Hybrid drives

A concept for economizing on fuel, for reducing CO_2 and pollutant emissions, and at the same time for increasing driving pleasure and driving comfort is provided by hybrid electric vehicles (Hybrid Electric Vehicle, HEV). For drive purposes these vehicles use both an internal-combustion engine and at least one electric motor (electrical machine). There are in this respect a multitude of HEV configurations which partly pursue different optimization objectives and which utilize to differing extents electrical energy to drive the vehicle.

Principle

There are essentially three objectives being pursued when hybrid electric drives (Fig. 1) are used: fuel economy, reduced emissions and increased torque and power ("driving pleasure"). Different hybrid concepts are used, depending on the objective being pursued. A distinction is basically made between *mild-hybrid* and *full-hybrid* vehicles, depending on their ability also to be able to run by pure electrical means.

In a *mild hybrid* the internal-combustion engine is assisted by an electric motor, which delivers additional drive power and braking power in different operating states. In a *full hybrid* as well the internal-combustion engine is combined with one (or two) electric motor(s). In additional to running on the internal-combustion engine and being assisted by the electric motor, this latter type also allows for purely electric driving.

Both hybrid concepts have a start/stop function, as is familiar from conventional start/stop systems. When the vehicle is stationary, e.g., when stopped at traffic lights, the internal-combustion engine is switched off. The avoidance of idling phases helps to save fuel. An automatic start/stop system can, depending on the level of hybridization, naturally also be used in vehicles with conventional drives.

Both mild-hybrid and full-hybrid systems require an electric energy accumulator, which powers the driving electric motor. This energy accumulator is usually a traction battery at a comparatively high voltage level.

The combination of electric and combustion-engine drive sources in the mild hybrid and full hybrid has various advantages over conventional drivetrains:

- The electric motor offers constantly high torques at low rotational speeds. In this

1 Principle of the hybrid drive using the example of a parallel hybrid

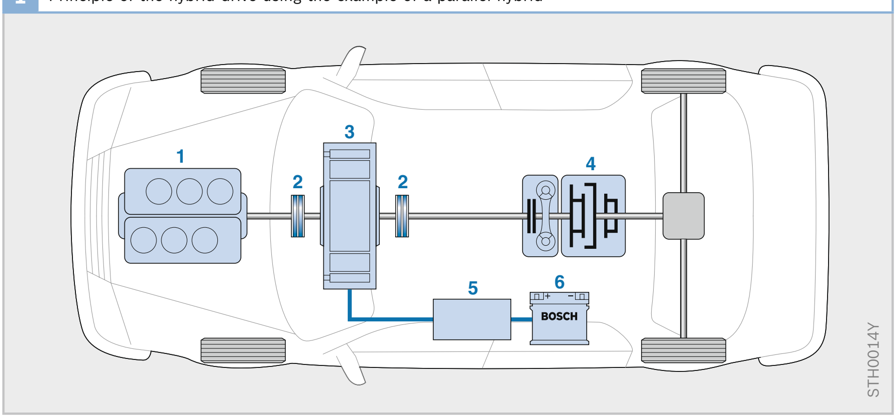

Fig. 1
1 Internal-combustion engine
2 Clutch
3 Electric motor
4 Transmission
5 Inverter
6 Battery

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way it ideally supplements the internal-combustion engine, whose torque only starts to increase at mid-range rotational speeds. The electric motor and internal-combustion engine together are thus able to deliver a high dynamic response from every driving situation (Fig. 2).
- The assistance provided by the electric motor makes it possible to operate the internal-combustion engine predominantly in the range of its best efficiency or in ranges in which only low pollutant emissions occur (operating-point optimization).
- The combination with an electric motor facilitates if necessary the use of a smaller internal-combustion engine while retaining the same overall power output (power-neutral downsizing).
- The combination with an electric motor facilitates if necessary the use of a higher-geared transmission while retaining the same levels of driving performance (downspeeding).

The hybrid systems also offer the possibility of fuel economy through the recovery of braking energy. Through generator operation of the electric motor (or if necessary by means of an additional generator), it is possible when braking to convert part of the vehicle's kinetic energy into electrical energy. The electrical energy is stored in the energy accumulator and can be used to drive the vehicle.

Operating modes

Depending on the operating state and required torque, the internal-combustion engine and the electric motor contribute to the drive power to different extents. The hybrid control system determines the torque distribution between the two drives (see section *Operating strategy*). The way in which the internal-combustion engine, electric motor(s) and energy accumulator interact defines the different operating modes: hybrid and electric driving, boosting, generator operation and recuperative braking.

Hybrid driving

Hybrid driving refers to all those states in which both the internal-combustion engine and the electric motor generate drive torque (Fig. 3). When distributing the drive torque, the hybrid control system takes into account – in addition to the optimization objective (fuel consumption, emissions) – in particular the state of charge of the energy accumulator.

