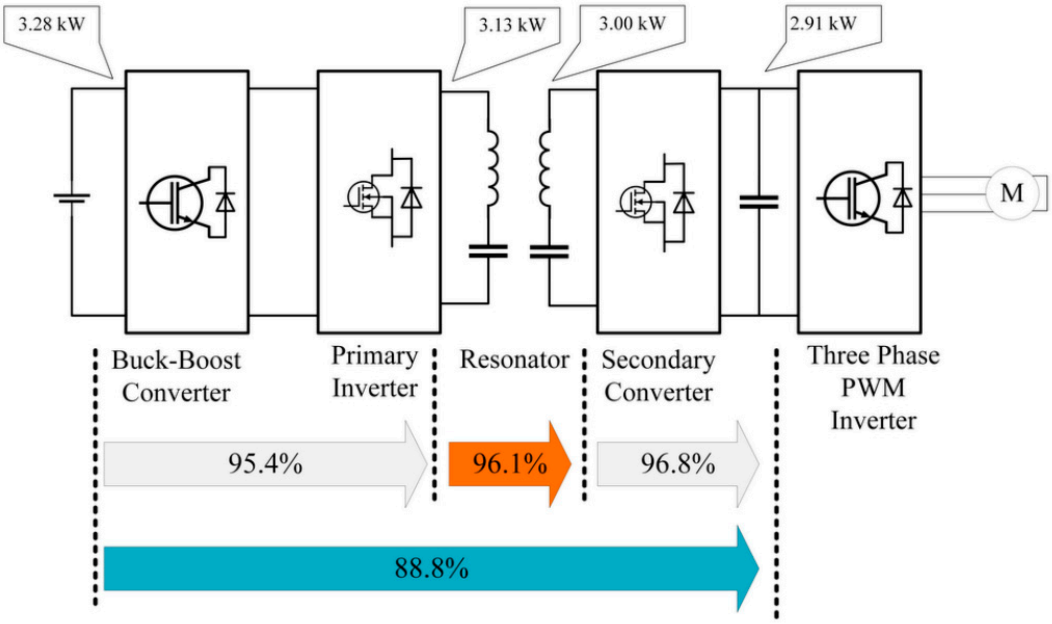


Figure 17. W-IWM setup showing efficiency at 100% torque reference. Adapted from [26].

3.2. HEV Setup

HEVs use both an electrical propulsion system and an ICE. Various ways in which these two can be set up to spin the wheels creates different configurations that can be summed up in four categories [4]:

(1) Series hybrid
(2) Parallel hybrid
(3) Series-parallel hybrid
(4) Complex hybrid

3.2.1. Series Hybrid

This configuration is the simplest one to make an HEV. Only the motor is connected to the wheels here, the engine is used to run a generator which provides the electrical power. It can be put as an EV that is assisted by an ICE generator [4]. Series hybrid drive train is shown in Figure 18. Table 2 shows the merits and demerits of this configuration.

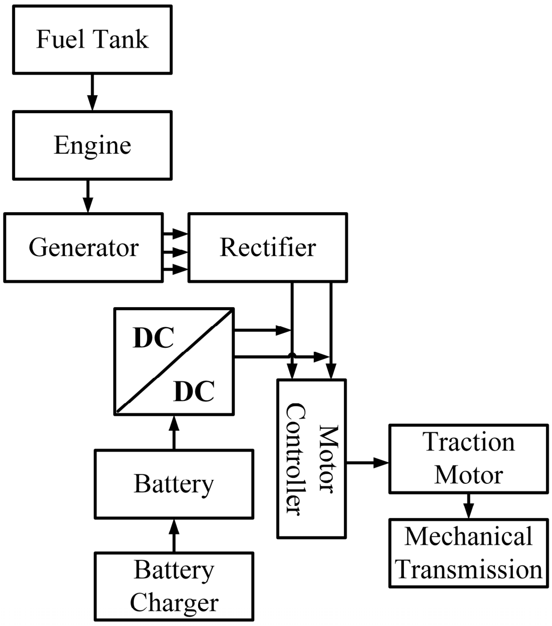


Figure 18. Drive train of series hybrid system. The engine is used to generate electricity only and supply to the motor through a rectifier. Power from the battery goes to the motor through a DC-DC converter [30].

Table 2. Advantages and limitations of series hybrid configuration. Adapted from [8].

Advantages	Efficient and optimized power-plant Possibilities for modular power-plant Optimized drive line Possibility of swift 'black box' service exchange Long lifetime Mature technology Fast response Capable of attaining zero emission
Limitations	Large traction drive system Requirement of proper algorithms Multiple energy conversion steps

3.2.2. Parallel Hybrid

This configuration connects both the ICE and the motor in parallel to the wheels. Either one of them or both take part in delivering the power. It can be considered as an IC engine vehicle with electric assistance [4]. The energy storages in such a vehicle can be charged by the electric motor by means of regenerative braking or by the ICE when it produces more than the power required to drive the wheels. Parallel hybrid drive train is shown in Figure 19. Table 3 shows the merits and demerits of this configuration, while Table 4 compares the series and the parallel systems.

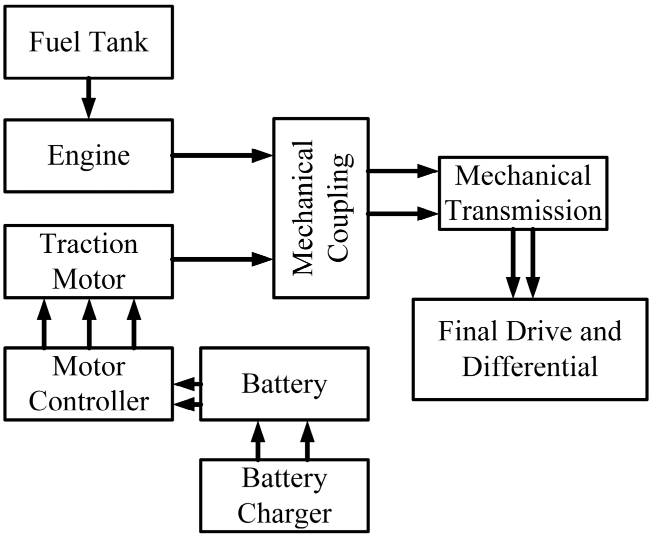


Figure 19. Drive train of parallel hybrid system. The engine and the motor both can run the can through the mechanical coupling [30].

Table 3. Advantages and limitations of parallel hybrid configuration. Adapted from [30].

Advantages	Capable of attaining zero emission Economic gain More flexibility
Limitations	Expensive Complex control Requirement of proper algorithms Need of high voltage to ensure efficiency

Table 4. Comparison of parallel and series hybrid configurations. Data from [8].

Parameters	Parallel HEV	Series HEV
Voltage	14 V, 42 V, 144 V, 300 V	216 V, 274 V, 300 V, 350 V, 550 V, 900 V
Power requirement	3 KW–40 KW	>50 KW
Relative gain in fuel economy (%)	5–40	>75

3.2.3. Series-Parallel Hybrid

In an effort to combine the series and the parallel configuration, this system acquires an additional mechanical link compared to the series type, or an extra generator when compared to the parallel type. It provides the advantages of both the systems but is more costly and complicated nonetheless. Complications in drive train are caused to some extent by the presence of a planetary gear unit [30]. Figure 20 shows a planetary gear arrangement: the sun gear is connected to the generator, the output shaft of the motor is connected to the ring gear, the ICE is coupled to the planetary carrier, and the pinion gears keep the whole system connected. A less complex alternative to this system is to use a transmotor, which is a floating-stator electric machine. In this system the engine is attached to the stator, and the rotor stays connected to the drive train wheel through the gears. The motor speed is the relative speed between the rotor and the stator and controlling it adjusts the engine speed for any particular vehicle speed [30]. Series-parallel hybrid drive train with planetary gear system is shown in Figure 21; Figure 22 shows the system with a transmotor.

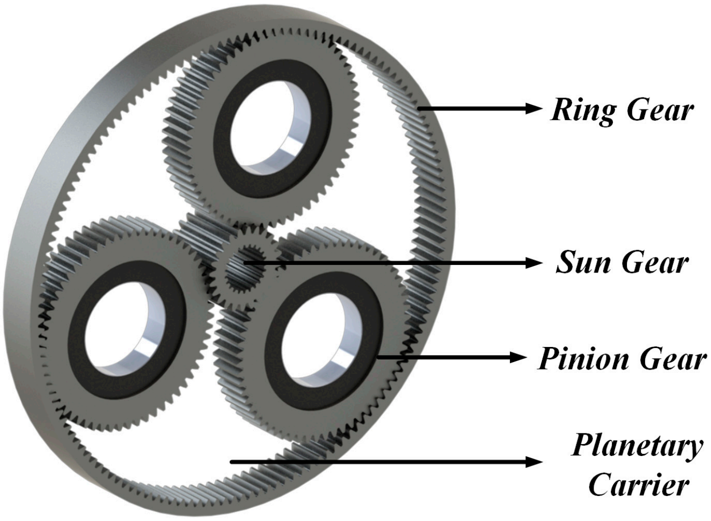


Figure 20. Planetary gear system [31].

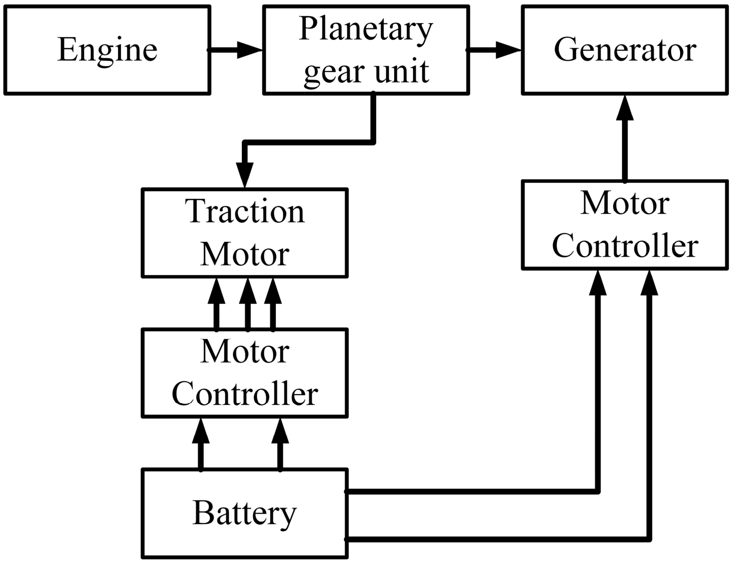


Figure 21. Drive train of series-parallel hybrid system using planetary gear unit. The planetary gear unit combines the engine, the generator and the motor [30].

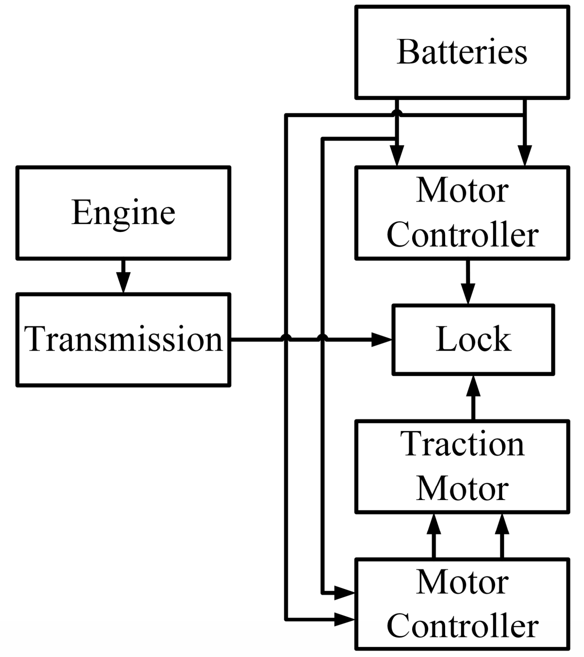


Figure 22. Drive train of series-parallel hybrid system using transmotor. The planetary gear system is absent in this arrangement [30].

3.2.4. Complex Hybrid

This system has one major difference with the series-parallel system, that is, it allows bidirectional flow of power whereas the series-parallel can provide only unidirectional power flow. However, using current market terminologies, this configuration is denoted as series-parallel system too. High complexity and cost are drawbacks of this system, but it is adopted by some vehicles to use dual-axle propulsion [4]. Constantly variable transmission (CVT) can be used for power splitting in a complex hybrid system or choosing between the power sources to drive the wheels. Electric arrangements can be used for such processes and this is dubbed as e-CVT, which has been developed and introduced by Toyota Motor Co. (Toyota City, Aichi Prefecture 471-8571, Japan). CVTs can be implemented hydraulically, mechanically, hydro-mechanically or electromechanically [32]. Two methods of power splitting—input splitting and complex splitting are shown in [32]. Input splitting got the name as it has a power split device placed at the transmission input. This system is used by certain Toyota and Ford models [32]. Reference [32] also showed different modes of these two splitting mechanisms and provided descriptions of e-CVT systems adopted by different manufacturers which are shown in Figures 23 and 24. Such power-split HEVs require two electric machines, wheels, an engine and a planetary gear (PG), combining all of them can be done in twenty-four different ways. If another PG is used, that number gets greater than one thousand. An optimal design incorporating a single PG is proposed in [31]. Four-wheel drive (4WD) configurations can benefit from using a two-motor hybrid configuration as it nullifies the need of a power transmission system to the back wheels (as they get their own motor) and provides the advantage of energy reproduction by means of regenerative braking [33]. Four-wheel drive HEV structure is shown in Figure 25. A stability enhancement scheme for such a configuration by controlling the rear motor is shown in [33].

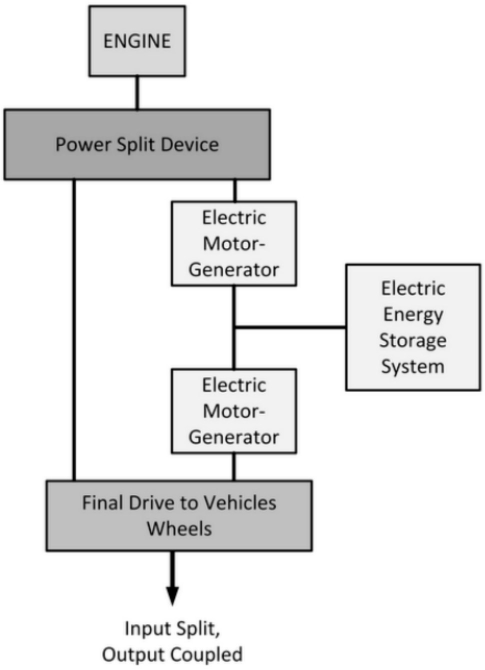


Figure 23. Input split e-CVT system. Adapted from [32].

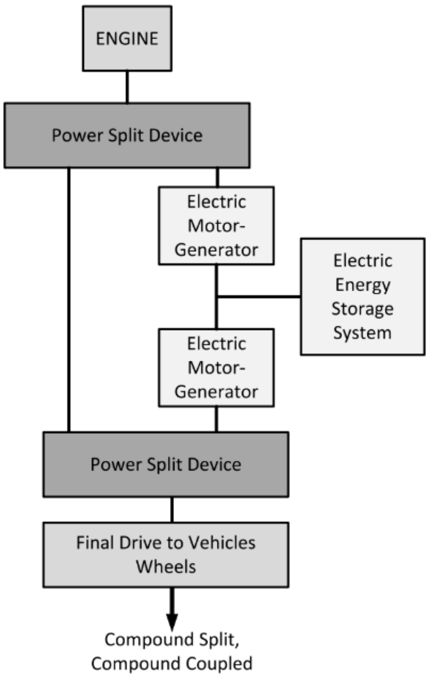


Figure 24. Compound split e-CVT system. Adapted from [32].

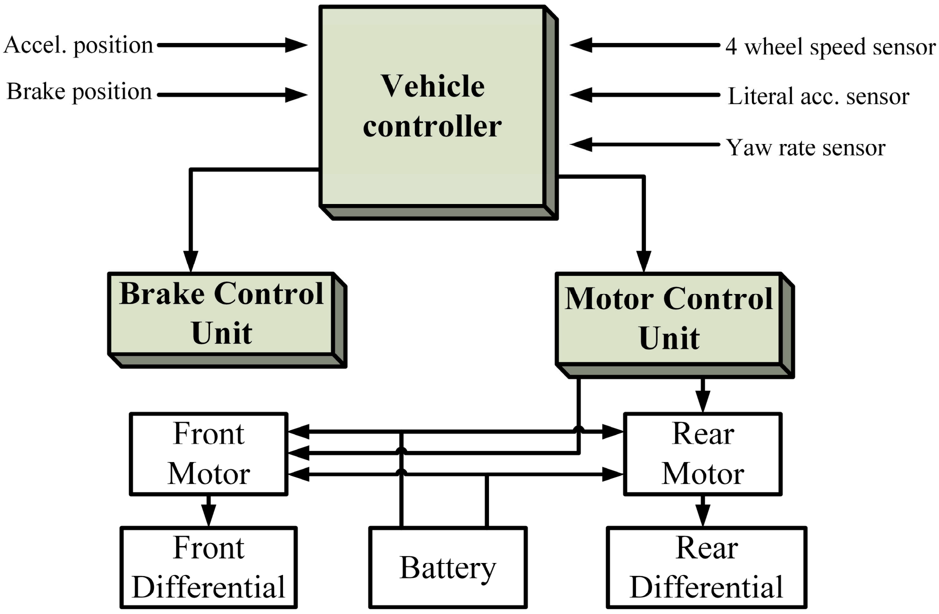


Figure 25. Structure for four-wheel drive HEV [32]. This particular system uses a vehicle controller which employs a number of sensors to perceive the driving condition and keeps the vehicle stable by controlling the brake control and the motor control units.

4. Energy Sources

EVs can get the energy required to run from different sources. The criteria such sources have to satisfy are mentioned in [4], high energy density and high power density being two of the most important ones [30]. There are other characteristics that are sought after to make a perfect energy source, fast charging, long service and cycle life, less cost and maintenance being a few of them. High specific energy is required from a source to provide a long driving range whereas high specific power helps to increase the acceleration. Because of the diverse characteristics that are required for the perfect source, quite a few sources or energy storage systems (ESS) come into discussion; they are also used in different combinations to provide desired power and energy requirements [4].

4.1. Battery

Batteries have been the major energy source for EVs for a long time; though of course, was time has gone by, different battery technologies have been invented and adopted and this process is still going on to attain the desired performance goals. Table 5 shows the desired performance for EV batteries set by the U.S. Advanced Battery Consortium (USABC).

Table 5. Performance goal of EV batteries as set by USABC. Data from [4].

	Parameters	Mid-Term	Long-Term
Primary goals	Energy density (C/3 discharge rate) (Wh/L)	135	300
	Specific energy (C/3 discharge rate) (Wh/kg)	80 (Desired: 100)	200
	Power density (W/l)	250	600
	Specific power (80% DOD/30 s) (W/kg)	150 (Desired: 200)	400
	Lifetime (year)	5	10
	Cycle life (80% DOD) (cycles)	600	1000
	Price (USD/kWh)	<150	<100
	Operating temperature (°C)	−30 to 65	−40 to 84
	Recharging time (hour)	<6	3 to 6
	Fast recharging time (40% to 80% SOC) (hour)	0.25	
Secondary goals	Self-discharge (%)	<15 (48 h)	<15 (month)
	Efficiency (C/3 discharge, 6 h charge) (%)	75	80
	Maintenance	No maintenance	No maintenance

Resistance to abuse	Tolerance	Tolerance
Thermal loss	3.2 W/kWh	3.2 W/kWh

Some of the prominent battery types are: lead-acid, Ni-Cd, Ni-Zn, Zn/air, Ni-MH, Na/S, Li-polymer and Li-ion batteries. Yong et al., also showed a battery made out of graphene for EV use whose advantages, structural model and application is described in [34]. Different battery types have their own pros and cons, and while selecting one, these things have to be kept in mind. In [35], Khaligh et al., provided key features of some known batteries which are demonstrated in Table 6. In Table 7, common battery types are juxtaposed to relative advantage of one battery type over the others.

Table 6. Common battery types, their basic construction components, advantages and disadvantages. Data from [35–44].

Battery Type	Components	Advantage	Disadvantage
Lead-acid	• Negative active material: spongy lead • Positive active material: lead oxide • Electrolyte: diluted sulfuric acid	• Available in production volume • Comparatively low in cost • Mature technology as used for over fifty years	• Cannot discharge more than 20% of its capacity • Has a limited life cycle if operated on a deep rate of SOC (state of charge) • Low energy and power density • Heavier • May need maintenance
NiMH (Nickel-Metal Hydride)	• Electrolyte: alkaline solution • Positive electrode: nickel hydroxide • Negative electrode: alloy of nickel, titanium, vanadium and other metals.	• Double energy density compared to lead-acid • Harmless to the environment • Recyclable • Safe operation at high voltage • Can store volumetric power and energy • Cycle life is longer • Operating temperature range is long • Resistant to over-charge and discharge	• Reduced lifetime of around 200–300 cycles if discharged rapidly on high load currents • Reduced usable power because of memory effect
Li-Ion (Lithium-Ion)	• Positive electrode: oxidized cobalt material • Negative electrode: carbon material • Electrolyte: lithium salt solution in an organic solvent	• High energy density, twice of NiMH • Good performance at high temperature • Recyclable • Low memory effect • High specific power • High specific energy • Long battery life, around 1000 cycles	• High cost • Recharging still takes quite a long time, though better than most batteries
Ni-Zn (Nickel-Zinc)	• Positive electrode: nickel oxyhydroxide • Negative electrode: zinc	• High energy density • High power density • Uses low cost material • Capable of deep cycle • Friendly to environment • Usable in a wide temperature range from −10 °C to 50 °C	• Fast growth of dendrite, preventing use in vehicles
Ni-Cd (Nickel-Cadmium)	• Positive electrode: nickel hydroxide • Negative electrode: cadmium	• Long lifetime • Can discharge fully without being damaged • Recyclable	• Cadmium can cause pollution in case of not being properly disposed of • Costly for vehicular application

Table 7. Cross comparison of different battery types to show relative advantages. Adapted from [45].

Advantages Over	**Lead-Acid**	**Ni-Cd (Nickel-Cadmium)**	**NiMH (Nickel–Metal Hydride)**	**Li-Ion (Lithium-Ion)**	
				Conventional	**Polymer**
Lead-acid		• Volumetric energy density • Gravimetric energy density • Range of operating temperature • Rate of self-discharge reliability	• Volumetric energy density • Gravimetric energy density • Rate of self-discharge	• Volumetric energy density • Gravimetric energy density • Rate of self-discharge	• Volumetric energy density • Gravimetric energy density • Rate of self-discharge • Design features
Ni-Cd (Nickel-Cadmium)	• Output voltage • Cost • Higher cyclability		• Volumetric energy density • Gravimetric energy density	• Volumetric energy density • Gravimetric energy density • Rate of self-discharge • Output voltage	• Volumetric energy density • Gravimetric energy density • Rate of self-discharge • Design features
NiMH (Nickel-Metal Hydride)	• Output voltage • Cost • Higher cyclability	• Range of operating temperature • Cost • Higher cyclability • Rate of self-discharge		• Volumetric energy density • Gravimetric energy density • Range of operating temperature	• Volumetric energy density • Gravimetric energy density • Range of operating temperature • Rate of self-discharge • Design features
Li-Ion (conventional)	• Cost • Safety • Higher cyclability • Re-cyclability	• Range of operating temperature • Cost • Safety • Higher cyclability • Recyclability	• Cost • Safety • Rate of discharge • Re-cyclability		• Volumetric energy density • Gravimetric energy density (potential) • Cost • Design features • Safety
Li-Ion (polymer)	• Cost • Higher cyclability	• Range of operating temperature • Higher cyclability • Cost	• Volumetric energy density • Cost • Higher cyclability	• Range of operating temperature • Higher cyclability	
Absolute advantages	• Cost • Higher cyclability	• Cost • Range of operating temperature	• Volumetric energy density	• Volumetric energy density • Gravimetric energy density • Range of operating temperature • Rate of self-discharge • Output voltage	• Volumetric energy density • Gravimetric energy density • Range of operating temperature • Rate of self-discharge • Output voltage • Design features

The battery packs used in EVs are made of numerous battery cells (Figure 26). The Tesla Model S, for example, has 7104 Li-Ion cells in the 85 kWh pack. All these cells are desired to have the same SOC at all times to have the same degradation rate and same capacity over the lifetime, preventing premature end of life (EOL) [46]. A power electronic control device, called a cell voltage equalizer, can achieve this feat by taking active measures to equalize the SOC and voltage of each cell. The equalizers can be of different types according to their construction and working principle. Resistive equalizers keep all the cells at the same voltage level by burning up the extra power at cells with higher voltages. Capacitive equalizers, on the other hand, transfers energy from the higher energy cells to the lower energy ones by switching capacitors. Inductive capacitors can be of different configurations: basic, Cuk, and single of multiple transformer based; but all of them transfer energy from higher energy cells to the ones with lower energy by using inductors [46–52]. All these configurations have their own merits and demerits, which are shown in Table 8; the schematics are shown in Figures 27 and 28. Table 9 shows comparisons between the equalizer types.

