# Chapter 2
# Energetic Efficiency of Vehicles Equipped with Hybrid and Electric Drive Systems

## 2.1 The Hybrid Drive System

Hybrid Electric Vehicle (HEV) are equipped with both an internal combustion engine and an electric motor, thus using two different sources of energy. Each of these engines can transmit the torque to the wheels through a parallel and/or mixed series system.

A hybrid vehicle uses two or more different power sources to get started. The hybrid vehicle combines a conventional drive system with a system which stocks recoverable energy in order to obtain a better yield, a lower fuel consumption and a lower emissions level.

The hybrid drive system has the following main elements [1]:

- electric batteries;
- electric motor;
- internal combustion engine;
- electric current generator;
- coupling elements to connect the mechanical system with the electric system;
- management system for the two drive systems.

The batteries or supercapacitors used by the electric motor are recharged by the internal combustion engine and/or from the energy generated during braking. Plug-in Hybrid Electric Vehicles (PHEV) have the particularity of allowing the electric batteries to charge by connecting the to an electricity network. This constructive model assures a greater autonomy for travelling in the electric mode.

The combination between the internal combustion engine and the electric motor is based on a perfect interaction between the modern command system and the optimized hybrid components. The management systems integrated in the hybrid vehicles assure the commutation between the electric, hybrid and internal combustion drive systems without affecting the comfort of the passengers.



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In this regard, the electronic command system has permanent access to the data coming from the sensors of the internal combustion engine, the electronic control unit, the batteries recharge state etc. The management system analyzes, regulates and commands in real time the interaction between the two drive systems [1].

An essential component is the adaptive clutch which allows a smooth commutation between gears. The clutch aims to assure that the electric motor and the internal combustion engine have the same speed at the time of the functioning mode change so that the vehicle movement should not be affected by the drive source change.

Presently a hybrid drive system consisting of an internal combustion engine and an electric motor, equipped with the Plug-in technology may be considered as a transitory solution towards the new technology based on an electric vehicle equipped with a Range Extender unit (REV), namely a vehicle equipped with an internal combustion engine which serves exclusively in recharging the accumulator and not for driving the vehicle.

This concept assures the usage of the electric energy on medium distances, within the conditions of using a minimum quantity of fossil fuel and implicitly producing lesser pollutant emissions. Unlike the serial hybrid vehicle, where the internal combustion engine assures the necessary power for the electric motor during almost 90 % of the functioning time, the electric vehicle with Range Extender functions exclusively based on the energy provided by the accumulator and the internal combustion engine only starts when the level of energy from within the accumulators drops under a certain level.

A functional cycle of a hybrid vehicle consists of an acceleration period, a period of driving at a constant velocity and a deceleration period (Fig. 2.1), from which one can observe that the power necessary for the first phase is much greater than the power necessary for driving at a constant velocity [2].

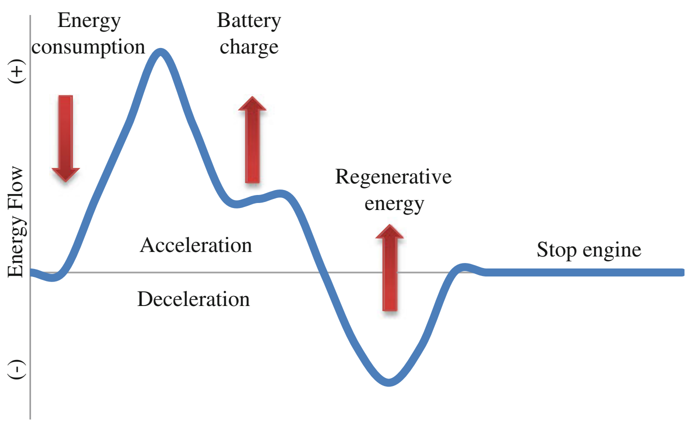



**Fig. 2.1** Functioning cycle of an hybrid vehicle [2]

By braking the vehicle, the internal combustion engine functions at idle speed and the kinetic energy obtained at deceleration is recovered and used to recharge the batteries. In the case of a hybrid vehicle the brakes take over the braking kinetic energy and the electric motor is used as generator and recharges the batteries. To maximize the power of the recuperative braking it is important for the stopping to be smooth and gradual—a sudden braking can lead to the activation of the anti-blocking system (ABS) and the loss of kinetic energy [3].

The drive systems which have besides an internal combustion engine in their composition at least another system which provides traction coupling for the wheels of the vehicle and which recovers some of the kinetic energy obtained at deceleration are also known as regenerative hybrid drive system [4].

The advantages of using hybrid vehicles are [5]:

- pollutant emissions (CO, $NO_x$, HC, PM, $CO_2$ etc.) under the values imposed by the EURO 6 norm and a reduced exposure of the passengers and pedestrians to these emissions;
- a decrease of pollutant emissions which have a negative impact on the surface of the historical buildings from the central areas;
- a decrease of vibrations which are harmful to the urban infrastructure and the historical buildings from the central areas;
- the assurance of a higher comfort for the passengers and the traffic participants through the lack of vibrations generated by high capacity internal combustion engines;
- the possibility of creating central areas with a more reduced pollution;
- lower maintenance costs due to the lack of internal combustion engine specific systems;
- reduced exploitation costs due to a lower price of electric energy compared to the classic fuel, taking into account the traveled distance.