2 Torque curve

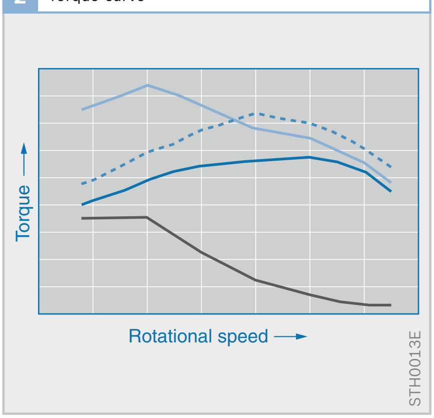


Fig. 2
— Resulting hybrid
-- Standard engine, 1.6 *l* displacement
— Engine, downsized, 1.2 *l* displacement
— Electric motor, 15 kW

3 Hybrid driving

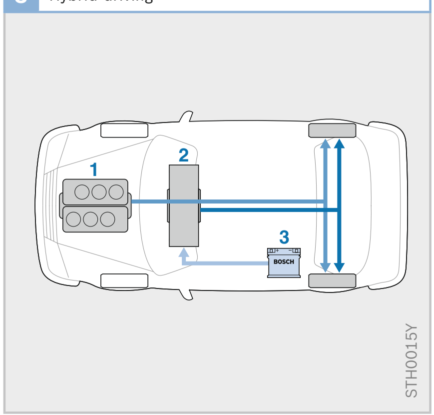


Fig. 3
1 Internal-combustion engine
2 Electric motor
3 Battery

Purely electric driving

Purely electric driving, in which the vehicle is driven over longer distances by the electric motor alone, is only possible with the full hybrid. The internal-combustion engine is decoupled from the electric motor for this purpose (Fig. 4). In this operating mode the vehicle can run virtually noiselessly and locally without emissions.

Boosting

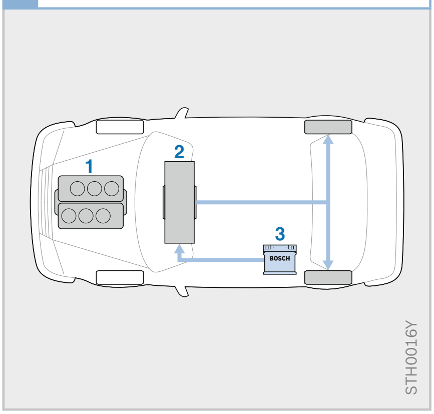
In boosting mode the internal-combustion engine and the electric motor deliver positive drive torque. Both deliver their maximum torque for the vehicle's maximum propulsion torque (Fig. 6).

Generator mode

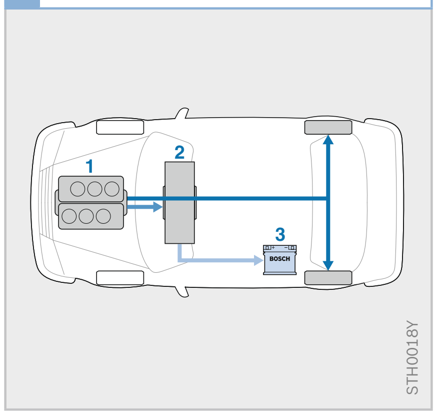
The electric energy accumulator is charged in generator mode. For this purpose the internal-combustion engine is operated in such a way as to deliver a greater amount of power than is needed for the desired propulsion of the vehicle. The excess amount of power is fed to the generator and converted into electrical energy, which is stored in the energy accumulator (Fig. 5).

The energy accumulator is also charged via the generator in overrun mode provided this is permitted by the battery state of charge.

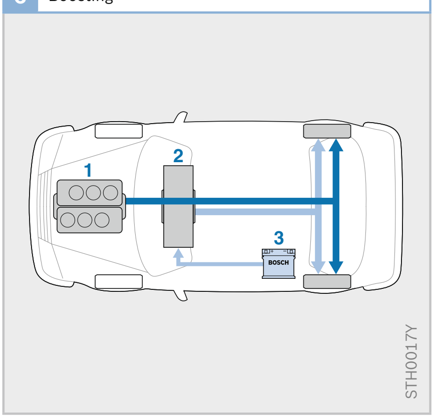
4 Purely electric driving



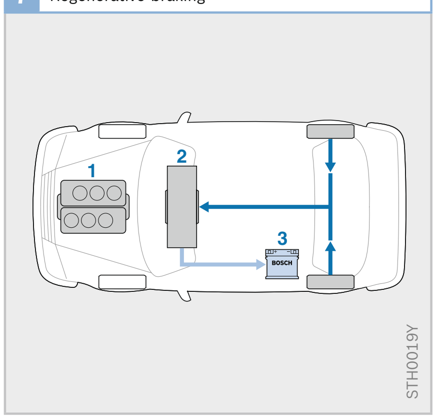
5 Generator mode



6 Boosting



7 Regenerative braking



Figs. 4 – 7
1 Internal-combustion engine
2 Electric motor
3 Battery

Regenerative braking

During regenerative braking the vehicle is not – or not only – braked by the service brake's friction torque, but instead by a generator braking torque of the electric motor. The electric motor is therefore operated like a generator and converts the vehicle's kinetic energy into electrical energy, which is stored in the energy accumulator (Fig. 7).