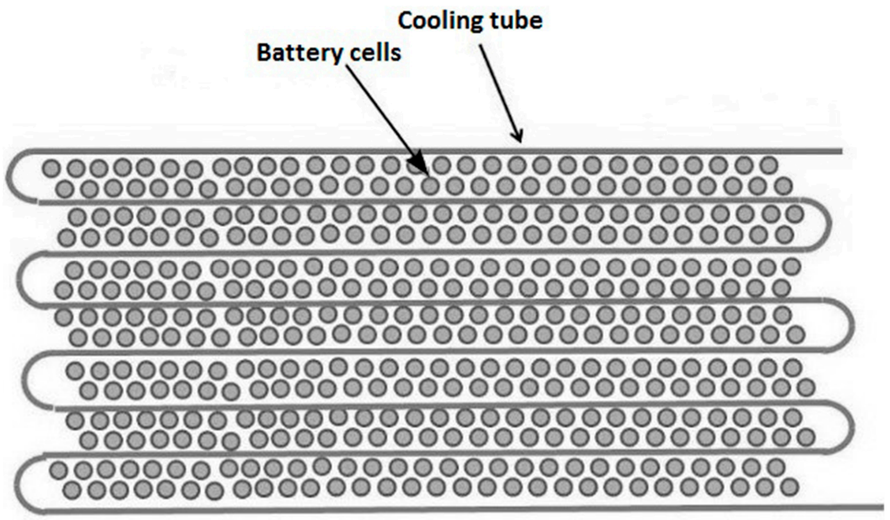
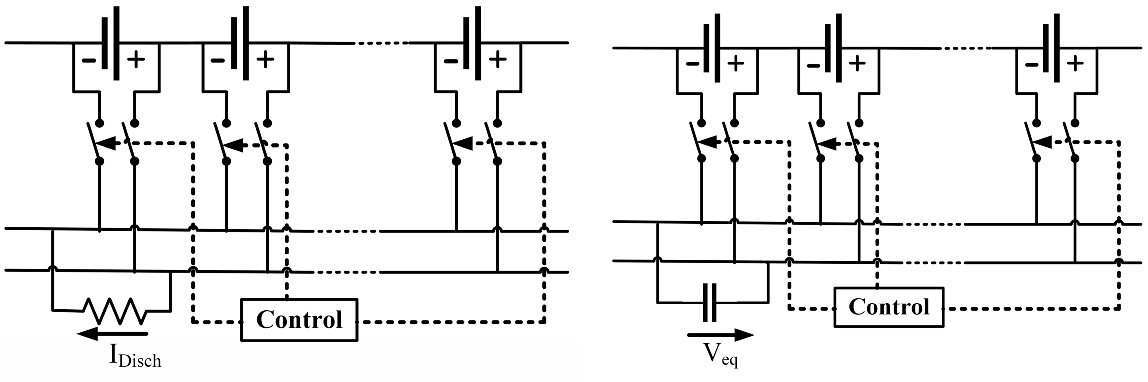
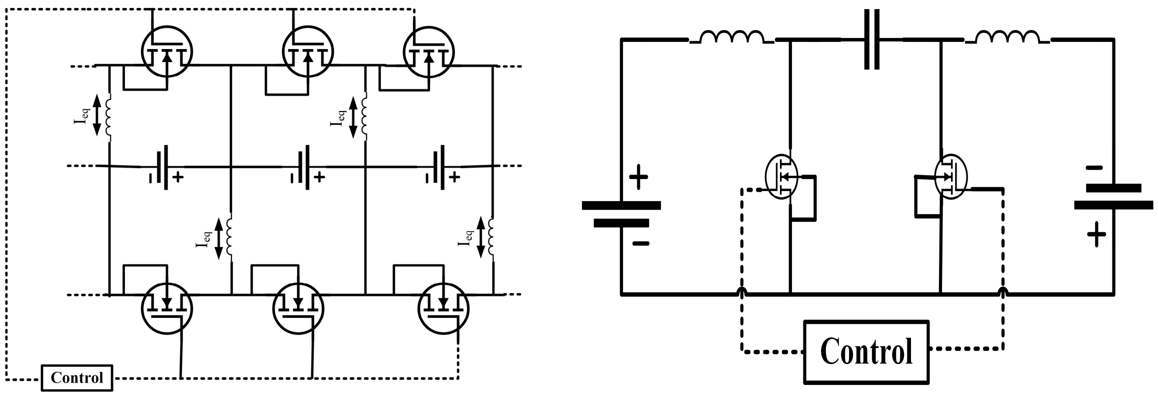


Figure 26. Battery cell arrangement in a battery pack. Cooling tubes are used to dissipate the heat generated in the battery cells.

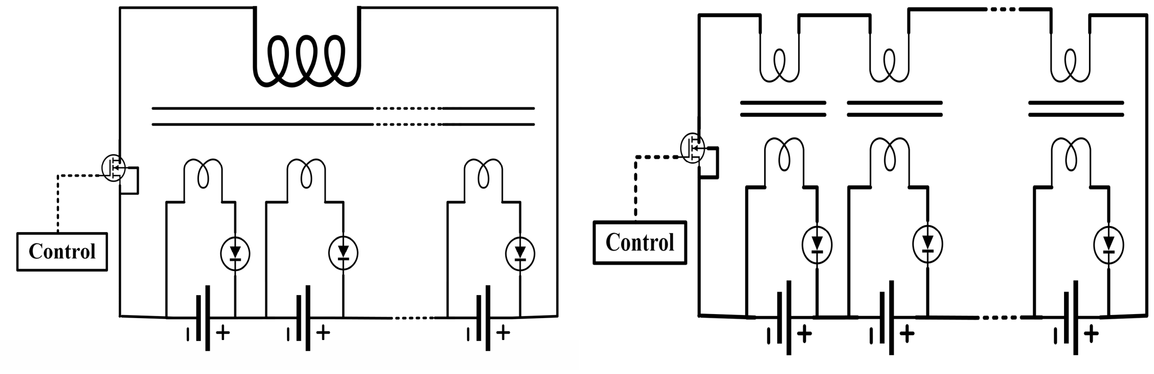


(**a**) (**b**)

Figure 27. Equalizer configurations: (**a**) Resistive equalizer, extra power from any cell is burned up in the resistance; (**b**) Capacitive equalizer, excess energy is transferred to lower energy cells by switching of capacitors.



(**a**) (**b**)



(**c**) (**d**)

Figure 28. Inductive equalizer configurations: (**a**) Basic; (**b**) Cuk; (**c**) Transformer based; (**d**) Multiple transformers based. Excess energy is transferred to lower energy cells by using inductors.

Table 8. Advantages and disadvantages of different equalizer types. Data from [46–52].

Equalizer Type	Advantage	Disadvantage
Resistive	• Cheapest, widely utilized for laptop batteries	• Inherent heating problem • Low equalizing current (300–500) mA • Only usable in the last stages of charging and flotation • Efficiency is almost 0% • All equalizing current transforms into heat for EV application, therefore not recommended
Capacitive	• Better current capabilities than resistive equalizers • No control issue • Simple implementation	• Unable to control inrush current • Potentially harmful current ripples can flow for big cell voltage differences • Cannot provide any required voltage difference which is essential for SOC equalization
Basic Inductive	• Relatively simple • Capable of transporting high amount of energy • Can handle complex control schemes like voltage difference control and current limitation • Can compensate for internal resistance of cells • Increased equalizing current • Not dependent on cell voltage	• Requires additional components to prevent ripple currents • Needs two switches in addition to drivers and controls in each cell • Current distribution is highly concentrated in neighboring cells because of switching loss
Cuk Inductive	• Has all the advantages of inductive equalizres • Can accommodate complex control and withstand high current	• Additional cost of higher voltage and current rated switches, power capacitors • Subjected to loss caused by series capacitor • A little less efficient than typical inductive equalizers • Faces problems during distributing equalizing currents all over the cell string • May need additional processing power
Transformer based Inductive	• Theoretically permits proper current distribution in all cells without addition control or loss	• Complex transformer with multiple secondary, which is very much challenging to mass produce • Not an option for EV packs • Cannot handle complex control algorithms
Multiple transformer based Inductive	• Separate transformers are used which are easier for mass production	• Still difficult to build with commercial inductors without facing voltage and current imbalance

Table 9. Comparison of equalizers; a ↑ sign indicates an advantage whereas the ↓ signs indicate drawbacks. Adapted from [46].

Equalizer Type	Equalizer Current	Current Distribution	Current Control	Current Ripple	Manufacture	Cost	Control
Resistive	↓ ↓	N/A	↑	↑ ↑ ↑	↑ ↑ ↑	↑ ↑ ↑	↑ ↑ ↑
Capacitive	↓	↑	↓ ↓	↓ ↓	↑ ↑	↑ ↑	↑ ↑
Basic Inductive	↑ ↑	↑	↑	↑ ↑	↑	↓	↓
Cuk	↑ ↑	↑	↑	↑ ↑ ↑	↓	↓ ↓	↓
Transformer	↑	↑ ↑ ↑	↓ ↓	↓ ↓	↓ ↓	↓ ↓	↑ ↑

Lithium-ion batteries are being used everywhere these days. It has replaced the lead-acid counterpart and became a mature technology itself. Their popularity can be justified by the fact that best-selling EVs, for example, Nissan Leaf and Tesla Model S—all use these batteries [53,54]. Battery parameters of some current EVs are shown in Table 10. Lithium batteries also have lots of scope to improve [55]. Better battery technologies have been discovered already, but they are not being pursued because of the exorbitant costs associated with their research and development, so it can be said that, lithium batteries will dominate the EV scene for quite some time to come.

Table 10. Battery parameters of some current EVs. Data from [5].

Model	Total Energy (kWh)	Usable Energy (kWh)	Usable Energy (%)
i3	22	18.8	85
C30	24	22.7	95
B-Class	36	28	78
e6	61.4	57	93
RAV4	41.8	35	84

4.2. Ultracapacitors (UCs)

UCs have two electrodes separated by an ion-enriched liquid dielectric. When a potential is applied, the positive electrode attracts the negative ions and the negative electrode gathers the positive ones. The charges get stored physically stored on electrodes this way and provide a considerably high power density. As no chemical reactions take place on the electrodes, ultra-capacitors tend to have a long cycle life; but the absence of any chemical reaction also makes them low in energy density [35]. The internal resistance is low too, making it highly efficient, but it also causes high output current if charged at a state of extremely low SOC [56,57]. A UC's terminal voltage is directly proportional to its SOC; so it can also operate all through its voltage range [35]. Basic construction of an UC cell is shown in Figure 29. EVs go through start/stop conditions quite a lot, especially in urban driving situations. This makes the battery discharge rate highly changeable. The average power required from batteries is low, but during acceleration or conditions like hill-climb a high power is required in a short duration of time [4,35]. The peak power required in a high-performance electric vehicle can be up to sixteen times the average power [4]. UCs fit in perfectly in such a scenario as it can provide high power for short durations. It is also fast in capturing the energy generated by regenerative braking [2,35]. A combined battery-UC system (as shown in Figure 30) negates each other's shortcomings and provides an efficient and reliable energy system. The low cost, load leveling capability, temperature adaptability and long service life of UCs make them a likable option as well [4,30].

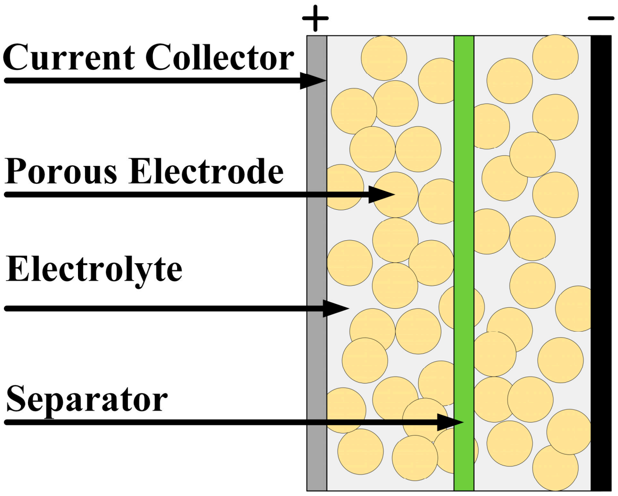


Figure 29. An UC cell; a separator keeps the two electrodes apart [58].

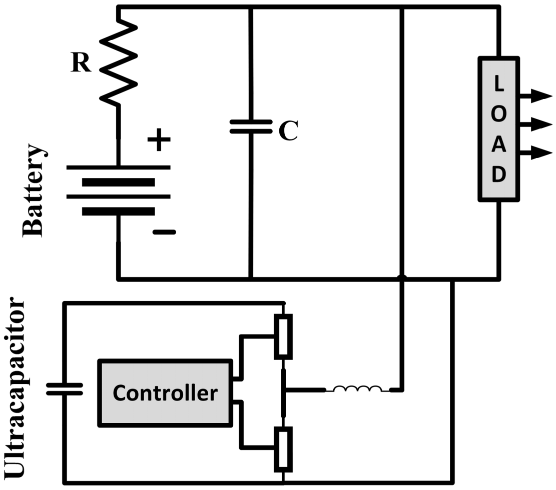


Figure 30. Combination of battery and UC to complement each-other's shortcomings [59].

4.3. Fuel Cell (FC)

Fuel cells generate electricity by electrochemical reaction. An FC has an anode (A), a cathode (C) and an electrolyte (E) between them. Fuel is introduced to the anode, gets oxidized there, the ions created travel through the electrolyte to the cathode and combine with the other reactant introduced there. The electrons produced by oxidation at the anode produce the electricity. Hydrogen is used in FCEVs because of its high energy content, and the facts it is non-polluting (producing only water as exhaust) and abundant in Nature in the form of different compounds such as hydrocarbons [4]. Hydrogen can be stored in different methods for use in EVs [4]; commercially available FCVs like the Toyota Mirai use cylinders to store it. The operating principle of a general fuel cell is demonstrated in Figure 31, while Figure 32 shows a hydrogen fuel cell. According to the material used, fuel cells can be classified into different types. A comparison among them is shown in Table 11. The chemical reaction governing the working of a fuel cell is stated below:

$$2H_2 + O_2 = 2H_2O \quad (1)$$

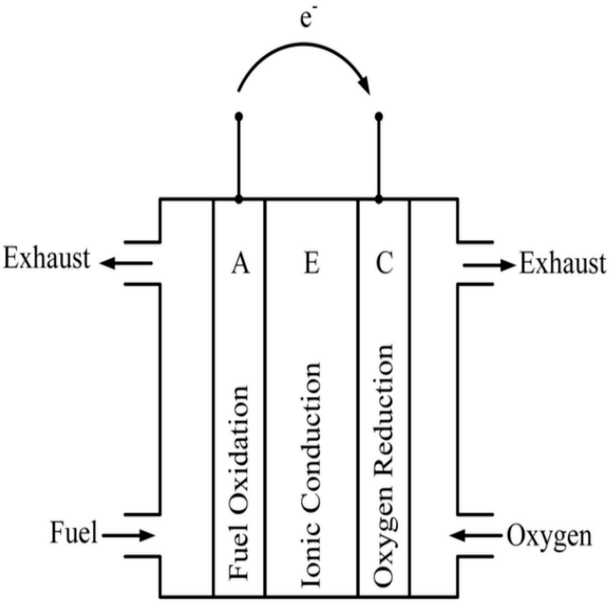


Figure 31. Working principle of fuel cell. Fuel and oxygen is taken in, exhaust and current is generated as the products of chemical reaction. Adapted from [4].

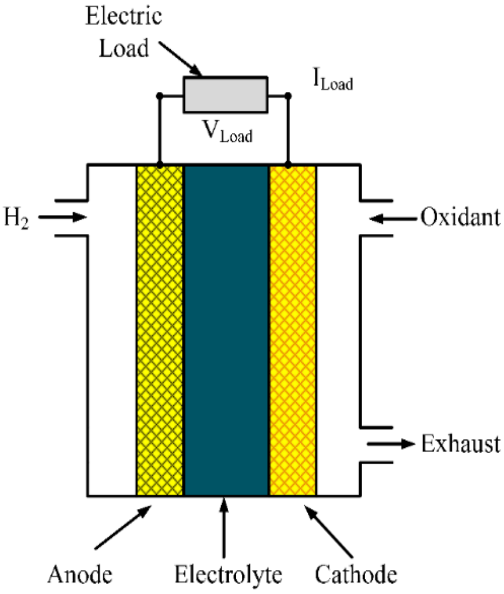


Figure 32. Hydrogen fuel cell configuration. Hydrogen is used as the fuel which reacts with oxygen and produces water and current as products. Adapted from [35].

Table 11. Comparison of different fuel cell configurations. Data from [2].

	PAFC	AFC	MCFC	SOFC	SPFC	DMFC
Working temp. (°C)	150–210	60–100	600–700	900–1000	50–100	50–100
Power density (W/cm^2)	0.2–0.25	0.2–0.3	0.1–0.2	0.24–0.3	0.35–0.6	0.04–0.25
Estimated life (kh)	40	10	40	40	40	10
Estimated cost (USD/kW)	1000	200	1000	1500	200	200

PAFC: Phosphoric acid fuel cell; AFC: Alkaline fuel cell; SOFC: Solid oxide fuel cell; SPFC: Solid polymer fuel cell, also known as proton exchange membrane fuel cell.

Fuel cells have many advantages for EV use like efficient production of electricity from fuel, noiseless operation, fast refueling, no or low emissions, durability and the ability to provide high density current output [24,60]. A main drawback of this technology is the high price. Hydrogen also have lower energy density compared to petroleum derived fuel, therefore larger fuel tanks are required for FCEVs, these tanks also have to capable enough to contain the hydrogen properly and to minimize risk of any explosion in case of an accident. FC's efficiency depends on the power it is supplying; efficiency generally decreases if more power is drawn. Voltage drop in internal resistances cause most of the losses. Response time of FCs is comparatively higher to UCs or batteries [35]. Because of these reasons, storage like batteries or UCs is used alongside FCs. The Toyota Mirai uses batteries to power its motor and the FC is used to charge the batteries. The batteries receive the power reproduced by regenerative braking as well. This combination provides more flexibility as the batteries do not need to be charged, only the fuel for the FC has to be replenished and it takes far less time than recharging the batteries.

4.4. Flywheel

Flywheels are used as energy storage by using the energy to spin the flywheel which keeps on spinning because of inertia. The flywheel acts as a motor during the storage stage. When the energy is needed to be recovered, the flywheel's kinetic energy can be used to rotate a generator to produce power. Advanced flywheels can have their rotors made out of sophisticated materials like carbon composites and are placed in a vacuum chamber suspended by magnetic bearings. Figure 33 shows a flywheel used in the Formula One (F1) racing kinetic energy recovery system (KERS). The major components of a flywheel are demonstrated in Figure 34. Flywheels offer a lot of advantages over other storage forms for EV use as they are lighter, faster and more efficient at absorbing power from regenerative braking, faster at supplying a huge amount of power in a short time when rapid acceleration is needed and can go through a lot of charge-discharge cycles over their lifetime. They are especially favored for hybrid racecars which go through a lot of abrupt braking and acceleration, which are also at much higher g-force than normal commuter cars. Storage systems like batteries or UCs cannot capture the energy generated by regenerative braking in situations like this properly. Flywheels, on the other hand, because of their fast response, have a better efficiency in similar scenarios, by making use of regenerative braking more effectively; it reduces pressure on the brake pads as well. The Porsche 911GT3R hybrid made use of this technology. Flywheels can be made with different materials, each with their own merits and demerits. Characteristics of some these materials are shown in Table 12; among the ones displayed in the table, carbon T1000 offers the highest amount of energy density, but it is much costlier than the others. Therefore, there remains a trade-off between cost and performance.

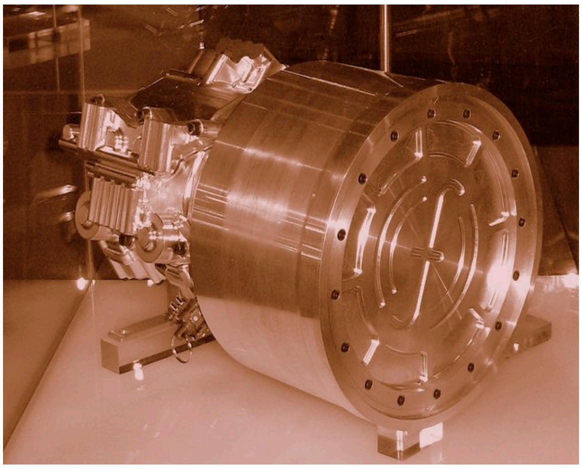


Figure 33. A flywheel used in the Formula One racing kinetic energy recovery system (KERS).

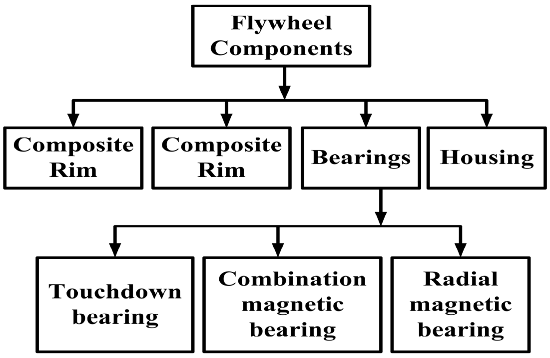


Figure 34. Basic flywheel components. The flywheel is suspended in tis hosing by bearings, and is connected to a motor-generator to store and supply energy [61].

Table 12. Characteristics of different materials used for flywheels [62].

Material		Density (kg/m³)	Tensile Strength (mpa)	Max Energy Density (mj/kg)	Cost (USD/kg)
Monolithic material	4340 steel	7700	1520	0.19	1
Composites	E-glass	2000	100	0.05	11
	S2-glass	1920	1470	0.76	24.6
	Carbon T1000	1520	1950	1.28	101.8
	Carbon AS4C	1510	1650	1.1	31.3

Currently, no single energy source can provide the ideal characteristics, i.e., high value of both power and energy density. Table 13 shows a relative comparison of the energy storages to demonstrate this fact. Hybrid energy storages can be used to counter this problem by employing one source for high energy density and another for high power density. Different combinations are possible to create this hybrid system. It can be a combination of battery and ultracapacitor, battery and flywheel, or fuel cell and battery [4]. Table 14 shows the storage systems used by some current vehicles.

Table 13. Relative energy and power densities of different energy storage systems [63].

Storage	Energy Density	Power Density
Battery	High	Low
Ultracapacitor	Low	High
Fuel cell	High	Low
Flywheel	Low	High

Table 14. Vehicles using different storage systems.

Storage System	Vehicles Using the System
Battery	Tesla Model S, Nissan Leaf
Fuel cell + battery	Toyota Mirai, Honda Clarity
Flywheel	Porsche 911GT3R Hybrid

5. Motors Used

The propulsion system is the heart of an EV [64–69], and the electric motor sits right in the core of the system. The motor converts electrical energy that it gets from the battery into mechanical energy which enables the vehicle to move. It also acts as a generator during regenerative action which sends energy back to the energy source. Based on their requirement, EVs can have different numbers of motors: the Toyota Prius has one, the Acura NSX has three—the choice depends on the type of the vehicle and the functions it is supposed to provide. References [4,23] listed the requirements for a motor for EV use which includes high power, high torque, wide speed range, high efficiency, reliability, robustness, reasonable cost, low noise and small size. Direct current (DC) motor drives demonstrate some required properties needed for EV application, but their lack in efficiency, bulky structure, lack in reliability because of the commutator or brushes present in them and associated maintenance requirement made them less attractive [4,30]. With the advance of power electronics and control systems, different motor types emerged to meet the needs of the automotive sector, induction and permanent magnet (PM) types being the most favored ones [23,30,70].

5.1. Brushed DC Motor

These motors have permanent magnets (PM) to make the stator; rotors have brushes to provide supply to the stator. Advantages of these motors can be the ability to provide maximum torque in low speed. The disadvantages, on the other hand, are its bulky structure, low efficiency, heat generated because of the brushes and associated drop in efficiency. The heat is also difficult to remove as it is generated in the center of the rotor. Because of these reasons, brushed DC motors are not used in EVs any more [70].

5.2. Permanent Magnet Brushless DC Motor (BLDC)

The rotor of this motor is made of PM (most commonly NdFeB [4]), the stator is provided an alternating current (AC) supply from a DC source through an inverter. As there are no windings in the rotor, there is no rotor copper loss, which makes it more efficient than induction motors. This motor is also lighter, smaller, better at dissipating heat (as it is generated in the stator), more reliable, has more torque density and specific power [4]. But because of its restrained field-weakening ability, the constant power range is quite short. The torque also decreases with increased speed because of back EMF generated in the stator windings. The use of PM increases the cost as well [30,70]. However, enhancement of speed range and better overall efficiency is possible with additional field windings [4,71]. Such arrangements are often dubbed PM hybrid motors because of the presence of both PM and field windings. But such arrangements too are restrained by complexity of structure; the speed ratio is not enough to meet the needs of EV use, specifically in off-roaders [30]. PM hybrid motors can also be constructed using a combination of reluctance motor and PM motor. Controlling the conduction angle of the power converter can improve the efficiency of PM BLDCs as well as speed range, reaching as high as four times the base speed, though the efficiency may decrease at very high speed resulting from demagnetization of PM [4]. Other than the PM hybrid configurations, PM BLDCs can be buried magnet mounted—which can provide more air gap flux density, or surface magnet mounted—which require less amount of magnet. BLDCs are useful for use in small cars requiring a maximum 60 kW of power [72]. The characteristics of PM BLDCs are shown in Figure 35.

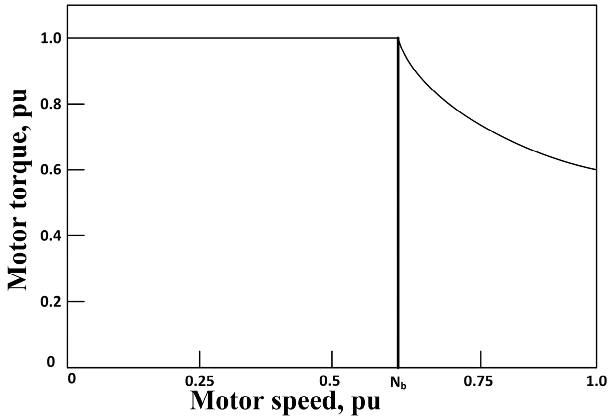


Figure 35. Characteristics of a Permanent Magnet Brushless DC Motor. The torque remains constant at the maximum right from the start, but starts to decrease exponentially for speeds over the base speed.

5.3. Permanent Magnet Synchronous Motor (PMSM)

These machines are one of the most advanced ones, capable of being operated at a range of speeds without the need of any gear system. This feature makes these motors more efficient and compact. This configuration is also very suitable for in-wheel applications, as it is capable of providing high torque, even at very low speeds. PMSMs with an outer rotor are also possible to construct without the need of bearings for the rotor. But these machines' only notable disadvantage also comes in during in-wheel operations where a huge iron loss is faced at high speeds, making the system unstable [73]. NdFeB PMs are used for PMSMs for high energy density. The flux linkages in the air-gap are sinusoidal in nature; therefore, these motors are controllable by sinusoidal voltage supplies and vector control [70]. PMSM is the most used motor in the BEVs available currently; at least 26 vehicle models use this motor technology [5].

5.4. Induction Motor (IM)

Induction motors are used in early EVs like the GM EV1 [23] as well as current models like the Teslas [54,74]. Among the different commutatorless motor drive systems, this is the most mature one [2]. Vector control is useful to make IM drives capable of meeting the needs of EV systems. Such a system with the ability to minimize loss at any load condition is demonstrated in [75]. Field orientation control can make an IM act like a separately excited DC motor by decoupling its field control and torque control. Flux weakening can extend the speed range over the base speed while keeping the power constant [30], field orientation control can achieve a range three to five times the base speed with an IM that is properly designed [76]. Three phase, four pole AC motors with copper rotors are seen to be employed in current EVs. Characteristics of IM are shown in Figure 36.

