International Journal of Modern Achievement in Science, Engineering and Technology (IJSET)
ISSN 3023-459X
DOI: 10.63053/ijset.79

Analysis Of Hybrid Vehicles and Examination of Their Structures, Power and Challenges

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ARTICLE INFO

Keywords:
Hybrid Vehicles, Fuel, Pollutants, Electric Energy, Battery.

ABSTRACT

One of the most important concerns of automobile companies and automotive industry activists is reducing the level of vehicle pollution and the damage they cause to the environment. This concern has become more serious, especially since the last years of the 20th century, when environmental activists and related organizations succeeded in establishing strict standards and laws regarding the level of vehicle pollution. Replacing gasoline and diesel with CNG gas was the first step towards creating less pollution in this industry. However, ideal success would be achieved when the use of any fossil fuel in cars was generally eliminated. Accordingly, replacing these fuels with healthy and environmentally safe fuels became a serious plan for automakers. Today, with the increasing price of fuel and the high costs of its refining, many people are moving towards using fuel-efficient cars. Hybrid cars are one of the best examples to meet this demand. A hybrid car, also known as a green car, uses two energy sources and a battery to move. The system of this type of dual electric car consists of a gasoline engine, an electric motor, and a battery, which aim to consume as little gasoline as possible and maximize the efficiency and performance of the car. A hybrid car stores the electrical energy produced by the electric motor in its battery and works by combining the combustion energy of gasoline or diesel; of course, in some types, the electrical energy of the battery may be produced by the internal combustion system or from regenerative brakes.

Introduction

Nowadays, due to the pollution caused by cars and the limitations of fossil fuels, car factories have taken an important step in dealing with this issue, including hybrid vehicles, fuel cell technology, gasoline direct-injection engines[1] , homogeneous charge compression ignition engines[2] and bifuel cars. High efficiency, low emissions, high mileage, optimal safety and competitive price are among the important features of hybrid cars. Many major automakers have started to produce these cars on a large scale. In this section, we will discuss the general outline of how it works, operating modes, advantages, disadvantages and the division of different hybrid car systems. On November 23, 1905, An American engineer named H. Piper built a hybrid car that was capable of accelerating up to 25 miles in 10 seconds. The engine of this car was a combination of a gasoline engine and an electric motor, which is known today as a hybrid engine. Piper patented his invention three and a half years later, but the rapid development of internal combustion engines with high power and torque at that time, as well as their ability to start without handles and most importantly, the low price of fossil fuels and the lack of environmental pollution, caused these types of cars to be ignored. In the wake of the oil crises of the 1970 s, these cars were again considered, but it was not until 1990, when the Partnership for a New Generation Vehicle [3]began in the United States, that these cars were not seriously pursued [1]. Today, hybrid cars have attracted the attention of major companies in the world and the success of these products has been so impressive.

Today's cars around the world mainly use fossil fuels. The decreasing trend of these fuels and the increase in their prices is one of the most important energy issues in all countries. Also, due to their large number, these types of cars cause many problems. In recent years, effective research and activities have been carried out to replace cars with cleaner fuels and better efficiency. Hybrid Electric, Electric and Hybrid Cell Cars Fuels are among the good options to replace fossil fuel cars. However, due to technology issues and high prices, these cars still do not have a significant number among the available cars. Each of these electric, hybrid-electric and fuel cell vehicles has its own advantages and limitations such as reliability, efficiency, price, adaptability to existing infrastructure, energy supply and maintainability. Among these vehicles, hybrid electric vehicles have the most advantages and capabilities to replace fossil fuel cars according to the existing technology and infrastructure.

Therefore, in the design and manufacture of these cars, many different technologies are hybridized with each other. For example, the powertrains of hybrid electric vehicles have two parts: mechanical and electric. The electrical part includes electric motors, drivers, power converters and controllers. The mechanical part, like ordinary cars, includes an internal combustion engine and other mechanical parts. In fact, the difference between hybrid electric cars and fossil fuel cars is the presence of an electric part in them [2]. In recent years, significant advances have been made in the field of power electronics, especially in the control (drive) of electric cars and various types of power converters. These advances in the field of power electronics have led to the development of electric vehicles, hybrid electric vehicles, and fuel cells. In these cars, a large part of the science of power electronics is used, including DC-to-DC conversion, DC-to-AC conversion, AC-to-DC conversion and motor drives. Therefore, there are many structures of DC cutters, AC and DC drives. Inverters and rectifiers have been studied and used in electric and hybrid electric vehicles. In addition to the structures of electronic power converters in these cars, many key and control methods have also been developed for these converters.

Hybrid electric vehicles also have limitations and challenges. Most of these challenges are related to power electronics. High reliability, power electronics technology, price, temperature, packaging, complexity in the structure, maintenance and services are among the issues related to power electronics in these types of cars. In this paper, the main structures of hybrid electric vehicles, the power electronics circuits used in them are discussed and the new research conducted in the field of each of them is addressed. Then, in order to show the research paths for the future, the challenges and issues related to power electronics in hybrid electric vehicles are introduced [3].

