NVH Analysis Techniques for Design and Optimization of Hybrid and Electric Vehicles
Chapter 2
Overview of EV and HEV powertrains

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1 Introduction

Alternative powertrains and drivelines offer a promising way to reduce fuel consumption, exhaust and noise emissions of modern vehicles. Alternative powertrains include electrical motors, fuel cell systems as well as hybrid drives. Starting with electric vehicles, these configurations are outlined in the following chapters.

1.1 Electric vehicles

The attribute "electric" describes vehicles driven by electric motors powered by batteries, range extenders as well as fuel cells. Common to all these powertrains is an electric motor which drives the vehicle. In battery powered cars, the required power is supplied entirely by a battery which is charged from the public electric network. The range extender is a compact unit consisting of a combustion engine, which drives a generator that charges the batteries. In this way, independency of the public electric power grid and a significant extension of the range is achieved. In fuel cell vehicles, the electrical energy is supplied by the fuel cell system, which is fed with hydrogen or methanol.

1.1.1 Battery-electric vehicle

In battery-electric vehicles (BEV), the traction batteries store energy supplied from the public power grid and are discharged during driving. Compared to others, the alternative drive system of a battery-electric vehicle includes a manageable number of components in a comparable simple and straight forward layout. It consists mainly of the electric machine(s) and the traction battery pack, as shown in Fig. 1 [1].

In an electric vehicle, the internal combustion engine which drives the auxiliary units is missing. Therefore, it must be replaced by several electrically driven auxiliary components.

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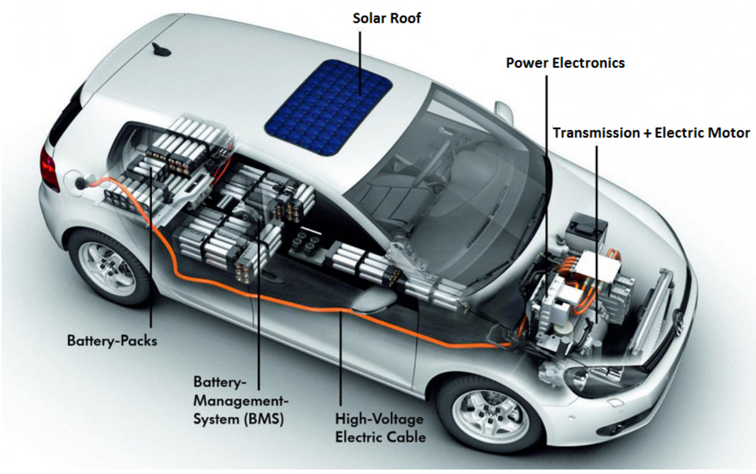

Fig. 1. Powertrain of a battery-electric vehicle (BEV)

This applies to the heating and air conditioning, as well as to steering and braking assistance. In particular, the power requirement of active heating or air conditioning can significantly reduce the range of a BEV. The average continuous power of the motor or motors corresponds to the desired maximum speed or continuous uphill driving ability. The short-term peak power, determines the acceleration.

The needed energy capacity, as well as the maximum available power of the battery, are obtained from the required vehicle range. Unlike fuel tanks, the operating behaviour of a battery depends strongly on temperature and charging level. Therefore, the battery may need to be actively heated or cooled. The energy required is taken from the battery and thus it further reduces the vehicle range. Additionally, due to the physical characteristics of the battery, when the battery is poorly charged, the discharge rate is reduced. Consequently, the vehicle performance is also reduced when the battery is about to become empty.

While electric motors have reached a high level of power density and efficiency, the traction batteries have to be further developed and improved. This applies to the range of BEVs, which is often limited to just 200 km. On the other side, the necessary charging time reduces the vehicle usability. It is limited not only by the charging rate of the battery, but also by the charging infrastructure. In Europe, 230 V outlets are usually protected by 16 A or 10 A fuses. The result is that, for example, a completely discharged 30 kWh battery requires about 8 to 13 hours charging time.

Higher charging power requires a three-phase connection. With fast charging, batteries may reach almost 80% in 30 mins. The required charging power is about 50 kW and exceeds the limits of common house connections. Public, fast charging stations, similar to petrol stations, can be an option here. But for this purpose, there is still need for development of standard charging procedures and interfaces in order to assure a safe and efficient charging regardless the manufacturer. Despite these difficulties, recharging at public charging stations, for example when the vehicle is parked while shopping or working, offers a possibility to increase the everyday driving performance and range.

Because of the limited energy content of the battery, it is important to design an electric vehicle as efficient (small and lightweight) as possible. When choosing the battery size, it is also important to make an optimal compromise taking into account cost and packaging issues as well as the typical usage of the car.

The driving performance and range requirements of cars used in city traffic are in line with the characteristics of a battery-powered electric vehicle. Due to its zero emissions and low noise, it offers advantages over conventional vehicles with internal combustion (IC) engines. On average, a private car is used in Germany for about 2.5 trips per day covering a total distance of almost 35 km [2].

It is also interesting to consider that the time between two successive rides is about 3 hours and this time can be used for intermediate charging. Nine hours overnight are also available for battery charging. Additionally, the power requirements in city driving conditions are comparable low. A peak power of about 10 to 15 kW is enough to cover most needs. With the driving and storage components available today, electric vehicles, which are designed for city driving, can already fulfil the performance and range requirements.

1.1.2 Range Extender

One way to reduce problems related to battery size and range as well as to broaden the application range of the vehicle it is offered by the range-extender. Instead of installing larger batteries in the vehicle, aiming at increasing its range, a generator unit can be integrated as shown in Fig. 2 [3].