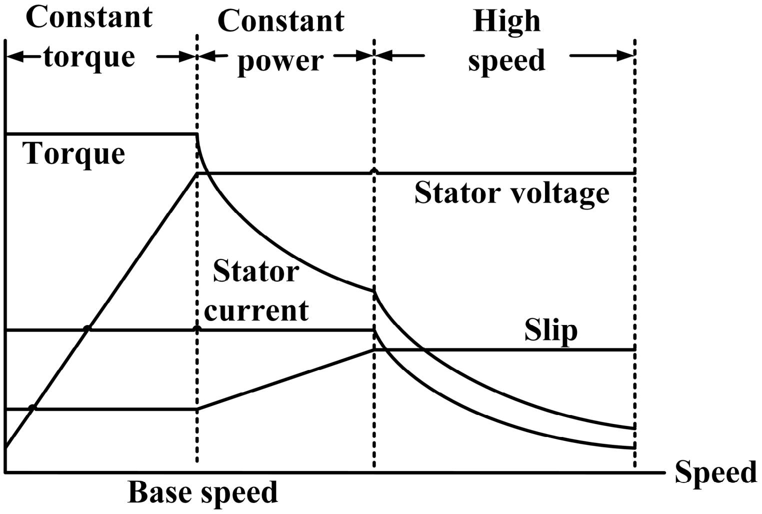


Figure 36. Induction motor drive characteristics. Maximum torque is maintained till base speed, and then decreases exponentially. Adapted from [4].

5.5. Switched Reluctance Motor (SRM)

SRMs, also known as doubly salient motor (because of having salient poles both in the stator and the rotor) are synchronous motors driven by unipolar inverter-generated current. They demonstrate simple and robust mechanical construction, low cost, high-speed, less chance of hazards, inherent long constant power range and high power density useful for EV applications. PM is not required for such motors and that facilitates enhanced reliability along with fault tolerance. On the downside, they are very noisy because of the variable torque nature, have low efficiency, and are larger in size and weight when compared to PM machines. Though such machines have a simple construction, their design and control are not easy resulting from fringe effect of slots and poles and high saturation of the pole-tips [4,23,30,70]. Because of such drawbacks, these machines did not advance as much as the PM or induction machines. However, because of the high cost rare-rare earth materials needed in PM machines, interest in SRMs are increasing. Advanced SRMs like the one demonstrated by Nidec in 2012 had almost interior permanent machine (IPM)-like performance, with a low cost. Reducing the noise and torque ripple are the main concerns in researches associated with SRMs [23]. One of the configurations that came out of these researches uses a dual stator system, which provides low inertia and noise, superior torque density and increased speed-range compared to conventional SRMs [77,78]. Design by finite element analysis can be employed to reduce the total loss [79], control by fuzzy sliding mode can also be employed to reduce control chattering and motor nonlinearity management [80].

5.6. Synchronous Reluctance Motor (SynRM)

A Synchronous Reluctance Motor runs at a synchronous speed while combining the advantages of both PM and induction motors. They are robust and fault tolerant like an IM, efficient and small like a PM motor, and do not have the drawbacks of PM systems. They have a control strategy similar to that of PM motors. The problems with SynRM can be pointed as the ones associated with controllability, manufacturing and low power factor which hinder its use in EVs. However, researches have been going on and some progress is made as well, the main area of concern being the rotor design. One way to improve this motor is by increasing the saliency which provides a higher power factor. It can be achieved by axially or transversally laminated rotor structures, such an arrangement is shown in Figure 37. Improved design techniques, control systems and advanced manufacturing can help it make its way into EV applications [23].

Figure 37. SynRM with axially laminated rotor [23].

5.7. PM Assisted Synchronous Reluctance Motor

Greater power factors can be achieved from SynRMs by integrating some PMs in the rotor, creating a PM assisted Synchronous Reluctance Motor. Though it is similar to an IPM, the PMs used are fewer in amount and the flux linkages from them are less too. PMs added in the right amount to the core of the rotor increase the efficiency with negligible back EMF and little change to the stator. This concept is free from the problems associated with demagnetization resulting from overloading and high temperature observed in IPMs. With a proper efficiency optimization technique, this motor can have the performance similar to IPM motors. A PM-assisted SynRM suitable for EV use was demonstrated by BRUSA Elektronik AG (Sennwald, Switzerland). Like the SynRM, PM-assisted SynRMs can also get better with improved design techniques, control systems and advanced manufacturing systems [23]. A demonstration of the rotor of PM-assisted SynRM is shown in Figure 38.

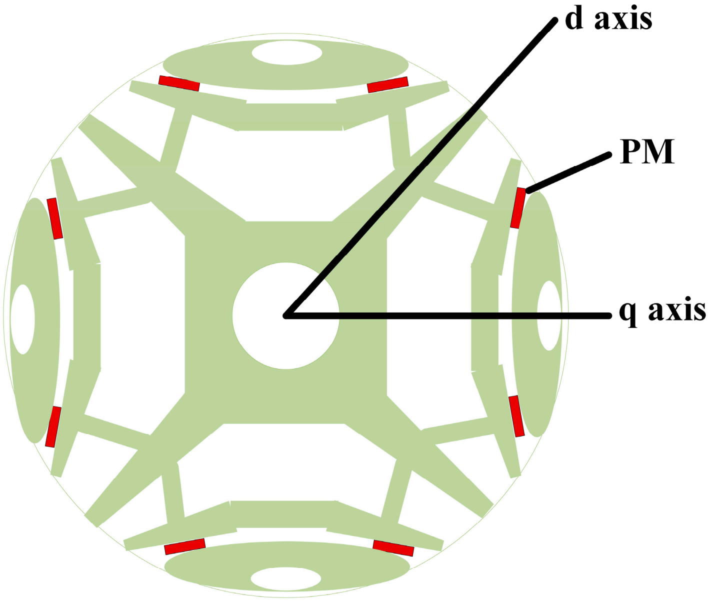


Figure 38. Permanent magnet (PM) assisted SynRM. Permanent magnets are embedded in the rotor [23].

5.8. Axial Flux Ironless Permanent Magnet Motor

According to [70], this motor is the most advanced one to be used in EVs. It has an outer rotor with no slot; use of iron is avoided here as well. The stator core is absent too, reducing the weight of the machine. The air gap here is radial field type, providing better power density. This motor is a variable speed one too. One noteworthy advantage of this machine is that the rotors can be fitted on lateral sides of wheels, placing the stator windings on the axle centrally. The slot-less design also improves the efficiency by minimizing copper loss as there is more space available [70].

Power comparison of three different motor types is conducted in Table 15. Table 16 compares torque densities of three motors. Table 17 summarizes the advantages and disadvantages of different motor types, and shows some vehicles using different motor technologies.

Table 15. Power comparison of different motors having the same size. Data from [72].

Motor Type	**Power (kW)**		**Base Speed**	**Maximum Speed**
	HEV	**BEV**		
IM	57	93	3000	12,000
SRM	42	77	2000	12,000
BLDC	75	110	4000	9000

Table 16. Typical torque density values of some motors. Data from [30].

Motor Type	**Torque/Volume (Nm/m³)**	**Torque/Cu Mass (Nm/kg Cu)**
PM motor	28860	28.7–48
IM	4170	6.6
SRM	6780	6.1

Table 17. Advantages, disadvantages and usage of different motor types.

Motor Type	Advantage	Disadvantage	Vehicles Used In
Brushed DC Motor	• Maximum torque at low speed	• Bulky structure • Low efficiency • Heat generation at brushes	Fiat Panda Elettra (Series DC motor), Conceptor G-Van (Separately excited DC motor)
Permanent Magnet Brushless DC Motor (BLDC)	• No rotor copper loss • More efficiency than induction motors • Lighter • Smaller • Better heat dissipation • More reliability • More torque density • More specific power	• Short constant power range • Decreased torque with increase in speed • High cost because of PM	Toyota Prius (2005)
Permanent Magnet Synchronous Motor (PMSM)	• Operable in different speed ranges without using gear systems • Efficient • Compact • Suitable for in-wheel application • High torque even at very low speeds	• Huge iron loss at high speeds during in-wheel operation	Toyota Prius, Nissan Leaf, Soul EV
Induction Motor (IM)	• The most mature commutatorless motor drive system • Can be operated like a separately excited DC motor by employing field orientation control		Tesla Model S, Tesla Model X, Toyota RAV4, GM EV1
Switched Reluctance Motor (SRM)	• Simple and robust construction • Low cost • High speed • Less chance of hazard • Long constant power range • High power density	• Very noisy • Low efficiency • Larger and heavier than PM machines • Complex design and control	Chloride Lucas
Synchronous Reluctance Motor (SynRM)	• Robust • Fault tolerant • Efficient • Small	• Problems in controllability and manufacturing • Low power factor	
PM assisted Synchronous Reluctance Motor	• Greater power factor than SynRMs • Free from demagnetizing problems observed in IPM		BMW i3
Axial Flux Ironless Permanent Magnet Motor	• No iron used in outer rotor • No stator core • Lightweight • Better power density • Minimized copper loss • Better efficiency • Variable speed machine • Rotor is capable of being fitted to the lateral side of the wheel		Renovo Coupe

6. Charging Systems

For charging of EVs, DC or AC systems can be used. There are different current and voltage configurations for charging, generally denoted as 'levels'. The time required for a full charge depends on the level being employed. Wireless charging has also been tested and researched for quite a long time. It has different configurations as well. The charging standards are shown in Table 18. The safety standards that should be complied by the chargers are the following [46]:

- SAE J2929: Electric and Hybrid Vehicle Propulsion Battery System Safety Standard
- ISO 26262: Road Vehicles—Functional safety
- ISO 6469-3: Electric Road Vehicles—Safety Specifications—Part 3: Protection of Persons Against Electric Hazards

- ECE R100: Protection against Electric Shock
- IEC 61000: Electromagnetic Compatibility (EMC)
- IEC 61851-21: Electric Vehicle Conductive Charging system—Part 21: Electric Vehicle Requirements for Conductive Connection to an AC/DC Supply
- IEC 60950: Safety of Information Technology Equipment
- UL 2202: Electric Vehicle (EV) Charging System Equipment
- FCC Part 15 Class B: The Federal Code of Regulation (CFR) FCC Part 15 for EMC Emission Measurement Services for Information Technology Equipment.
- IP6K9K, IP6K7 protection class
- −40 °C to 105 °C ambient air temperature

Table 18. Charging standards. Data from [81].

Standard	Scope	
IEC 61851: Conductive charging system	IEC 61851-1	Defines plugs and cables setup
	IEC 61851-23	Explains electrical safety, grid connection, harmonics, and communication architecture for DCFC station (DCFCS)
	IEC 61851-24	Describes digital communication for controlling DC charging
IEC 62196: Socket outlets, plugs, vehicle inlets and connectors	IEC 62196-1	Defines general requirements of EV connectors
	IEC 62196-2	Explains coupler classifications for different modes of charging
	IEC 62196-3	Describes inlets and connectors for DCFCS
IEC 60309: Socket outlets, plugs, and couplers	IEC 60309-1	Describes CS general requirements
	IEC 60309-2	Explains sockets and plugs sizes having different number of pins determined by current supply and number of phases, defines connector color codes according to voltage range and frequency.
IEC 60364		Explains electrical installations for buildings
SAE J1772: Conductive charging systems		Defines AC charging connectors and new Combo connector for DCFCS
SAE J2847: Communication	SAE J2847-1	Explains communication medium and criteria for connecting EV to utility for AC level 1&2 charging
	SAE J2847-2	Defines messages for DC charging
SAE J2293	SAE J2293-1	Explains total EV energy transfer system, defines requirements for EVSE for different system architectures
SAE J2344		Defines EV safety guidelines
SAE J2954: Inductive charging		Being developed

6.1. AC Charging

AC charging system provides an AC supply that is converted into DC to charge the batteries. This system needs an AC-DC converter. According to the SAE EV AC Charging Power Levels, they can be classified as below:

- Level 1: The maximum voltage is 120 V, the current can be 12 A or 16 A depending on the circuit ratings. This system can be used with standard 110 V household outlets without requiring any special arrangement, using on-board chargers. Charging a small EV with this arrangement can take 0.5–12.5 h. These characteristics make this system suitable for overnight charging [5,46,81].
- Level 2: Level 2 charging uses a direct connection to the grid through an Electric Vehicle Service Equipment (EVSE). On-board charger is used for this system. Maximum system ratings are 240 V, 60 A and 14.4 kW. This system is used as a primary charging method for EVs [46,81].
- Level 3: This system uses a permanently wired supply dedicated for EV charging, with power ratings greater than 14.4 kW. 'Fast chargers'—which recharge an average EV battery pack in no more than 30 min, can be considered level 3 chargers. All level 3 chargers are not fast chargers

though [46,82]. Table 19 shows the AC charging characteristics defined by Society of Automotive Engineers (SAE).

Table 19. SAE (Society of Automotive Engineers) AC charging characteristics. Data from [44,80].

AC Charging System	Supply Voltage (V)	Maximum Current (A)	Branch Circuit Breaker Rating (A)	Output Power Level (kW)
Level 1	120 V, 1-phase	12	15	1.08
	120 V, 1-phase	16	20	1.44
Level 2	208 to 240 V, 1-phase	16	20	3.3
	208 to 240 V, 1-phase	32	40	6.6
	208 to 240 V, 1-phase	≤80	Per NEC 635	≤14.4
Level 3	208/480/600 V	150–400	150	3

6.2. DC Charging

DC systems require dedicated wiring and installations and can be mounted at garages or charging stations. They have more power than the AC systems and can charge EVs faster. As the output is DC, the voltage has to be changed for different vehicles to suit the battery packs. Modern stations have the capability to do it automatically [46]. All DC charging systems has a permanently connected Electric Vehicle Service Equipment (EVSE) that incorporates the charger. Their classification is done depending on the power levels they supply to the battery:

- Level 1: The rated voltage is 450 V with 80 A of current. The system is capable of providing power up to 36 kW.
- Level 2: It has the same voltage rating as the level 1 system; the current rating is increased to 200 A and the power to 90 kW.
- Level 3: Voltage in this system is rated to 600 V. Maximum current is 400 A with a power rating of 240 kW. Table 20 shows the DC charging characteristics defined by Society of Automotive Engineers (SAE).

Table 20. SAE (Society of Automotive Engineers) DC charging characteristics. Data from [46].

DC Charging System	DC Voltage Range (V)	Maximum Current (A)	Power (kW)
Level 1	200–450	≤80	≤36
Level 2	200–450	≤200	≤90
Level 3	200–600	≤400	≤240

6.3. Wireless Charging

Wireless charging or wireless power transfer (WPT) enjoys significant interest because of the conveniences it offers. This system does not require the plugs and cables required in wired charging systems, there is no need of attaching the cable to the car, low risk of sparks and shocks in dirty or wet environment and less chance of vandalism. Forerunners in WPT research include R&D centers and government organizations like Phillips Research Europe, Energy Dynamic Laboratory (EDL), US DOT, DOE; universities including the University of Tennessee, the University of British Columbia, Korea Advance Institute of Science and Technology (KAIST); automobile manufacturers including Daimler, Toyota, BMW, GM and Chrysler. The suppliers of such technology include Witricity, LG, Evatran, HaloIPT (owned by Qualcomm), Momentum Dynamics and Conductix-Wampfler [27]. However, this technology is not currently available for commercial EVs because of the health and safety concerns associated with the current technology. The specifications are determined by different standardization organizations in different countries: Canadian Safety Code 6 in Canada [83], IEEE C95.1 in the USA [84], ICNIRP in Europe [85] and ARPANSA in Australia [86]. There are different technologies that are being considered to provide WPT facilities. They differ in the operating frequency, efficiency, associated electromagnetic interference (EMI), and other factors.

Inductive power transfer (IPT) is a mature technology, but it is only contactless, not wireless. Capacitive power transfer (CPT) has significant advantage at lower power levels because of low cost and size, but not suitable for higher power applications like EV charging. Permanent magnet coupling power transfer (PMPT) is low in efficiency, other factors are not favorable as well. Resonant inductive power transfer (RIPT) as well as On-line inductive power transfer (OLPT) appears to be the most promising ones, but their infrastructuret may not allow them to be a viable solution. Resonant antennae power transfer (RAPT) is made on a similar concept as RIPT, but the resonant frequency in this case is in MHz range, which is capable of damage to humans if not shielded properly. The shielding is likely to hinder range and performance; generation of such high frequencies is also a challenge for power electronics [87]. Table 21 compares different wireless charging systems in terms of performance, cost, size, complexity, and power level. Wireless charging for personal vehicles is unlikely to be available soon because of health, fire and safety hazards, misalignment problems and range. Roads with WPT systems embedded into them for charging passing vehicles also face major cost issues [27]. Only a few wireless systems are available now, and those too are in trial stage. WiTricity is working with Delphi Electronics, Toyota, Honda and Mitsubishi Motors. Evatran is collaborating with Nissan and GM for providing wireless facilities for Nissan Leaf and Chevrolet Volt models. However, with significant advance in the technology, wireless charging is likely to be integrated in the EV scenario, the conveniences it offers are too appealing to overlook.

Table 21. Comparison of wireless charging systems.

Wireless Charging System	**Performance**			**Cost**	**Volume/Size**	**Complexity**	**Power Level**
	Efficiency	**EMI**	**Frequency**				
Inductive power transfer (IPT)	Medium	Medium	10–50 kHz	Medium	Medium	Medium	Medium/High
Capacitive power transfer (CPT)	Low	Medium	100–500 kHz	Low	Low	Medium	Low
Permanent magnet coupling power transfer (PMPT)	Low	High	100–500 kHz	High	High	High	Medium/Low
Resonant inductive power transfer (RIPT)	Medium	Low	1–20 MHz	Medium	Medium	Medium	Medium/Low
On-line inductive power transfer (OLPT)	Medium	Medium	10–50 kHz	High	High	Medium	High
Resonant antennae power transfer (RAPT)	Medium	Medium	100–500 kHz	Medium	Medium	Medium	Medium/Low

For the current EV systems, on-board AC systems are used for the lowest power levels, for higher power, DC systems are used. DC systems currently have three existing standards [16]:

- Combined Charging System (CCS)
- CHAdeMO (CHArge de MOve, meaning: 'move by charge')
- Supercharger (for Tesla vehicles)

The powers offered by CCS and CHAdeMO are 50 kW and 120 kW for the Supercharger system [88,89]. CCS and CHAdeMO are also capable of providing fast charging, dynamic charging and vehicle to infrastructure (V2X) facilities [6,90]. Most of the EV charging stations at this time provides level 2 AC charging facilities. Level 3 DC charging network, which is being increased rapidly, is also available for Tesla cars. The stations may provide the CHAdeMO standard or the CCS, therefore, a vehicle has to be compatible with the configuration provided to be charged from the station. The CHAdeMO system is favored by the Japanese manufacturers like Nissan, Toyota and Honda whereas the European and US automakers, including Volkswagen, BMW, General Motors and Ford, prefer the CCS standard. Reference [5] discusses the charging systems used by current EVs along with the time required to get them fully charged.

7. Power Conversion Techniques

Batteries or ultracapacitors (UC) store energy as a DC charge. Normally they have to obtain that energy from AC lines connected to the grid, and this process can be wired or wireless. To deliver this energy to the motors, it has to be converted back again. These processes work in the reverse direction as well i.e., power being fed back to the batteries (regenerative braking) or getting supplied to grid when the vehicle in idle (V2G) [91]. Typical placement of different converters in an EV is shown in Figure 39 along with the power flow directions. This conversion can be DC-DC or DC-AC. For all this conversion work required to fill up the energy storage of EVs and then to use them to propel the vehicle, power converters are required [72], and they come in different forms. A detailed description of power electronics converters is provided in [92]. Further classification of AC-AC converters is shown in [93]. A detailed classification of converters is shown in Figure 40.

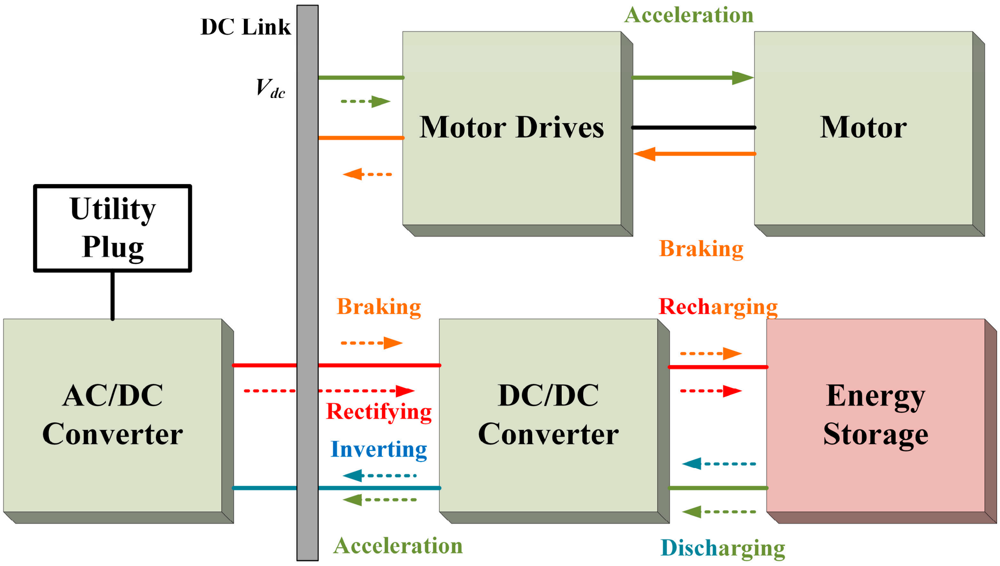


Figure 39. Typical placements of different converters in an EV. AC-DC converter transforms the power from grid to be stored in the storage through another stage of DC-DC conversion. Power is supplied to the motor from the storage through the DC-DC converter and the motor drives [72].

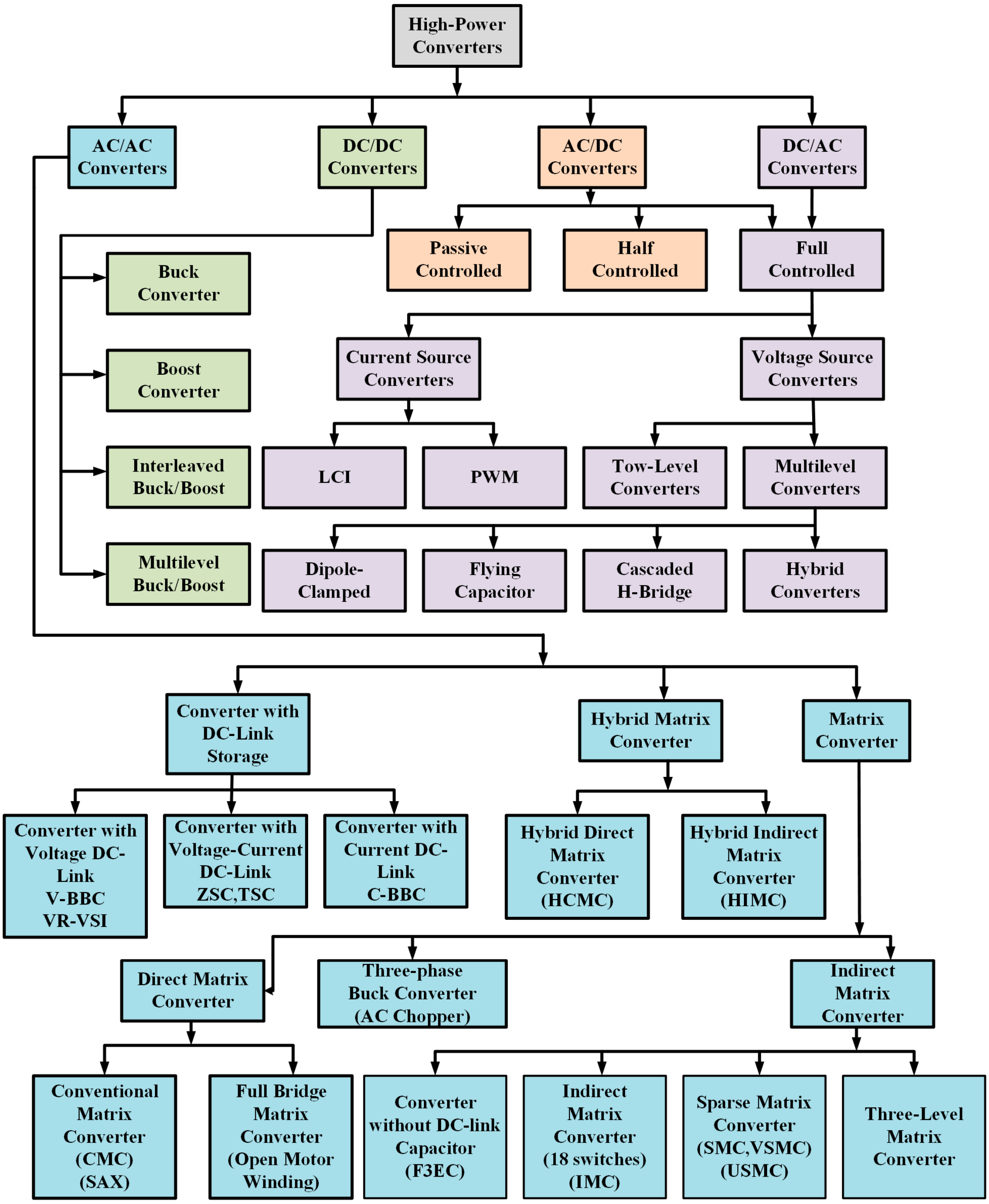


Figure 40. Detailed classification of converters. Data from [92,93].

7.1. Converters for Wired Charging

DC-DC boost converter is used to drive DC motors by increasing the battery voltage up to the operating level [72]. DC-DC converters are useful to combine a power source with a complementing energy source [94]. Figure 41 shows a universal DC-DC converter used for DC-DC conversion. It can be used as a boost converter for battery to DC link power flow and as a buck converter when the flow is reversed. The operating conditions and associated switching configuration is presented in Table 22. DC-DC boost converters can also use a digital signal processor [95].

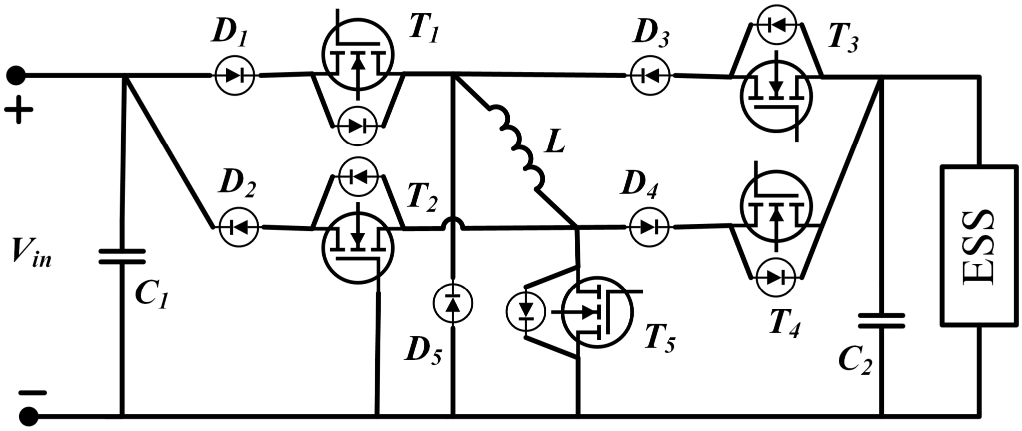


Figure 41. Universal DC-DC converter [72].