2. Hybrid Vehicle

A hybrid car is a product of a fusion of two different yet complementary technologies, namely the

GDI[1]
HCCI[2]
PNGV[3]

combustion engine and the electric motor. These cars, taking advantage of this clever combination, seek to achieve a balance between powerful performance and optimal fuel consumption. In hybrid cars, both engines work in harmony, providing the optimal state for the car in different driving conditions. For example, at low speeds or in traffic, the electric motor takes over propulsion, while the combustion engine shuts down. This leads to a significant reduction in fuel consumption and emissions. As speed increases or more acceleration is required, the combustion engine comes into play and helps the electric motor to provide the power needed by the vehicle. One of the unique features of hybrid cars is the ability to charge their batteries through braking. In this process, the kinetic energy of the vehicle is converted into electrical energy during braking and stored in batteries. This stored energy is transferred back to the electric motor when needed, helping the car to move. In addition to the environmental benefits, hybrid cars have other benefits. These cars generally have better acceleration than conventional cars and offer a smoother ride. Also, their maintenance costs are usually lower due to their simpler structure and the use of fewer parts. Due to the numerous advantages of hybrid cars, these cars are considered as one of the viable options for the future of the automotive industry. With the advancement of technology and the reduction in the price of batteries, it is expected that hybrid cars will become more popular in the future and play an important role in reducing air pollution and dependence on fossil fuels. A hybrid car, also known as a green car, uses two power sources and a battery for its movement. The system of this type of dual electric car consists of a gasoline engine, an electric motor and a battery, which aim to consume as little gasoline as possible and maximize the efficiency of the car [4]. A hybrid car stores the electrical energy generated by the electric motor in its battery and works by combining the combustion energy of gasoline or diesel, although in some types the electrical energy of the battery may be generated by the internal combustion system or from the regenerative brakes.

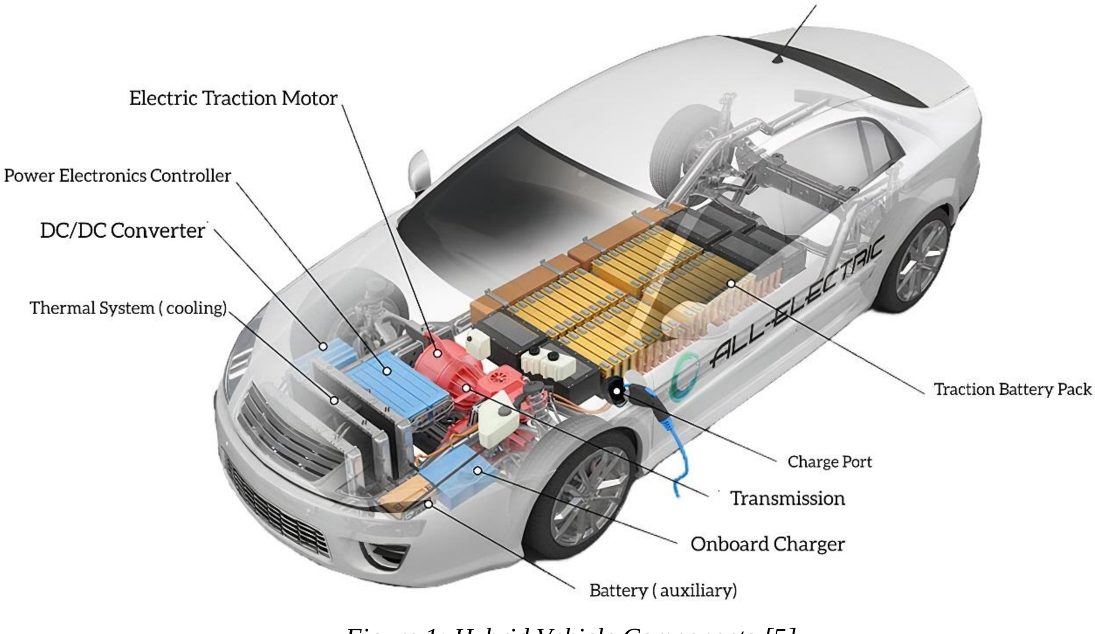


Figure 1: Hybrid Vehicle Components [5]

3. Types of Electric Motor Used in Hybrid Vehicle

An electric vehicle consists of the energy source, the auxiliary and the electric propulsion subsystems, which includes an electronic controller, power converter, mechanical transmission and electric motor. The block diagram of an electric vehicle illustrates these major components and their interconnections.

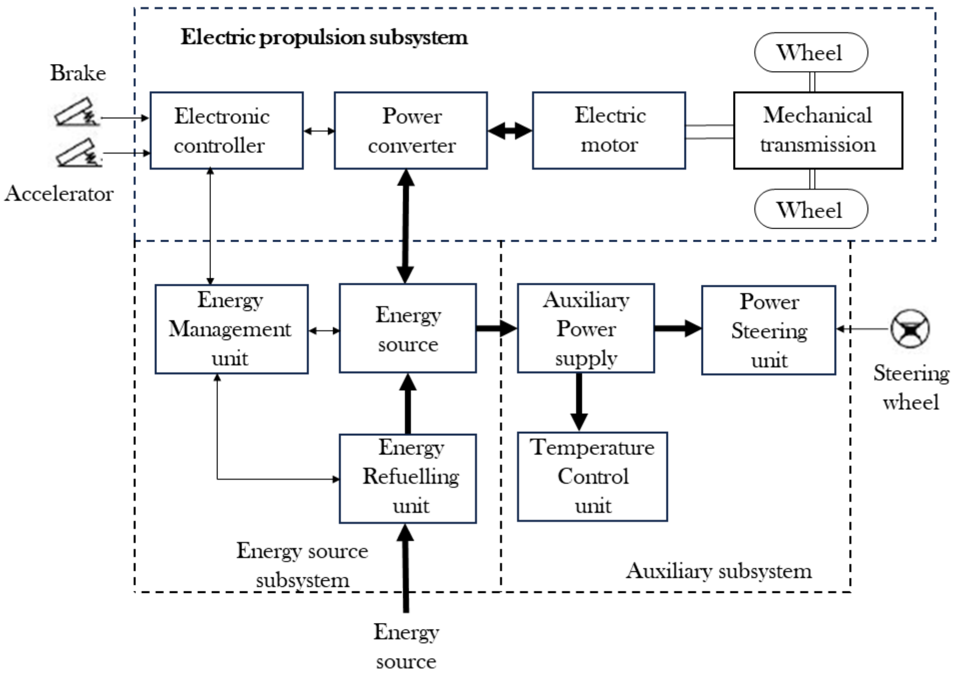


Figure 2: Block of diagram of electric vehicle [6]

The development of electrical drives dates back to the 18th century, when Faraday demonstrated the principle of electromagnetic induction. Following this invention, electric motors were developed and played an important role in hybrid vehicles, enabling them to switch between electric and gasoline power. There are two main categories of electric motors used in hybrids: AC motors and DC motors. Each type has its own advantages and disadvantages that make them suitable for different applications in the hybrid system. Typically, an electric motor consists of a rotor, stator, windings, air gap and commutators/converters. Depending on the arrangement of these components, different types of electric motors are constructed.