The disadvantages of using hybrid vehicles [5]:

- during the cold season the lower temperatures affect the stocking capacity of the batteries and also the loading time, which limits the traveled distance and also extends the loading time;
- diminished transport capacity because of the mass of the batteries used to fuel the electric motor;
- for the Plug-in hybrid system, investments are necessary for acquisitioning charging stations for the batteries;
- the acquisition price for hybrid buses is approximately double the classic buses price.

## 2.2 Classification of Hybrid Drive Systems

Hybrid drive systems can be classified in two categories: serial and parallel, which can themselves be combined in many subcategories according to the constructive architecture.

The serial hybrid drive system relies on two energy sources which power a sole electric motor, called the propulsion motor. The internal combustion engine is coupled with an electric generator which fuels the electric motor through a rectifier. The internal combustion engine functions in the maximum efficiency area because it is coupled to the motor wheels; this allows the usage of an internal combustion engine with high speed and low coupling.

Because the electric motors have an almost ideal coupling-velocity characteristic they do not need transmissions with multiple gears; also more electric motors can be used to operate each wheel individually. This configuration allows the mechanical coupling between the wheels, thus assuring the control of the vehicle traction individually on each motor wheel.

The management of the transmission is simplified because there is a mechanical decoupling between the motor wheels and the internal combustion engine.

The disadvantages of the serial hybrid system are [5]:

- the mechanical energy generated by the internal combustion engine is transformed in electric energy by the generator, which fuels the electric motor and transforming it again in traction mechanical energy, thus resulting a lower efficiency for the vehicle;
- the electric generator used increases the weight and costs of the vehicle;
- the electric motor must have a sufficiently high power to assure the propulsion of the vehicle in maximum performance conditions.

The parallel hybrid drive system assures a parallel distribution of the power flow generated by the internal combustion engine and the electric motor to start the motor wheels. Because the two motors are coupled to the axel of the wheels via two gearboxes, the power flow can be provided by the internal combustion engine, by the electric motor or by both. The coupling of the two motors is made through a velocity summing device.

The electric motors used for hybrid vehicles are three-phase machines of alternative current, divided in the following categories [6]:

- asynchronous motors (ASM);
- synchronous motors with permanent magnets (PSM—Permanent Synchronous Motor);
- transversal flux motors (TFM);
- motors with reversed magnetic resistance (SRM—Switched Reluctance Motor).

Another method of classifying the hybrid vehicles is according to the power characteristics of different types of hybrid vehicles (Table 2.1).The classification of hybrid systems from the point of view of the transmission is presented in Fig. 2.2.

**Table 2.1** Power characteristics of hybrid vehicles

| Type | Micro hybrid | Medium hybrid | Total hybrid |
|---|---|---|---|
| Electric motor power | 2…10 kW | 4…20 kW | >20 kW |
| Electric motor coupling | <90 Nm | <500 Nm | <500 Nm |
| Tension | 14…42 V | ≥42 V | 100…650 V |

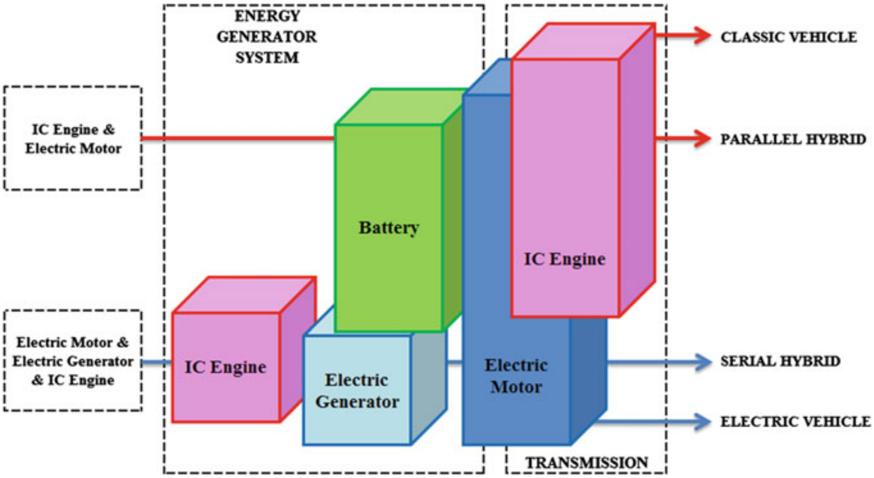



**Fig. 2.2** Hybrid drive structure

Hybrid vehicles can also be classified according to the type of fuel used to power the internal combustion engine. This classification is as it follows:

- compression ignition engine fueled with diesel fossil fuel;
- compression ignition engine fueled with biodiesel blend;
- spark-ignition engine fueled with gasoline fossil fuel;
- spark-ignition engine powered by a bioethanol based blend;
- compression ignition engine fueled with CNG.

The connection between the components through which the energy flow of the hybrid vehicle passes and the control part is called constructive architecture. From the point of view of the constructive architecture, the hybrid vehicles can be divided in two big categories: the ones with serial transmission and the ones with parallel transmission [7].