Regenerative braking is also known as recuperative braking or as recuperation.

Start/stop function

Both mild hybrid and full hybrid have a start/stop function (Fig. 8). But even vehicles with conventional drives can be equipped with a start/stop system.

Function

When the vehicle is stopped, the engine ECU checks whether

- no gear is engaged,
- the speed sensor of the antilock braking system indicates zero,
- the electronic battery sensor is signaling sufficient energy for a starting process.

When these vehicles are satisfied, the engine is automatically switched off.

As soon as the clutch is actuated the starter receives the signal to restart the engine. The engine is started quickly and quietly and is immediately ready for operation again.

Components

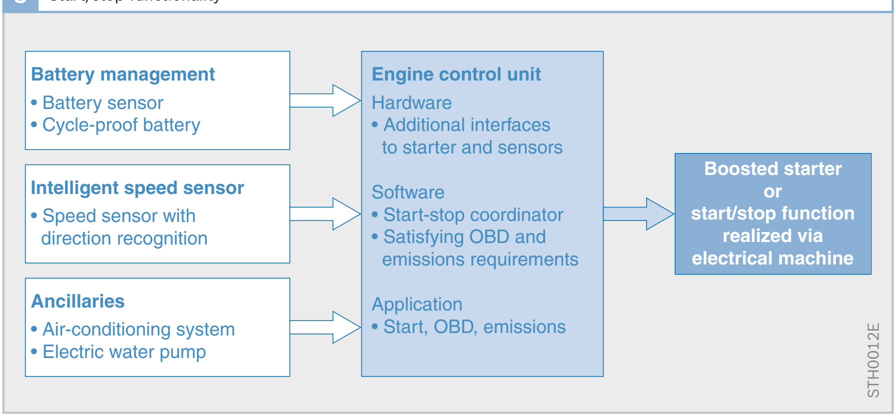
In the start/stop system a reinforced starter (Fig. 9, no. 1) replaces the conventional starter.

The start/stop system requires an adapted engine management system (4), which has additional interfaces to the starter and sensors. Since the start/stop system is an emission-relevant system, it must satisfy the requirements of OBD (on-board diagnosis), i.e., it must be monitored in driving mode and exhaust-gas-relevant faults must be stored in the ECU's fault memory.

Because of the many starting processes it has to manage, the battery (2) must be cycle-proof. It is monitored by a battery sensor, which before the internal-combustion engine is automatically switched off checks the battery state of charge and signals this to the engine ECU.

Ancillaries such as, for example, the A/C compressor, which are normally driven via the internal-combustion engine and are also required during the standstill phases, must be electrically driven or replaced by

8 Start/stop functionality



9 Components of the start/stop system

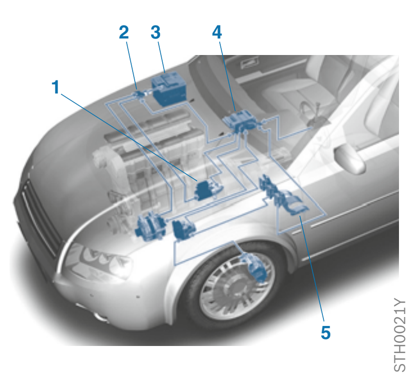


Fig. 9
1 Starter
2 Battery sensor
3 Battery
4 Engine ECU with start/stop function
5 Pedals and sensors

other solutions. This also applies to the mild hybrid and the full hybrid, in which the start/stop function can be realized by means of the electric motor.

Fuel economy

Fuel savings of 3.5 % to 4.5 % can be achieved by the start/stop system in the New European Driving Cycle.

Degrees of hybridization

The degree of hybridization indicates the extent to which distribution of the drive power can be varied between the internal-combustion engine and the electric motor. A distinction is made between mild hybrid and full hybrid, depending on the degree of hybridization. They differ essentially in the power output of the electric motor or with regard to the amount which the electric drive contributes to the overall drive power. They also differ with regard to the energy content of the electric accumulator.

Mild hybrid

Function

The mild hybrid (Fig. 10) offers in addition to the start/stop function the possibility of recuperative braking (1) and of torque assistance by the electric motor (2). The electric motor delivers an additional torque, which is added to the internal-combustion engine's torque. The energy accumulator (4) makes available for this purpose an electrical power output of normally up to 20 kW. This output is mainly used for starting and accelerating at low engine speeds.