Table 22. Operating conditions for universal DC-DC converter. Adapted from [88].

Direction	Mode	T_1	T_2	T_3	T_4	T_5
V_{dc} to V_{batt}	Boost	On	Off	Off	On	PWM
V_{dc} to V_{batt}	Buck	PWM	Off	Off	On	Off
V_{batt} to V_{dc}	Boost	Off	On	On	Off	PWM
V_{batt} to V_{dc}	Buck	Off	On	PWM	Off	Off

According to [72], dual inverter is the most updated technology to drive AC motors like permanent magnet synchronous motors (PMSMs), shown in Figure 42. For dual voltage source applications, the system of Figure 43 is used [96]. These inverters operate on space vector PWM. For use on both PMSMs and induction motors (IMs), a bidirectional stacked matrix inverter can be used; such a system is shown in Figure 44.

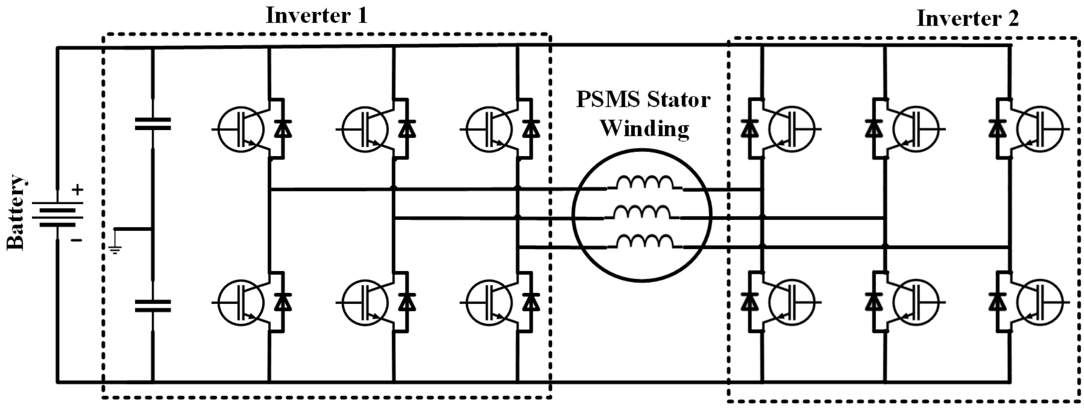


Figure 42. Dual inverter for single source [72].

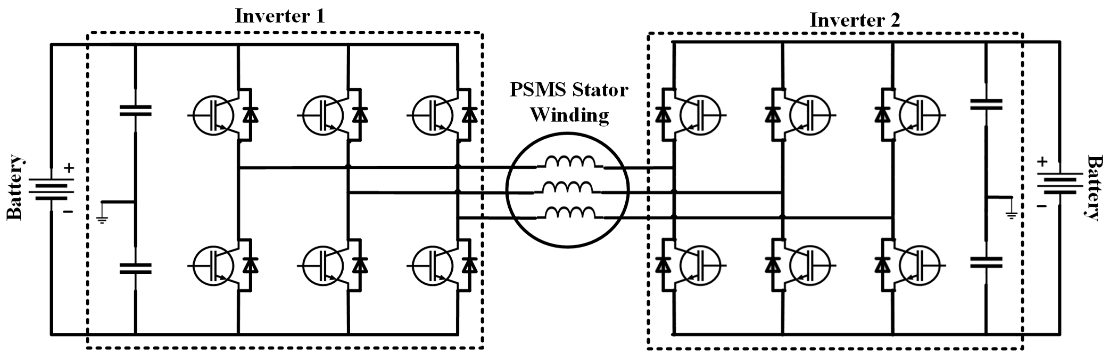


Figure 43. Dual inverter with dual sources [72].

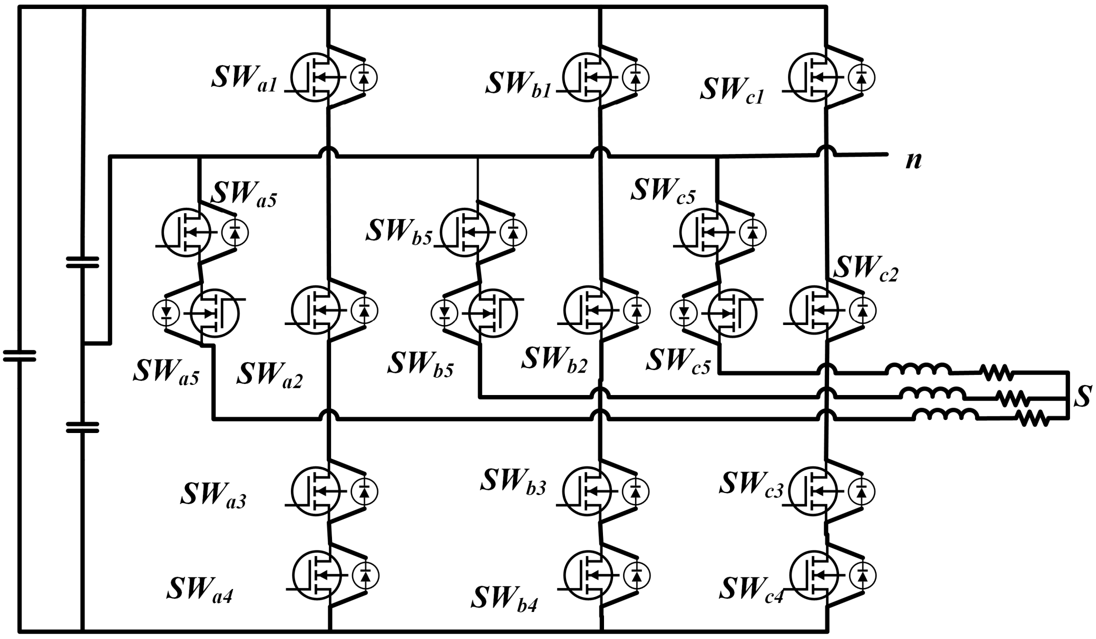


Figure 44. Novel stacked matrix inverter as shown in [97].

Some notable conventional DC-DC converters are: phase-shift full-bridge (PSFB), inductor-inductor-capacitor (LLC), and series resonant converter (SRC). A comparison of components used in these three converters is presented in [98], which is demonstrated here in Table 23. The DC-DC converters used are required to have low cost, weight and size for being used in automobiles [99]. Interleaved converters are a preferable option regarding these considerations, it offers some other advantages as well [100–103], though using it may increase the weight and volume of the inductors compared to the customary single-phase boost converters [99]. To solve this problem, Close-Coupled Inductor (CCI) and Loosely-Coupled Inductor (LCI) integrated interleaved converters have been proposed in [99]. In [48] converters for AC level-1 and level-2 chargers are shown by Williamson et al., who stated that Power Factor Correction (PFC) is a must to acquire high power density and efficiency. Two types of PFC technique are shown here: single-stage approach and two-stage approach. The first one suits for low-power use and charge only lead-acid batteries because of high low frequency ripple. To avoid these problems, the second technique is used.

Table 23. Comparison of components used in PSFB, LLC and SRC converter. Adapted from [98].

Item	PSFB	LLC	SRC
Number of switch blocks	4	4	4
Number of diode blocks	4	4	4
Number of transformers	1	1	2
Number of inductors	1	0	0
Additional capacitor	Blocking capacitor	-	-
Output filter size	Small	-	Large

In [34], Yong et al., presented the front end AC-DC converters. The Interleaved Boost PFC Converter (Figure 45) has a couple of boost converters connected in parallel and working in 180° out of phase [104–106]. The ripple currents of the inductors cancel each other. This configuration also provides twice the effective switching frequency and provides a lower ripple in input current, resulting in a relatively small EMI filter [103,107]. In Bridgeless/Dual Boost PFC Converter (Figure 46), the gating signals are made identical here by tying the power-train switches. The MOSFET gates are not made decoupled. Rectifier input bridge is not needed here. The Bridgeless Interleaved Boost PFC Converter (Figure 47) is proposed to operate above the 3.5 kW level. It has two MOSFETS and uses two fast diodes; the gating signals have a phase difference of 180°.

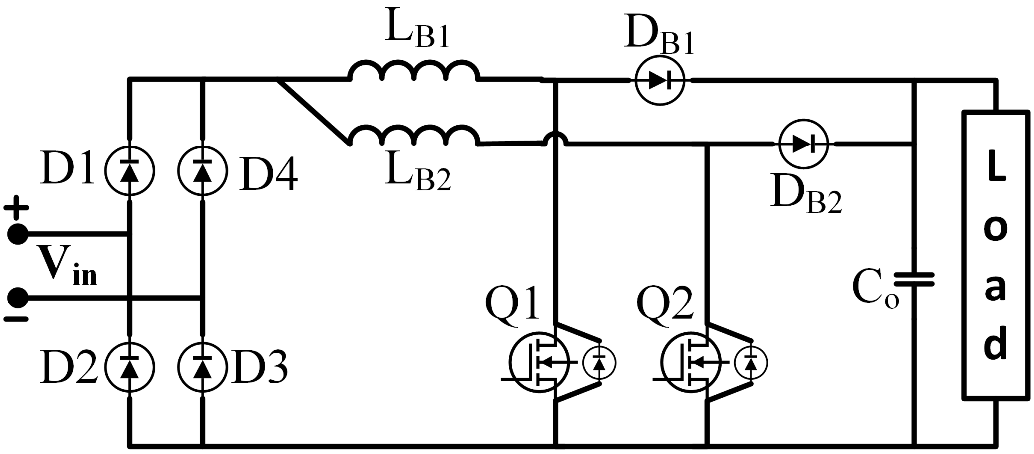


Figure 45. Interleaved Boost PFC Converter [46].

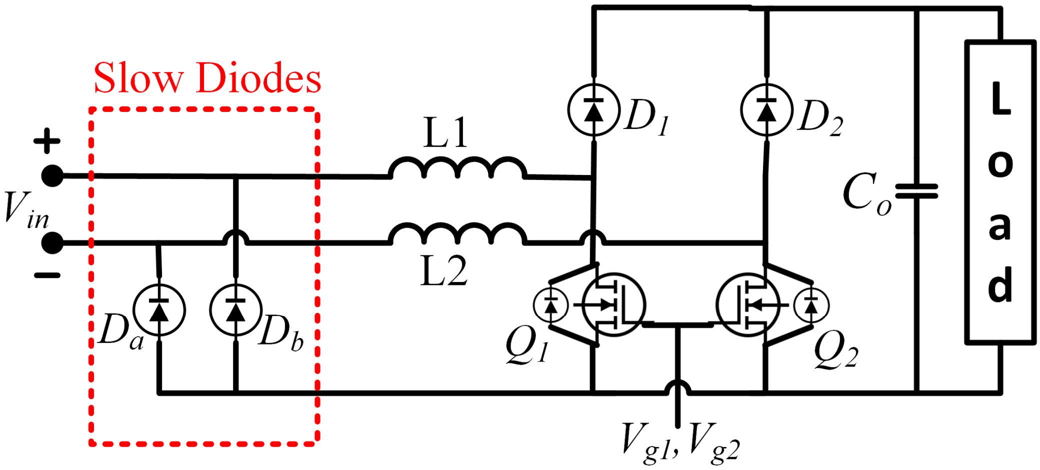


Figure 46. Bridgeless/Dual Boost PFC Converter. Adapted from [46].

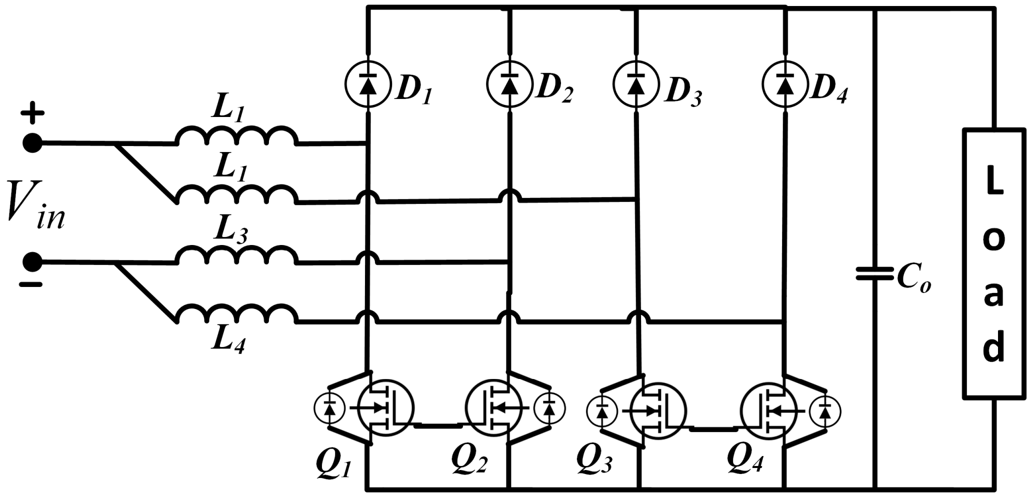


Figure 47. Bridgeless Interleaved Boost PFC Converter [46].

Williamson et al., presented some isolated DC-DC converter topologies in [44]. The ZVS FB Converter with Capacitive Output Filter (Figure 48) can achieve high efficiency as it uses zero voltage switching (ZVS) along with the capacitive output filters which reduces the ringing of diode rectifiers. The trailing edge PWM full-bridge system proposed in [107]. The Interleaved ZVS FB Converter with

Voltage Doubler (Figure 49) further reduces the voltage stress and ripple current on the capacitive output filter, it reduces the cost too. Interleaving allows equal power and thermal loss distribution in each cell. The number of secondary diodes is reduced significantly by the voltage doubler rectifier at the output [34]. Among its operating modes, DCM (discontinuous conduction mode) and BCM (boundary conduction mode) are preferable. The Full Bridge LLC Resonant Converter (Figure 50) is widely used in telecom industry for the benefits like high efficiency at resonant frequency. But unlike the telecom sector, EV applications require a wide operating range. Reference [41] shows a design procedure for such configurations for these applications.

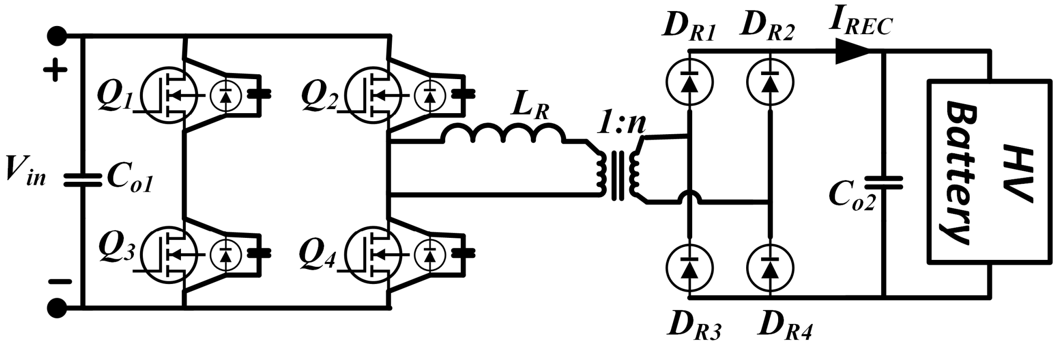


Figure 48. ZVS FB Converter with Capacitive Output Filter [46].

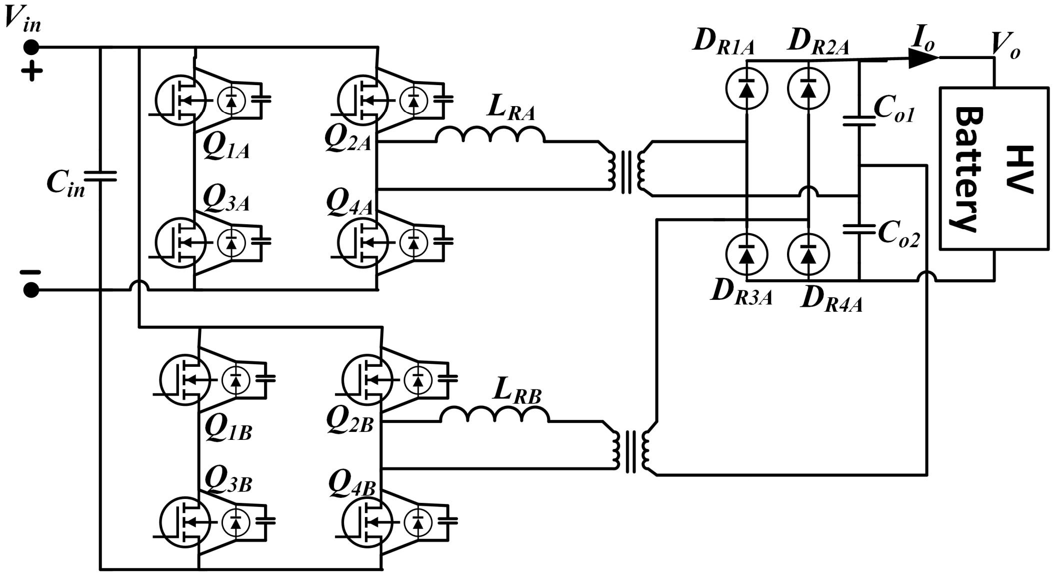


Figure 49. Interleaved ZVS FB Converter with Voltage Doubler [46].

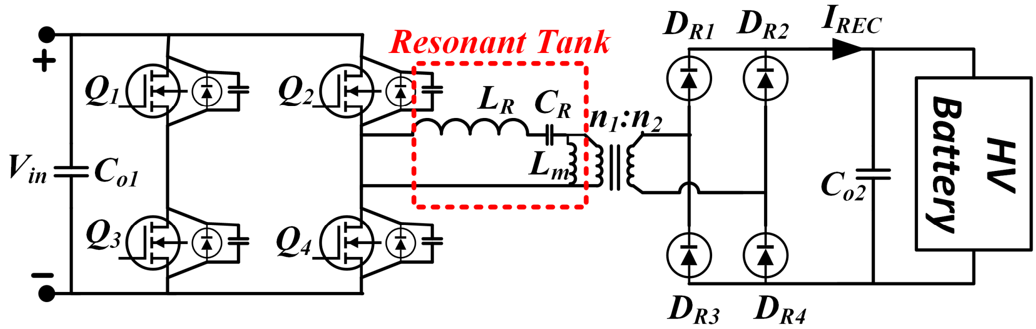


Figure 50. Full Bridge LLC Resonant Converter. Adapted from [46].

Balch et al., showed converter configurations that are used in different types of EVs in [42]. In Figure 51, a converter arrangement for a BEV is shown. An AC-DC charger is used for charging the battery pack here while a two-quadrant DC-DC converter is used for power delivery to the DC bus form the battery pack. This particular example included an ultracapacitor as well. An almost similar arrangement was shown in [42] for PHEVs (Figure 52) where a bidirectional DC-DC converter was used between the DC bus and the battery pack to facilitate regeneration. Use of integrated converter in PHEV is shown in Figure 53. Figure 54 shows converter arrangement for a PFCV; this configuration is quite similar to one shown for BEV, but it contains an additional boost converter to adjust the power produced by the fuel cell stack to be sent to the DC bus.

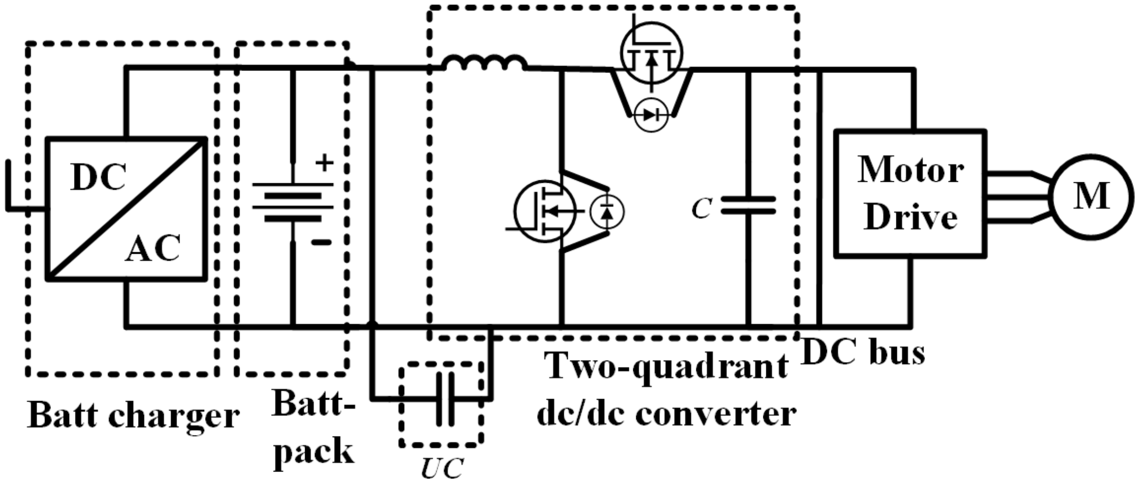


Figure 51. Converter placement in a pure EV [35]. The charger has an AC-DC converter to supply DC to the battery from the grid, whereas the DC-DC converter converts the battery voltage into a value required to drive the motor.

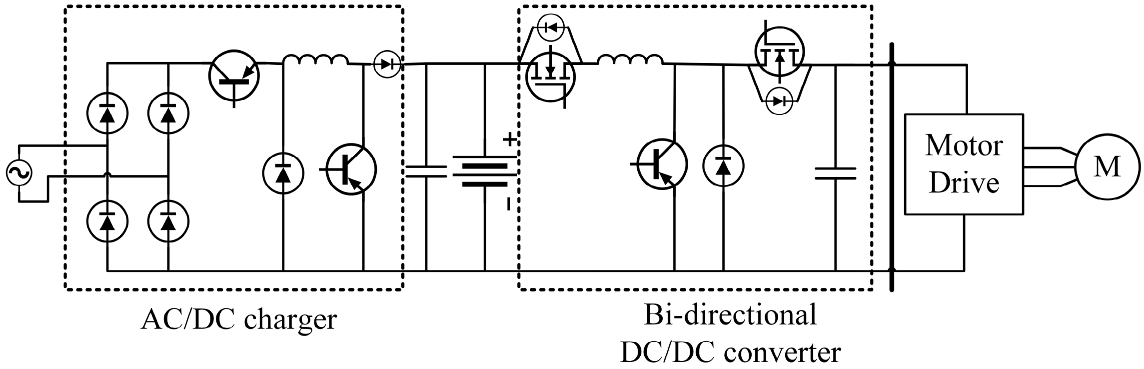


Figure 52. Cascaded converter to use in PHEV. Adapted from [35]. A bidirectional DC-DC converter is used between the DC bus and the battery pack to allow regenerated energy to flow back to the battery from the motor.

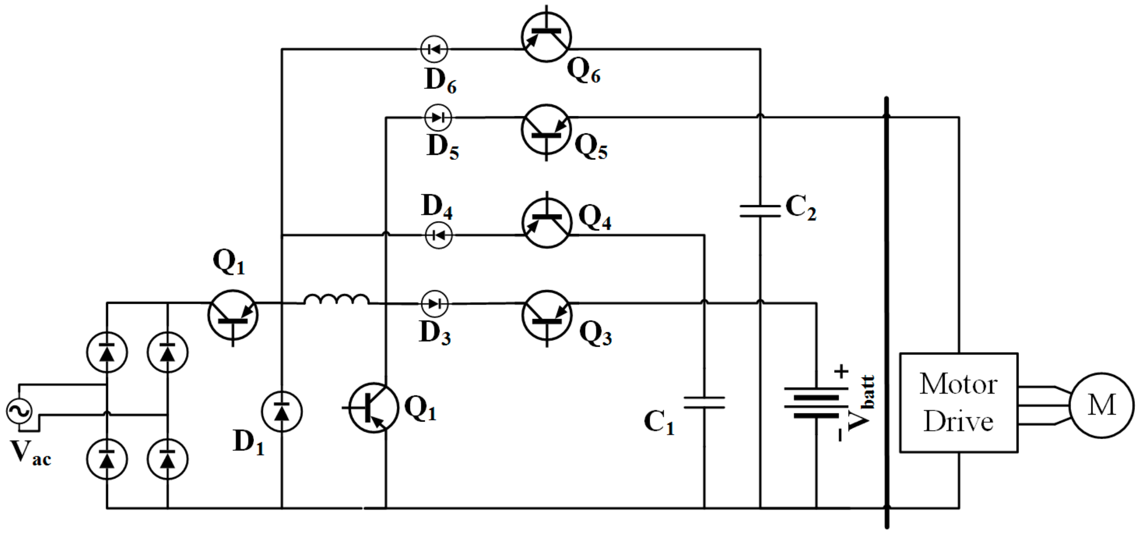


Figure 53. Integrated converter used in PHEV [35].

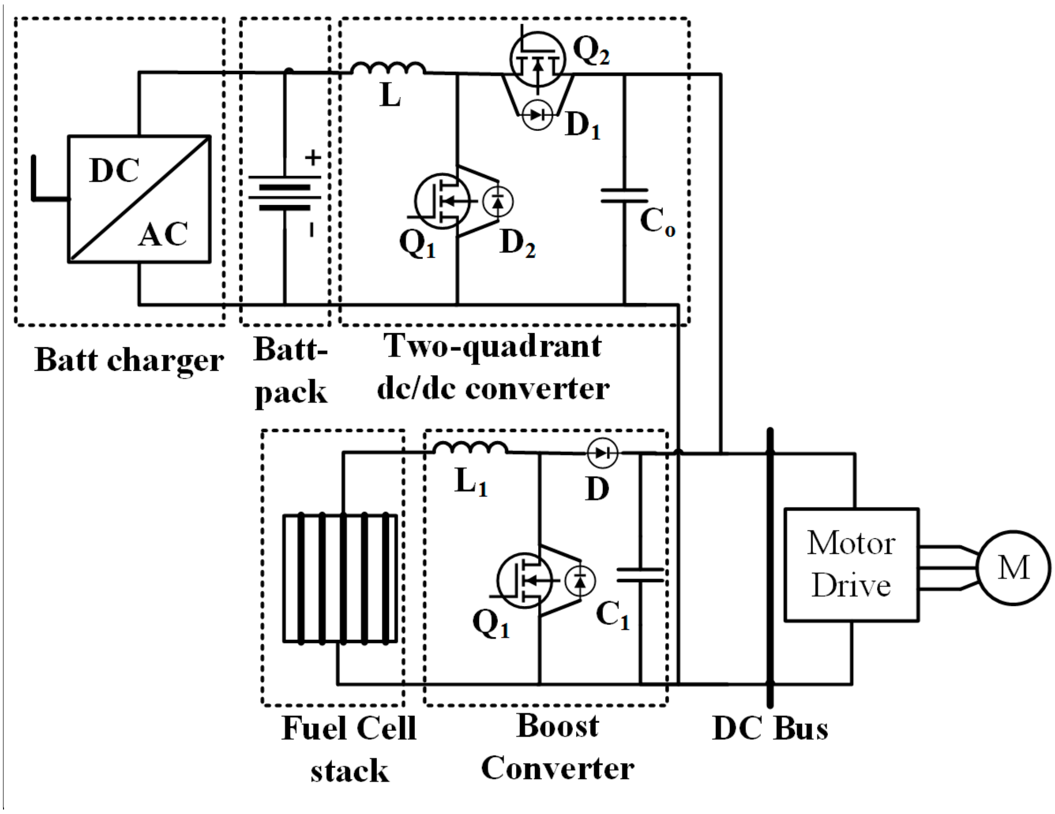


Figure 54. Converter arrangement in PFCV. Adapted from [35]. An AC-DC converter is used to convert the power from the grid; DC-DC converter is used for power exchange between the DC bus and battery; boost converter is used to make the voltage generated from the fuel cell stack suitable for the DC bus.