The hybrid vehicles with a serial transmission of the energy flow or Serial Hybrid (Fig. 2.3) have no mechanical connection between the internal combustion engine and wheel drive shaft, and the propulsion is assured by the electric motor.

The internal combustion engine stimulates a generator and the electric motor uses the generated electric current to start the wheels of the vehicle. This model is called the serial hybrid system because the power flow to the wheels of the vehicle

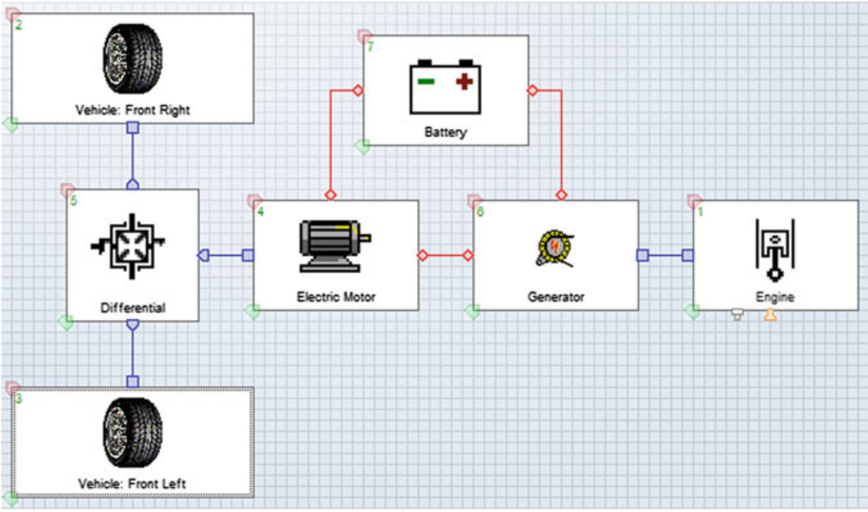



**Fig. 2.3** Serial hybrid architecture

acts like a system in series. A serial hybrid system can be used in the case of an electric motor which can be easily maintained in a stable domain of its functioning and which is also capable of providing an energy surplus to the electric motor which, in turn, can charge the battery [5, 8].

The power transmitted from the internal combustion engine must go through the generator towards the electric motor, thus reducing the energetic efficiency of the system because each transformation has an energy loss effect.

The efficiency of the motor-transmission group is approximatively 70–80 % lower than the efficiency of a conventional mechanical clutch which has an efficiency of almost 98 %. In the case of a long distance drive the internal combustion engine must compensate the energy losses, thus the serial hybrid system is 20–30 % less efficient than the parallel hybrid system. The use of a motor for each motor wheel leads to the elimination of mechanical transmission elements (gearbox, differential) and can eliminate the flexible couplings. The advantage of motors placed on each wheel includes a more simplified traction control with gearing in all wheels which also allows the use of lower access ramps—in the case of buses.

Hybrid vehicles with a parallel transmission of the energy flow or Parallel Hybrid (Fig. 2.4) have an internal combustion engine connected to the wheel drive shaft, but also a generator with the role of charging the batteries system. The system is called parallel because the power flow is transmitted towards the motor wheels in parallel [7].

The electric motor is mechanically connected to the internal combustion engine through a clutch. This system can assure an extra coupling, which leads to higher dynamic performances. Furthermore, the torque of the internal combustion engine can be transmitted directly to the axels no matter the state of the electric motor [1].

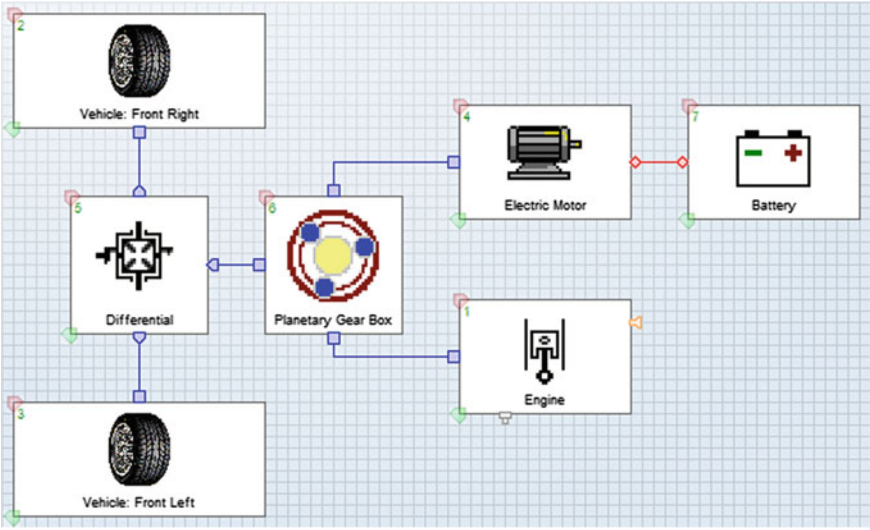



**Fig. 2.4** Parallel hybrid architecture

In the parallel hybrid system both the internal combustion engine and the electric motor transmit power to the wheels, but this power can be provided by the two motors concomitantly, the system easily adapting to some predestined typical situations. The battery is recharged by the commutation of the electric motor to work as a generator, and the electric current from the batteries is used as an effective power flow to starts the wheels of the vehicle.