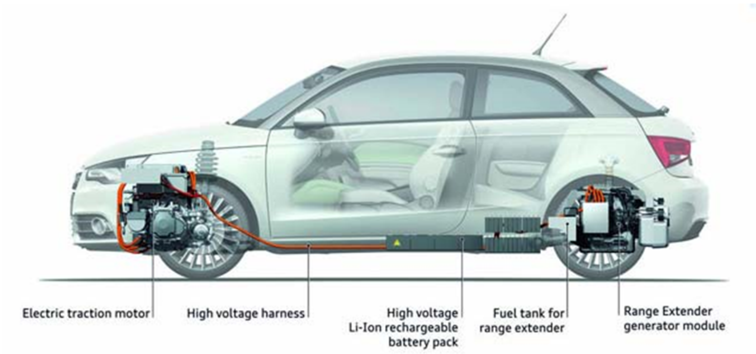

Fig. 1.2 Powertrain of a vehicle equipped with a range extender

In this configuration, a compact internal combustion engine drives a generator. The typical function is shown in Fig. 3. If the charging level of the battery reaches a pre-set low limit or the performance requirements are permanently high, the range extender engine starts and generates electrical power for the traction motor or, in other words, it charges the traction battery above the mentioned low-level.

In this way, the capacity of the battery can be chosen according to an average range resulting in relative small and inexpensive batteries. In conclusion, such a powertrain consisting of a power generator and a small battery that can be more cost-effective than a system with only battery-electric drive and a correspondingly large battery.

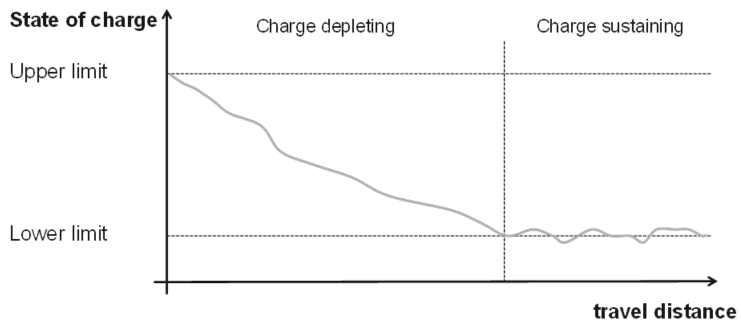

Fig. 1.3 Operating modes of an electric vehicle with range-extender

The power of the generator is usually not high enough to guarantee the maximum vehicle speed. It is based rather on an average, low demand of power (A design according to the maximum continuous power results in a serial hybrid vehicle).

1.1.3 Powertrain of fuel cell electric vehicles

Fuel cell electric vehicles (FCEV) use fuel cells to generate electricity for the electric drive system as shown in Fig. 4 [4].

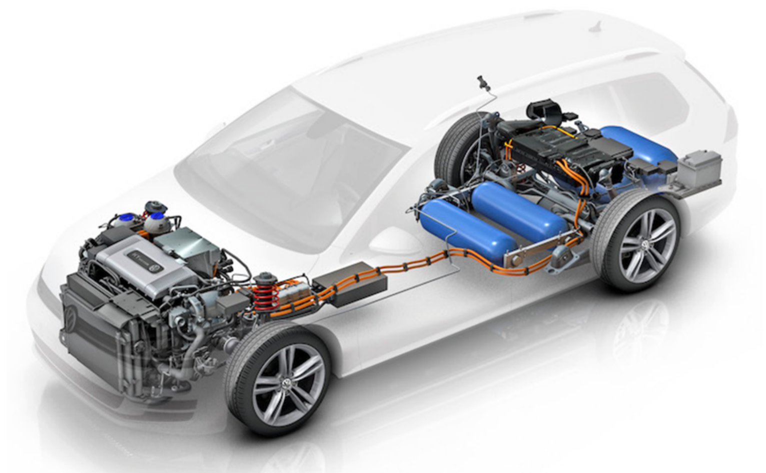

Fig. 4. Powertrain of a fuel cell electric vehicle (FCEV)

The fuel cell is an electrochemical converter, which transforms the chemical energy contained in the fuel directly into electricity. For the operation of a fuel cell, a number of auxiliary units is required. Fig. 5 shows a simple fuel cell system [5].

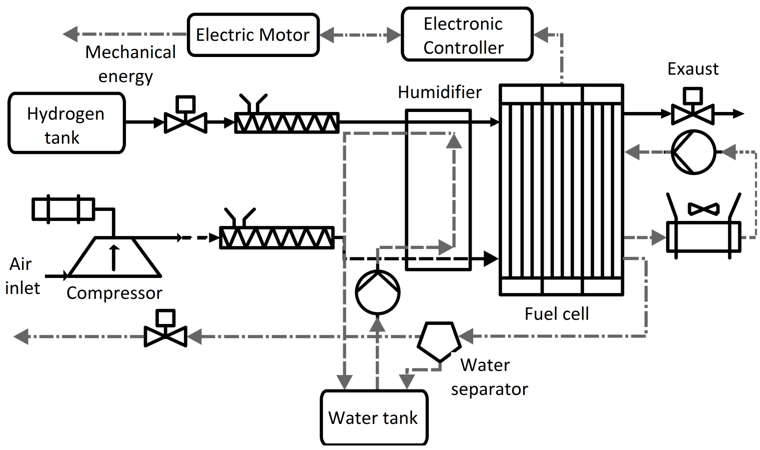

Fig. 5. Lay-out of a fuel cell system

The system shown in Fig. 5 uses pure hydrogen as a fuel in the anode. The ambient air delivers on the cathode side the oxygen required to generate water. The hydrogen is stored in a tank either highly pressurized in gas form or deep-cooled and liquefied. The hydrogen is humidified and supplied to the anode under a slight overpressure.

Ambient air is condensed by a compressor to the pressure level of the anode and then humidified and supplied to the cathode. The cathode exhaust gas, generated by the electrochemical reaction in the fuel cell, is fed to a condenser which liquefies the water contained in the exhaust gas. This water is re-used in the humidifier.

In some cases, the anode operates as a "dead-end", meaning that the hydrogen supply is controlled so that all fuel is fed to the reaction and completely consumed. Since the exhaust gas is still at higher pressure level, it can produce mechanical work in the so-called expander, which partially covers the power requirement of the compressor. In addition, a part of the power produced by the fuel cell is used to drive the compressor via an electric motor. The remaining power is converted so that it corresponds to the current-voltage requirements of the particular application, and is then supplied to the consumer.