Bidirectional converters allow transmission of power from the motors to the energy sources and also from vehicle to grid. Novel topologies for bidirectional AC/DC-DC/DC converters to be used in PHEVs are being researched [103,108–112], such a configuration in shown in Figure 55. Kok et al., showed different DC-DC converter arrangements for EVs using multiple energy sources in [94] which are presented in Figure 56. The first system has both battery and ultracapacitor added in cascade, while the second one has them connected in parallel. The third one shows a system employing fuel cells, and battery for backup. In [113], Koushki et al., classified bidirectional AC-DC converters into two main groups: Low frequency AC-High frequency AC-DC (Figure 57), and Low frequency AC-DC- High frequency AC-DC (Figure 58). The first kind can also be called single-stage converters where the latter may be described as two-stage, which can be justified from their topologies. Converters employed for EV application are compiled in Table 24. From this table, it is evident that step down converters are required for charging the batteries from a higher voltage grid voltage, bidirectional converters are needed for providing power flow in both directions, and specialized converters such as the last three, are needed for better charging performances.

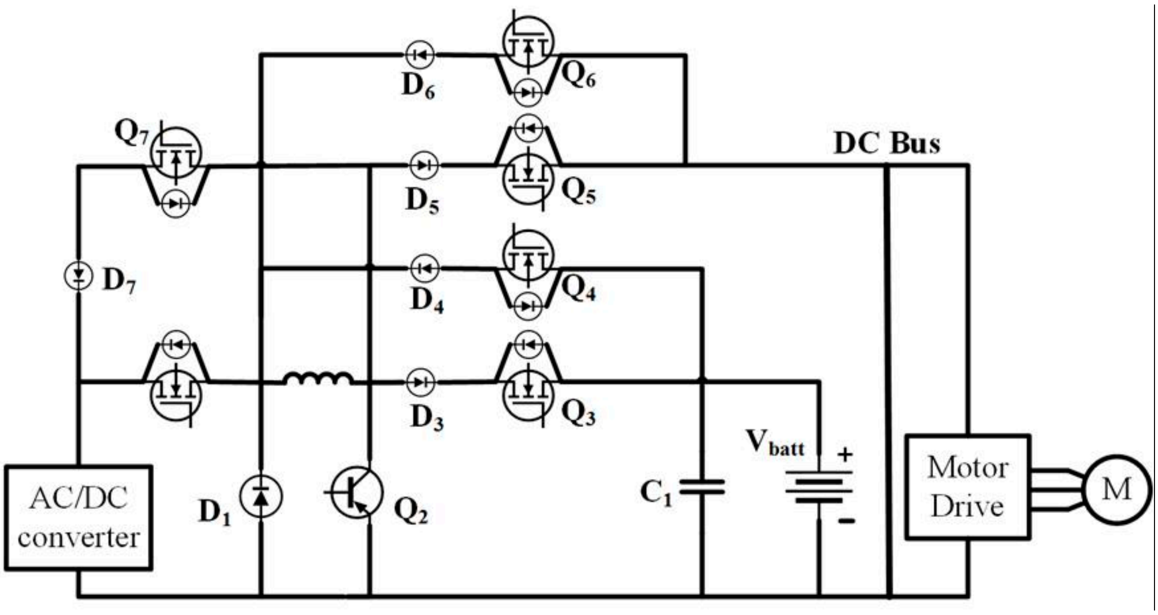
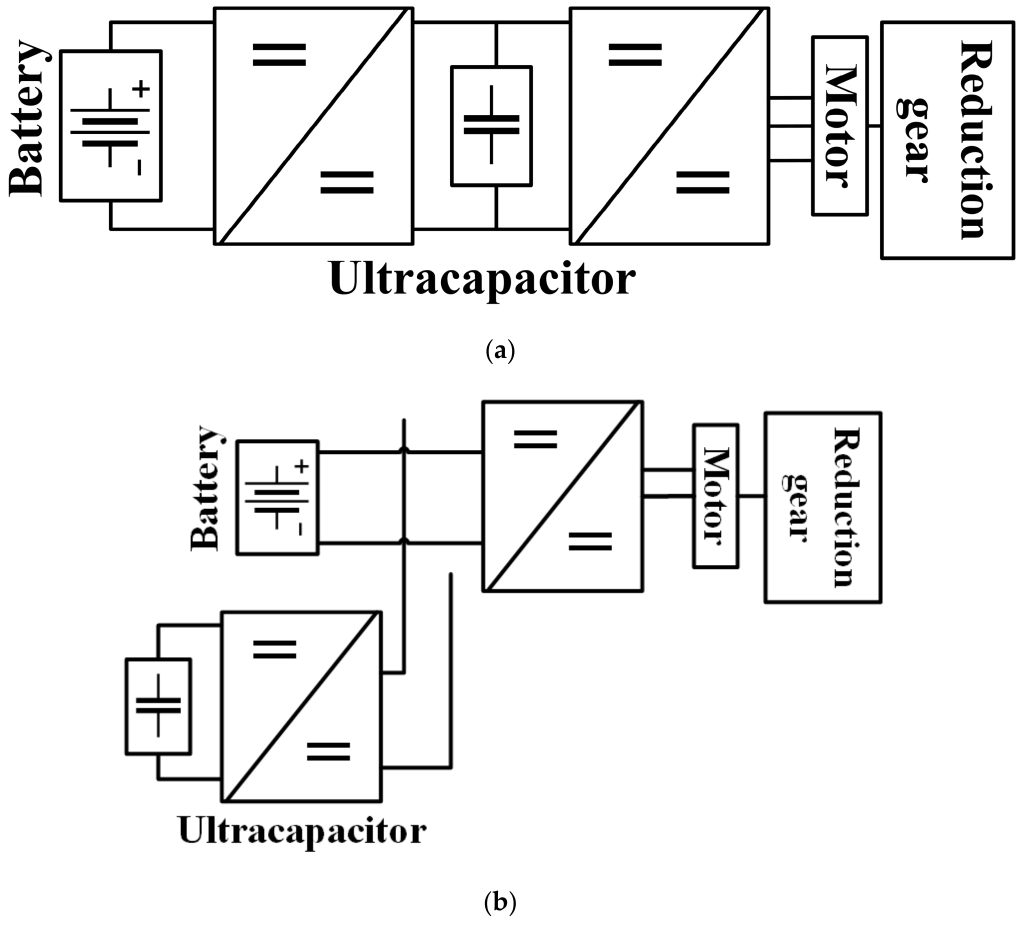
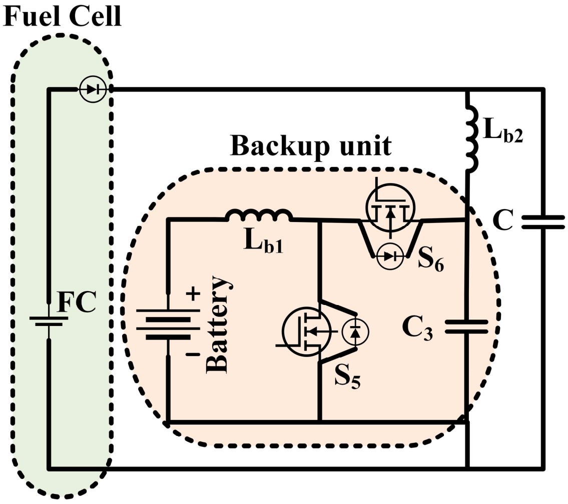


Figure 55. Integrated bidirectional AC/DC-DC/DC converter [33].



(**a**)

(**b**)



(**c**)

Figure 56. Converter arrangements as shown in [94]: (**a**) Cascaded connection; (**b**) Parallel connection; (**c**) Fuel cell with battery backup. Adapted from [94].

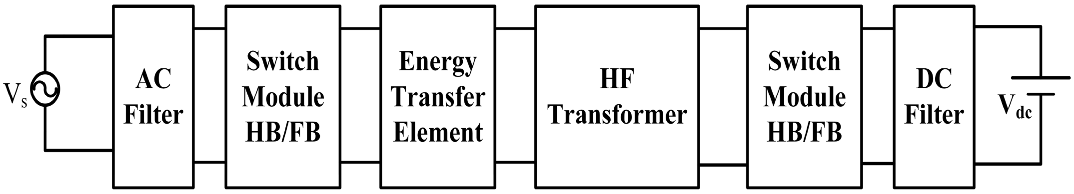


Figure 57. Low frequency AC-High frequency AC-DC converter, also called single-stage converter [113].

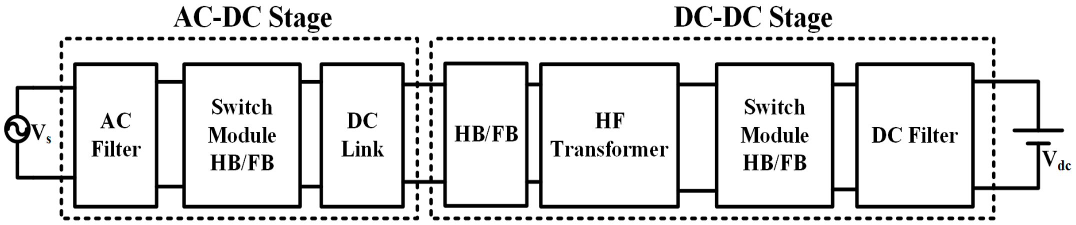


Figure 58. Low frequency AC-DC-High frequency AC-DC converter, also called two-stage converter. Adapted from [113].

Table 24. Converters with EV application displaying their key features and uses in EVs.

Configuration	Reference	Operation	Key Features	Application in EV
Buck converter	Bose [92]	Step down	Can operate in continuous or discontinuous mode	Sending power to the battery
Buck-Boost converter	Bose [92]	Step up and step down	Two quadrant operation of chopper	Regenerative action
Interleaved Boost PFC converter	Williamson et al. [46]	Step up with power factor correction	Relatively small input EMI filter	Charging
Bridgeless/Dual Boost PFC Converter	Williamson et al. [46]	Step up with power factor correction	Does not require rectifier input bridge	Charging

ZVS FB Converter with Capacitive Output Filter	Williamson et al. [46]	AC-DC conversion	Zero voltage switching	Charging

AC-DC converters are used to charge the batteries from AC supply-lines; DC-DC converters are required for sending power to the motors from the batteries. The power flow can be reversed in case of regenerative actions or V2G. Bidirectional converters are required in such cases. Different converter configurations have different advantages and shortcomings which engendered a lot of research and proliferation of hybrid converter topologies.

7.2. Systems for Wireless Charging

Wireless charging or wireless power transfer (WPT) uses a principle similar to transformer. There is a primary circuit at the charger end, from where the energy is transferred to the secondary circuit located at the vehicle. In case of inductive coupling, the voltage obtained at the secondary side is:

$$v_2 = L_2(di_2/dt) + M(di_1/dt) \quad (2)$$

M is the mutual inductance and can be calculated by:

$$M = k\sqrt{(L_1L_2)} \quad (3)$$

The term k here is the coupling co-efficient; L_1 and L_2 are the inductances of primary and secondary circuit. Figure 59 shows the 'double D' arrangement for WPT which demonstrates the basic principle of wireless power transfer by means of flux linkages. A variety of configurations can be employed for wireless power transfer; some of them meet a few desired properties to charge vehicles. Inductive WPT, shown in Figure 60a, is the most rudimentary type, transfer power from one coil to another just like the double D system. Capacitive WPT (Figure 60b) uses a similar structure as the inductive system, but it has two coupling transformers at its core. Low frequency permanent magnet coupling power transfer (PMPT) is shown in Figure 60c; it uses a permanent magnet rotor to transmit power, another rotor placed in the vehicle acts as the receiver. Resonant antennae power transfer (RAPT) (Figure 60d) uses resonant antennas for wireless transfer of power. Resonant inductive power transfer (RIPT), shown in Figure 60e, uses resonance circuits for power transfer. Online power transfer (OLPT) has a similar working principle as RIPT, it can be used in realizing roadways that can charge vehicles wirelessly by integrating the transmitter with the roadway (pilot projects using similar technology placed them just beneath the road surface), and equipping vehicles with receivers to collect power from there. Schematic for this system is shown in Figure 60f. Characteristics of these systems are shown in Table 25.

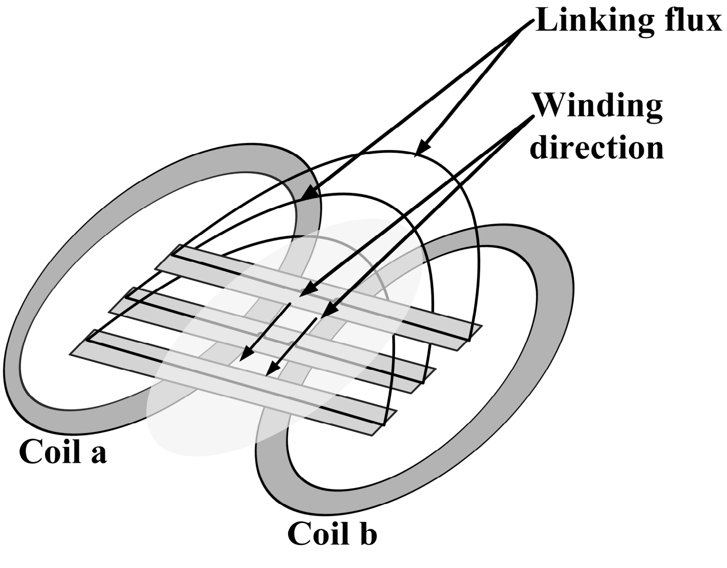
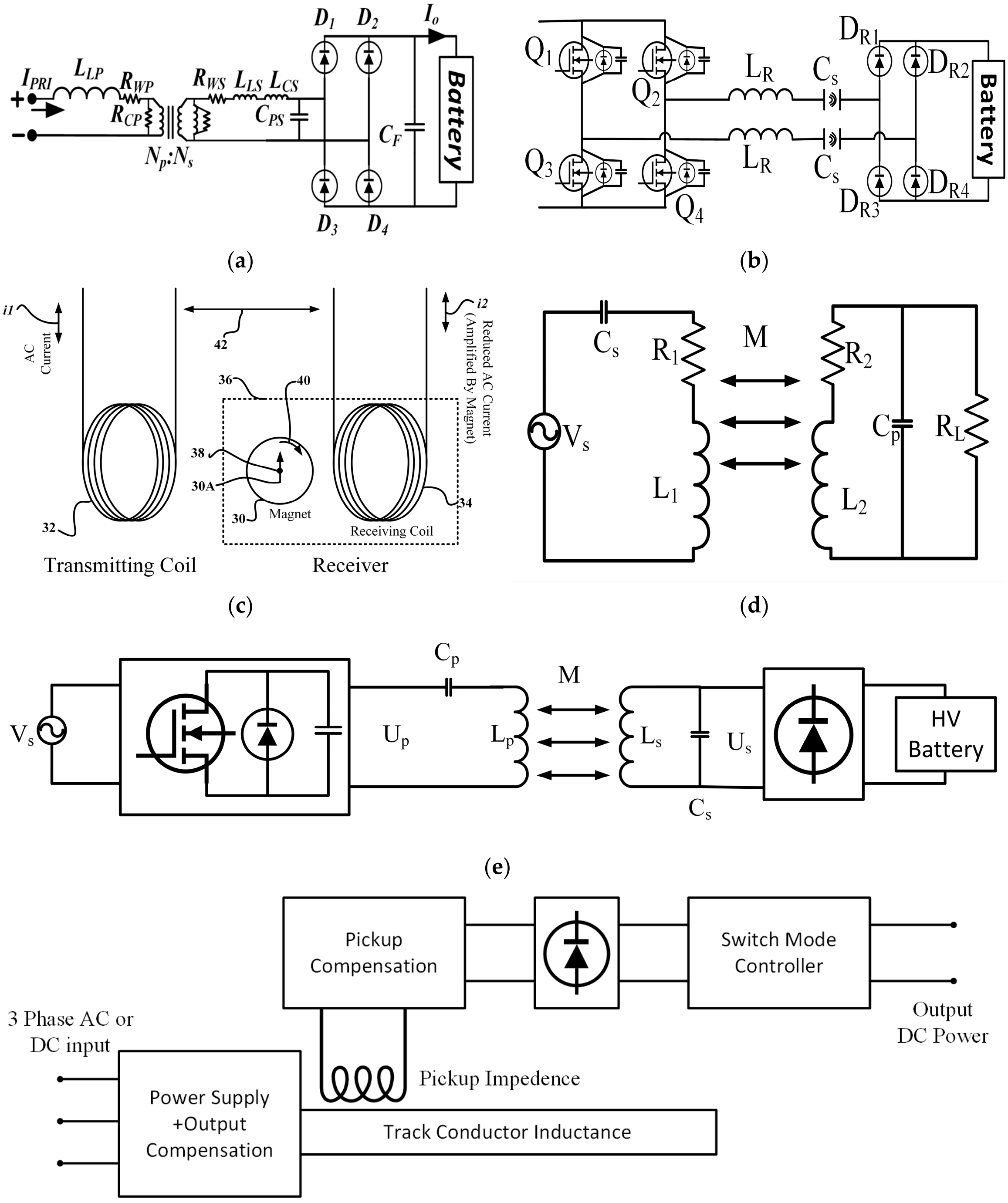


Figure 59. Double D arrangement for WPT. Fluxes generated in one coil cut the other one and induces a voltage there, enabling power transfer between the coils without any wired connection [27].



(**a**) (**b**)

(**c**) (**d**)

(**e**)

(**f**)

Figure 60. Different configurations used for wireless power transfer over the years: (**a**) Inductive WPT; (**b**) Capacitive WPT; (**c**) Low frequency permanent magnet coupling power transfer (PMPT); (**d**) Resonant antennae power transfer (RAPT); (**e**) Resonant inductive power transfer (RIPT); (**f**) Online power transfer (OLPT).

Table 25. Characteristics of wireless charging systems [87].

Technology	Characteristics
Inductive WPT	• It is not actually wireless, just does not require any connection. • Primary and secondary coils are sealed in epoxy. • Can provide power of either 6.6 kW or 50 kW. • Coaxial winding transformer can be used to place all the transformer core materials off-board. • Losses including geometric effects, eddy current loss, EMI are mainly caused by nonlinear flux distribution. • A piecewise assembly of ferrite core and dividing the secondary winding symmetrically can help minimizing the losses.
Capacitive WPT	• Capacitive power transfer or CPT interface is built with two coupling transformers at the center; the rest of the system is similar to inductive WPT. • Capacitive interface is helpful in reducing the size and cost of the required galvanic isolating parts. • Cheaper and smaller for lower power applications, but not preferred for high power usage. • Useful in consumer electronics, may not be sufficient for EV charging.
Low frequency permanent magnet coupling power transfer (PMPT)	• The transmitter is a cylinder-shaped, permanent magnet rotor driven by static windings placed on the rotor, inside it if the rotor is hollow, or outside the motor, separated by an air-gap. • The receiver is placed on the vehicle, similar to the transmitter in construction. • Transmitter and receiver have to be within 150 mm for charging. • Because of magnetic gear effect, the receiver rotor rotates at the same speed as the transmitter and energy is transferred. • The disadvantages may be the vibration, noise and lifetime associated with the mechanical components used.
Resonant inductive power transfer (RIPT)	• Most popular WPT system. • Uses two tuned resonant tanks or more, operating in the same frequency in resonance. • Resonant circuits enable maximum transfer of power, efficiency optimization, impedance matching, compensation of magnetic coupling and magnetizing current variation. • Can couple power for a distance of up to 40 cm. • Advantages include extended range, reduced EMI, operation at high frequency and high efficiency.
Online power transfer (OLPT)	• Has a similar concept like RIPT, but uses a lower resonant frequency. • Can be used for high power applications. • This system is proposed to be applied in public transport system in [87]. • The primary circuit—a combination of the input of resonant converter and distributed primary windings is integrated in the roadway. This primary side is called the 'track'. • The secondary is placed in vehicles and is called the 'pickup coil'. • Supply of this system is high voltage DC or 3-phase AC. • It can provide frequent charging of the vehicles while they are on the move, reducing the required battery capacity, which will reduce the cost and weight of the cars. • The costs associated with such arrangement may also make its implementation unlikely.

Resonant antennae power transfer (RAPT)	• This system uses two resonant antennas, or more, with integrated resonant inductances and capacitances. The antennas are tuned to identical frequencies. • Large WPT coils are often used as antennas; resonant capacitance is obtained there by controlled separation in the helical structure. • The frequencies used are in MHz range. • Can transfer power efficiently for distances up to 10 m. • The radiations emitted by most of such systems exceed the basic limits on human exposure and are difficult to shield without affecting the range and performance. • Generating frequencies in the MHz range is also challenging and costly with present power electronics technologies.

8. Effects of EVs

Vehicles may serve the purpose of transportation, but they affect a lot of other areas. Therefore, the shift in the vehicle world created by EVs impacts the environment, the economy, and being electric, the electrical systems to a great extent. EVs are gaining popularity because of the benefits they provide in all these areas, but with them, there come some problems as well. Figure 61 illustrates the impacts of EVs on the power grid, environment and economy.

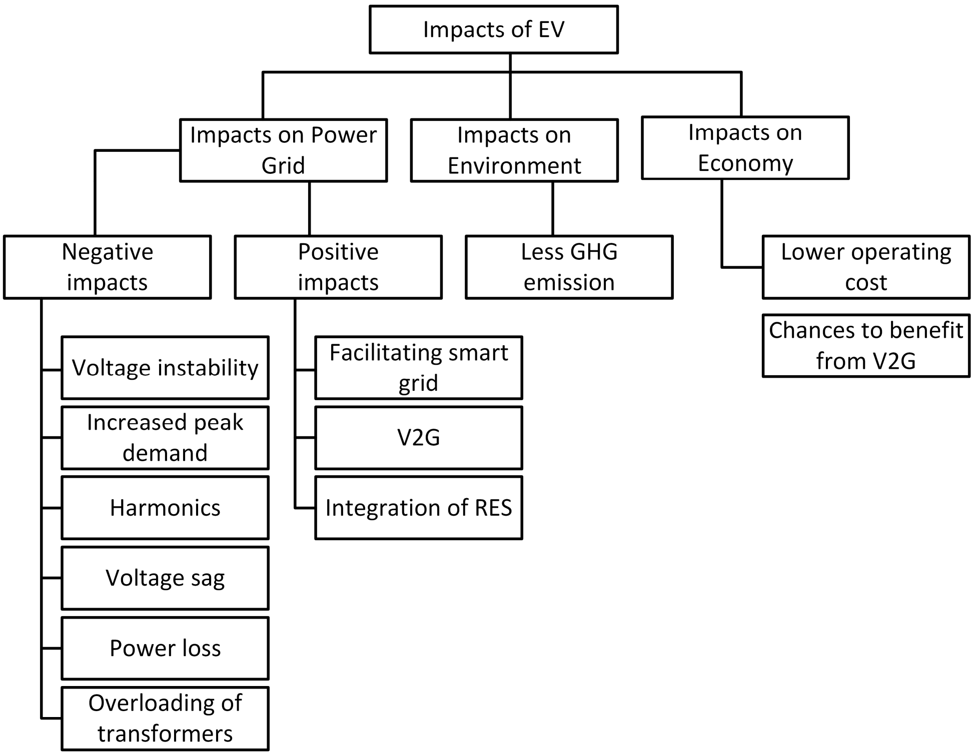


Figure 61. A short list of the impacts of EVs on the power grid, environment and economy.

8.1. Impact on the Power Grid

8.1.1. Negative Impacts

EVs are considered to be high power loads [114] and they affect the power distribution system directly; the distribution transformers, cables and fuses are affected by it the most [115,116]. A Nissan Leaf with a 24 kWh battery pack can consume power similar to a single European household. A 3.3 kW charger in a 220 V, 15 A system can raise the current demand by 17% to 25% [117]. The situation gets quite alarming if charging is done during peak hours, leading to overload on the system, damage of the system equipment, tripping of protection relays, and subsequently, an increase in the infrastructure cost [117]. Charging without any concern to the time of drawing power from the grid is denoted as uncoordinated charging, uncontrolled charging or dumb charging [117,118]. This can lead to the addition of EV load in peak hours which can cause load unbalance, shortage of energy, instability, and decrease in reliability and degradation of power quality [116,119]. In case of the modified IEEE 23 kV distribution system, penetration of EVs can deviate voltage below the 0.9 p.u. level up to 0.83 p.u., with increased power losses and generation cost [118]. Level 1 charging from an 110 V outlet does not affect the power system much, but problems arise as the charging voltage increases. Adding an EV for fast charging can be equivalent to adding several households to the grid. The grid is likely to be capable of withstanding it, but distribution networks are designed with specific numbers of households kept into mind, sudden addition of such huge loads can often lead to problems. Reducing the charging time to distinguish their vehicles in the EV market has become the current norm among the manufacturers, and it requires higher voltages than ever. Therefore, mitigating the adverse effects is not likely by employing low charging voltages.