Although it has a more simple structure, the parallel hybrid system cannot use the power provided by the internal combustion engine to both start the wheels and to simultaneously charge the battery. To keep and put to maximum use the energy provided by the internal combustion engine, some systems like the power-assisted steering and the air conditioning are powered by the electric motor and are not attached to the internal combustion engine, fact which permits the functioning of these systems at constant velocities without being influenced by the speed of the internal combustion engine [8].

Parallel hybrid systems can be differentiated by the way in which the two energy generating motors are mechanically coupled. If they are coupled on a parallel axis the velocity should be identical. When only one of the motors is being used, the other one must function at idle speed or it must be connected through a clutch.

Hybrid vehicles with a mixed serial-parallel transmission of the energy flow or the Serial-Parallel Hybrid combines the advantages of the serial hybrid system with the advantages of the parallel hybrid system in order to maximize the advantages of both systems.

The two drive systems are used according to the driving conditions, so as to start the motor wheels only the electric motor can be used, or both the electric motor and the internal combustion engine to reach a level of maximum efficiency. The system

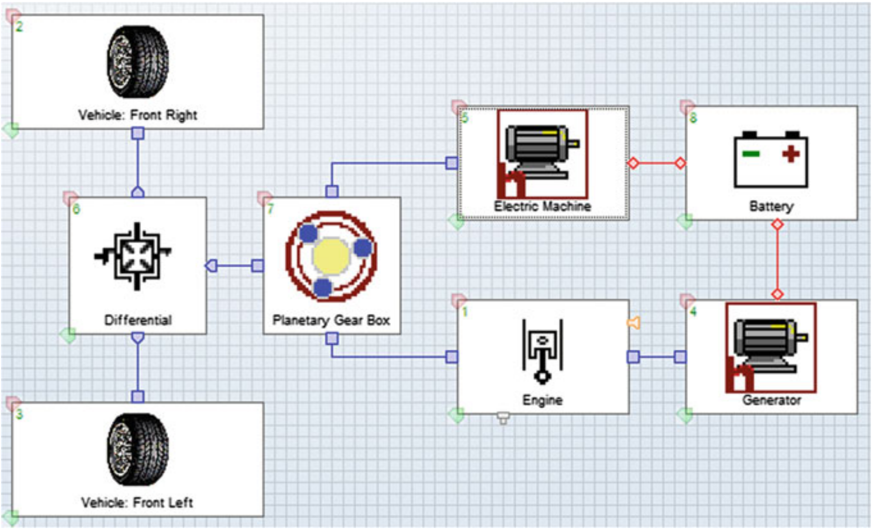



**Fig. 2.5** Power split hybrid architecture

can start the motor wheels while also generating electric current through a generator powered by the internal combustion engine.

The hybrid system with a mixt transmission of the energy flow can be divided in the following categories: Power Split Hybrid, Serial-Parallel Hybrid, and Serial-Parallel with Transmission Hybrid [7].

Power Split Hybrid (Fig. 2.5) is the system where the energy generated by the internal combustion engine is transmitted through a differential mechanism towards the wheels, but concomitantly it will start a current generator which will create a brake torque for the motor.

The electric current obtained will be used to fuel the electric motor coupled to the wheel drive shaft, which will supplement the brake torque derived from the thermal engine thus causing the energy flow to be transmitted both via the mechanical system and the electric system, resulting separate power flows [9].

Serial-Parallel Hybrid (Fig. 2.6) is the system where the power generated by the internal combustion engine will start a current generator which will create a brake torque for the motor, and the obtained electric current will be used to fuel the electric motor coupled to the wheel drive shaft which will supplement the brake torque provided by the thermal engine [7].

Serial-Parallel with Transmission Hybrid (Fig. 2.7) is the system where the energy generated by the internal combustion engine will start a current generator which will create a brake torque for the motor and the electric current obtained will be used to fuel the electric motor coupled to the wheel drive shaft, which will supplement the brake torque provided by the thermal engine and, concomitantly, the internal combustion engine will also be coupled to the wheel drive shaft, with the possibility to select the drive mode [7].