Induction motors are the most common type of AC motors used in hybrids. They are strong, reliable, and relatively inexpensive. Induction motors work by creating a rotating magnetic field in the stator that induces current in the rotor. This current then interacts with the stator's magnetic field to generate torque and rotation. In addition to induction motors, synchronous motors also play a significant role in hybrid vehicles. These motors operate at a constant speed and in harmony with the AC frequency. They are commonly used in high-performance hybrids because of their efficiency and ability to regenerate energy when braking. However, they are more expensive and complex than induction motors.

Apart from AC motors, DC motors are also widely used in hybrid vehicles. Brushed DC motors are the simplest type of DC motors, featuring a brush and a commutator to reverse the flow of current in the rotor and keep it spinning. They are relatively inexpensive and have good controllability, but their lifespan is limited due to brush wear, requiring regular maintenance. On the other hand, brushless DC motors eliminate the need for brushes and commutators by using electronic controls to reverse current in the rotor. This makes them more efficient and reliable than brushed DC motors, with longer lifespans and lower maintenance requirements. Additionally, they are more compact and lighter, making them ideal for hybrid applications [7].

The below table compares different electric motors used in hybrid and electric vehicles based on performance criteria. PM BLDC and PM Syn motors have the highest efficiency and power density that make them ideal for high-performance EVs, while Induction motors offer greater reliability and lower costs and they are more economical choice. DC BLDC motors require minimal maintenance but score lower in efficiency. SR motors have moderate performance but higher noise levels. The choice of electric motors in vehicles depends on a balance between efficiency, cost and reliability. Higher performance options offer greater energy savings, while more affordable alternatives ensure wider accessibility and practical implementation in large-scale production.

Table 1: performance evaluation of Electric Motor [8]

Comparison parameters	**DC**	**Induction**	**SR**	**PM syn**	**PM BLDC**
Power density	2	3	3.5	4.5	5
Efficiency	2	3	3.5	4.5	5
Controllability	5	4	3	4	4
Reliability	3	5	5	4	4
Maturity	5	5	4	5	4
Costlevel	4	5	4	3	3
Noiselevel	3	5	2	5	5
Maintenance	1	5	5	5	5
Total	25	35	30	35	35

Now that we have analyzed the types of electric motors in vehicles, it is important to note that hybrid vehicles have a Gasoline-Electric Hybrid Structure, which consists of a combination of an internal combustion engine (gasoline) and an electric motor, along with a battery to supply electrical energy.

The gasoline engines in hybrid cars are similar to those used in conventional vehicles. However, the difference is that these engines are smaller in hybrid cars and incorporate more advanced technology to reduce fuel consumption and increase efficiency. The fuel tank in hybrid cars primarily serves as a means of storing energy for the gasoline engine. Gasoline produces more energy than a battery; for example, 1,000 pounds of battery power is equivalent to a gallon (or 7 pounds) of gasoline. The gasoline engine plays an important role in a hybrid car, but its performance differs significantly from that of a regular car engine. Unlike conventional car engines, which run continuously, the hybrid engine can automatically shut down when the car stops and restart as needed. This feature significantly reduces fuel consumption and emissions. Additionally, hybrids often use smaller and more efficient gasoline engines compared to conventional cars, as the electric motor compensates for the lack of power, particularly at low speeds. The hybrid system also prioritizes engine operation at its most efficient range, avoiding low-load situations where fuel efficiency is poor.

The electric motor in hybrid cars is highly advanced. In these motors, sophisticated electrical systems allow them to function as both a motor and a generator. For instance, the motor can draw energy from the batteries when the car needs to accelerate, and when slowing down, it can act as a generator to recover energy and return it to the batteries. A generator is similar to an electric motor but is designed specifically to generate electrical energy and it is commonly used in series hybrid systems. The batteries in hybrid cars serve as a means of storing energy for the electric motor. Unlike gasoline in a fuel tank, which can only power a gasoline engine, the electric motor in hybrid cars not only provides energy for driving but can also store recovered energy in the batteries. These two energy sources—gasoline and electricity—can be combined in hybrid vehicles in various ways, which will be explored in detail in the following sections [9].

4. Power Electronics and Dedicated Components in Hybrid Electric Vehicles

Power electronics converters play a crucial role in hybrid electric vehicles, where the electrical system consists of both DC and AC sections. The use of power converters in these cars is necessary for the conversion of different forms of voltage and for power management and control. Therefore, the electrical system in a hybrid electric car has several DC-to-DC, DC-to-AC, and AC-to-DC converters. It has multiple functions such as driving the motor, connecting the parts (such as the DC-to-DC converter that is placed between the battery and the inverter), charging the batteries, and feeding the peripheral consumers.

Several inverters are used in hybrid electric vehicles, the most important of which is the three-phase inverter related to the main motor drive, which applies the voltage with the required amplitude and frequency to the motor. This inverter, which is made of high-power and high-speed power semiconductor switches, has capacitors on the DC side, sensors, filters, and control systems. Also, this inverter acts as a rectifier when the motor acts as a generator to transfer power from the motor to the battery. In other words, this inverter must be bidirectional. There are also several small inverters used to power other small engines or in-car consumers.