Purely electric driving is only possible when the internal-combustion engine is under coupled motion, since it cannot be decoupled from the electric motor. Such an operating state is useful in energy terms only if the drag torque of the internal-combustion engine is not too great. Mild hybrids are therefore often combined with internal-combustion engines which demonstrate the possibility of cylinder shutoff.

Design

The mild hybrid is realized as a parallel hybrid, i.e., internal-combustion engine and electric motor are positioned on the same shaft (crankshaft).

In addition to the conventional low-voltage electrical system (14 V) for supplying the loads/consumers, a traction electrical system with a clearly higher voltage is provided to feed the electric drive.

For a detailed design, see section *Parallel hybrid*.

Fuel economy

The fuel savings of a mild hybrid compared with a conventional vehicle can be up to 15 % in the New European Driving Cycle (NEDC).

Full hybrid

Function

The full hybrid (Fig. 10) can, in contrast to the mild hybrid, be driven over longer distances with the electric drive alone. The internal-combustion engine does not rotate during electric driving. The voltage of the traction electrical system or the battery usually ranges between 200 and 350 V.

Design

The full hybrid can be realized with a parallel or serial flow of energy or can be a combination of parallel and serial flows of energy. The parallel flow of energy can be represented by one electric drive. To realize a serial flow of power, there must be two electric drives in the drivetrain.

In a parallel hybrid with two clutches (P2-HEV) an interrupting clutch is fitted between the internal-combustion engine and the electric motor. This enables the internal-combustion engine to be decoupled from the electric motor for purely electric driving.

For a detailed design, see section *Parallel hybrid*.

A full hybrid with combined serial and parallel power flows is realized by a power-branching system, in which the central transmission element is a planetary-gear set.

For a detailed design, see section *Power-branching hybrid*.

Fuel economy

The fuel savings of a full hybrid can be up to 30 % in the New European Driving Cycle.

Plug-in hybrid

Full hybrids can alternatively also be designed as plug-in hybrids. These offer the possibility of charging the traction battery externally (e.g., from the power socket) via a corresponding charger. Here it is advisable to use a larger battery in the vehicle so as to be able to cover shorter distances by purely electrical means and to use the hybrid drive for longer journeys only.

The greatest challenge currently facing plug-in hybrids is posed by disadvantages with regard to costs and weight of the larger battery. Furthermore the limited charging power of the domestic power sockets results in long charging times.

10 Components of the hybrid system (mild and full hybrid)

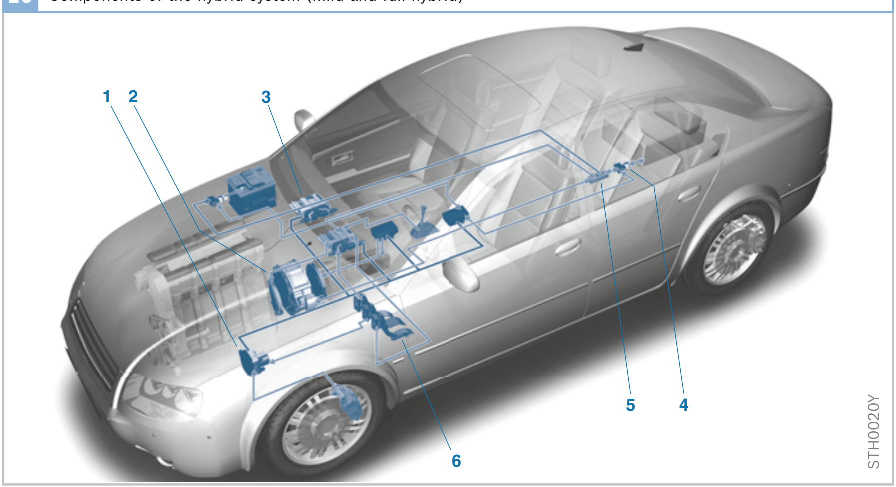


Fig. 10
1 Regenerative braking system
2 Electric motor (IMG)
3 Hybrid and engine ECU
4 High-voltage battery and battery-management system
5 Inverter
6 Pedals and sensors

Drive configurations

Series hybrid drive

The series hybrid drive (S-HEV) is characterized by the series connection of the energy converters (electric motors and internal-combustion engine) (Fig. 11). The series arrangement requires, in addition to the internal-combustion engine, two electric motors, where one operates as a generator and the other as a motor. The internal-combustion engine is not connected to the powered axle.

First the kinetic energy of the internal-combustion engine is converted by a generator (3) into electrical energy. The pulse-controlled inverter (5) converts the power output based on the driver command and supplies the second electric motor (4), which is responsible for driving the wheels. This means that the power output necessary to move the vehicle is transferred exclusively from the electric motor (4) to the drive shaft.