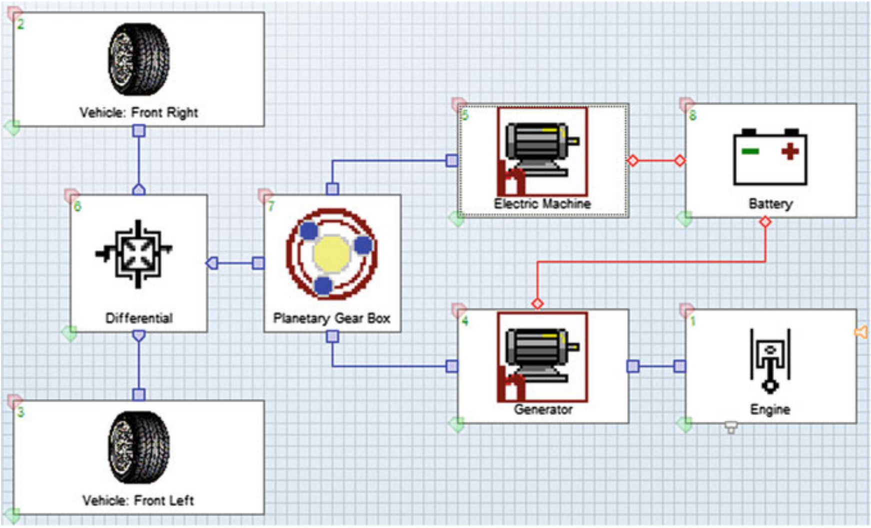



**Fig. 2.6** Serial-parallel hybrid architecture

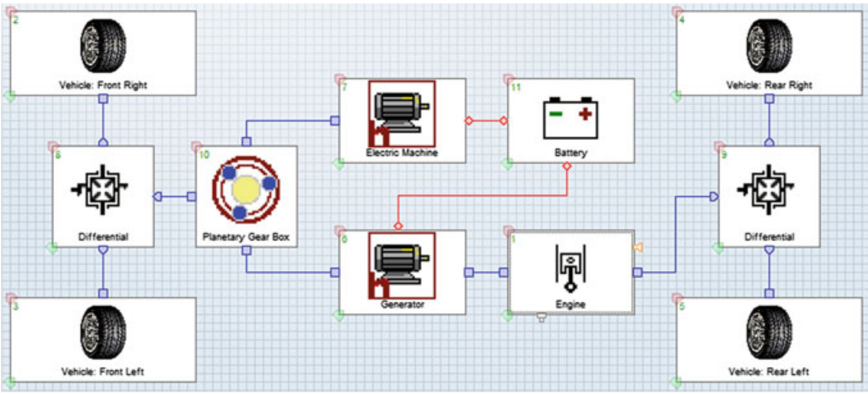



**Fig. 2.7** Serial-parallel with transmission hybrid architecture

The great advantage of this system is the power divider, which is a connection element between the internal combustion engine, the electric motor and the current generator, and which has the role of adjusting the power flow which goes towards the shaft. Thus, the system functions as a serial model when the internal combustion engine starts the generator and fuels the electric motor, or as a parallel model when the internal combustion engine transmits the power directly towards the shaft, while being supplemented by the electric motor fueled by the batteries.

The management process of the control and functioning of the internal combustion engine and of the electric motor equipping a hybrid vehicle has the constructive-functional characteristics of the fuel injection systems, electric systems, energy management systems, sensor systems, drive systems and also of the ECUs. Performance improvement of the hybrid vehicles, optimization of energy flow distribution, and reduction of fuel consumption and of pollutant emission are the desired goals of all major manufacturer of the automotive industry, but their main objective is reaching a low economic pole. This objective can be reached through an efficient management of the intelligent systems which control and coordinate the processes and phenomena taking place while a hybrid vehicle is running.

The management of the energy provided by the internal combustion engine, respectively by the electric motor, but also the control over the drive mode can be achieved with the help of the ECU, which—as opposed to classic vehicles—have the role of controlling and coordinating the distribution of the energy flow generated by the two drive systems.

The management of the drive system is based on the steps taking place in the functioning process of a hybrid vehicle, thus:

- When the vehicle starts off, hybrid vehicles use only the electric motors, powered by the battery, while the IC Engine remains shut off. An IC Engine cannot produce high torque in the low speed range, whereas electric motors can, delivering a very responsive and smooth start (Fig. 2.8a) [10].
- IC Engine is not energy efficient in running a vehicle in the low-speed range. On the other hand, electric motors are energy efficient in running a vehicle in the low-speed range. Therefore, hybrid vehicles use the electric energy stored in its battery to run the vehicle on the electric motors in low-speed range. If the battery charge level is low, the IC Engine is used to turn on the generator to supply power to the electric motors (Fig. 2.8b) [10].
- Hybrid vehicles use the IC Engine in the speed range in which it operates with good energy efficiency. The power produced by the IC Engine is used to drive the wheels directly, and depending on the driving conditions, part of the power is distributed to the generator. Power produced by the generator is used to feed the electric motors, to supplement the IC Engine. By making use of the engine/motor dual powertrain, the energy produced by the IC Engine is transferred to the road surface with minimal loss. If the battery charge level is low, the power output from the IC Engine is increased to increase the amount of electricity generated to recharge the battery (Fig. 2.8c) [10].
- Since hybrid vehicles operate the internal combustion engine in its high efficiency range, the internal combustion engine may produce more power than is necessary to drive the car. In this case, the surplus power is converted to electric energy by the generator to be stored in the battery (Fig. 2.8d) [10].
- When strong acceleration is called for the power from the battery is supplied to the electric motors to supplement driving power. By combining the power from the internal combustion engine and the electric motors, hybrid vehicles deliver power comparable to vehicles having one class larger engine displacement of one class higher (Fig. 2.8e) [10].