Most of the currently available fuel cell vehicle propulsion systems follow a hybrid approach and use an energy storage system, often a battery, in order to cover peak power requirements. It allows the recovery of a portion of the braking energy (recuperation), but depending on the design, it has high weight and additional space requirements. A problem of a powertrain without intermediate storage is the dynamics of the overall system, i.e. the response to a sudden change of the accelerator- (gas-) pedal position.

The design guidelines followed to choose the power rating of the fuel cell and the battery are the same as in an in-line hybrid vehicle. The fuel cell system provides the power necessary to achieve the maximum speed and continuous climbing ability, while the battery is designed as an intermediate, temporary storage in accordance with the power peaks in regenerative braking or full acceleration. In this way, the fuel cell system can be smaller in powertrains featuring a battery than in systems without it.

The battery also ensures a spontaneous reaction to sudden power requirements overriding the limited dynamics of the fuel cell system. Further, the battery can supply power immediately during a cold start of the system, while the fuel cell system has not yet reached its full potential.

1.1.4 Vehicle examples

In the following some vehicles available on the market are briefly introduced.

- *Battery electric vehicle*

As example of a BEV, the Mitsubishi iMiEV is shown in Fig. 6 [6]. Its rear wheels are driven by a permanent-magnet synchronous motor rated at 35 kW. Energy is stored in a Li-Ion battery with 16 kWh capacity. The energy consumption is 12.5 kWh/km in the NEDC (New European Driving Cycle), the range reaches 160 km. The vehicle has a top speed of 130 km/h [7].

Fig. 6. Mitsubishi iMiEV

- *EV with range extender*

The BMW i3, shown in Fig.7, is available on the market since November 2013 [8]. The vehicle is powered by a 125 kW electric motor installed over the rear wheels and achieves a top speed of 150 km/h. As a range extender, a water-cooled two-cylinder gasoline engine with 0.65 l displacement is installed. Its power of 28 kW is used to recharge the Li-Ion battery whose capacity is 21.6 kWh.

Fig. 7. BMW i3: EV with range extender

In order to increase the efficiency, the body is made of Carbon Fiber Reinforced Plastic (CFK). On the other hand, low rolling resistance tires of size 155/70 R19 are used. The electric range is 130 – 150 km and the additional range, with range extender operation, is 120 – 160 km. In the NEDC, the energy consumption is 12.9 kWh/km [9].

- *Fuel cell electric vehicle*

After the presentation of several concept cars, Honda launched in 2008 the small-series production of the Honda FCX Clarity shown in Fig. 8 [10]. It was offered in the US and Japan as a leased car. The vehicle has a PEM fuel cell stack rated at 100 kW power and a 100 kW electric motor [11].

Fig. 8. Honda FCX Clarity: Fuel cell electric vehicle

In addition, a Li-Ion battery with 1.2 kWh capacity is utilized. The hydrogen tank has a capacity of 171 l or 4 kg. This is enough for a range of about 450 km. The hydrogen consumption is about 0.9 kg/100km. Top speed of the vehicle is 161 km/h.

1.2. Hybrid vehicles

Hybrid vehicles (HV) are called vehicles powered by at least two discrete distinct on-board motors (energy converters) and storage systems. The most common configuration is the combination of an internal combustion engine including its tank with one or more electric motors. For the selection of the second power source, i.e. the electric motor or motors, it is important to consider that the above definition does not include recuperation of energy aiming to exploit it later when needed. The bi-directional operation of the electric machine (as motor or generator) is a decisive feature, which provides further options and makes the hybrid drive meaningful. For example, when braking, the kinetic energy can be transformed, stored in the storage system of the vehicle and recovered when needed.

The benefits of the hybrid drive outcome from the combination of the advantages of the internal combustion engine and the electric machine. The typical long range of the internal combustion engine results from the high energy density of liquid fuels and the possibility of rapid refuelling. Electric machines on the other hand allow for emission-free driving and regenerative braking.

1.2.1 Classification of hybrid drives acc. to electrification grade

Several terms have been established aiming at classifying the hybrid drives according to the grade of electrification [12]. Fig. 9 shows the features and power levels of the vehicle as well as the usual voltage of the traction battery.

Start / stop systems enable the combustion engine to stop when the vehicle stands still. Such systems are now standard in conventional vehicle powertrains also.

Micro hybrids are drives which enable a simple regenerative braking or recuperation by means of the alternator or the integrated starter-generator in addition to the start / stop feature. Apart from versions that use the conventional starter and the alternator, the use of a belt-driven starter/generator or an electric motor coupled directly on the crankshaft is an additional possible configuration. Usually such drive systems operate at higher voltage levels in order to implement the necessary electric power.

Mild hybrid drives allow for both boosting and regenerative braking. Exclusively electric driving is not possible, with the exception of driving under conditions requiring low power.

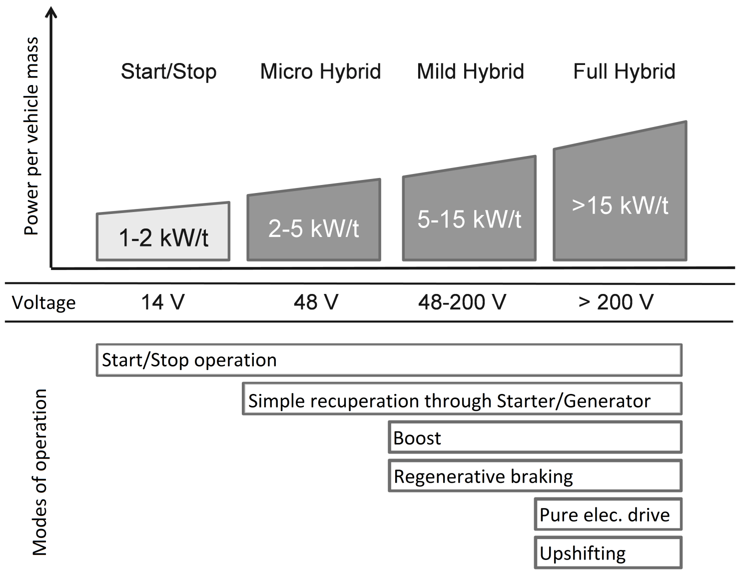

Fig. 9. Classification of hybrid drives

Full hybrid drives enable electric driving in addition to all previously mentioned functions. Depending on the performance of the electrical components, the speed and autonomy range, where exclusively electric driving is possible, may vary. The energy for electric driving is gained by upshifting the operation point of the ICE.