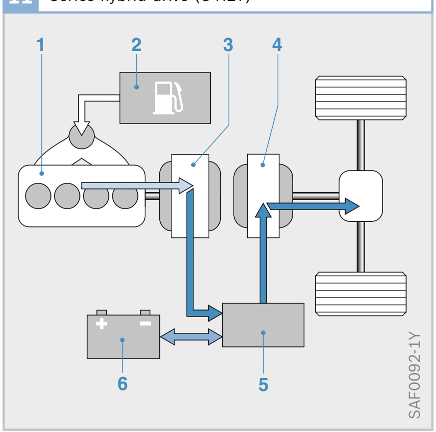
The advantage of this drivetrain arrangement is that the operating point of the internal-combustion engine can be freely selected as long as the requested electrical energy is made available. Depending on the operating strategy, the internal-combustion engine with its power output can follow the current demand or it can operate uniformly at the most efficient operating point and deliver excess energy to the battery. Operation at the most efficient operating point provides for particularly low pollutant emissions – with the exception of NO_X emissions.

It must be borne in mind that both electric motors must be of sufficient size to be able to consume or deliver the power of the internal-combustion engine. The high power capability of the electric motors also has the advantage that even marked vehicle decelerations can be recuperated.

A disadvantage of this arrangement lies in the multiple energy conversion and the associated losses of efficiency. Starting out from the customary mid-range losses of the individual components, there is a total loss of approximately 30 %. Further disadvantages are high costs, component size and high excess weight. The use of this arrangement in passenger cars is therefore very limited.

The series hybrid drive is used in heavy commercial vehicles, such as, for example, diesel-electric drives in locomotives, and in buses which are driven in urban traffic with high levels of stop-and-go operation.

11 Series hybrid drive (S-HEV)



12 Series-parallel hybrid drive (SP-HEV)

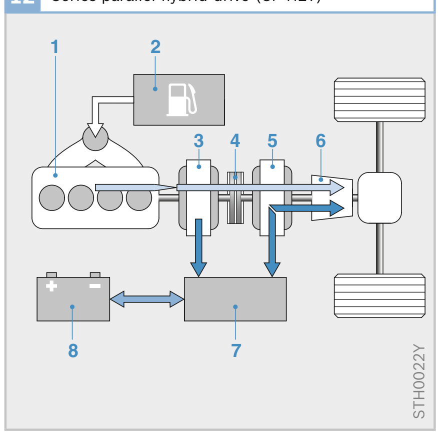


Fig. 11
1 Internal-combustion engine
2 Tank
3 Generator
4 Electric motor
5 Inverter
6 Battery

Fig. 12
1 Internal-combustion engine
2 Tank
3 Generator
4 Clutch
5 Electric motor
6 Transmission
7 Inverter
8 Battery

The series-parallel hybrid (SP-HEV) represents a special form of the series concept (Fig. 12). It differs from the series drivetrain arrangement in that it has a clutch which connects the two electric motors. When the clutch is open, the system behaves like the above-mentioned S-HEV. When the clutch is closed, the internal-combustion engine can deliver its power directly to the powered axle, which corresponds to a parallel drivetrain topology. The disadvantages of the S-HEV with regard to costs, space and excess weight remain, but the electric motors can be of smaller design in that the transmittable power in series operation does not have to cover the vehicle's full drive power aimed for. The series operation range can be limited to smaller power outputs, since at higher speeds and power requirements parallel operation is to be preferred, also because if a better overall drive efficiency.

Parallel hybrid drive

Unlike the series and power-branching concepts, parallel drivetrain topologies require only one electric motor (Fig. 13). This can be operated like both a generator and a motor, and is mechanically connected to the internal-combustion engine's crankshaft. This involves a torque addition, where the torques of the drives (internal-combustion engine and electric motor) can be freely varied while the rotational speeds are in fixed proportion to each other. In addition, when the clutch is closed, a purely mechanical power transmission from the internal-combustion engine to the powered axle is possible, irrespective of the state of the electric motor. The overall efficiency is thus higher than in the other hybrid topologies.

Direct connection of the electric motor to the internal-combustion engine has however a disadvantageous effect on the capacity to freely select the operating point, since the rotational speeds of both assemblies is determined by the transmission ratio and the driving speed. This can be altered by a transmission shift, but only for both assemblies in the same way. When a range transmission is used, the rotational speed of the drive combination of electric motor and internal-combustion engine therefore cannot be continuously freely selected.

A fundamental advantage of the parallel hybrid is the possibility of maintaining the conventional drivetrain in wide ranges. This has a positive effect both on space and vehicle production, and also on the usual driveability and customer acceptance. The development and implementation expenditure of the parallel drivetrain topology for passenger cars is, when compared with series and power-branching concepts, low since lower electrical power outputs are required and the necessary adaptations when converting a conventional drivetrain are fewer.

The parallel hybrid drive is further subdivided according to the number of clutches and the positioning of the electric motor. The most frequently encountered design variations are explained in the following.