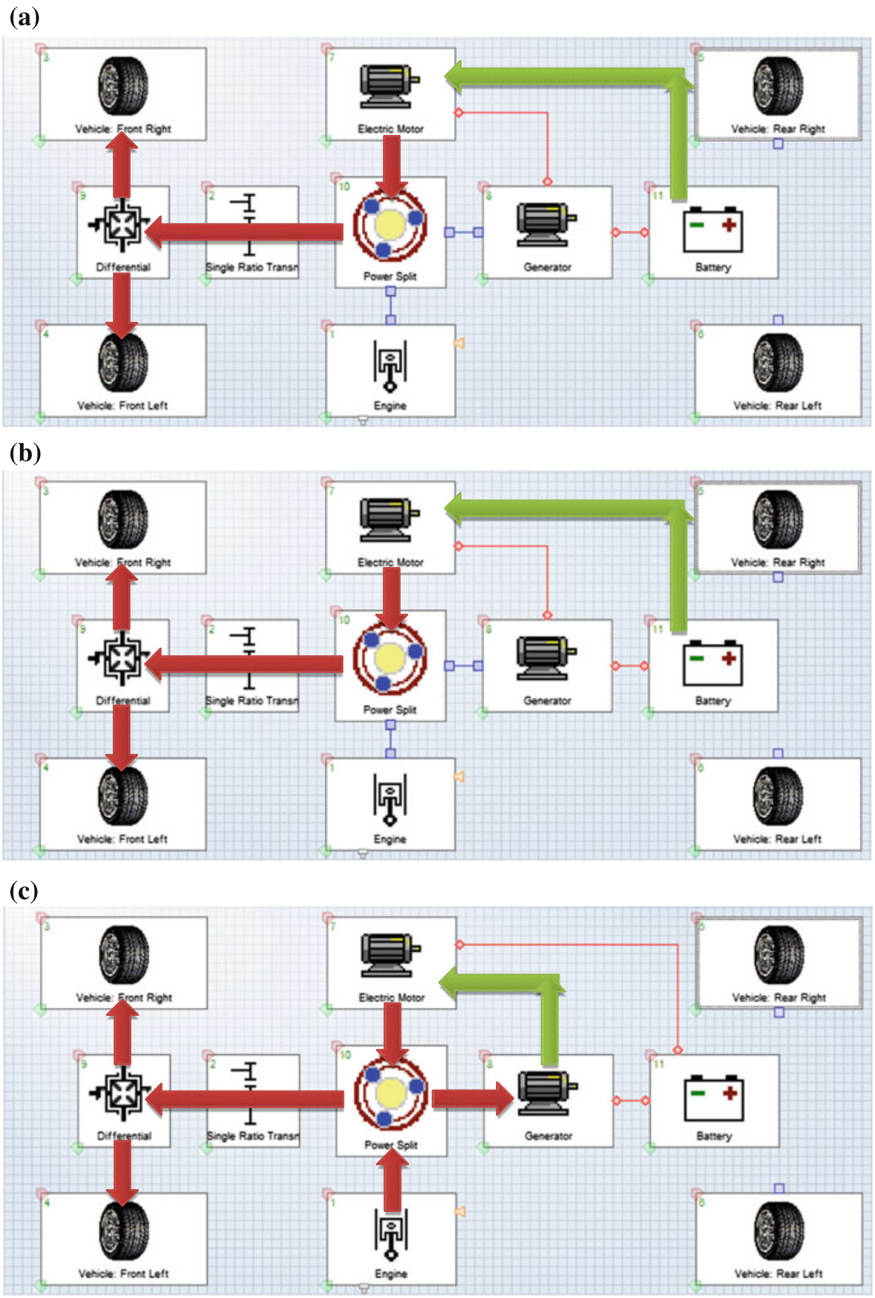
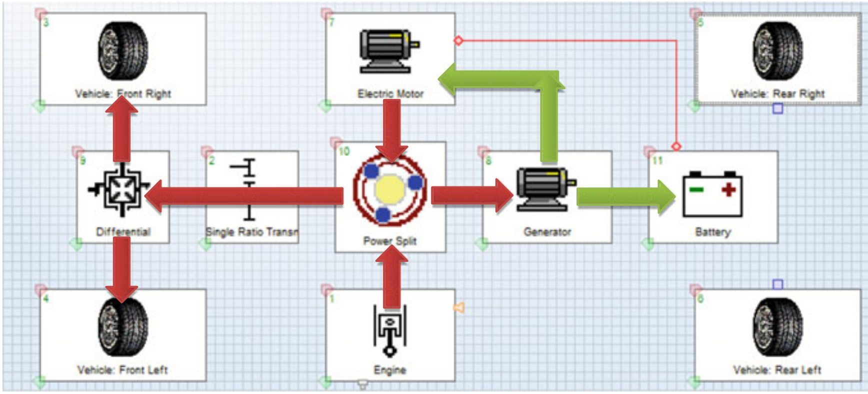



**Fig. 2.8** The operation of the hybrid vehicle: **a** starting off, **b** low speed driving, **c** cruising, **d** cruising/recharging, **e** full acceleration, **f** deceleration/energy regeneration, **g** at rest