Another classifying criterion is how the battery is charged. In contrast to the previously discussed so-called stand-alone hybrid drives, in the plug-in hybrids, the battery is charged externally, before driving while the vehicle stands. The electric mode is in the foreground.

1.2.2 Classification of hybrid drives acc. to engine coupling

In addition to the functional aspects, the coupling of the internal combustion engine and the electric machine or machines is another criterion to classify the hybrid vehicles [13]. In the following, relevant variants are presented and explained by examples.

- *In-line hybrid drive*

In the in-line hybrids, the components are arranged along the same axis. As shown in Fig. 10, the internal combustion engine is permanently coupled to a generator which produces electrical energy. It is used either directly by the e-motor to drive the vehicle, or stored in an accumulator.

Besides batteries, capacitors with high power density the so-called "supercaps" (supercapacitors) may be used as energy storage system. The combustion engine may operate either following the driving requirements or independently of the instantaneous power needs, in the so-called phlegmatic mode. In extreme setups, it operates exclusively at the optimum point regarding fuel consumption and emissions.

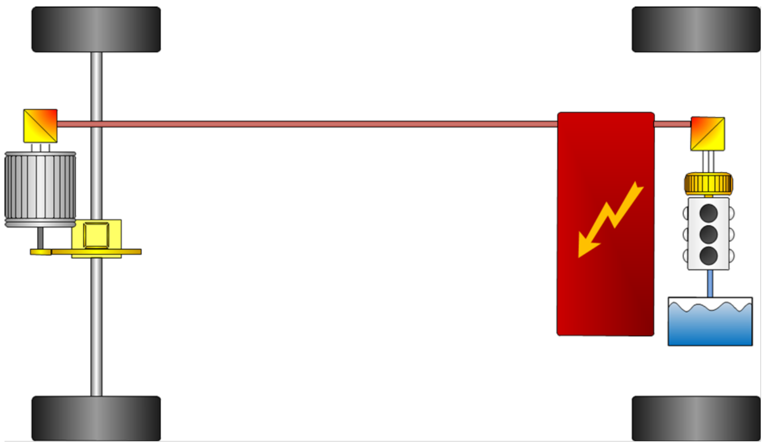

Fig. 10. In-line hybrid drive

However, this optimization of the combustion engine operation has the drawback of multiple energy conversion. The mechanical energy of the combustion engine is first converted by the generator in electrical energy, and then stored in the battery if not immediately needed. Finally, it is converted back into mechanical energy in the driving e-motor. The associated energy losses can be compensated only by the optimized operation of the IC engine, if the driving profile is quite dynamic and accelerations and decelerations predominate, as for example in the case of city buses.

Especially for low-floor buses, the installation of individual drives either near or inside the wheels (hub e-motors) may be beneficial. The direct mechanical coupling of the engine and the wheels is omitted offering thus a clear packaging advantage.

Further, the power transmission to more than one axle can be realized in a relative simple way. It increases both the traction and power gain rate at recuperative braking. The disadvantage is that the traction motors alone must provide all the power needed. This high technical effort is associated with corresponding high costs. Furthermore, the resulting unsprung wheel masses are increased by the e-motors and should be considered in the suspension design.

IC engine and generator must provide the peak continuous power for uphill driving or to achieve the maximum speed. The power output of the internal combustion engine and the generator can be selected smaller than that of the electric traction motor, because it can be fed simultaneously by the accumulator.

- *Parallel hybrid drive*

In parallel hybrid drives, as shown in Fig. 11, both the combustion engine and the electric motor can drive the vehicle via a direct mechanical connection to the wheels. Typically, only one electric motor is needed. It can be integrated in the conventional drive line at many points. It is of advantage that a parallel drive can be relatively easily developed from a conventional one.

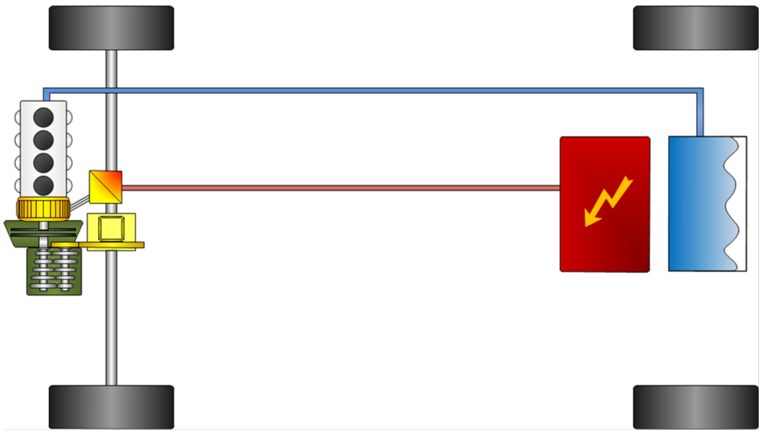

Fig. 11. Parallel hybrid drive

The electric machine can be coupled directly to the internal combustion engine. Therefore, it can operate as an integrated starter / generator, control the start / stop function, actuate the upshifting of the operation point of the ICE and ensure regenerative braking. Exclusively electric driving makes rarely sense, because in this arrangement, the IC engine always rotates at the same speed with the electric motor causing thus drag losses. Such a drive arrangement is shown in Fig. 11. It is typically used in mild hybrid vehicles with an electric motor power of approximately 20 kW.

If the combustion engine and the electric machine are connected by a clutch, as shown in Fig. 12, the two motors can operate independently from each other. Electric driving is therefore possible and the gear ratios of the transmission can also be used in electric mode. Engine start can be made by an additional starter or by properly controlling the clutches.