Most of these inverters are unidirectional power single-phase with an H-bridge structure. In this section, the structures of three-phase inverters related to the main motor drive are examined. PWM, Multilevel, and Z-Source inverters are some of the most commonly used structures in the main electric motor drive. However, other structures have recently been proposed for these converters for use in electric and hybrid electric vehicles, including matrix converters and converters made with WBG semiconductor switches.

Currently, the most widely used inverters are two-level inverters, which are especially widely used in motor drives. Currently, in electric and hybrid electric vehicles, these inverters are the most widely used inverters for driving motors due to their high reliability, simplicity, low volume, and low price. The most appropriate way to control these inverters is a method of hidden pulse modulation. The amplitude, frequency, and harmonics in the output voltage of the inverter are easily controlled by this method. In these inverters, IGBT switches with reverse diode are used. The main disadvantage of this inverter is that the range of its output voltage base component cannot exceed the input DC voltage range. On the other hand, the DC voltage of the batteries is very low. Therefore, in order to have a high amplitude AC voltage, this inverter needs an increasing DC-to-DC converter in its input. Also, the output voltage of this inverter has high harmonic components.

A new generation of inverters that have been developed a lot in recent years are multi-level inverters. The output voltage of these inverters is quasi-sinusoidal and they are better than two-level inverters in terms of amplitude and harmonic components. In order to use these inverters in hybrid electric vehicles, they must be structured and modulated in such a way that they can return power to the battery. Most multi-level inverter structures require multiple separate DC sources. While it is difficult to create an independent DC source in hybrid electric vehicles, multi-level inverters that work with only one DC source are more suitable for use in these vehicles. Z-SOURCE Inverters can be one of the most suitable inverters for use in electric, hybrid-electric and fuel cell vehicles. In addition to the Z-Source inverter, the QZ-Source inverter is also recommended for use in cars. These inverters can provide a longer output voltage range than a two-level inverter. In fact, these inverters do not require a separate DC-to-DC converter to increase the DC voltage. Also, these inverters have a simple and inexpensive structure.

In hybrid electric vehicles, several DC-to-DC converters are used for different applications. In general, the application of these converters is to connect DC chains with different voltage levels in the vehicle. If the main drive motor is a DC motor, a battery-powered DC-to-DC converter is used to control the motor. Due to the fact that the voltage of the batteries is low, a DC-to-DC converter is placed between the battery and the inverter to increase the DC voltage. Another category of DC-to-DC converters aftermarket feeders are used in the car such as sensors, control circuits, etc. These types of converters are mainly half-bridge and full-bridge or resonant type [10,11].

In addition to power electronics systems, various technical components and parts are also used in vehicles, including the engine, fuel system, electrification system, power transmission system, suspension system, and cooling system, which are essential for proper vehicle operation. Another category of components includes systems that support overall vehicle functionality, such as control circuits and power distribution units. These systems are mainly designed to ensure efficient performance and integration within the vehicle . For example, the transmission system and power transmission of the hybrid vehicle are responsible for the operation or disabling of the electric motor and the internal combustion engine of the vehicle. The task of the transmission system goes beyond connecting and disconnecting power sources. It actively manages the interaction between the internal combustion engine and the electric motor based on various factors. When the battery is full, the electric motor is centered and drives the vehicle until it runs out of charge. As the battery is discharged, the internal combustion engine is gradually inserted to provide additional power and maintain optimal efficiency. When driving at low speeds, the electric motor works to minimize emissions and fuel consumption. At higher speeds or under heavy acceleration, the internal combustion engine kicks in and provides the necessary power. Additionally, in hilly roads or heavy traffic, the combined effort of both engines may be required for optimal performance. The gearbox adapts accordingly, ensuring adequate power and torque.

If we want to identify a second fundamental system in hybrid vehicles, undoubtedly, the braking system would be one of the most critical components. In hybrid vehicles, the braking system operates on a regenerative principle. In this system, an electric motor is utilized for braking, significantly reducing reliance on friction-based braking mechanisms. The electric motor captures the vehicle's kinetic energy and converts it into electrical energy, which is subsequently stored in the batteries. Through this process, the electric motor functions as a generator, enhancing energy efficiency and overall vehicle performance.

The third crucial system analyzed in hybrid vehicles is the cooling system, which is essential for thermal management, ensuring the efficient operation of both the internal combustion engine and the electric powertrain components. Hybrid vehicles generate heat from multiple sources, including the battery pack, power electronics, and the engine. To prevent overheating and maintain optimal efficiency, sophisticated liquid cooling or air-cooling systems are employed. Battery thermal management systems[4] are particularly critical, as excessive heat can degrade battery performance and lifespan. These systems regulate temperature through dedicated coolant loops, heat exchangers and sometimes even phase-change materials or active cooling strategies, such as refrigerant-based cooling. Effective thermal management enhances energy efficiency, extends component life and ensures reliable operation under varying environmental and driving conditions.

5. Types of Hybrid Electrical Vehicle[5]

Hybrid means a combination of two or more sources that has multiple powered sources that could drive the vehicle separately to propel the vehicle. There are many other hybridization configurations designed as fuel cell, gas turbine, pneumatic, ethanol, electric drive, solar, hydraulic and much more developed in recent years. Among these techniques, the most proven and established procedure is electric motor and an internal combustion[6] engine. The one form of HEV is gasoline with an engine as a fuel converter and other is a bi-directional energy storage system. Nowadays, efficiency-improving technologies are used in HEVs named as regenerative braking, which converts kinetic energy into electrical energy to charge a battery. As we know, the conventional IC engine produces lots of harmful gases, wastage of fuel during heavy traffic and many more. HEV is used to overcome all the disadvantages of IC engine by switching to power transmission through the motor and shutting off the engine Another advantage of HEVs is that when the fuel tank gets empty while driving the engine, then the vehicle can be driven on electric power with its maximum range. Hybrid vehicles can be classified based on two perspectives, which will be analyzed in the following section.