**(d)**

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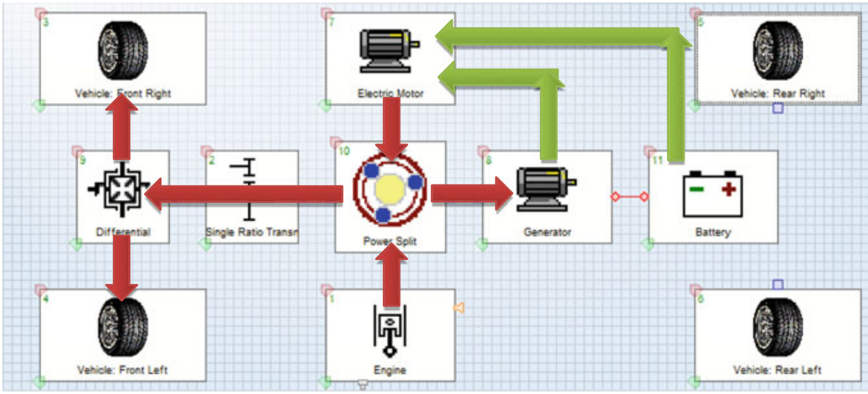


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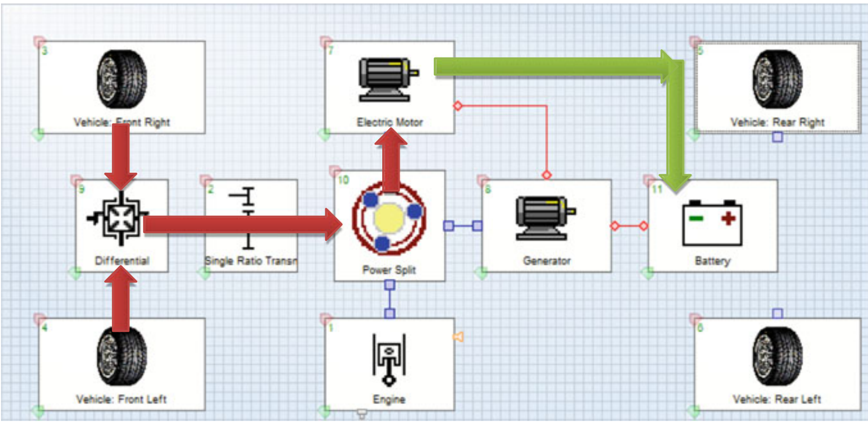


**Fig. 2.8** (continued)

(g)

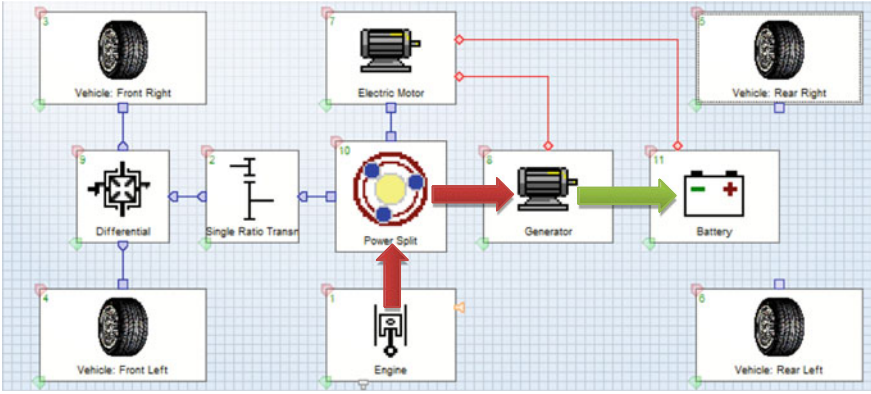


**Fig. 2.8** (continued)

- Under braking or when the accelerator is lifted, hybrid vehicles use the kinetic energy of the car to let the wheels turn the electric motors, which function as regenerators. Energy that is normally lost as friction heat under deceleration is converted into electrical energy, which is recovered in the battery to be reused later (Fig. 2.8f) [10].
- The internal combustion engine, the electric motors and the generator are automatically shut down when the vehicle comes to rest. No energy is wasted by idling. If the battery charge level is low, the internal combustion engine is kept running to recharge it. In some cases, the internal combustion engine may be turned on in conjunction with the auxiliary systems switch operation (Fig. 2.8g) [10].

## 2.3 The Electric Drive System

The vehicles powered exclusively by a rechargeable battery are called battery electric vehicles (BEV) (Fig. 2.9).

The following are the parts composing an electric vehicle [1]:

- the rolling system composed of pneumatic wheels for steering (front) and motor wheels (back), mounted on two axels: steering axel (front) and rear axel (back);
- the steering mechanism with which the steering of the front wheels is achieved;
- the main transmission consisting of: reduction gear, mechanical differential and planetary axels;
- the chassis, on which the electric vehicle body is mounted and on which the electric traction motor is attached;
- the powertrain consisting of: electric drive motor, generator and electric battery.