This parallel drive arrangement is realized in many hybrid vehicles, such as the Porsche Panamera Hybrid, Audi Q5 Hybrid and VW Touareg Hybrid. The rating of the electric motor alone determines the power in exclusive electric driving mode. Since it can operate concurrently with the IC engine, it can be chosen smaller than usually. This design improves its average utilization as compared with a vehicle with a conventional drive.

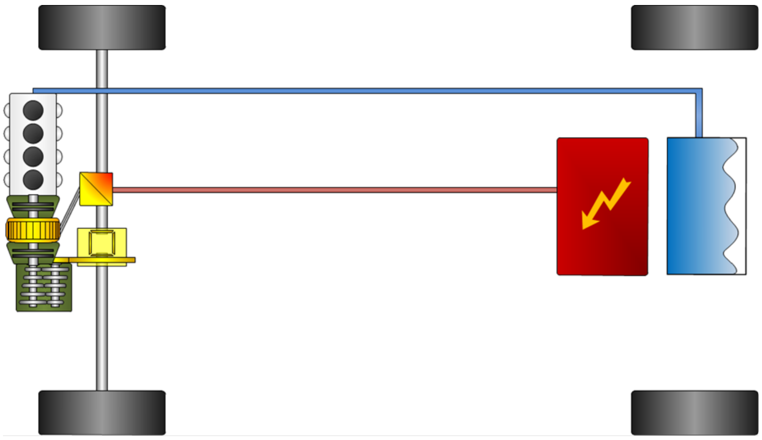

Fig. 12. Parallel hybrid with additional clutch

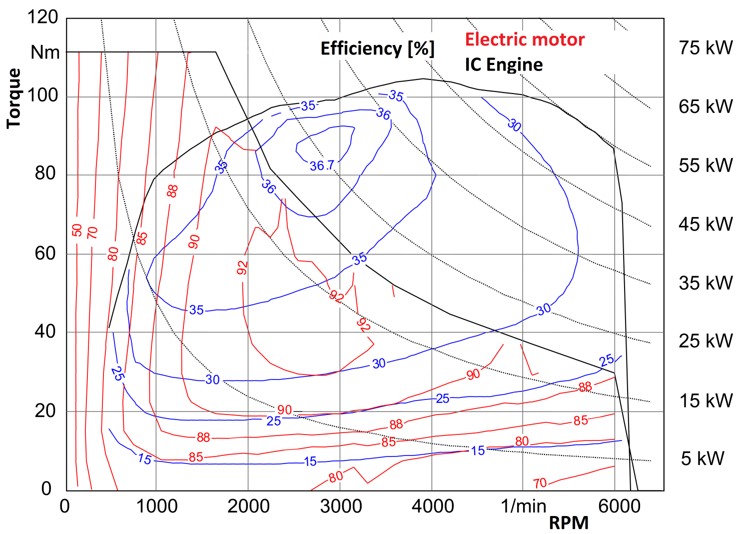

Fig. 13. Overlap of IC engine and e-motor maps in a parallel hybrid drive

A key issue in the design of a parallel hybrid drive is the dimensioning of the components of the electrical branch compared to the internal combustion engine. Since higher power electrical components are becoming increasingly available, wider operating ranges can be covered solely by the e-motor provided that the IC engine is decoupled. This mode of operation is meaningful in regimes, where the IC engine has low efficiency, i.e. in the partial load range. Therefore, it is required that the e-motor covers in terms of performance at least this regime. An example of such a superposition of the characteristic fields of an IC engine and an e-motor is shown in Fig. 13 [14].

Another alternative is to install the electric motor at the output of the gearbox. This has the advantage that no power losses occur in the transmission when operating in exclusive electric mode. Additionally, the electric motor can compensate the interruption in the power flow from the IC engine when shifting gears. A disadvantage, however, is that the electric motor operates in a quite extensive speed range. Therefore, the transmission ratio must be chosen in such a way that the maximum allowed speed of the e-motor is not exceeded when travelling at top speed.

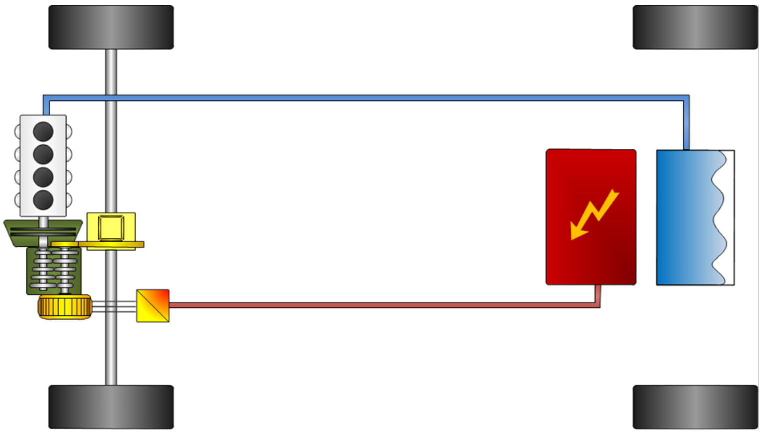

Fig. 14. Hybrid drive with the e-motor at the gearbox output

Thus, a low transmission ratio is selected. Consequently, lower torque is available for acceleration when starting. A correspondingly high-torque engine can compensate this drawback. Its performance is then actually oversized. Fig. 14 shows such arrangement.

From the functional point of view, this is similar to a configuration where the front axle is driven conventionally and the rear axle electrically, as shown in Fig. 15.

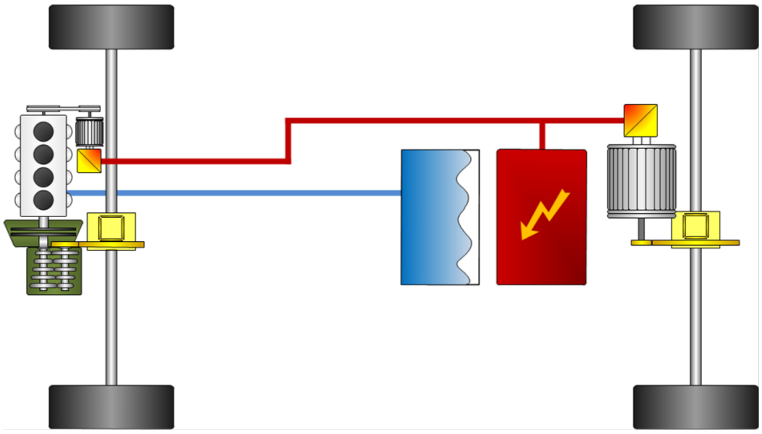

Fig. 15. Parallel hybrid drive featuring driving force addition

The power outputs of both motors are added, not as usually in a gearbox, but via the road surface.