Parallel hybrid with one clutch

In the parallel hybrid with only one clutch (P1-HEV; Fig. 13) the electric motor is rigidly connected to the internal-combustion engine's crankshaft such that the electric motor cannot be operated independently of the engine. For this reason, during regenerative braking, the engine must be under coupled motion, i.e., the engine's drag torque is lost as recuperation potential. Purely electric driving is indeed theoretically possible, but the engine must also be under coupled motion here. The resulting losses and noise and vibration problems prohibit this vehicle operation. Merely purely electric gliding is representable from a certain speed. Here the electric motor delivers the propulsion torque for maintaining the speed and the drag power of the engine.

In the simplest version of the P1-HEV a crankshaft starter-generator is used, where the electric motor is only responsible for starting the internal-combustion engine and for supplying the vehicle electrical system. Thanks to an additional electrical accumulator and higher electric-motor power capability, it is possible to design a full mild hybrid which additionally facilitates support of the engine by the electric motor and recovery of the braking energy.

Parallel hybrid with two clutches

To facilitate purely electric driving and regenerative braking to the full extent (without drag losses), an additional clutch is required between the internal-combustion engine and the electric motor (Fig. 14). Based on the number of clutches, this topology is known as P2-HEV. In recuperation phases or for electric driving the engine is disconnected from the drivetrain and switched off when the second clutch is opened. In this way the vehicle's deceleration energy can be recovered without drag losses and stored in the battery. Recuperation is merely limited by the power limits of the electric motor.

Even for electric driving the engine does not have to be under coupled motion such that slow creeping becomes comfortably possible. It is also possible to use the electric motor's full power output for electric driving without power losses to place the engine under coupled motion. However, it must be possible for the engine to be restarted by the electric motor at any time, and thus some of the electric motor's power capability must be reserved for this purpose.

The greatest challenges faced by the P2-HEV concept lie in accommodating the second clutch in the smallest space available and in restarting the engine from electric driving without compromising on comfort.

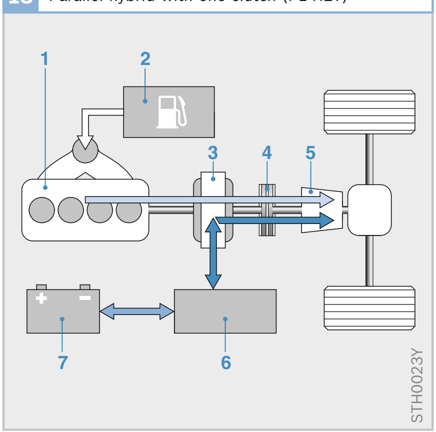
Axle-split parallel hybrid (AS-HEV)

In the P1-HEV and P2-HEV the electric motor and internal-combustion engine are arranged on a common powered axle in front of the transmission. Both drive assemblies thus always operate at the same rotational speed. One way of eliminating this uniformity of speed is to split the drive assemblies between the two vehicle axles. This topology is know as axle-split hybrid (AS-HEV).

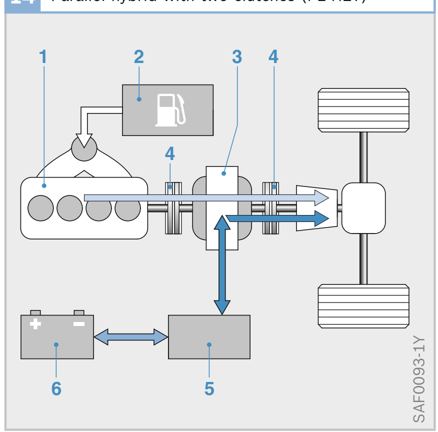
Fig. 13
1 Internal-combustion engine
2 Tank
3 Electric motor (IMG)
4 Clutch
5 Transmission
6 Inverter
7 Battery

Fig. 14
1 Internal-combustion engine
2 Tank
3 Electric motor/generator
4 Clutch
5 Inverter
6 Battery

13 Parallel hybrid with one clutch (P1-HEV)



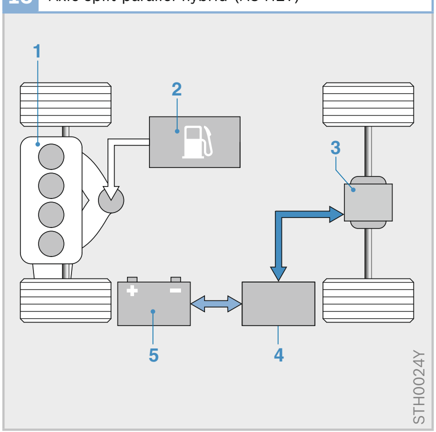
14 Parallel hybrid with two clutches (P2-HEV)



In the AS-HEV the internal-combustion engine and the electric motor are not directly connected to each other mechanically, but instead act on different vehicle axles (Fig. 15). Traction-force addition is thus realized via the road. Regenerative braking and electric driving are effected on front-wheel-drive vehicles via the electric rear axle, while the unaltered conventional drivetrain drives the front axle. When both assemblies are active as an engine/motor, this gives rise to a four-wheel drive. The torques between front and rear axles can be freely varied here between the respective power limits.