5.1 Powertrain Configuration-Based Hybrid Vehicles

A series hybrid system is also known as a range extender. In this system, as shown in Figure 3, the combustion engine drives an electric generator to charge a battery and provide power to make the electric motor. In this system, the electric motor is the only means of supplying power to the vehicles. The generator gives supply to both batteries as well as the motor that drives the vehicle. These vehicles have a large battery pack and a large motor with a small IC engine. In this system, there is no mechanical connection between the IC engine and transmission. Thus, IC can operate at maximum efficiency to satisfy the required power of the vehicle. The only disadvantage of this connection is the high cost of batteries and its components.

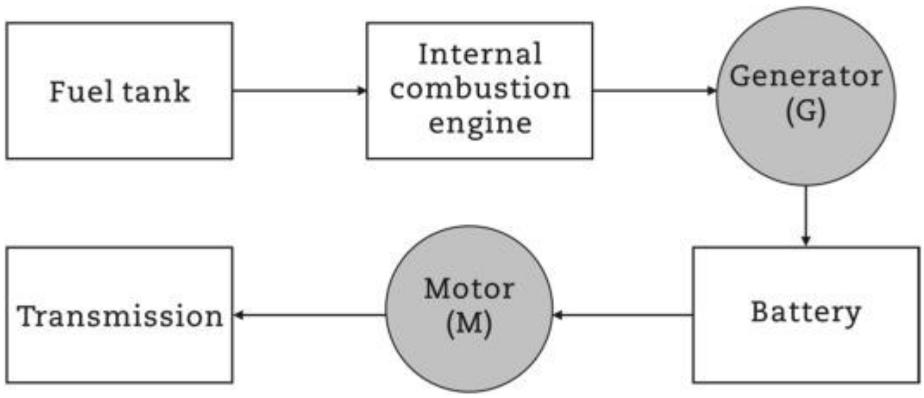
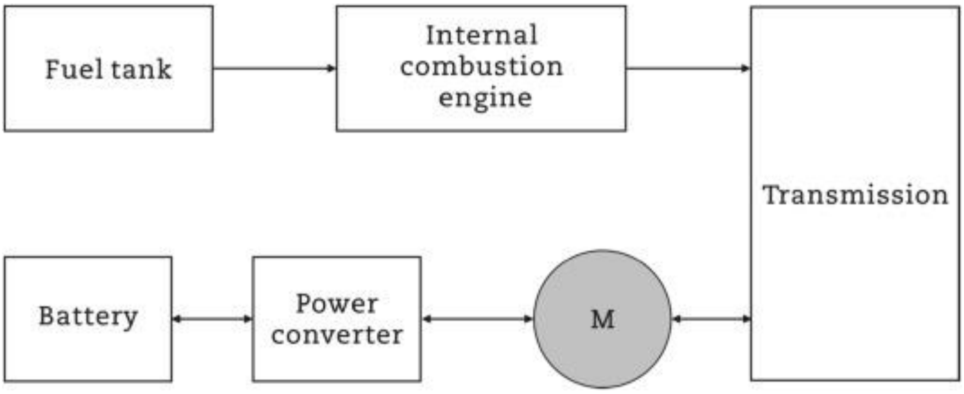


Figure 3: Series hybrid electric vehicle [12]

BTMS[4]
HEV[5]
IC[6]

In the parallel hybrid system, the parallel connection is connected with an IC engine and electric motor for mechanical transmission. Usually, the IC engine operates as a primary means and electric motor acts as a backup or torque power booster. The advantage of this system is that EV requires lightweight and smaller batteries. The batteries in the parallel mode can be recharged during regenerative braking and during cruising. As shown in Figure 4, there is a fixed mechanical link between the EV wheels and the motor. Hence, the battery can't be charged when the car is not moving.

Figure 4: Parallel hybrid electric vehicle [12]



A combination of both series and the parallel hybrid system is known as a combined hybrid or series-parallel system. The principle of this system is the decoupling of the power supplied by the engine from the energy derived by the driver. There is a second connection between the engine and the drive axle: mechanical and electrical. This is the most complicated system due to the interconnection of both mechanical and electrical power, through which it allows to split power paths as explained in Figure 6. This is the most expensive system for real-time applications. Hence, the parallel hybrid system is mostly used in HEVs.

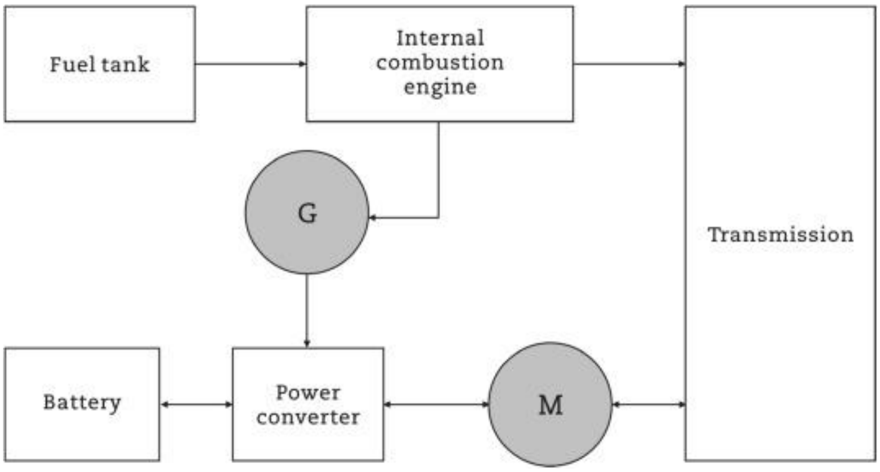


Figure 5: series-parallel hybrid electric vehicle [13]

5.2 Hybridization Level-Based Hybrid Vehicles

In plug-in hybrid cars, also known as PHEVs, an external power source is required to charge the batteries. These vehicles are capable of running on either electricity or gasoline. They are hybrids that can be plugged into the power grid for battery charging. In general operation, the vehicle has a medium-capacity battery, allowing it to achieve a range of several dozen kilometers, with excellent acceleration and top speeds compared to conventional gasoline-powered vehicles. The use of plug-in hybrid cars reduces concerns about running out of battery power, as they can switch to the gasoline engine, providing greater confidence to the driver. The time required to fully charge the battery varies depending on the battery size and the charging method used.