In this arrangement, the conventional engine and gearbox can be taken directly from series production. The effort to drive electrically the second axle is comparable low. When standing the battery can be charged by the starter / generator. An additional advantage is that, at least temporarily, a four-wheel-drive mode can be enabled, within the operational range of the battery and starter / generator. Examples of vehicles following this architecture are the Peugeot 3008 Hybrid 4 and the Volvo V60 Plug-In Hybrid.

- *Combined hybrid drives*

The combined hybrid drives merge the characteristics of the in-line and parallel concepts.

When a parallel hybrid drive having the electric machine at the input of the transmission is coupled to a second electric machine coupled directly to the IC engine, then this arrangement is called combined hybrid drive. When the coupling is disengaged, a serial mode of operation is enabled. The IC engine produces electric power through the directly coupled electric machine (functioning as generator) that can be used by the second electric machine (functioning as motor) for driving or charging the batteries. The directly coupled electric machine provides also the ability to quickly start the IC engine. The serial mode of operation is useful for driving situations that require low power and high dynamics. An example is a prolonged stop-and-go driving that cannot be accomplished exclusively electrically due to the limited capacity of the batteries. The power of the second directly coupled electric machine is not required to be high (about 5-10 kW for a passenger car). It can be also used in combination for boosting.

Another variant is possible, when a serial hybrid is outfitted with an option that allows the IC engine to drive the wheels directly. Hence, it is possible to minimize the losses that are entailed by the double energy conversion, via a clutch and gearbox having a fixed ratio that roughly approximates a fifth gear, since the motor is directly driving the wheels. This can be useful for highway speeds. Additional possibilities for raising the load and boosting are also possible. The operating point and in direct connection the rotational speed of the ICE is firmly set through the ratio. Volkswagen follows this concept in the so-called Twin Drive-System.

- *Power-split hybrid drives*

In power-split hybrid drives, the mechanical power of the IC engine is transmitted via two paths to the wheels. The first part of the power is transmitted mechanically and directly via the main power path. The rest follows an auxiliary path, which is comprised of two electric machines that operate as motor and generator forming thus a continuously variable transmission. Alternatively, it is also possible to implement in the auxiliary path either a mechanical or a hydraulic transmission operating in the same manner as the motor-generator offering a continuously variable transmission ratio. Since only a part of the power is transferred via the auxiliary path, it is evident that the power loss is far less compared to an in-line hybrid that exclusively utilizes electric power transmission. In order to split and recombine the power, planetary (epicyclic) gear-trains play an important role. The resulting system is a continuously variable transmission that enables the flexible selection of the operating point of the IC engine. The battery pack is not used during power transmission, but it enables the operation of the regenerative breaking and electric driving mode.

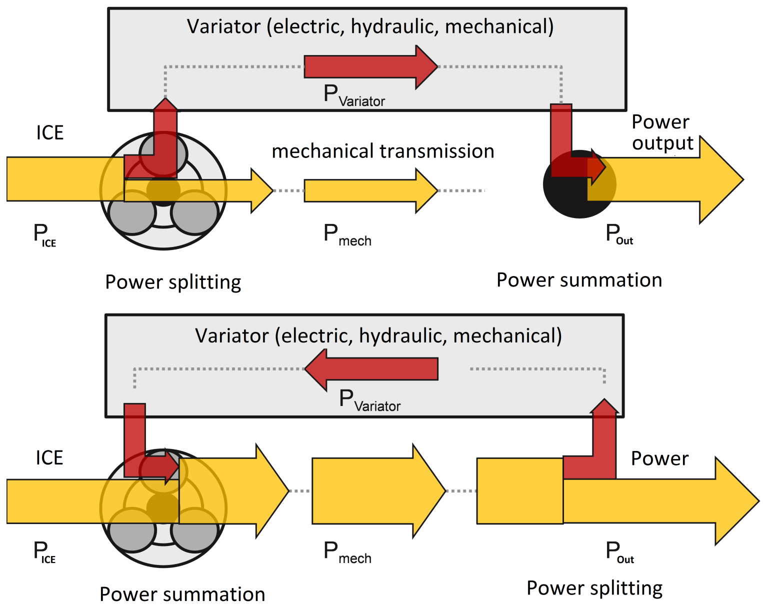

Fig. 16. Power flow in a power-split hybrid drive with and without reactive power

Fig. 16 shows how the power is transmitted in a power-split hybrid drive. The power in the auxiliary path can flow in both directions and the planetary gear-train can operate in power splitting or power summing mode. The power flow in these two operation modes is shown in the upper and lower half of the figure respectively.

In power summing mode, a part of the power is taken from the output and transmitted back to the input of the planetary gearbox, added to the IC engine power and transmitted to the wheels via the main power flow path. The power in the mechanical main path is larger than the part transferred by the gearbox. The power in the auxiliary path circulates and causes power loss, although it does not contribute to the drive. Therefore, it is characterized as reactive power. Due to the higher power loss, this operating mode should be avoided as much as possible.

The layout of a power split hybrid drive is shown in Fig. 17. The IC engine is connected to the carrier of the planetary gearbox. The first electric machine A is coupled to the sun gear and operates mainly as a generator, while the second electric machine B is coupled to the ring gear through which the power is transferred to the wheels.

