Chapter 15
Electric Power Steering Systems

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15.1 Introduction

A change of hydraulic systems to solely electrically operated steering systems (Electric Power Steering, EPS) has taken place in passenger car steering systems during the last years. The use of these systems was originally limited to small vehicles, because the power density of the electronic parts and the energy available from the on-board wiring was not sufficient to serve bigger vehicles and higher steering powers. New technologies enable the general use of EPS in the superclass now. Various EPS varieties have established themselves in the individual vehicle classes in the market (see Fig. 15.1). These systems will be described in Sect. 15.2 in more detail.

The advantage of electric power-assisted steering in comparison to HPS is that it is activated only when needed. This is called a power-on-demand system, i.e. energy is fed only when the car is steered. A rather low average energy consumption is the result, leading to better mileage and less CO_2 emission. Figure 15.2 shows the petrol and CO_2 reduction for a middle class vehicle with a 2.0 l petrol engine. Note that the savings in fuel consumption and CO_2 emission achieved in NEDC and by end customer driving are of a similar scale.

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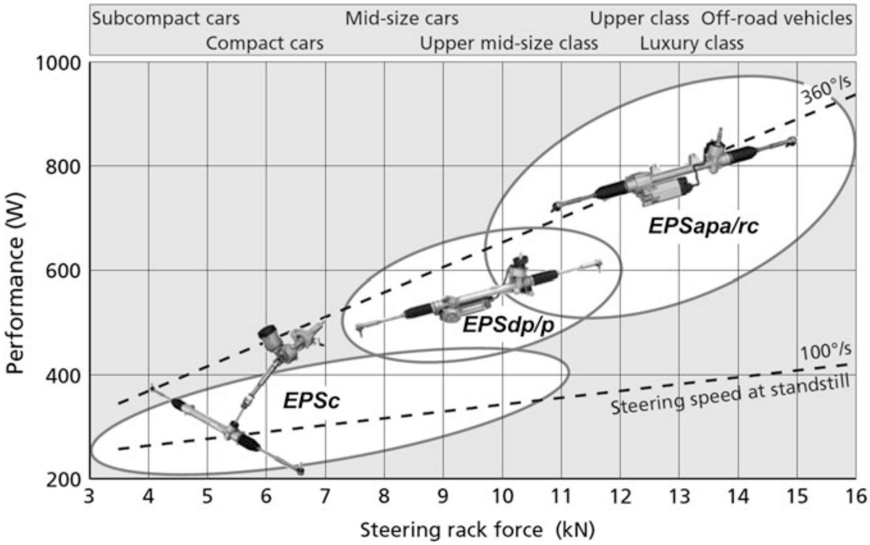


Fig. 15.1 Operational areas of steering systems in different vehicle and power classes

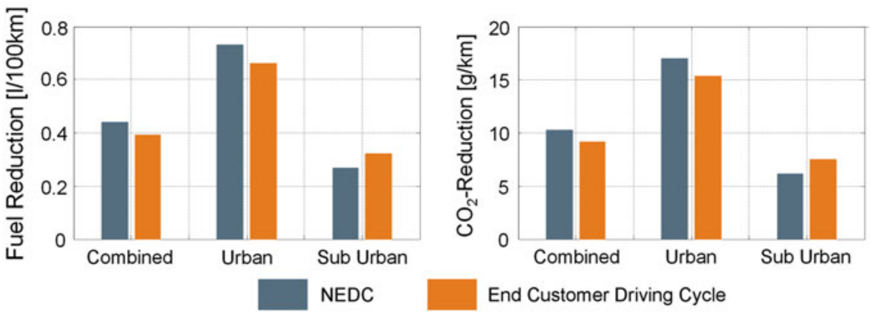


Fig. 15.2 Saving of EPS in comparison to a conventional HPS. The results of the NEDC (New European Driving Cycle) and driving by the end customer are comparable. The measurements were taken at a BMW 320i

High requirements for less consumption and emission make the use of EPS indispensable in all vehicle classes.

Another advantage of EPS is the additional functionality that meets higher requirements for vehicle safety, ride comfort and driver-assist. Examples are, e.g., parking assistants that guide the vehicle automatically into a parking spot by intervention into the steering. Systems like Lane Departure Warning should be mentioned, too. They warn the driver by a superposed torque at the steering wheel when the lane is unintentionally left. Therefore, functions like Lane Departure Warning contribute to improving road safety. More functions will be found in Sect. 15.6.