It becomes clear that an essential difference exists between the AS-HEV and the other parallel hybrids when the vehicle is stationary. When the axle is stationary, the electric motor in the AS-HEV cannot generate electrical power. Thus the vehicle electrical system must be supplied and air conditioning effected when stationary by other means. This is possible, for example, using a powerful generator on the engine. With the aid of a DC/DC converter the generator can charge the high-voltage battery even when the vehicle is stationary and supply the high-voltage loads/consumers.

15 Axle-split parallel hybrid (AS-HEV)



There are various advantages to connecting the electric motor to its own vehicle axle:

- Package: The conventional drivetrain does not have to be altered.
- The engine and electric motor can be run at different rotational speeds, thus allowing high-speed concept to be used for the electric motor as well.
- High levels of efficiency are achieved in recuperation and electric driving.
- There is no need for the engine to be started by the electric motor (but a separate starter is required).

Disadvantageous aspects of the AS-HEV are:

- A separate starter is needed for the engine.
- A configuration of the torque and speed ranges of the electric motor without transmission to the vehicle's entire driving range is required. (Alternative: an additional simple transmission for the electric motor, e.g., 2-speed.)
- When stationary the high-voltage battery cannot be charged (only with additional measures, e.g., DC/DC converter).
- Supply of the 12V vehicle electrical system when stationary must be ensured (e.g.,. 12V generator).
- Monitoring of driving dynamics (ESP) is required for both axles.

Electric 4WD functionality

In the AS-HEV a four-wheel drive (4WD) is realized by the combination of a conventional drive and an electrically driven axle. An electric final drive can also be combined with any other hybrid configuration in order thereby to realize electric 4WD functionality.

Fig. 15
1 Internal-combustion engine
2 Tank
3 Electric motor
4 Inverter
5 Battery

Parallel hybrid with different transmissions

The parallel hybrid can basically be realized with all transmission types, where a combination with particular transmissions produces special advantages. It is particularly worth highlighting in this respect the dual-clutch transmission (DCT). This consists of two sub-transmissions, which can select different gears independently of each other. This creates the possibility of connecting the electric motor to one of these sub-transmissions and running it in a different gear from the engine (Fig. 16). In this way it is possible to optimize the electric motor's operating point in some ranges independently of the engine's operating point, which opens up an additional efficiency potential.

Power-branching hybrid drive

Principle

The core element of the power-branching hybrid topology is the planetary-gear set (Fig. 18). In this gear set the power output of the internal-combustion engine is split into two paths. This involves a mechanical path, where power can be transmitted directly to the wheels by gear teeth, and an electrical path. As well as the engine and output, an electric motor (Fig. 17, no. 7) acts on the third shaft of the planetary-gear set. The load point of this electric motor serves to transfer the engine's rotational speed and load according to the drive requirements into wheel speed and output torque.

In a planetary-gear set the rotational speeds of two shafts always determine the rotational speed of the third shaft. The torque ratios between the three shafts are similarly determined in this way. The result of this is that a transmission of power in the mechanical path is only possible where the electric motor draws power and converts it into electrical power. Because electrical power is constantly generated in this way, it is neither possible nor for efficiency reasons sensible to store this power in a battery. For this reason, a second electric motor (4), which is mounted directly on the output shaft, is used to close an electrical path and directly convert the arising electrical power back into mechanical power. Thus a drive request, which is made up of a wheel speed and a desired wheel torque, gives rise to a pre-

Fig. 16
1 Internal-combustion engine
2 Tank
3 Transmission
4 Electric motor (SMG)
5 Inverter
6 Battery

16 Parallel hybrid with dual-clutch transmission

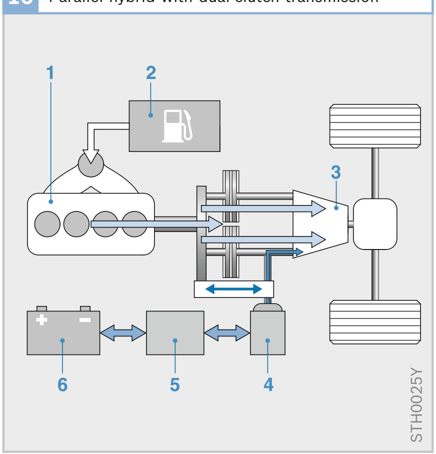
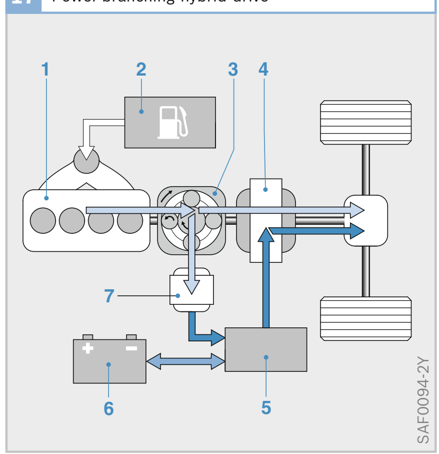