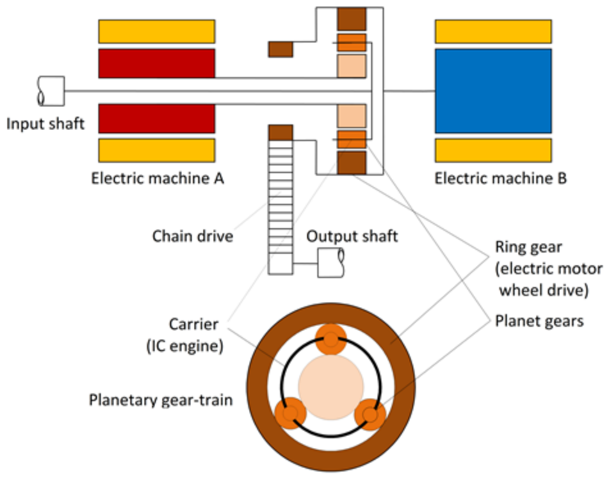

Fig. 17. Layout of a power split hybrid drive

The nomogram shown in Fig. 18 clarifies the operation of the power-split drive. In a planetary gear-train, the ratio of the component torques remains constant. Each operation point is represented by a straight line. On the dotted vertical axes, the rotational speed of each component of the planetary gear-train is shown.

While standing, no component is rotating (line 1). In order to start the IC engine when the vehicle stands still, the electric machine A (generator) operates as motor and spins up the IC engine (line 2). In order to accelerate the vehicle, the rotational speed of the ring gear and the IC engine must be raised, so that more power can be produced. This results in the conditions described by line 3. The rotational speed of the generator sinks. The IC engine drives with positive torque, while the generator rotates forwards and is driven with negative torque, thus producing electric power, which will be used by the electric machine B to drive the vehicle.

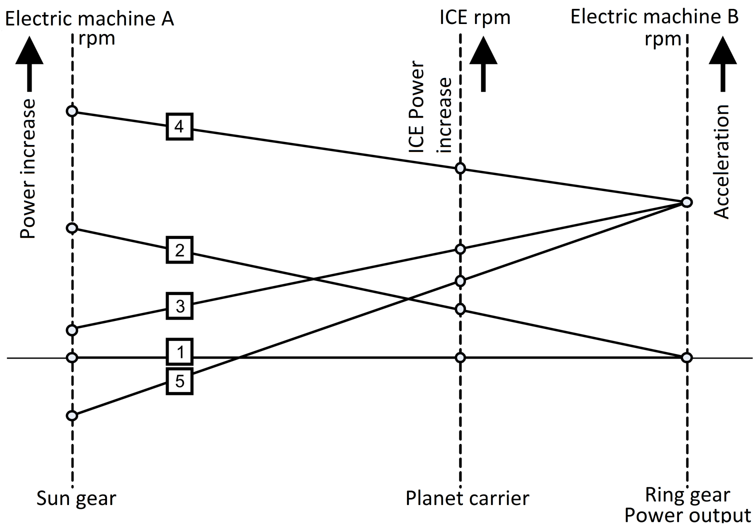

Fig. 18. Nomogram showing the rotational speed relationships in the planetary gear-train

When driving at the same speed, a faster acceleration is required, the rotational speed of the IC engine must be raised as well as the speed of the generator (line 4).

For operation of the IC engine at reduced rotational speed (overdrive), the rpm of the generator must be lowered even further. This can lead to the reversal of the rotation direction of the generator (line 5). Since the torque of the IC engine must be supported by the negative torque of the generator, the operation mode of the electric machine A (generator) switches over to motor mode. Since it now operates as motor, it has to draw power from the driving motor (electric machine B), which must also switch and operate as a generator in order to produce power. Reactive power is now circulating the system and therefore the efficiency is decreased. Despite that, this operation is useful in order to achieve a "long" gear ratio that produces the overdrive effect achieving better efficiency of the IC engine and hence a higher overall efficiency.

Similarly, stopping the IC engine while driving leads to negative rotation speed of the generator. At very high speeds is not possible to stop the IC engine, since the rpm limit of the generator will be exceeded.

Such transmission designs enable all modes of operation of a full hybrid. While electric driving, including regenerative breaking only the traction motor is active.

Starting and stopping of the IC engine is made possible with the aid of the generator. The power output of the IC engine can be increased and a fraction of the electric power produced by the generator can be used to charge the batteries (operating point upshift). In contrast to the parallel hybrids with fixed gear ratios, the rotational speed of the IC engine can be freely set in order to let it operate in the most fuel-efficient map region. The power of the traction motor must be adequate enough in order to achieve purely electric mode of operation with fixed gear ratio. This dictates a powerful traction motor (electric machine B). The power of the generator is lower than the IC engine. In comparison to the parallel hybrid powertrains, the cost is higher since two electric machines are needed. On the other side, gearboxes and clutches are omitted.

The discussed powertrain is used for example by Toyota in Prius, Auris and Yaris Hybrid. Similarly, Ford selected for its Ford Fusion and C-Max Hybrid a power split design. In Lexus LX 400 and LX 600 hybrids, the same concept is expanded by a downstream planetary stage, which offers two ratios for the axles allowing thus higher velocity range, without using an overdrive operation avoiding thus operation power summing mode.

An additional variant can be found in the Lexus SUV GS 450h Hybrid. Here the front axle is coupled to a power-split hybrid drive, while the rear axle is driven, when required, by a third electric motor. Hence, a power increase is possible via the road as in in parallel systems. Rear axle driving is activated not only in cases of limited traction, but also when the driving conditions require it in order to improve stability, e.g. during cornering.

Depending on the position of the power splitting gear-train, two different variants are possible. When this is in the input, the power of the IC engine is divided to a main and an auxiliary path, which are recombined at the output, so that the torque of the traction motor can enter the transmission. However, when the power splitting gear-train is at the output, the generator coupled to the IC engine splits the power and transmits some energy to the electrical auxiliary path. At the drive output then the power is summed up by a planetary gear-train that is coupled to the second motor. Such designs are used in the Opel Ampera and the Chevrolet Volt. Both of these models are plug-in hybrids. The normal operation mode is fully electric, in which the electric machine B is used to drive the vehicle (Mode: Electric Drive 1). At higher power demands both electric machine (A and B) can operate as motors and used for driving the vehicle (Mode: Electric Drive 2). An additional mode of operation is the in-line mode. Here the IC engine would start and provide electric power through the electric machine A, which would operate as generator, similar to an in-line hybrid powertrain. The electric machine B drives the vehicle. Only at elevated speeds, when the power requirement is high and the batteries are discharged, the system switches to the power-split operation mode.