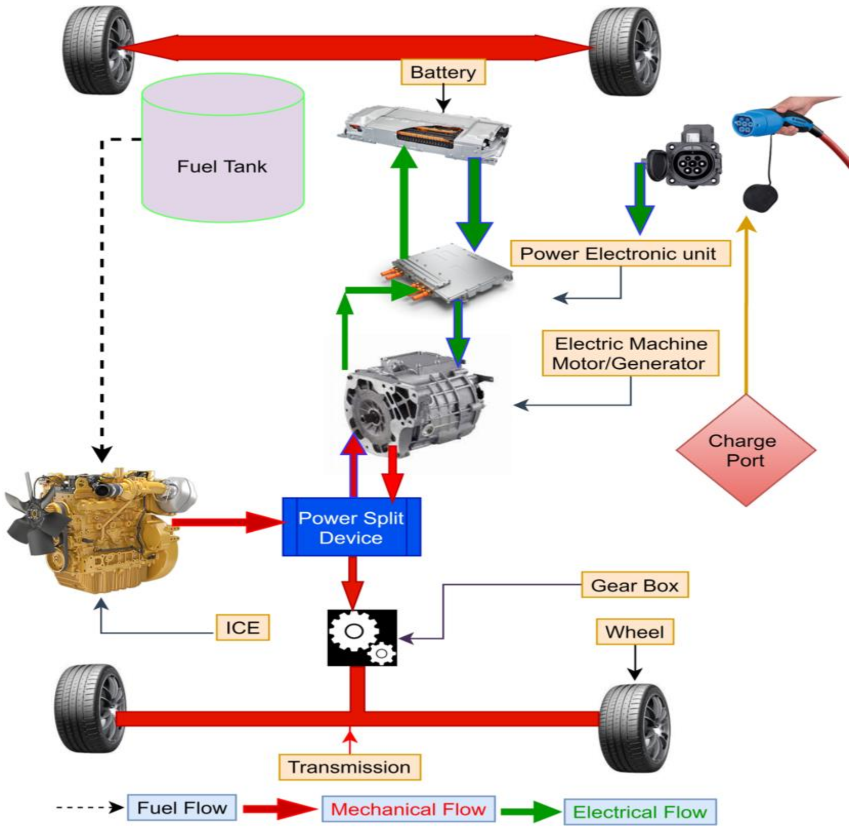


Figure 6: plug-in hybrid electric vehicle block diagram [14]

As seen in the block diagram above, the Plug-in Hybrid Electric Vehicle system integrates multiple energy sources, including a fuel tank, internal combustion engine[7], battery, electric motor/generator and power electronics unit. The fuel tank supplies fuel to the ICE, which generates mechanical power transmitted to the wheels through the power split device and transmission. The battery powers the electric motor, which can also act as a generator to recharge the battery through regenerative braking. The power electronic unit manages energy flow between the battery, electric motor and charging port. The power split device ensures optimal power distribution, switching between the ICE and electric motor based on driving conditions. The charge port allows external charging, reducing reliance on fossil fuels. The gearbox optimizes power transmission, while regenerative braking converts kinetic energy into electrical energy for battery recharging. Energy flow is represented by different arrows: black (fuel flow), red (mechanical power) and green (electrical power). This hybrid system enhances efficiency, reduces emissions, and provides a flexible energy source for modern vehicles.

Mild Hybrid Electric Vehicles[8] integrate an internal combustion engine and an electric motor in a parallel hybrid system. Unlike full hybrids, MHEVs cannot operate solely on electric power but use the electric motor to support the ICE, improving fuel efficiency and reducing emissions. The electric motor replaces the alternator and starter motor, enabling smoother engine start-stop functionality and power assist during acceleration. Regenerative braking captures and stores kinetic energy lost during deceleration, converting it into electrical energy to charge the battery. The battery system in MHEVs is typically 12V, 24V, or 48V, significantly smaller than full hybrids or plug-in hybrids. The system automatically shuts off the engine when the vehicle is idle and restarts when needed, reducing fuel consumption. MHEVs do not require external charging as they self-charge through regenerative braking and energy recovered from the ICE. Their cost is lower compared to full hybrid or plug-in hybrid vehicles, making them an accessible option for consumers seeking better fuel economy without the need for charging infrastructure.

ICE[7]
MHEV[8]