To avoid these effects, and to provide efficient charging with the available infrastructure, coordinated charging (also called controlled or smart charging) has to be adopted. In this scheme, the EVs are charged during the time periods when the demand is low, for example, after midnight. Such schemes are beneficial in a lot of ways. It not only prevents addition of extra load during peak hours, but also increases the load in valley areas of the load curve, facilitating proper use of the power plants with better efficiency. In [116], Richardson et al., showed that a controlled charging rate can make high EV penetration possible in the current residential power network with only a few upgrades in the infrastructure. Geng et al., proposed a charging strategy in [120] comprising of two stages aimed at providing satisfactory charging for all connected EVs while shifting the loads on the transformers. On the consumer side, it can reduce the electricity bill as the electricity is consumed by the EVs during off peak hours, which generally have a cheaper unit rate than peak hours. According to [121], smart charging systems can reduce the increase investment cost in distribution system by 60%–70%. The major problems that are faced in the power systems because of EVs can be charted as following:

- Voltage instability: Normally power systems are operated close to their stability limit. Voltage instabilities in such systems can occur because of load characteristics, and that instability can lead to blackouts. EV loads have nonlinear characteristics, which are different than the general industrial or domestic loads, and draw large quantities power in a short time period [81,122]. Reference [123] corroborated to the fact that EVs cause serious voltage instability in power systems. If the EVs have constant impedance load characteristics, then it is possible for the grid to support a lot of vehicles without facing any instability [81]. However, the EV loads cannot be assumed beforehand and thus their power consumptions stay unpredictable; addition of a lot of EVs at a time therefore can lead to violation of distribution constraints. To anticipate these loads properly, appropriate modeling methods are required. Reference [124] suggested tackling the instabilities by damping the oscillations caused by charging and discharging of EV batteries using a wide area control method. The situation can also be handled by changing the tap settings of transformers [125], by a properly planned charging system, and also by using control systems like fuzzy logic controllers to calculate voltages and SOCs of batteries [81].
- Harmonics: The EV charger characteristics, being nonlinear, gives raise high frequency components of current and voltage, known as harmonics. The amount of harmonics in a system can be expressed by the parameters total current harmonic distortion (THD_i) and total voltage harmonic distortion (THD_v):

$$THD_i = \frac{\sqrt{\sum_{h=2}^{H} I_h^2}}{I_1} \times 100\% \tag{4}$$

$$THD_v = \frac{\sqrt{\sum_{h=2}^{H} V_h^2}}{V_1} \times 100\% \tag{5}$$

Harmonics distort the voltage and current waveforms, thus can reduce the power quality. It also causes stress in the power system equipment like cables and fuses [122]. The present cabling is capable of withstanding 25% EV penetration if slow charging is used, in case of rapid charging, the amount comes down to 15% [126]. Voltage imbalance and harmonics can also give rise to current flow in the neutral wire [127,128]. Different approaches have been adopted to determine the effects of harmonics due to EV penetration. Reference [127] simulated the effects of harmonics using Monte Carlo analysis to determine the power quality. In [129] the authors showed that THD_v can reach 11.4% if a few number of EVs are fast charging. This is alarming as the safety limit of THD_v is 8%. According to Melo et al. [130], THD_i also becomes high, in the range of 12% to 14%, in case of fast charging, though it remains in the safe limit during times of slow charging. Studies conducted in [131] show the modern EVs generate less THD_i than the conventional ones, though their THD_v values are higher. However, with increased number of EVs, there are chances of harmonics cancellation because of different load patterns [132,133]. Different EV chargers can produce different phase angles and magnitudes which can lead to such cancellations [133]. It is also possible to reduce, even eliminate harmonics by applying pulse width modulation in the EV chargers [132]. High THD_i can be avoided by using filtering equipment at the supply system [134].

- Voltage sag: A decrease in the RMS value of voltage for half a cycle or 1 min is denoted as voltage sag. It can be caused by overload or during the starting of electric machines. Simulation modeled with an EV charger and a power converter in [135] stated 20% EV penetration can exceed the voltage sag limit. Reference [136] stated that 60% EV penetration is possible without any negative impact is possible if controlled charging is employed. The amount, however, plummets to 10% in case of uncontrolled charging. Leemput et al., conducted a test employing voltage droop charging and peak shaving by EV charging [137]. This study exhibited considerable decrease in voltage sag with application of voltage droop charging. Application of smart grid can help in great extents in mitigating the sag [138].
- Power loss: The extra loss of power caused by EV charging can be formulated as:

$$\mathrm{PL}_{\mathrm{E}} = \mathrm{PL}_{\mathrm{EV}} - \mathrm{PL}_{\mathrm{original}} \quad (6)$$

  $\mathrm{PL}_{\mathrm{original}}$ is the loss occurred when the EVs are not connected to the grid and PLEV is the loss with EVs connected. Reference [121] charted the increased power loss as high as 40% in off peak hours considering 60% of the UK PEVs to be connected to distribution system. Uncoordinated charging, therefore, can increase the amount of loss furthermore. Taking that into account, a coordinated charging scheme, based on objective function, to mitigate the losses was proposed in [139]. Coordinated charging is also favored by [140,141] to reduce power losses significantly. Power generated in the near vicinity can also help minimizing the losses [142], and distributed generation can be quite helpful in this prospect, with the vehicle owners using energy generated at their home (by PV cells, CHP plants, etc.) to charge the vehicles.

- Overloading of transformers: EV charging directly affects the distribution transformers [81]. The extra heat generated by EV loads can lead to increased aging rate of the transformers, but it also depends on the ambient temperature. In places with generally cold weather like Vermont, the aging due to temperature is negligible [81]. Estimation of the lifetime of a transformer is done in [143], where factors taken into account are the rate of EV penetration, starting time of charging and the ambient temperature. It stated that transformers can withstand 10% EV penetration without getting any decrease in lifetime. The effect of level 1 charging, is in fact, has negligible effect on this lifetime, but significant increase in level 2 charging can lead to the failure of transformers [144]. Elnozahy et al., stated that overloading of transformer can happen with 20% PHEV penetration for level 1 charging, whereas level 2 does it with 10% penetration [145]. According to [122], charging that takes place right after an EV being plugged in can be detrimental to the transformers.
- Power quality degradation: The increased amount of harmonics and imbalance in voltage will degrade the power quality in case of massive scale EV penetration to the grid.

8.1.2. Positive Impacts

On the plus side, EVs can prove to be quite useful to the power systems in a number of ways:

- Smart grid: In the smart grid system, intelligent communication and decision making is incorporated with the grid architecture. Smart grid is highly regarded as the future of power grids and offers a vast array of advantages to offer reliable power supply and advanced control. In such a system, the much coveted coordinated charging is easily achievable as interaction with the grid system becomes very much convenient even from the user end. The interaction of EVs and smart grid can facilitate opportunities like V2G and better integration of renewable energy. In fact, EV is one the eight priorities listed to create an efficient smart grid [117].
- V2G: V2G or vehicle to grid is a method where the EV can provide power to the grid. In this system, the vehicles act as loads when they are drawing energy, and then can become dynamic energy storages by feeding back the energy to the grid. In coordinated charging, the EV loads are applied in the valley points of the load curve, in V2G; EVs can act as power sources to provide during peak hours. V2G is realizable with the smart grid system. By making use of the functionalities of smart grid, EVs can be used as dynamic loads or dynamic storage systems. The power flow in this system can be unidirectional or bidirectional. The unidirectional system is analogous to the coordinated charging scheme, the vehicles are charged when the load is low, but the time to charge the vehicles is decided automatically by the system. Vehicles using this scheme can simply be plugged in anytime and put there; the system will choose a suitable time and charge it. Smart meters are required for enabling this system. With a driver variable charging scheme, the peak power demand can be reduced by 56% [117]. Sortomme et al., found this system particularly attractive as it required little up gradation of the existing infrastructure; creating a communication system in-between the grid and the EVs is all that is needed [146]. The bidirectional system allows vehicles to provide power back to the grid. In this scenario, vehicles using this scheme will supply energy to the grid from their storage when it is required. This method has several appealing aspects. With ever increasing integration of renewable energy sources (RES) to the grid, energy storages are becoming essential to overcome their intermittency, but the storages have a very high price. EVs have energy storages, and in many cases, they are not used for a long time. Example for this point can be the cars in the parking lots of an office block, where they stay unused till the office hour is over, or vehicles that are used in a specific time of the year, like a beach buggy. Studies also revealed that, vehicles stay parked 95% of the time [117]. These potential storages can be used when there is excess generation or low demand and when the energy is needed, it is taken back to the grid. The vehicle owners can also get economically beneficial by selling this energy to the grid. In [147], Clement-Nyns et al., concluded that a combination of PHEVs can prove beneficial to distributed generation sources by providing storage for the excess generation, and releasing that to the grid later. Bidirectional charging, however, needs chargers capable of providing power flow in both directions. It also needs smart meters to keep track of the units consumed and sold, and advanced metering architecture (AMI) to learn about the unit charges in real time to get actual cost associated with the charging or discharging at the exact time of the day. The AMI system can shift 54% of the demand to off-peak periods, and can reduce peak consumption by 36% [117]. The bidirectional system, in fact, can provide 12.3% more annual revenue than the unidirectional one. But taking the metering and protections systems required in the bidirectional method, this revenue is nullified and indicates the unidirectional system is more practical. Frequent charging and discharging caused by bidirectional charging can also reduce battery life and increase energy losses from the conversion processes [81,117]. In a V2G scenario, operators with a vehicle fleet are likely to reduce their cost of operation by 26.5% [117]. Another concept is produced using the smart grid and the EVs, called virtual power plant (VPP), where a cluster of vehicles is considered as a power plant and dealt like one in the system. VPP architecture and control is shown in Figure 62. Table 26 shows the characteristics of unidirectional and bidirectional V2G.

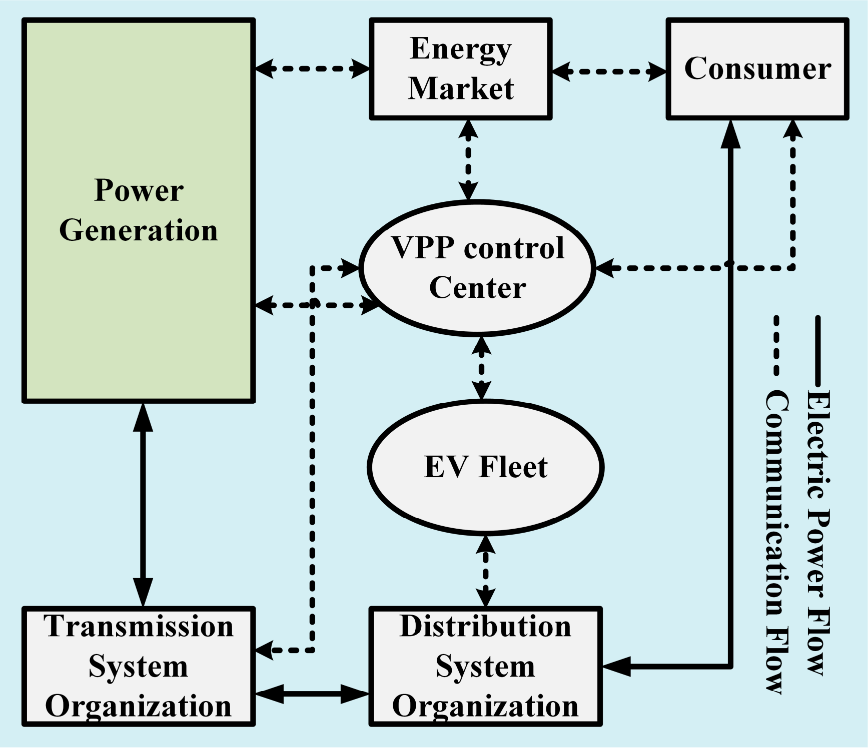


Figure 62. VPP architecture and control [117].

Table 26. Unidirectional and bidirectional V2G characteristics. Adapted from [1].

V2G System	Description	Services	Advantages	Limitations
Unidirectional	Controls EV charging rate with a unidirectional power flow directed from grid to EV based on incentive systems and energy scheduling	• Ancillary service—load levelling	• Maximized profit • Minimized power loss • Minimized operation cost • Minimized emission	• Limited service range
Bidirectional	Bidirectional power flow between grid and EV to attain a range of benefits	• Ancillary service—spinning reserve • Load leveling • Peak power shaving • Active power support • Reactive power support/Power factor correction • Voltage regulation • Harmonic filtering • Support for integration of renewable	• Maximized profit • Minimized power loss • Minimized operation cost • Minimized emission • Prevention of grid overloading • Failure recovery • Improved load profile • Maximization of renewable energy generation	• Fast battery degradation • Complex hardware • High capital cost • Social barriers

- Integration of renewable energy sources: Renewable energy usage becomes more promising with EVs integrated into the picture. EV owners can use RES to generate power locally to charge their EVs. Parking lot roofs have high potential for the placement of PV panels which can charge the vehicles parked underneath as well as supplying the grid in case of excess generation [148–150], thus serving the increase of commercial RES deployment. The V2G structure is further helpful to integrate RES for charging of EVs, and to the grid as well, as it enables the selling of energy to the grid when there is surplus, for example, when vehicles are parked and the system knows the user will not need the vehicle before a certain time. V2G can also enable increased penetration of wind energy (41%–59%) in the grid in an isolated system [121]. References [151–154] worked with different architectures to observe the integration scenario of wind energy with EV assistance. Figure 63 demonstrates integration of wind and solar farm with conventional coal and nuclear power grid with EV charging station employing bidirectional V2G. Table 27 shows the types of assistance EVs can provide for integrating renewable energy sources to the grid.

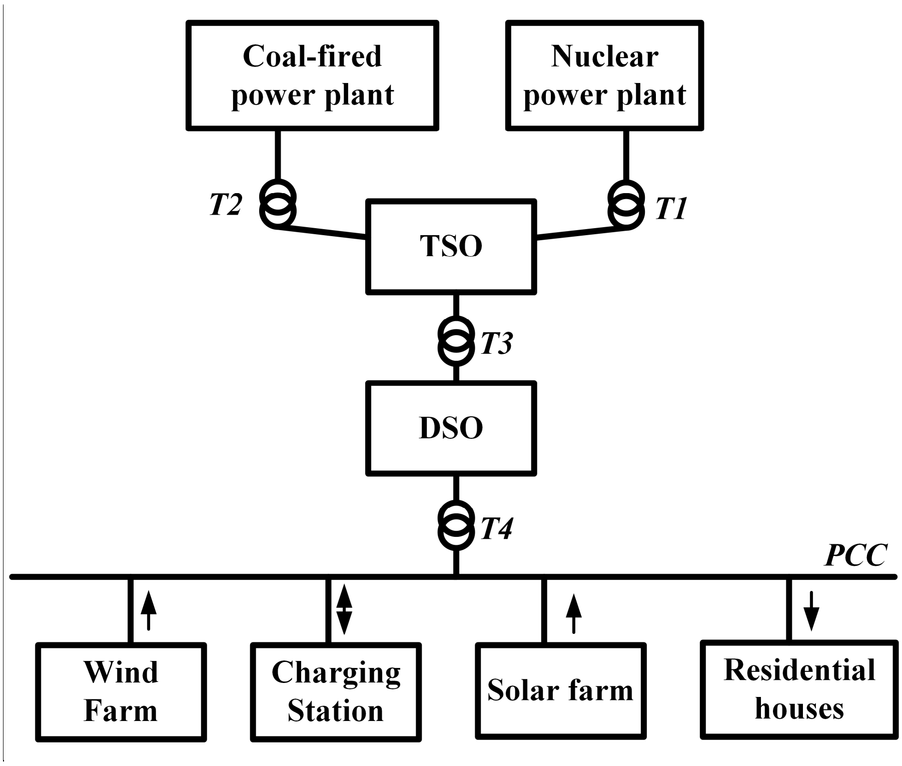


Figure 63. Wind and solar integration in the grid with the help of EV in V2G system. TSO stands for transmission system organization; DSO for distribution system organization; T1 to T4 represent the transformers coupling the generation, transmission, and distribution stages [117].

Table 27. Scopes of assisting renewable energy source (RES) integration using EV. Adapted from [1].

Interaction with RES	Field of Application	Contribution
Solar PV	Smart home	• Implementation of PV and EV in smart home to reduce emission • Development of stand-alone home EV charger based on solar PV system • Development of future home with uninterruptable power by implementing V2G with solar PV
	Parking lot	• Analysis of EV charging using solar PV at parking lots • Scheduling of charging and discharging for intelligent parking lot
	Grid distribution network	• Assessment of power system performance with integration of grid connected EV and solar PV • Development of EV charging control strategy for grid connected solar PV based charging station • Development of optimization algorithm to coordinate V2G services
	Micro grid	• Development of generation scheduling for micro grid consisting of EV and solar PV
Wind turbine	Grid distribution network	• Determination of EV interaction potential with wind energy generation • Development of V2G systems to overcome wind intermittency problems
	Micro grid	• Development of coordinating algorithm for energy dispatching of V2G and wind generation
Solar PV and wind turbine	Smart home	• Development of control strategy for smart homes with grid-interactive EV and renewable sources

	Parking lot	• Design of intelligent optimization framework for integrating renewable sources and EVs
	Grid distribution network	• Potential analysis of grid connected EVs for balancing intermittency of renewable sources • Emission analysis of EVs associated with renewable generation • Development of optimized algorithm to integrate EVs and renewable sources to the grid
	Micro grid	• Development of V2G control for maximized renewable integration in micro grid

8.2. Impact on Environment

One of the main factors that propelled the increase of EVs' popularity is their contribution to reduce the greenhouse gas (GHG) emissions. Conventional internal combustion engine (ICE) vehicles burn fuels directly and thus produce harmful gases, including carbon dioxide and carbon monoxide. Though HEVs and PHEVs have IC engines, their emissions are less than the conventional vehicles. But there are also theories that the electrical energy consumed by the EVs can give rise to GHG emission from the power plants which have to produce more because of the extra load added in form of EVs. This theory can be justified by the fact that the peak load power plants are likely to be ICE type, or can use gas or coal for power generation. If EVs add excess load during peak hours, it will lead to the operation of such plants and will give rise to CO_2 emission [155]. Reference [156] also stated that power generation from coal and natural gas will produce more CO_2 from EV penetration than ICEs. However, all the power is not generated from such resources. There are many other power generating technologies that produce less GHG. With those considered, the GHG production from power plants because of EV penetration is less than the amount produced by equivalent power generation from ICE vehicles. The power plants also produce energy in bulk, thus minimizing the per unit emission. With renewable sources integrated properly, which the EVs can support strongly, the emission from both power generation and transportation sector can be reduced [115]. Over the lifetime, EVs cause less emission than conventional vehicles. This parameter can be denoted as well-to-wheel emission and it has a lower value for EVs [157]. In [158], well-to-wheel and production phases are taken into account to calculate the impact of EVs on the environment. This approach stated the EVs to be the least carbon intensive among the vehicles. Denmark managed to reduce 85% CO_2 emission from transportation by combining EVs and electric power. EVs also produce far less noise, which can highly reduce sound pollution, mostly in urban areas. The recycling of the batteries raises serious concerns though, as there are few organizations capable of recycling the lithium-ion batteries fully. However, like the previous nickel-metal and lead-acid ones, lithium-ion cells are not made of caustic chemicals, and their reuse can reduce 'peak lithium' or 'peak oil' demands [81].

8.3. Impact on Economy

From the perspective of the EV owners, EVs provide less operating cost because of their superior efficiency [22]; it can be up to 70% where ICE vehicles have efficiencies in the range of 60% to 70% [159]. The current high cost of EVs is likely to come down from mass production and better energy policies [3] which will further increase the economic gains of the owners. V2G also allows the owners to obtain a financial benefit from their vehicles by providing service to the grid [160]. The power service providers benefit from EV integration mainly by implementing coordinated charging and V2G. It allows them to adopt better peak shaving strategies as well as to integrate renewable sources. EV fleets can lead to $200 to $300 savings in cost per vehicle per year [161,162].

8.4. Impacts on Motor Sports

Hybrid technologies are not used extensively in motor sports to enhance the performance of the vehicles. Electric vehicles now have their own formula racing series named 'Formula E' [163] which started in Beijing in September 2014. Autonomous EVs are also being planned to take part in a segment of this series called 'Roborace'.

9. Barriers to EV Adoption

Although electric vehicles offer a lot of promises, they are still not widely adopted, and the reasons behind that are quite serious as well.

9.1. Technological Problems

The main obstacles that have frustrated EVs' domination are the drawbacks of the related technology. Batteries are the main area of concern as their contribution to the weight of the car is significant. Range and charging period also depend on the battery. These factors, along with a few others, are demonstrated below:

9.1.1. Limited Range

EVs are held back by the capacity of their batteries [4]. They have a certain amount of energy stored there, and can travel a distance that the stored energy allows. The range also depends on the speed of the vehicle, driving style, cargo the vehicle is carrying, the terrain it is being driven on, and the energy consuming services running in the car, for example air conditioning. This causes 'range anxiety' among the users [81], which indicates the concern about finding a charging station before the battery drains out. People are found to be willing to spend up to $75 extra for an extra range of one mile [164]. Though even the current BEVs are capable of traversing equivalent or more distance than a conventional vehicle can travel with a full tank (Tesla Model S 100D has a range of almost 564 km on 19″ wheels when the temperature is 70 °C and the air conditioning is off [24], the Chevrolet Bolt's range is 238 miles or 383 km [165]), range anxiety remains a major obstacle for EVs to overcome. This does not affect the use of EVs for urban areas though, as in most cases this range is enough for daily commutation inside city limits. Range extenders, which produce electricity from fuel, are also available with models like BMW i3 as an option. Vehicles with such facilities are currently being called as Extended Range Electric Vehicles (EREV).

9.1.2. Long Charging Period

Another major downside of EVs is the long time they need to get charged. Depending on the type of charger and battery pack, charging can take from a few minutes to hours; this truly makes EVs incompetent against the ICE vehicles which only take a few minutes to get refueled. Hidrue et al., found out that, to have an hour decreased from the charging time; people are willing to pay $425–$3250 [164]. A way to make the charging time faster is to increase the voltage level and employment of better chargers. Some fast charging facilities are available at present, and more are being studied. There are also the fuel cell vehicles that do not require charging like other EVs. Filling up the hydrogen tank is all that has to be done in case of these vehicles, which is as convenient as filling up a fuel tank, but FCVs need sufficient hydrogen refueling stations and a feasible way to produce the hydrogen in order to thrive.

9.1.3. Safety Concerns

The concerns about safety are rising mainly about the FCVs nowadays. There are speculations that, if hydrogen escapes the tanks it is kept into, can cause serious harm, as it is highly flammable. It has no color either, making a leak hard to notice. There is also the chance of the tanks to explode in case of a collision. To counter these problems, the automakers have taken measures to ensure the integrity of the tanks; they are wrapped with carbon fibers in case of the Toyota Mirai. In this car, the hydrogen handling parts are placed outside the cabin, allowing the gas to disperse easily in case of any leak, there are also arrangements to seal the tank outlet in case of high-speed collision [166].

9.2. Social Problems

9.2.1. Social Acceptance

The acceptance of a new and immature technology, along with its consequences, takes some time in the society as it means change of certain habits [167]. Using an EV instead of a conventional vehicle means change of driving patters, refueling habits, preparedness to use an alternative transport in case of low battery, and these are not easy to adopt.

9.2.2. Insufficient Charging Stations

Though public charging stations have increased a lot in number, still they are not enough. Coupled with the lengthy charging time, this acts as a major deterrent against EV penetration. Not all the public charging stations are compatible with every car as well; therefore it also becomes a challenge to find a proper charging point when it is required to replete the battery. There is also the risk of getting a fully occupied charging station with no room for another car. But, the manufacturers are working on to mitigate this problem. Tesla and Nissan have been expanding their own charging networks, as it, in turn means they can sell more of their EVs. Hydrogen refueling stations are not abundant yet as well. It is necessary as well to increase the adoption of FCVs. In [168], a placement strategy for hydrogen refueling stations in California is discussed. It stated that a total of sixty-eight such stations will be sufficient to provide service to FCVs in the area. To get the better out of the remaining stations, there are different trip planning applications, both web based and manufacturer provided, which helps to obtain a route so that there are enough charging facilities to reach the destination.

9.3. Economic Problems

High Price

The price of the EVs is quite high compared to their ICE counterparts. This is because of the high cost of batteries [81] and fuel cells. To make people overlook this factor, governments in different countries including the UK and Germany, have provided incentives and tax breaks which provide the buyers of EVs with subsidies. Mass production and technological advancements will lead to a decrease in the prices of batteries as well as fuel cells. Affordable EVs with a long range like the Chevrolet Bolt has already appeared in the market, while another vehicle with the same promises (the Tesla Model 3) is anticipated to arrive soon. Figure 64 shows the limitations of EVs in the three sectors. Table 28 demonstrates the drawbacks in key factors, while Table 29 suggests some solutions for the existing limitations.

10. Optimization Techniques

To make the best out of the available energy, EVs apply various aerodynamics and mass reduction techniques, lightweight materials are used to decrease the body weight as well. Regenerative braking is used to restore energy lost in braking. The restored energy can be stored in different ways. It can be stored directly in the ESS, or it can be stored by compressing air by means of hydraulic motor, springs can also be employed to store this energy in form of gravitational energy [169].

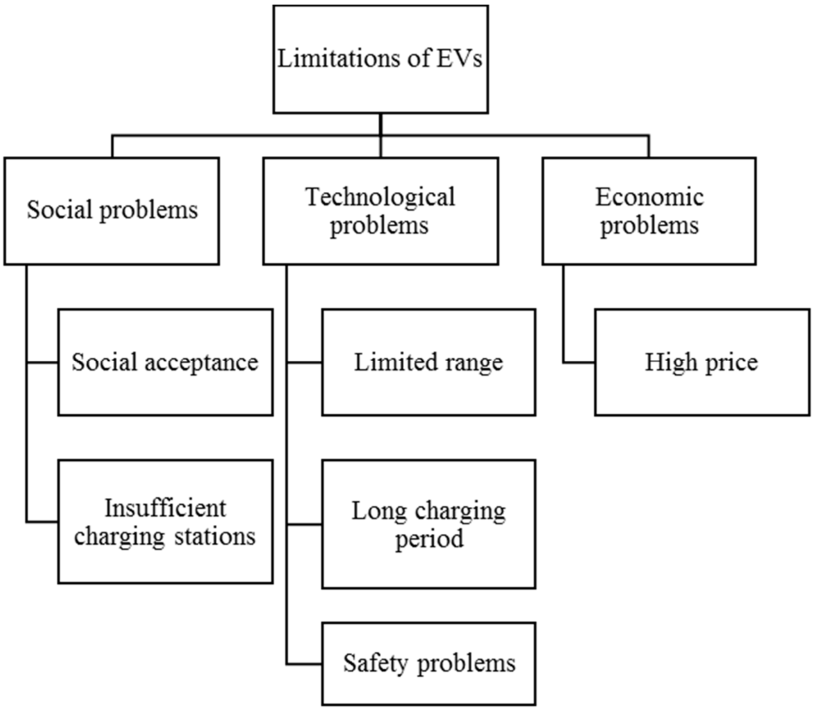


Figure 64. Social, technological, and economic problems faced by EVs.

Table 28. Hurdles in key EV factors. Adapted from [170].