- *Plug-in hybrid*

The aim of driving as often as possible in a pure electric mode demands in plug-in hybrids a severely larger battery pack. Apart from the already described powertrains, the battery is transformed from a relatively small to a much larger pack that is charged externally and is discharged during operation similarly to a fuel tank. Such drives allow exclusively electric operation up to 20 -50 km/h with zero local emissions. This requires correspondingly powerful electric motors. On the one hand, the power must be present to enable city driving with the associated necessary accelerations. On the other hand, the stored energy of the battery must be sufficient to cover the driving range. The two modes of operation are similar to those of an electric vehicle equipped with a range extender, depending on the state of charge and the distance covered, as already shown in Fig. 2.

The size of the IC engine plays an important role in the comparison with the range extender electric vehicles. In plug-in hybrids a comparably much more powerful electric motor is used. It is used when accelerating or to reach the top speed of the vehicle. In the range-extender electric vehicles however, the power output of the IC engine is chosen with the battery charging function in mind.

The advantage of the plug-in hybrid concept is that emission-free and quiet driving is made possible to a great extent. In addition, the operating costs are reduced. Recharging the battery from the public power grid has a lower cost than the consumed fuel, if the same route is covered exclusively powered by the IC engine. The operation range is significantly higher compared to an electric vehicle. However, this concept has some disadvantages. The battery pack of a plug-in hybrid is significantly bigger compared to an autonomous hybrid, in which the battery is exclusively charged by the IC engine. That means additional weight, production costs and market price, because the specific production costs of the batteries are still at a high level. Consequently, increasing the electrical range results in significantly higher costs. Finally, following a holistic approach, it is necessary to consider the indirect emissions due to power production.

1.2.3 Vehicle examples

Some examples of vehicles already available in market that feature the previously described powertrain architectures are presented in this section.

- *In-line hybrid*

Although not available in series passenger cars, they are implemented in line buses of various manufacturers. For example, the Mercedes-Benz Citaro G BlueTec Hybrid articulated bus is shown in Fig. 19 [15].

Fig. 19. Mercedes-Benz Citaro G BlueTec articulated bus with in series Hybrid drive.

In this vehicle instead of the conventional 7.2 l six cylinders in-line Diesel engine, a smaller 4.8 l Diesel engine driving a 160 kW generator is installed. Through this downsizing, a weight reduction of about 500 kg is achieved. At the middle and rear axles, four in-wheel electric motors are placed each with 80 kW power, i.e. 320 kW in total.

The energy content of the Li-ion battery is rated quite large at 27 kWh, so that a second generation model can be designed as plug-in hybrid allowing a distance of about 10 km to be covered purely electric. Depending on the operating conditions, up to 20% reduction of fuel consumption can be achieved.

- *Parallel hybrid*

An example of the numerous of full hybrid vehicles is the Peugeot 3008 Hybrid 4 as shown in Fig. 20 [16]. It is worldwide the first full hybrid production car equipped with a Diesel engine.

Fig. 20. Peugeot 3008 Hybrid 4

The combination of ICE (120 kW) at the front and the permanent magnet synchronous motor (PMSM) electric motor (27 kW) at the rear, allows an all-wheel drive. Together they provide a combined power of 147 kW. As battery pack a Ni-MH Battery is used. The fuel consumption is advertised as 3.8 l/100 km [17].

- *Power-split hybrids*

The Toyota Prius is the first large series production hybrid vehicle (1997). The version shown in Fig. 21 [18] the Toyota Prius+ is available since March 2016.

Fig. 21. Toyota Prius+

The 1.8 l petrol engine has a power output of 73 kW and the electric motor of 60 kW. The hybrid drive has a max power of about 100 kW. The vehicle reaches a top speed of 165 km/h. The advertised fuel consumption is 4.1 l/100km and the CO2 emissions are 96 g/km [19].

- *Plug-in hybrid*

The launch of the BMW i8 Concept took place in 2013 [20]. The drive of this plug-in hybrid vehicle consists of a supercharged 1.5 litre three-cylinder petrol engine with 170 kW power. The electric motor achieves a power output of 96 kW. As an energy storage, a Li-ion battery pack with 7 kWh capacity of is used. The vehicle is shown in Fig. 22 [21].

Fig. 22. The BMW i8concept

The range of the vehicle when driven purely electric is 37 km, while it rises to 600 km when driven by the IC engine.

The advertised fuel consumption is 2.1 l/100 km (CO2 emissions 49 g/km), the maximum speed is 120 km/h in electric and 250 km/h in hybrid mode. Through targeted lightweight design utilizing crash-proof CFK material, a weight reduction of 50% was achieved, compared to conventional steel design.

2 Conclusion

The "electrification" of vehicle powertrains as well as the "decarbonisation" of fuels are important development targets for several reasons such as limited oil – resources and independence of oil import, climate change and reduction of exhaust gas emissions, noise pollution and reduction of noise emissions, etc.

Internal combustion engines will power our vehicles still for a long time. They offer a proven and cost effective powertrain technology with a big potential for improvements.

Hybrid vehicles offer a reasonable alternative in terms of further exhaust gas and noise reductions. The different technologies and operation strategies are well developed and more and more hybrid vehicles (passenger cars, buses) are already available on the market. By the way, this is an excellent opportunity to build up based "serial know-how" for the development and production of electrical powertrain components and control systems.

Electric vehicles will find a first application in short run operation. Big improvements of batteries are still needed as well as an expansion of the charging infrastructure.

In addition, fuel cell vehicles convince in terms of a long driving range, which customers know from cars with combustion engines. The powertrain components of fuel cell vehicles as well as the hydrogen filling infrastructure require further developments. In the long term fuel cell vehicles are an interesting and very promising technology.

At the end, the customer decides on the market success of the different powertrain systems (cost benefit, acceptance, etc).

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