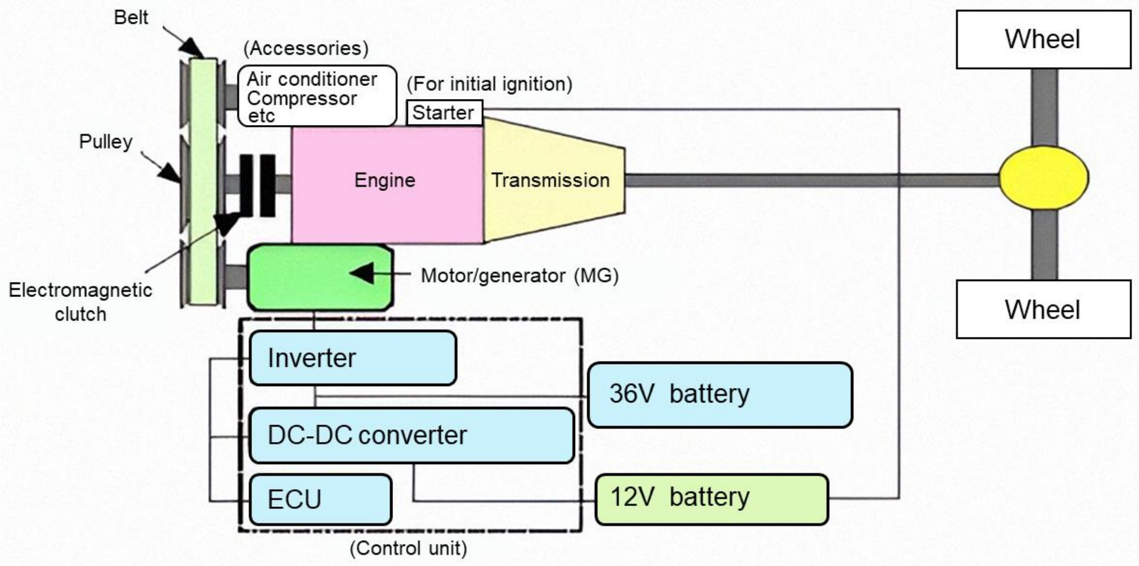


Figure 7: Mild-hybrid-vehicle-system block diagram [15]

Figure 7 illustrates a Mild Hybrid Vehicle System by showing the interaction between the internal combustion engine, electric motor/generator and various electrical components. The diagram highlights the engine, which serves as the primary power source, supported by an electromagnetic clutch and motor/generator. The motor/generator is responsible for assisting the engine, capturing regenerative braking energy and converting it into electrical energy. This energy is then stored in a 36V battery, which supplies power to auxiliary components and provides assistance during acceleration. Additionally, a 12V battery is included for standard vehicle electronics and starting functions. A pulley and belt system connects the motor/generator to the engine. The electromagnetic clutch is crucial for engaging and disengaging the motor/generator, allowing it to either assist the engine or act as a generator to recharge the battery. The transmission system links the engine's power to the wheels, enabling vehicle movement. To manage power distribution, an inverter converts stored DC electricity into AC electricity for the motor/generator. A DC-DC converter steps down voltage from the 36V battery to 12V, ensuring compatibility with traditional vehicle electronics. The Electronic Control Unit orchestrates these components, optimizing power flow between the engine, battery, and motor/generator based on driving conditions. The system allows for mild hybrid functions, such as start-stop technology, regenerative braking, and engine power assistance, improving fuel efficiency while reducing emissions. However, unlike full hybrids or plug-in hybrids, a mild hybrid cannot operate on electric power alone; it only supplements the engine.

In Full Hybrid Cars, the electric motor and the gasoline engine are able to operate individually. This means that the electric motor can provide the power needed to start the car, but its battery capacity is low and the car can usually only travel a few kilometers on its own with an electric motor. It eliminates charging from external sources and the battery is charged by storing its own energy. In this way, the full hybrid does not require an external charger. In these cars, when the electric motor is sufficiently charged and provides the necessary power, it is only used, but when more power is needed for acceleration or the electric motor is not sufficiently charged, the gasoline engine also enters the circuit.

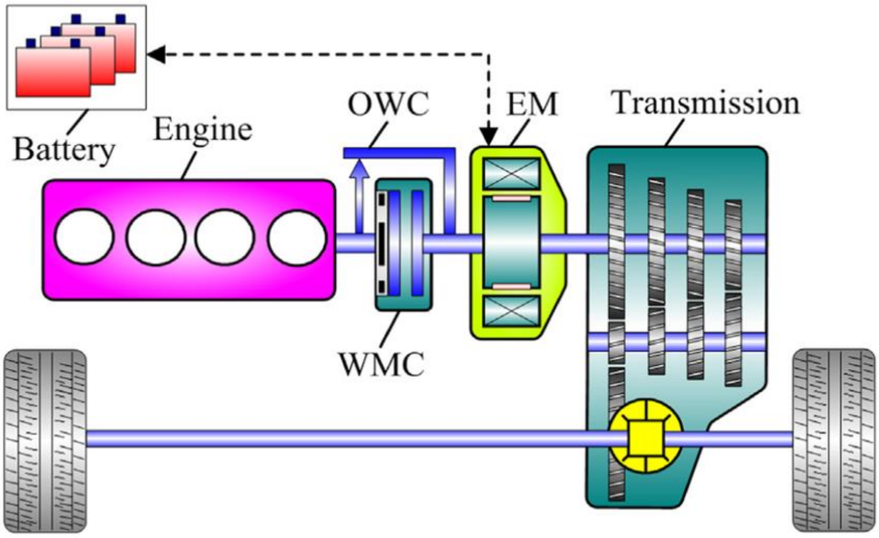


Figure 8: Configuration of a Single-Motor Full Hybrid Vehicle [16]

The schematic diagram represents the powertrain structure of a full hybrid vehicle with a single electric motor, an internal combustion engine and a transmission system. The battery supplies electrical power to the electric motor and stores regenerated energy during braking through regenerative braking, eliminating the need for external charging, unlike plug-in hybrids. The internal combustion engine provides power when the battery is low or during high-speed driving, working alongside the electric motor to optimize fuel efficiency and reduce emissions. The engine start-up process is controlled through the wet multi-disk clutch[9]. The electric motor operates as the primary drive unit at low speeds and during idle conditions, functioning independently in EV mode (pure electric mode) or together with the engine in HEV mode. It assists in acceleration and provides torque fill during gear shifts while also generating electricity via regenerative braking, which is stored back in the battery. The one-way clutch[10] ensures smooth engine startup by allowing the engine to connect or disconnect from the driveline. It unlocks when the engine speed is lower than the EM speed and locks for synchronization. The wet multi-disk clutch facilitates the transition between EV mode and hybrid mode, engaging and disengaging based on driving conditions while reducing power loss and ensuring smooth transmission shifts. The transmission system distributes power to the wheels efficiently, working with both the electric motor and engine torque to optimize power distribution. It is equipped with multiple gears to provide the best balance between power and efficiency. The wheels and drivetrain receive power from either the engine, motor, or both, with the hybrid system adjusting torque distribution based on driving conditions and road load.