Fig. 17
1 Internal-combustion engine
2 Tank
3 Planetary-gear set
4 Electric motor
5 Inverter
6 Battery
7 Generator

17 Power-branching hybrid drive

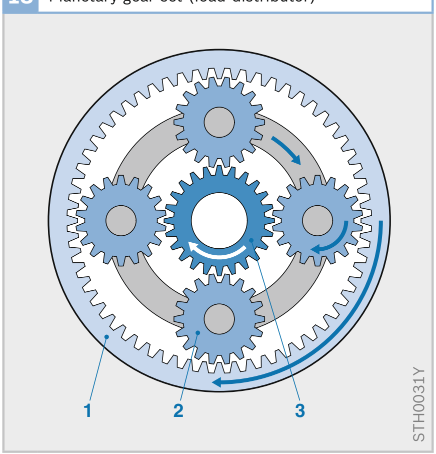


ferred engine speed, which is set using the speed of the first electric motor (7). The desired wheel torque is generated by the engine and transmitted partly via the mechanical path and partly via the electrical path to the wheels.

As in all hybrid vehicles the battery (6) serves to influence specifically the drivetrain operating state. The desired wheel torque can with the aid of the battery result in either a higher or a lower load state. By using the energy stored in the battery, it is possible to avoid very poor engine efficiency ranges, whereby the electric motor (4) alone provides for propulsion of the vehicle and the internal-combustion engine is switched off.

The PS-HEV, as is mass-produced by Toyota in the Prius model, has the arrangement described. The two paths combine the fundamental principles of the series and parallel hybrid drives, which is why the power-branching drive is also referred to as a series-parallel topology.

18 Planetary-gear set (load distributor)



Continuously variable transmission

A significant advantage of the power-branching concept lies in the Continuously Variable Transmission [CVT] behavior and thus with the associated free selection of the internal-combustion engine's operating point. Moreover, the drivetrain can be realized without a conventional transmission and in particular without gearshift and clutch elements, which results in high driving comfort without traction-force interruption and in reduced mechanical components.

On the other hand, decoupling the engine speed from the driving speed can give rise to a more unusual driving feel – especially for European car drivers. In this respect it is comparable with the driveability of vehicles with conventional CVT transmissions.

System limits

The previously discussed limitations of a series hybrid with regard to the dimensioning of the electric motors and the efficiency chain are lessened in the power-branching concept. Because a significant amount of drive energy is transported via the electrical path, powerful electric motors are required – depending on the layout of the drivetrain. The necessary energy-conversion processes have an effect on the overall efficiency of the drive – particularly if the vehicle is to be used over a wide driving-speed range. The upshot of this is that the great savings potential that the vehicle demonstrates in urban traffic is not manifested to this extent in long-distance or interstate driving.

In order to obtain an improvement in this field, vehicles are currently being developed which have two driving modes and are therefore known as two-mode hybrids.

Fig. 18
1 Internal gear: drives the vehicle's powered axle
2 Planetary gears: drive the internal gear
3 Sun gear: drives the generator

Two-mode hybrid

Fig. 19 shows a possible design for a two-mode hybrid. In this example the two-mode hybrid has two electrical CVT drive positions and one purely mechanical transmission. It is possible through the possibilities of combining the input and output shafts of the planetary-gear set to achieve improved efficiency over a wide spread of driving speeds.

The direct mechanical gear step is made possible by the use of two clutches. The excellent overall efficiency and the many degrees of freedom of this concept are offset by the system's high complexity and relatively high costs.

19 Two-mode hybrid

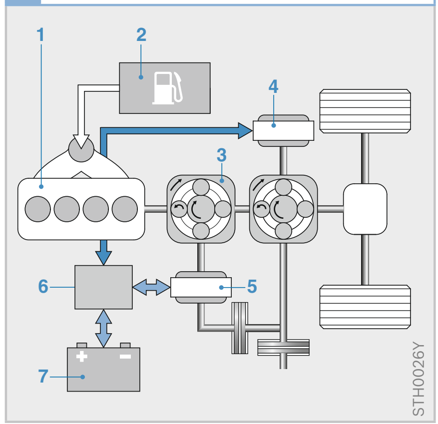


Fig. 19
1 Internal-combustion engine
2 Tank
3 Planetary-gear set
4 Electric motor (SMG)
5 Electric motor (SMG)
6 Inverter
7 Battery