Factor	Hurdles
Recharging	Weight of charger, durability, cost, recycling, size, charging time
Hybrid EV	Battery, durability, weight, cost
Hydrogen fuel cell	Cost, hydrogen production, infrastructure, storage, durability, reliability
Auxiliary power unit	Size, cost, weight, durability, safety, reliability, cooling, efficiency

Table 29. Tentative solutions of current limitations of EVs.

Limitation	Probable Solution
Limited range	Better energy source and energy management technology
Long charging period	Better charging technology
Safety problems	Advanced manufacturing scheme and build quality
Insufficient charging stations	Placement of sufficient stations capable of providing services to all kinds of vehicles
High price	Mass production, advanced technology, government incentives

Formula One vehicles employ kinetic energy recovery systems (KERSs) to use the energy gathered during braking to provide extra power during accelerating. The Porsche 911 GT3R hybrid uses a flywheel energy storage system to store this energy. The energy consuming accessories on a car include power steering, air conditioning, lights, infotainment systems etc. Operating these in an energy efficient way or turning some of these off can increase the range of a vehicle. LEDs can be used for lighting because of their high efficiency [169]. Table 30 shows different methods of recovering the energy lost during braking.

Table 30. Different methods of recovering energy during braking [169].

Storage System	Energy Converter	Recovered Energy	Application
Electric storage	Electric motor/generator	~50%	BEV, HEV
Compressed gas storage	Hydraulic motor	>70%	Heavy-duty vehicles
Flywheel	Rotational kinetic energy	>70%	Formula One (F1) racing
Gravitational energy storage	Spring storage system	-	Train

Aerodynamic techniques are used in vehicles to reduce the drag coefficient, which reduces the required power. Power needed to overcome the drag force is:

$$P_d = \frac{1}{2}\rho v^3 A C_d \tag{7}$$

Here C_d is the drag coefficient, the power to overcome the drag increases if the drag coefficient's value increases. The Toyota Prius claims a drag coefficient of 0.24 for the 2017 model, the same as the Tesla Model S. The 2012 Nissan Leaf SL had this value set at 0.28 [171].

To ensure efficient use of the available energy, different energy management schemes can be employed [6]. Presented different control strategies for energy management which included systems using fuzzy logic, deterministic rule and optimization based schemes. Geng et al., worked on a plug-in series hybrid FCV. The objective of their control system was to consume the minimum amount of hydrogen while preserving the health of the proton exchange membrane fuel cell (PEMFC) [172]. The control system was comprised of two stages; the first stage determined the SOC and control references, whereas the second stage determined the PEMFC health parameters. This method proved to be capable of reducing the hydrogen consumption while increasing the life-time to the fuel cell. Another intelligent management system is examined in [173] by Murphey et al., which used machine learning combined with dynamic programming to determine energy optimization strategies for roadway and traffic-congestion scenarios for real-time energy flow control of a hybrid EV. Their system is simulated using a Ford Escape Hybrid model; it revealed the system was effective in finding out congestion level, optimal battery power and optimal speed. Geng et al., proposed a control mechanism for energy management for a PHEV employing batteries and a micro turbine in [174]. In this work, they introduced a new parameter, named the "energy ratio", to produce the equivalent factor (EF) which was used in the popular Equivalent Consumption Minimization Strategy (ECMS) to deduce the minimum driving cost by applying Pontryagin's minimum principle. This method claimed to reduce the cost by 7.7–21.6%. In [175], Moura et al., explored efficient ways to split power demand among different power sources of mid-sized sedan PHEVs. They used a number of drive cycles, rather than a single one, assessed the potential of depleting charge in a controlled manner, and considered relative pricing of fuel and electricity for optimal power management of the vehicle.

11. Control Algorithms

Control systems are crucial for proper functioning of EVs and associated systems. Sophisticated control mechanisms are required for providing a smooth and satisfactory ride quality, for providing the enough power when required, estimating the energy available from the on-board sources and using them properly to cover the maximum distance, charging in a satisfactory time without causing burden on the grid, and associated tasks. Different algorithms are used in these areas, and as the EV culture is becoming more mainstream, need for better algorithms are on the rise.

Driving control systems are required to assist the driver in keeping the vehicle in control, especially at high speeds and in adverse conditions such as slippery surfaces caused by rain or snow. Driving control systems such as traction control, cruise control, and different driving modes have been being applied in conventional vehicles for a long time. Application of such systems appeared more efficient in EVs as the driving forces of EVs can be controlled with more ease, with less conversion required in-between the mechanical and the electrical domains. In any condition, forces act on a vehicle at different directions; for a driving control system, if is essential to perfectly perceive these forces, along with other sensory inputs, and provide torques to the wheels to maintain desired stability. In Figure 65, the forces in different direction acting on each wheel of a car is shown in a horizontal plane. In [176], Magallan et al., proposed and simulated a control system to utilize the maximum torque in a rear-wheel-drive EV without causing the tires to skid. The model they worked on had independent driving systems for the two rear wheels. A sliding mode system, based on a *LuGre* dynamic friction model, was used to estimate the vehicle's velocity and wheel slip on unknown road surfaces. Utilizing these data, the control algorithm determined the maximum allowable traction force, which was applied to the road by torque controlling of the two rear motors. Juyong Kang et al., presented an algorithm aimed at driving control systems for four-wheel-drive EVs in [177]. Their vehicle model had two motors driving the front and the rear shafts. The algorithm had three parts: a supervisory level for determine the desirable dynamics and control mode, an upper level computing the yaw moment and traction force inputs, and a lower level determining the motor and braking commands. This system proved useful for enhancing lateral stability, maneuverability, and reducing rollover. Figure 66 shows the acting components of this system on a vehicle model while Figure 67 shows a detailed diagram of the system with the inputs, controller levels, and actuators. Tahami et al., introduced a stability system for driving assistance for all-wheel drive EVs in [25]. They trained a neural network to produce a reference yaw rate. A fuzzy logic controller dictated independent wheel torques; a similar controller was used for controlling wheel slip. This system is shown in Figure 68. In [178], Wang et al., showed a system to assist steering using differential drive for in-wheel drive system. A proportional integral (PI) closed loop control system was used here to monitor the reference steering position. It was achieved by distributing torque at the front wheels. Direct yaw moment control and traction control were also employed to make the differential drive system better. This approach maintained the lateral stability of the vehicle, and improved stability at high speeds. The structure of this system is shown in Figure 69. In a separate study conducted by Nam et al., lateral stability of an in-wheel drive EV was attained by estimating the sideslip angle of the vehicle employing sensors to measure lateral tire forces [179]. In this study, a state observer was proposed which was derived from extended-Kalman-filtering (EKF) method and was evaluated by implementing in an experimental EV alongside Matlab/Simulink-Carsim simulations.

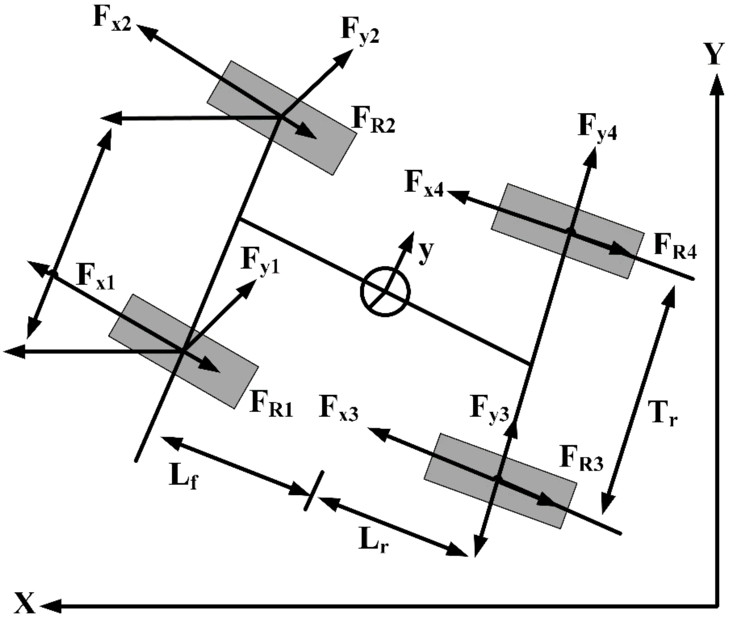


Figure 65. Forces acting on the wheels of a car. Each of the wheels experience forces in all three directions, marked with the 'F' vectors. L_f and L_r show the distances of front and rear axles from the center of the vehicle, while T_r shows the distance between the wheels of an axle. Adapted from [25].

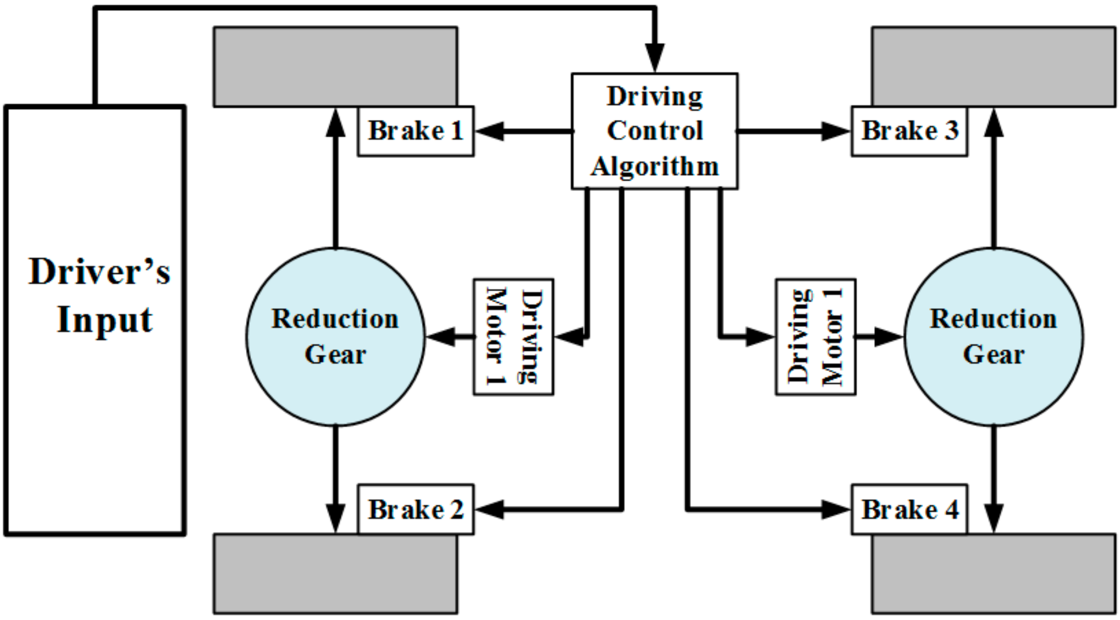


Figure 66. Main working components of the driving control system for four-wheel-drive EVs proposed by Juyong Kang et al. The driving control algorithm takes the driver's inputs, and then determines the actions of the brakes and the motors according to the control mode [177].

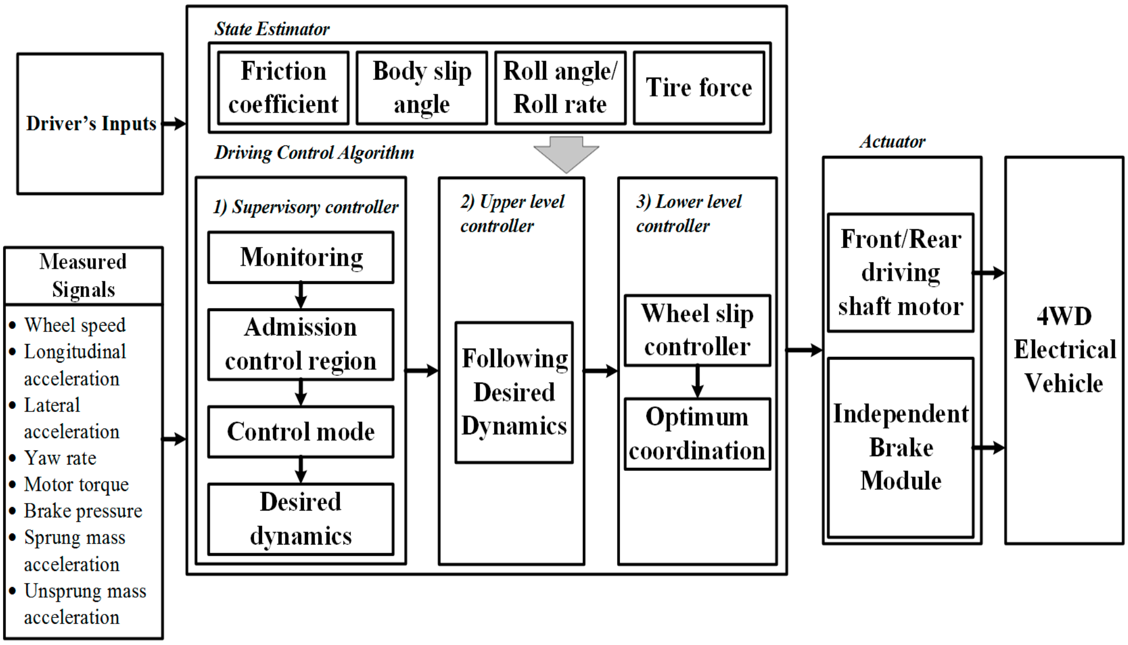


Figure 67. Working principle of the control system proposed by Kang et al. The system uses both the driver's commands and sensor measurements as inputs, and then drives the actuators as determined by the three level control algorithms. Adapted from [177].

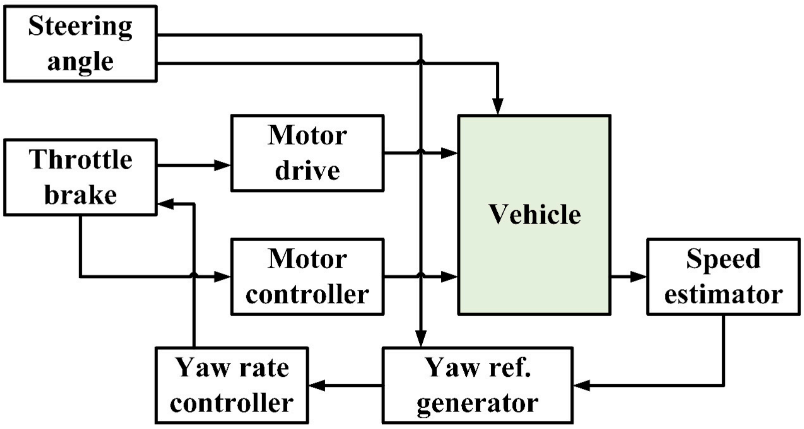


Figure 68. Working principle of vehicle stability system proposed by Tahami et al. A neural network was used in the yaw reference generator [25].

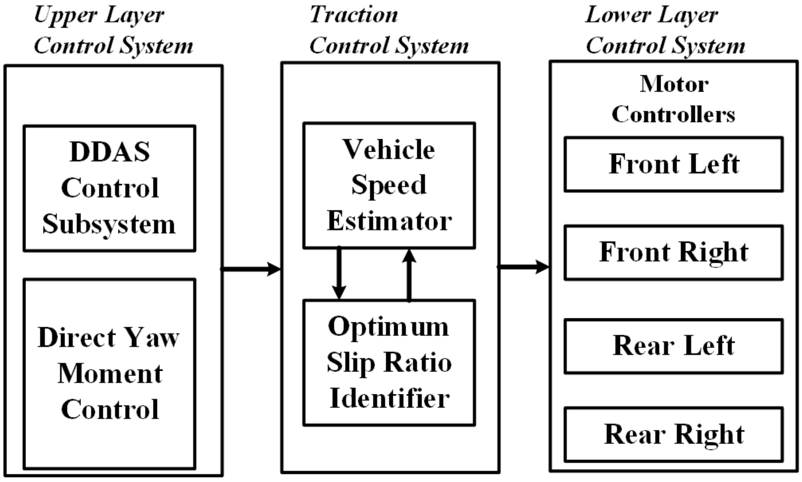


Figure 69. Independent torque control system proposed by Wang et al., Differential drive assisted steering (DDAS) subsystem and direct yaw moment control subsystem creates the upper layer. The traction control subsystem processes the inputs, and the controlling is done through the lower layer [178].

Energy management is a big issue for EVs. Proper measurement of the available energy is crucial for calculating the range and plans the driving strategy thereafter. For vehicles with multiple energy sources (e.g., HEVs), efficient energy management algorithms are required to make proper use of the energy on-board. Zhou et al., proposed a battery state-of-charge (SOC) measuring algorithm for lithium polymer batteries which made use of a combination of particle filter and multi-model data fusion technique to produce results real time and is not affected by measurement noise [180]. They used different battery models and presented the tuning strategies for each model as well. Their multi-model approach proved to be more effective than single model methods for providing real time results. Working principle of this system is shown in Figure 70. Moura et al., explored efficient ways to split power demand among different power sources of mid-sized sedan PHEVs in [175], which can be used for other vehicle configurations as well. Their method made use of different drive cycles, rather than using a single one; assessed the potential of depleting charge in a controlled manner; and considered relative pricing of fuel and electricity to optimally manage the power of the vehicle. In [181], Hui et al., presented a novel hybrid vehicle using parallel hybrid architecture which employed a hydraulic/electric synergy configuration to mitigate the drawbacks faced by heavy hybrid vehicles using a single energy source. Transition among the operating modes of such a vehicle is shown in Figure 71. They developed an algorithm to optimize the key parameters and adopted a logic threshold approach to attain desired performance, stable SOC at the rational operating range constantly, and maximized fuel economy. The operating principle of this system is shown in Figure 72. Chen et al., proposed an energy management algorithm in [182] to effectively control battery current, and thus reduce fuel usage by allowing the engine operate more effectively. Quadratic programming was used here to calculate the optimum battery current. In [183], Li et al., used fuzzy logic to create a new quantity: battery working state or BWS which was used in an energy management system run by fuzzy logic to provide proper power division between the engine and the battery. Simulation results proved this approach to be effective in making the engine operate in the region of maximum fuel efficiency while keeping the battery away from excess discharging. Yuan et al., compared Dynamic Programming and Pontryagin's Minimum Principle (PMP) for energy management in parallel HEVs using Automatic Manual Transmission. The PMP method proved better as it was more efficient to implement, required considerably less computational time, and both of the systems provided almost similar results [184]. In [185], Bernard et al., proposed a real time control system to reduce hydrogen consumption in FCEVs by efficiently sharing power between the fuel cell arrangement and the energy buffer (ultracapacitor or battery). This control system was created from an optimal control theory based non-causal optimization algorithm. It was eventually implemented in a hardware arrangement built around a 600 W fuel cell arrangement. In an attempt to create an energy management system for a still-not-commercialized PHEV employing a micro turbine, Geng et al., used an equivalent consumption minimization strategy (ECMS) in [174] to estimate the optimum driving cost. Their system used the battery SOC and the vehicle telemetry to produce the results, which were available in real time and provided driving cost reductions of up to 21.6%.

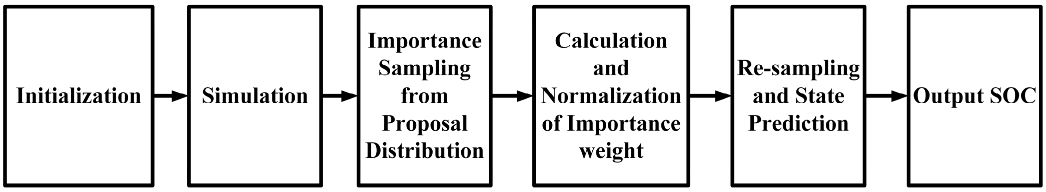


Figure 70. Working principle of the SOC measuring algorithm proposed by Zhou et al. [180].

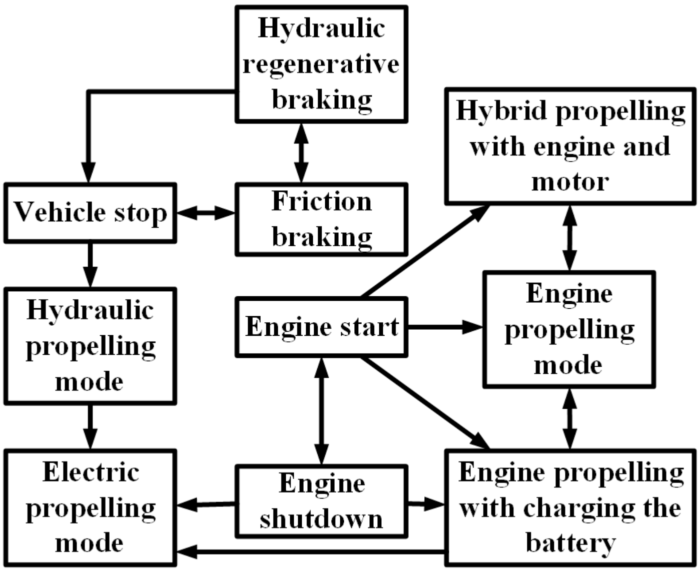


Figure 71. Transition of the operating modes of the vehicle used in [181] by Hui et al. From engine start to shutdown through stops, the vehicle can use either the hydraulic or the electric system, or it can use both.

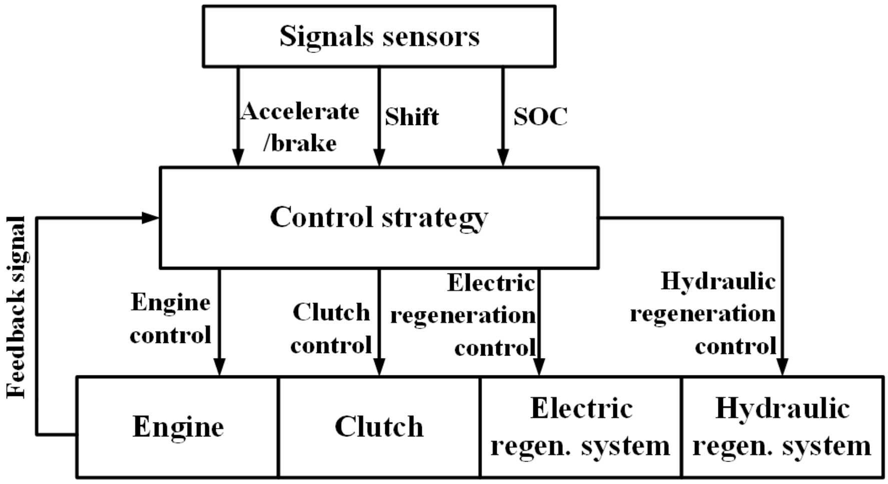


Figure 72. Operating principle of the control system proposed by Hui et al. The control strategy drives the actuating systems according to the decisions made from the sensor inputs. Adapted from [181].

As pointed out in Section 8, the grid is facing some serious problems with the current rise in EV penetration. Reducing the charging time of the vehicles while creating minimal pressure on the grid has become difficult goal to achieve. However, ample research has already been done on this matter and a number of charging system algorithms have been proposed to attain satisfactory charging performance.

In [186], Su et al., presented an algorithm (shown in Figure 73) capable of providing charge intelligently to a large fleet of PHEVs docked at a municipal charging station. This algorithm—which used the estimation of distribution (EDA) algorithm—considered real-world factors such as remaining charging time, remaining battery capacity, and energy price. The load management system proposed by Deilami et al., in [140] considered market energy prices that vary with time, time zones preferred by EV owners by priority selection, and random plugging-in of EVs—for providing coordinated charging in a smart grid system. It then used the maximum sensitivities selection (MSS) optimization technique to enable EVs charge as soon as possible depending on the priority time zones while maintaining the operation criteria of the grid such as voltage profile, limits of generation, and losses. This system was simulated using an IEEE 23 kV distribution system modified for this purpose. Mohamed et al., designed an energy management algorithm to be applied in EV charging parks incorporating renewable generation such as PV systems [187]. The system they developed used a fuzzy controller to manage the charging/discharging times of the connected EVs, power sharing among them, and V2G services. The goal of this system was to minimize the charging cost while reducing the impact on the grid as well as contributing to peak shaving. The flowchart associated to this system is shown in Figure 74.

To alleviate the problems at the distribution stage of the grid—which is highly affected by EV penetration—Geng et al., proposed a charging strategy comprising of two stages aimed at providing satisfactory charging for all connected EVs while shifting the loads on the transformers [120]. The first stage utilized Pontryagin's minimum principle and was based on the concept of dynamic aggregator; it derived the optimal charging power for all the EVs in the system. The second stage used fuzzy logic to distribute the power calculated in the first stage among the EVs. According to the authors, the system was feasible to be implemented practically [120]. In [116], Richardson et al., employed a linear programming based technique to calculate the optimal rate of charging for each EV connected in a distribution network to enable maximized power delivery to the vehicles while maintaining the network limits. This approach can provide high EV penetration possible in existing residential power systems with no or a little upgrade. Sortomme et al., developed an algorithm to maximize profit from EV charging in a unidirectional V2G system where an aggregator is present to manage the charging [146]. Table 31 summarizes the algorithms presented in this section.

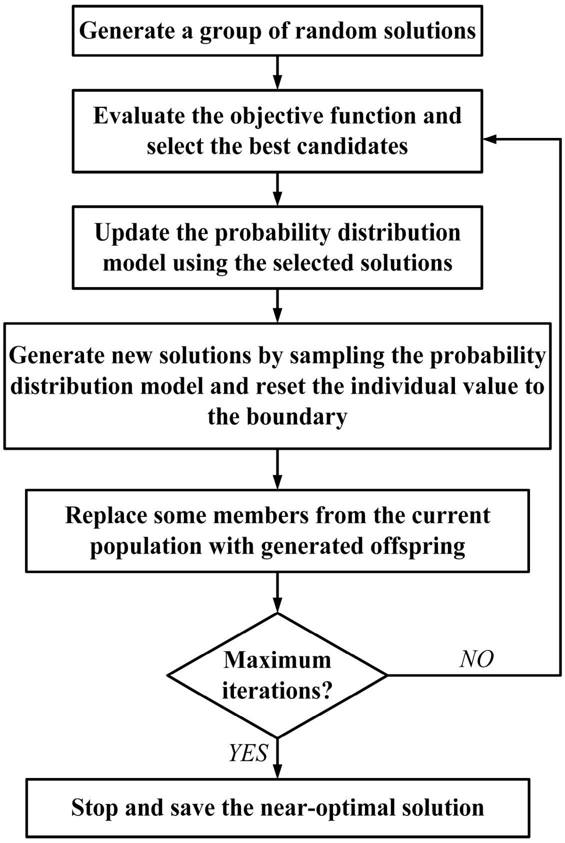


Figure 73. Intelligent charging algorithm proposed by Su et al., for a municipal charging station [186].