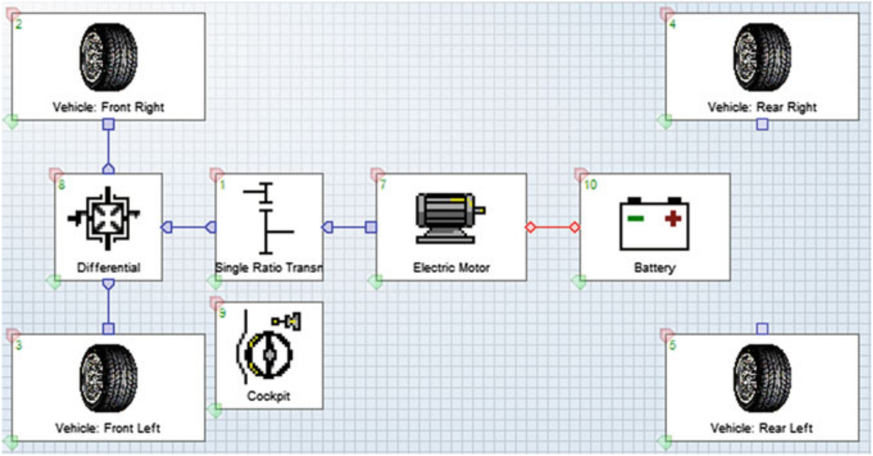


**Fig. 2.9** Electric vehicle architecture

The buses using the electric drive system do not use an internal combustion engine, like the hybrid buses, because it is integrally based on the rechargeable electric batteries which set in motion the electric motor. Some buses, also known as opportunity charged electric buses, recharge on route—either in recharging points set on the circuit of the bus, or at the first or last stop. Other buses, known as night electric buses have their own batteries and they recharge during the night. Another recharging regime is that of combining the two methods of recharging during the night and of completing the charge level in the battery during the time the bus is in use [11].

The reduction of emissions generated by the electric vehicles depends on the mode in which the electric energy is produced, namely between 30 % in the case the electricity is generated from the national network with $CO_2$ emissions and up until 100 % in the case where the electricity is generated from renewable electricity sources.

Electric buses do not generate emissions through the exhaust pipe, which means zero local emissions. Although they require a greater initial investment, the electric buses offer the advantage of cost savings regarding the fuel and less maintenance costs due to a reduced number of components in motion.

By making a comparison between conventional buses and electric buses, the latter present a series of advantages, namely [2]:

- silent and vibration-free functioning, thus reducing the noise pollution;
- lack of local pollutant emissions;
- independence towards fossil fuels;
- high energetic efficiency;
- use of electric braking and energy regenerative braking;
- possibility of individual motor wheel drive.

The main disadvantages of electric vehicles are the following:

- the energy and power density of the batteries is significantly lower than that of the fuels (the energy density for a gasoline internal combustion engine is 10,000 Wh/kg and the energy density for an electric motor is 200 Wh/kg), fact which leads to a decreasing autonomy of electric vehicles (100–200 km) as opposed to the autonomy of classic vehicles (400–800 km), respectively a lower maximum velocity of electric vehicles (100–130 km/h) as opposed to the classic vehicles (180–200 km/h), also the accelerations achieved by electric vehicles are inferior to those of classic vehicles;
- the necessity of existent charging stations for batteries and the necessary recharging time: hours for a complete charge and tens of minutes for a partial recharge;
- the prices for electric vehicles are much higher than the prices for classic vehicles.

## 2.4 Classification of Electric Drive Systems

Electric drive systems can be classified according to the electric motor with which they are equipped. The technical characteristics of electric motors are presented in Table 2.2. Electric vehicles can also be classified according to the electric energy supply mode [6]:

- electric vehicles powered autonomously from own electric sources;
- non-autonomous electric vehicles, powered through a contact line from external electric sources.

**Table 2.2** Technical-functional characteristics of electric motors [6]

| Type of motor | Contacts | Coupling | Price | Maintenance | Efficiency | Complexity |
|---|---|---|---|---|---|---|
| DC with series excitation | Yes | Low | Medium | Yes | Low | Low |
| DC with separate excitation | Yes | Low | Medium | Yes | Low | Low |
| DC with permanent magnets | Yes | Medium | High | Yes | Medium | Low |
| AC asynchronous | No | Medium | Low | No | Low | High |
| DC brushless | No | High | High | No | High | Low |
| Variable reluctance | No | High | Low | No | Medium | Medium |

**Table 2.3** Technical-functional characteristics of the batteries [6]

| Types of batteries | Energy density (Wh/kg) (Wh/l) | | Specific power (W/kg) | Cycles of recharge/discharge | Industrial availability |
|---|---|---|---|---|---|
| Pb-Acid | 31–40 | 75–90 | 90–125 | 600–1000 | Yes |
| Ni-Cd | 45–58 | 80–95 | 190 | 2000 | Yes |
| NiMH | 55–60 | 100–130 | 175 | – | No |
| Ni-Fe | 50–60 | 80–95 | 110 | 1000–1500 | No |
| Na-S | 80–100 | 110–135 | 100–120 | 500 | No |
| Li | 80–120 | 100–120 | 70 | >200 | No |

According to the type of path, electric vehicles are classified as follows:

- electric vehicles with a guided path, conventional or nonconventional;
- electric vehicles with an air cushion or magnetic cushion;
- electric vehicles without a guided path (road).

Another type of classification of electric drive systems is according to the type of batteries they are equipped with. The technical characteristics of the types of batteries used are presented in Table 2.3.

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