As illustrated in Figure 8, there is a smooth transition between pure electric mode and hybrid mode through a four-phase transition control strategy. The electric motor reduces fuel consumption by taking over low-speed operations and assisting the engine during acceleration. The wet clutch and one-way clutch minimize torque fluctuations, ensuring a smooth driving experience. The intelligent coordination between the engine, motor, and transmission ensures optimal performance with reduced emissions. The system has the ability to run on electric power alone, features regenerative braking that recharges the battery, ensures seamless engine start and stop using advanced clutch mechanisms, and provides torque coordination between the engine and motor to avoid sudden jerks. The four-phase control strategy optimizes the transition from electric-only mode to hybrid mode. This system represents a significant improvement in hybrid vehicle drivability and efficiency, making it an ideal choice for fuel-conscious and eco-friendly driving.

6. Advantages, Disadvantages and Challenges of Hybrid Cars

Hybrid cars are designed to achieve lower fuel consumption by incorporating advanced energy management systems, which help reduce fuel usage and greenhouse gas emissions. By relying on an electric motor at low speeds and during stop-and-go conditions, hybrid cars reduce air pollution, leading to cleaner urban air. The use of the electric motor in such conditions also lowers fuel costs, particularly in city traffic, where fuel consumption is typically higher. Additionally, hybrid cars produce less noise than traditional

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WMC[9]
OWC[10]

internal combustion engine vehicles. Since electric motors operate more quietly, they help reduce noise pollution and enhance the quality of life in urban environments. Some models integrate energy recovery systems that capture and reuse energy generated during braking and deceleration, further increasing fuel efficiency. The electric motor's ability to provide high torque at lower speeds improves acceleration, handling and the overall driving experience.

Despite these benefits, hybrid cars also have disadvantages. One major drawback is their higher initial cost compared to non-hybrid models, which can discourage some customers from purchasing them. Hybrid vehicles also tend to be heavier due to their large, heavy electric batteries, which can reduce efficiency and limit performance agility. Additionally, maintenance and repair costs can be higher, especially after the warranty period ends. Their specialized electrical and mechanical systems require complex and costly repairs, particularly when battery replacements are necessary. Another issue is the reduced cargo space caused by the placement of large battery packs, limiting storage capacity. Moreover, hybrid batteries have a limited lifespan and need to be replaced after several years, adding an additional expense for owners. Some hybrids may also experience a slight delay in response when accelerating or braking due to the transition between electric and fuel-based systems, which can affect the overall driving experience [17].

Maintenance challenges are another concern for hybrid vehicles. Hybrid batteries tend to be weaker than those in conventional cars, have a shorter lifespan and are expensive to replace. Factors such as frequent battery use, urban driving and the reliance on electric power instead of the internal combustion engine contribute to their faster degradation. The catalytic converter, an essential component in reducing toxic gas emissions, faces additional issues in hybrid cars. Since hybrids operate using both a gasoline engine and an electric motor, the gasoline engine only activates when extra power is needed. As a result, the catalytic converter is exposed to higher temperatures and thermal fluctuations, making it more prone to damage and costly to replace. The emission system designed to capture gasoline vapors from the fuel tank, can also fail more frequently in hybrid vehicles. A malfunctioning this system can cause fuel vapor leaks, leading to air pollution and fuel odors inside the vehicle. Oxygen sensors, which regulate the fuel-air mixture, do not necessarily fail more often in hybrids than in conventional cars. However, when they malfunction, the engine control unit may incorrectly adjust the fuel and air mixture, increasing fuel consumption.

Despite these challenges, hybrid cars offer significant potential in reducing fuel consumption and emissions, improving air quality and creating a more sustainable automotive industry. Addressing issues related to infrastructure, production costs, government policies and technical expertise is essential for the successful development and widespread adoption of hybrid vehicles in the other emerging markets [18].

Table 2: An overview of the performance of hybrid cars [17,18]

Advantages	**Disadvantages**	**Challenges**
Reduced fuel consumption	High initial cost	Need for infrastructure
Lower emissions	Heavy batteries	High import costs
Cleaner urban air	Less cargo space	High production costs
Lower fuel costs	High maintenance and repair costs	Challenges related to pricing and economic feasibility
Quieter operation	Response delay	Lack of government support
Better acceleration	Limited battery lifespan	Low consumer awareness
Energy recovery	Complex maintenance	Technical issues

7. Conclusion

Hybrid vehicles represent a significant step towards reducing dependence on fossil fuels and minimizing environmental pollution. By combining internal combustion engines with electric motors, these vehicles achieve higher fuel efficiency, lower emissions, and improved performance. Over the years, advancements in power electronics, battery technologies and regenerative braking systems have enhanced the performance and long-term viability of hybrid electric vehicles. However, challenges such as high production costs, battery-related limitations and the need for improved charging and energy supply infrastructure continue to pose barriers to the widespread adoption of these types of vehicles.

Despite these challenges, hybrid vehicles offer a practical solution to bridging the gap between traditional fuel-based vehicles and fully electric cars. As technology evolves, improvements in battery efficiency, drive optimization and cost reduction will make hybrid vehicles increasingly accessible to consumers.

Governments and policymakers also play a crucial role in promoting hybrid technologies through incentives and regulatory frameworks. With ongoing research and innovation, hybrid vehicles will significantly contribute to the future of cleaner and more sustainable transportation, reducing greenhouse gas emissions and enhancing energy efficiency in the automotive industry.

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