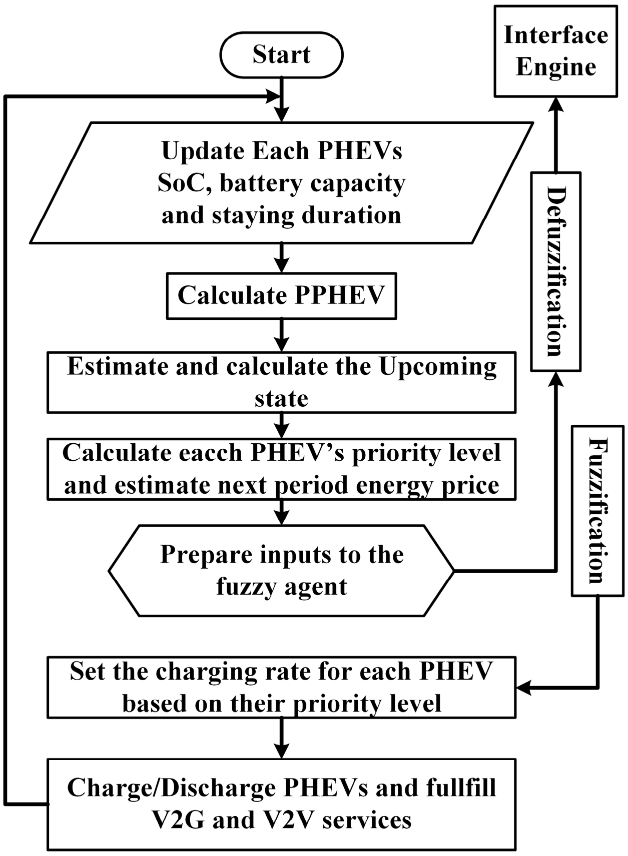


Figure 74. Flowchart of the management system proposed by Mohamed et al. [187].

Table 31. Summary of the control algorithms presented.

References	Algorithm Based on	Application
Magallan et al. [176]	*LuGre* dynamic friction model	Driving control system in rear-wheel-drive EV
Kang et al. [177]	Optimization-based control allocation strategy	Driving control system in four-wheel-drive EV
Tahami et al. [25]	Fuzzy logic	Driving control system in all-wheel-drive EV
Wang et al. [178]	Proportional-integral (PI) closed loop control system	Driving control system in in-wheel-drive EV
Nam et al. [179]	Extended Kalman filtering (EKF) method	Driving control system in in-wheel-drive EV
Zhou et al. [180]	Particle filter and multi-model data fusion	SOC measurement for lithium polymer batteries
Moura et al. [175]	Markov process	Power splitting in mid-sized sedan PHEV
Hui et al. [181]	Torque control strategy	Heavy hybrid vehicles using a single energy source
Chen et al. [182]	Quadratic programming	Reduction of fuel consumption by effective battery current control
Li et al. [183]	Fuzzy logic	Attaining maximum fuel efficiency without excess discharging of battery
Yuan et al. [184]	Dynamic Programming and Pontryagin's Minimum Principle	Efficient energy management in parallel HEV using Automatic Manual Transmission or AMT
Bernard et al. [185]	Non-causal optimization algorithm	Reduction of hydrogen consumption in FCEV
Geng et al. [174]	Equivalent consumption minimization strategy (ECMS)	Energy management in PHEV employing microturbine
Su et al. [186]	Estimation of distribution (EDA) algorithm	Intelligent charging of large fleet of PHEVs docked at a municipal charging station
Deilami et al. [140]	Maximum sensitivities selection (MSS) optimization	Load management system for intelligent charging
Mohamed et al. [187]	Fuzzy controller	V2G system for EV charging parks incorporating renewable generation
Geng et al. [120]	Pontryagin's minimum principle, fuzzy logic	Load shifting while charging EVs in the distribution network
Richardson et al. [116]	Linear programming	Enabling high EV penetration in existing residential power system network
Sortomme et al [146]	Preferred operating point (POP) algorithm	Maximizing profit from EV charging through an aggregator

12. Global EV Sales Figures

The electric vehicle market is growing much faster than the conventional vehicle market, and in some regions EVs are catching up with ICE vehicles in terms of the number of units sold. China has become the largest market for EVs, its market claiming 35.4% of the worldwide EV scene in 2017, an exorbitant rise from the mere 6.3% in 2013 [188]. Chinese consumers bought a world-topping 24.38 million passenger electric vehicles in 2016. China has the greatest number of manufacturers, led by BYD autos, which sold 96,000 EVs in 2016. This drive in China is fueled by government initiatives adopted to promote EV use to mitigate the country's serious air pollution. However, the majority of Chinese vehicles are in the $36,000 range and offers limited range, but high-end vehicles manufacturing is on the rise in China too. This huge market has attracted major carmakers all over the world—Ford, Volkswagen, Volvo, and General Motors—who have their own EVs in the Chinese market and are poised to introduce more models in the coming years [189]. Figure 75 shows the ten highest selling EVs in China in 2016.

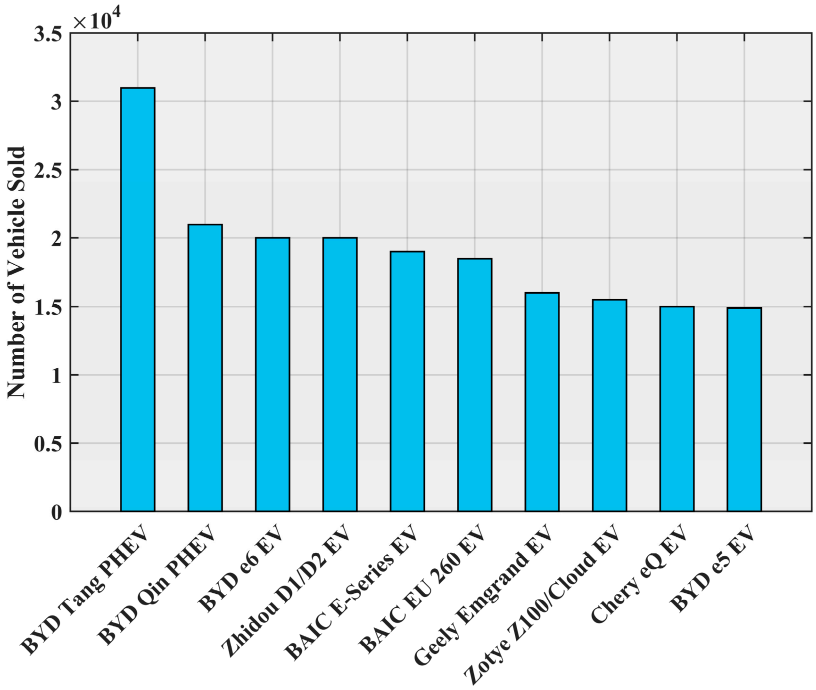


Figure 75. Top ten EVs in China in 2016 according to the number of units sold. Data from [190].

From a global perspective, sales of EV grew by 36% in the USA; Europe saw a growth of 13%, while Japan observed a decrease of 11% in the same period. BYD dominated the global market with a 13.2% share, followed by Tesla in second place (9.9%); the other major contributors can be listed as Volkswagen Group, BMW Group, Nissan, BAIC, and Zoyte. However, the Tesla Model S remained the best-selling EV in 2016 with 50,935 units sold, followed by the Nissan Leaf EV with 49,818 units [191]. The top ten best-selling vehicles around the globe in shown in Figure 76.

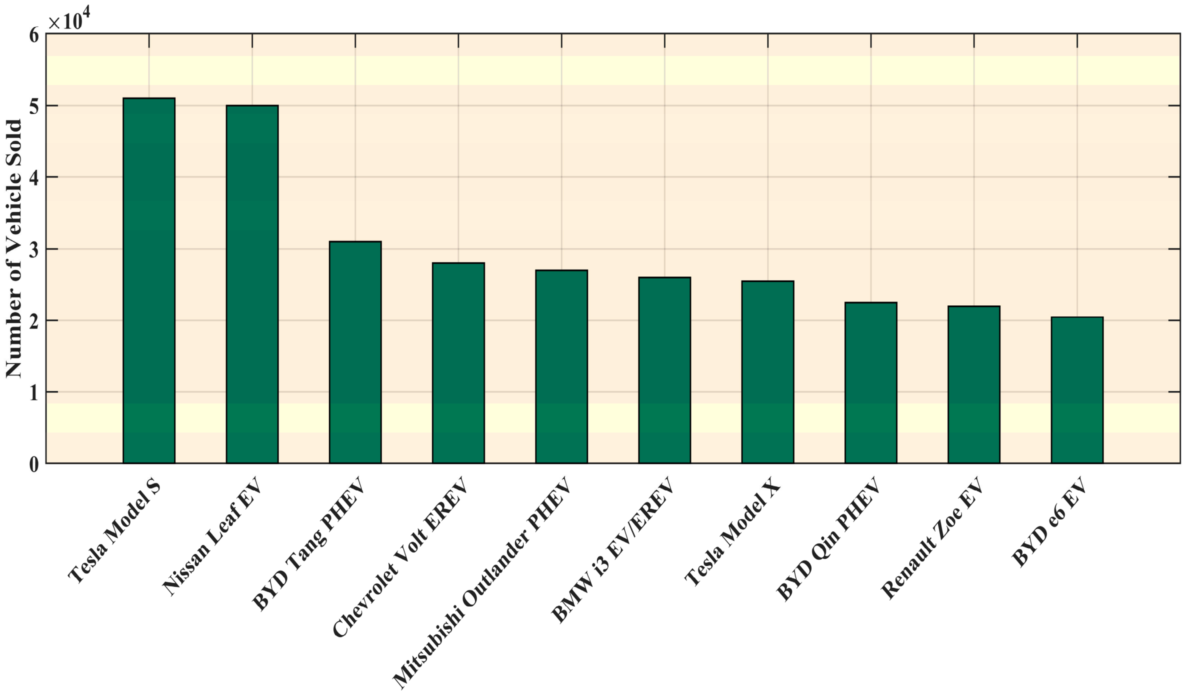


Figure 76. Top ten best-selling EVs globally in 2016. Data from [191].

The American market was dominated predictably by the Tesla Model S in 2016, 28,821 of these were sold; Chevrolet Volt EREV sold 24,739 units, thus securing the second place. The third place was achieved by another Tesla, the Model X; 18,192 of these SUVs were sold in 2016 [192]. The ten best-selling EVs in the USA in 2016 are shown in Figure 77.

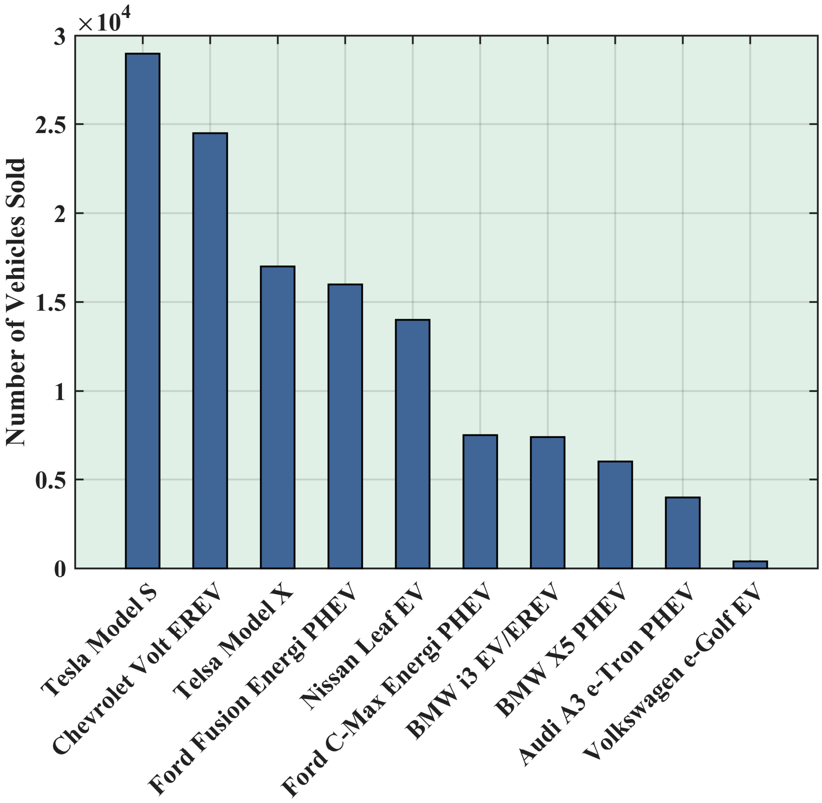


Figure 77. Top ten best-selling EVs in the USA in 2016. Data from [192].

The Renault Zoe was the best-selling BEV in Europe in 2016, with 21,338 units sold, followed by the Nissan Leaf with 18,614 units. In the PHEV segment, the Mitsubishi Outlander PHEV was the market leader in Europe in 2016, with 21,333 units sold; the Volkswagen Passat GTE held the second position with 13,330 units [193]. Figures 78 and 79 shows the BEV and PHEV market shares in Europe in 2016.

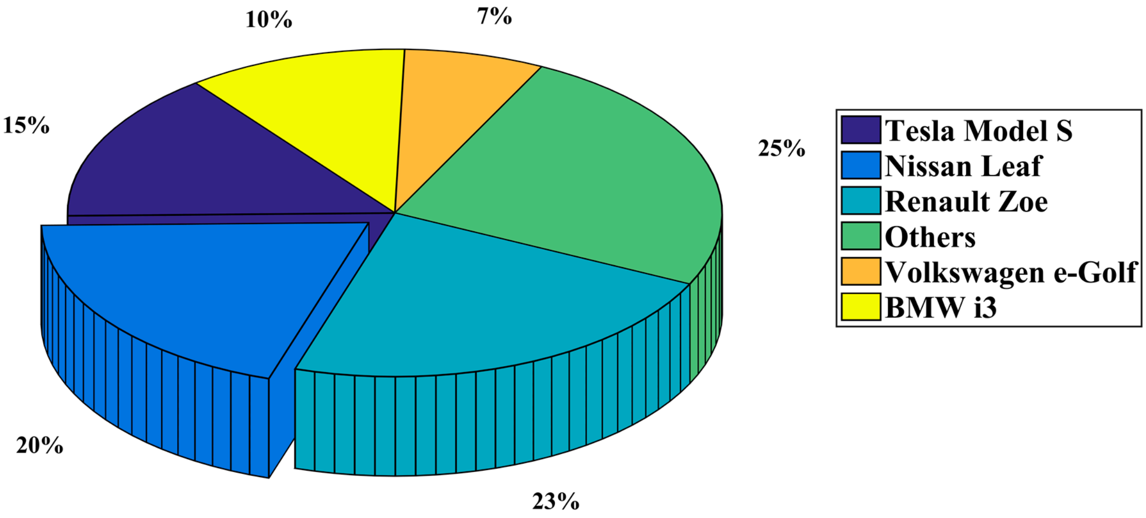


Figure 78. BEV market shares in Europe in 2016. Data from [193].

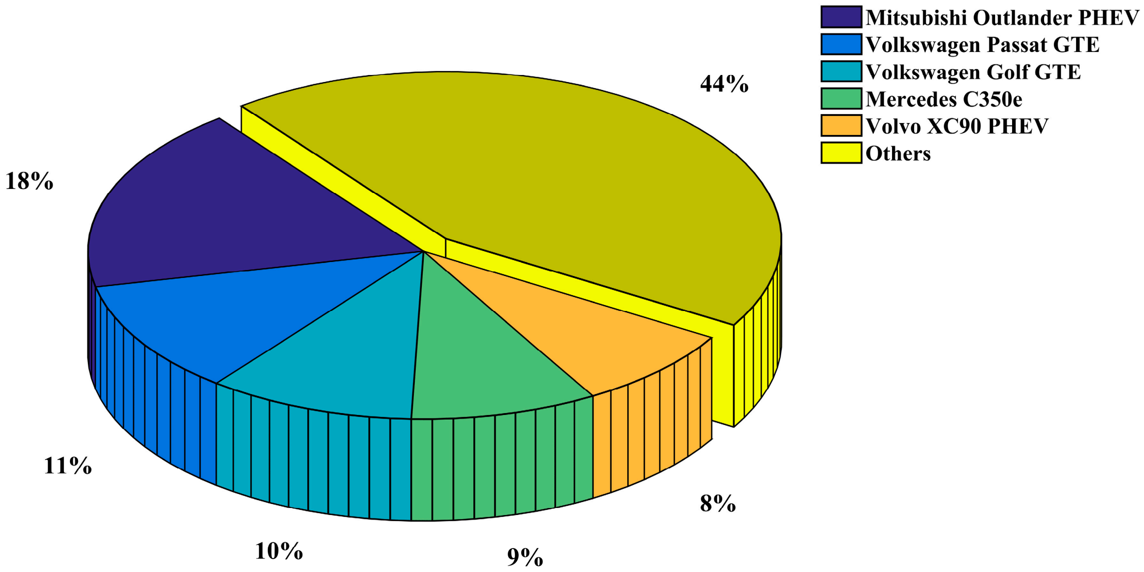


Figure 79. PHEV market shares in Europe in 2016. Data from [193].

13. Trends and Future Developments

The adoption of EVs has opened doors for new possibilities and ways to improve both the vehicles and the systems associated with it, the power system, for example. EVs are being considered as the future of vehicles, whereas the smart grid appears to be the grid of the future [194,195]. V2G is the link between these two technologies and both get benefitted from it. With V2G comes other essential systems required for a sustainable EV scenario—charge scheduling, VPP, smart metering etc. The existing charging technologies have to improve a lot to make EVs widely accepted. The charging time has to be decreased extensively for making EVs more flexible. At the same time, chargers and EVSEs have to able to communicate with the grid for facilitating V2G, smart metering, and if needed, bidirectional charging [23]. Better batteries are a must to take the EV technology further. There is a need for batteries that use non-toxic materials and have higher power density, less cost and weight, more capacity, and needs less time to recharge. Though technologies better than Li-ion have been discovered already, they are not being pursued industrially because of the huge costs associated with creating a working version. Besides, Li-ion technology has the potential to be improved a lot more. Li-air batteries could be a good option to increase the range of EVs [23]. EVs are likely to move away from using permanent magnet motors which use rare-earth materials. The motors of choice can be induction motor, synchronous reluctance motor, and switched reluctance motor [23]. Tesla is using an induction motor in its models at present. Motors with internal permanent magnet may stay in use [23]. Wireless power transfer systems are likely to replace the current cabled charging system. Concepts revealed by major automakers adopted this feature to highlight their usefulness and convenience. The Rolls-Royce 103EX and the Vision Mercedes-Maybach 6 can be taken as example for that. Electric roads for wireless charging of vehicles may appear as well. Though this is not still viable, the situation may change in the future. Recent works in this sector includes the work of Electrode, an Israeli startup, which claims to be able to achieve this feat in an economic way. Vehicles that follow a designated route along the highway, like trucks, can get their power from overhead lines like trains or trams. It will allow them to gather energy as long as their route resides with the power lines, then carry on with energy from on-board sources. Such a system has been tested by Siemens using diesel-hybrid trucks from Scania on a highway in Sweden [196]. New ways of recovering energy from the vehicle may appear. Goodyear has demonstrated a tire that can harvest energy from the heat generated there using thermo-piezoelectric material. There are also chances of solar-powered vehicles. Until now, these have not appeared useful as installed solar cells only manage to convert up to 20% of the input power [70]. Much research is going on to make the electronics and sensors in EVs more compact, rugged and cheaper—which in many cases are leading to advanced solid state devices that can achieve these goals with promises of cheaper products if they can be mass-produced. Some examples can be the works on gas sensors [197], smart LED drivers [198], smart drivers for automotive alternators [199], advanced gearboxes [200], and compact and smart power switches to weather harsh conditions [201]. The findings of [202–208] may prove helpful for studies regarding fail-proof on-board power supplies for EVs. The future research topics will of course, revolve around making the EV technology more efficient, affordable, and convenient. A great deal of research has already been conducted on making EVs more affordable and capable of covering more distance: energy management, materials used for construction, different energy sources etc. More of such researches are likely to go on emphasizing on better battery technologies, ultracapacitors, fuel cells, flywheels, turbines, and other individual and hybrid configurations. FCVs may get significant attention in military and utility-based studies, whereas the in-wheel drive configuration for BEVs may be appealing to researchers focusing on better urban transport systems. Better charging technologies will remain a crucial research topic in near future. This is one of the areas the EV technology is lacking very badly; wireless charging technologies are very likely to attract more researchers' attention. A lot of research has already been done incorporating EVs and the grid: the challenges and possibilities that the EVs bring with them to the existing grid and also to the grid of the future. With more implementation of smart grids, distributed generation, and renewable energy sources, researches in these fields are likely to increase. And as researches in the entire aforementioned field's increase, exploration for better algorithms to run the systems is bound to rise. Figure 80 shows the major trends and sectors for future developments for EVs.

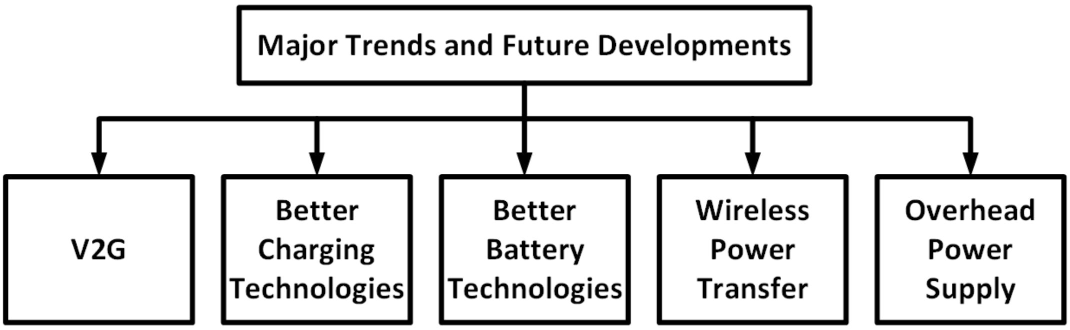


Figure 80. Major trends and sectors for future developments for EV.

14. Outcomes

The goal of this paper is to focus on the key components of EV. Major technologies in different sections are reviewed and the future trends of these sectors are speculated. The key findings of this paper can be summarized as follows:

- EVs can be classified as BEV, HEV, PHEV, and FCEV. BEVs and PHEVs are the current trends. FCEVs can become mainstream in future. Low cost fuel cells are the main prerequisite for that and there is need of more research to make that happen. There are also strong chances for BEVs to be the market dominators with ample advancement in key technologies; energy storage and charging systems being two main factors. Currently FCVs appear to have little chance to become ubiquitous, these may find popularity in niche markets, for example, the military and utility vehicles.
- EVs can be front wheel drive, rear wheel drive, even all-wheel drive. Different configurations are applied depending on the application of the vehicle. The motor can also be placed inside the wheel of the vehicle which offers distinct advantages. This configuration is not commercially abundant now, and has scopes for more study to turn it into a viable product.
- The main HEV configurations are classified as series, parallel, and series-parallel. Current vehicles are using the series-parallel system mainly as it can operate in both battery-only and ICE-only modes, providing more efficiency and less fuel consumption than the other two systems.

- Currently EVs use batteries as the main energy source. Battery technology has gone through significant changes, the lead-acid technology is long gone, as is the NiMH type. Li-ion batteries are currently in use, but even they are not capable enough to provide the amount of energy required to appease the consumers suffering from 'range anxiety' in most cases. Therefore the main focus of research in this area has to be creating batteries with more capacity, and also with better power densities. Metal-air batteries can be the direction where the EV makers will head towards. Lithium-sulfur battery and advanced rechargeable zinc batteries also have potential provide better EVs. Nevertheless, low cost energy sources will be sought after always as ESS cost is one of the major contributors to high EV cost.
- Ultracapacitors are considered as auxiliary power sources because of their high power densities. If coupled with batteries, ultracapacitors produce a hybrid ESS that can satisfy some requirements demanded from an ideal source. Flywheels are also being used, especially because of their compact build and capability to store and discharge power on demand. Fuel cells can also be used more in the future if FCVs gain popularity.
- Different types of motors can be employed for EV use. The prominent ones can be listed as induction motor, permanent magnet synchronous motor, and synchronous reluctance motor. Induction motors are being extensively these days, they can also dominate in future because of their independence on rare-earth material permanent magnets.
- EVs can be charged with AC or DC supply. There are different voltage levels and they are designated accordingly. Higher voltage levels provide faster charging. DC supplies negate the need of rectification from AC, which reduces delay and loss. However, with increased voltage level, the pressure on the grid increases and can give rise to harmonics as well as voltage imbalance in an unsupervised system. Therefore, there are ample chances of research in the field of mitigating the problems associated with high-voltage charging.
- Two charger configurations are mainly available now: CCS and CHAdeMO. These two systems are not compatible with each other and each has a number of automakers supporting them. Tesla also brought their own 'supercharger' system, which provides a faster charging facility. It is not possible to determine now which one of these will prevail, or if both will co-exist, technical study is needed to find out the most useful one of these configurations or ways to make them compatible with each other.
- Whatever the charging system is, the charging time is still very long. This is a major disadvantage that is thwarting the growth of the EV market. Extensive research is needed in this sector to provide better technologies that can provide much faster charging and can be compatible with the small time required to refill an ICE vehicle. Wireless charging is also something in need of research. With all the conveniences it promises, it is still not in a viable form to commercialize.
- EV impacts the environment, power system, and economy alongside the transportation sector. It shows promises to reduce the GHG emissions as well as efficient and economical transport solutions. At the same time, it can cause serious problems in the power system including voltage instability, harmonics, and voltage sag, but these shortcomings may be short-lived if smart grid technologies are employed. There are prospects of research in the areas of V2G, smart metering, integration of RES, and system stability associated with EV penetration.
- EVs employ different techniques to reduce energy loss and increase efficiency. Reducing the drag coefficient, weight reduction, regenerative braking, and intelligent energy management are some of these optimization techniques. Further research directions can be better aerodynamic body designs, new materials with less weight and desired strength, ways to generate and restore the lost energy.
- Different control algorithms have been developed for driving assist, energy management, and charging. There is lots of room left for more research into charging and energy management algorithms. With increased EV penetration in the future, demands for efficient algorithms are bound to increase.

15. Conclusions

EVs have great potential of becoming the future of transport while saving this planet from imminent calamities caused by global warming. They are a viable alternative to conventional vehicles that depend directly on the diminishing fossil fuel reserves. The EV types, configurations, energy sources, motors, power conversion and charging technologies for EVs have been discussed in detail in this paper. The key technologies of each section have been reviewed and their characteristics have been presented. The impacts EVs cause in different sectors have been discussed as well, along with the huge possibilities they hold to promote a better and greener energy system by collaborating with smart grid and facilitating the integration of renewable sources. Limitations of current EVs have been listed along with probable solutions to overcome these shortcomings. The current optimization techniques and control algorithms have also been included. A brief overview of the current EV market has been presented. Finally, trends and ways of future developments have been assessed followed by the outcomes of this paper to summarize the whole text, providing a clear picture of this sector and the areas in need of further research.

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