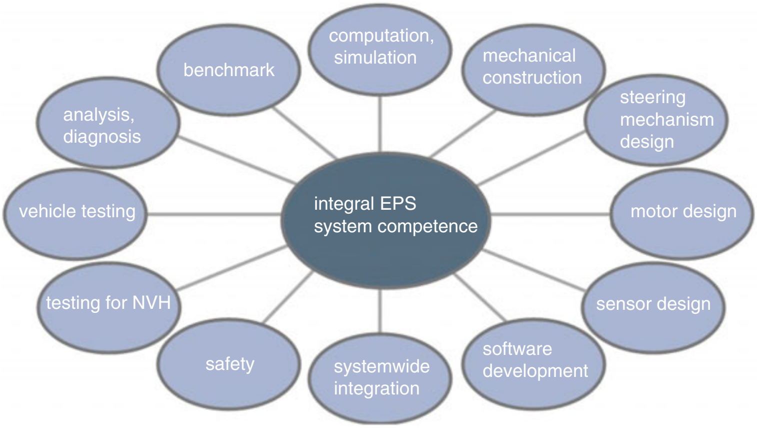


Fig. 15.3 Scopes of EPS development

The development departments of the steering system manufacturers were facing new challenges in making EPS available in series. The development of such a complicated mechatronic system and the applying safety requirements demanded many new processes of development which had not been required for HPS up to now. Safety standards IEC 61508 and ISO 26262 should be specifically mentioned here (see Sect. 15.5).

With EPS, particular attention has to be paid to the acoustic response of the on-board system. Servo motors and gearbox layers of the EPS unit emit noise (vibrations) that had not been present before. They should not be perceived by the driver as annoying, hence, the development of every individual component and their on-board assembly has to consider the acoustic transmission paths. Simulation tools are used early on for doing so.

Figure 15.3 presents the various scopes of EPS development. The interaction of all the mentioned scopes is indispensable to develop an excellent steering system.

15.1.1 Analogies of EPS and HPS

This section will discuss the essential differences of the configuration and function of HPS and EPS units.

Figure 15.4 shows that the HPS has many individual parts (pump, hoses, gear etc.) that are usually assembled on-board, not before. Then the system has to be hydraulically filled and the connections tested for leakage.

The EPS, though, is supplied to the vehicle manufacturer as a complete and tested unit. Only the electric connection to the vehicle has to be established to start running the steering.

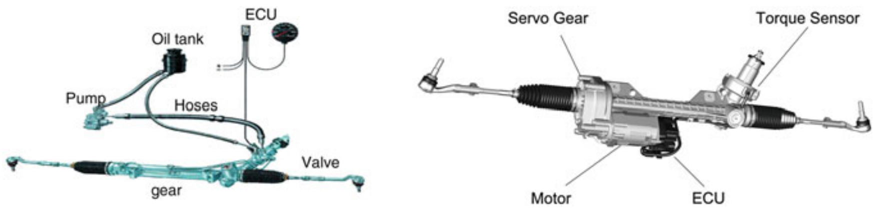


Fig. 15.4 Less complexity in EPS in comparison to HPS. EPS requires no additional parts

The two systems differ in the generation of the power-assist as follows:

- **HPS** generate the power-assist in a hydraulic cylinder which is connected to the rack. A hydraulic pump supplies the cylinder with hydraulic energy. It is actuated by a rotary disk valve (see Sect. 11.3).
- **EPS** generates the power-assist by means of an electric motor whose force is fed into the rack or steering column by a servo gear unit. The electric motor is powered by the on-board wiring. The motor is actuated by power electronics integrated into the electric ECU of the EPS.

With both steering systems, the detection of the driver's intention is crucial for providing the required power-assist. The systems detect it as follows:

- in an **HPS,** a rotary disk valve is connected to a torsion bar. This component is accommodated in the steering driveline between wheel and gear. If the driver steers, the torsion bar is twisted and the rotary disk valve opens one way. Pressure is applied to one side of the hydraulic cylinder, and the power-assist is active. The level of the power-assist is a mechanical function of the valve characteristic (see Sect. 11.10).
- **EPS** uses torque sensors to identify the driver's purpose. As in the hydraulic system, a torsion bar is twisted when a steering movement is initiated (see Sect. 15.3.3). Now the required power-assistance is computed in the EPS-ECU using the measured torsion bar torque. It is a benefit that the power-assist characteristics can be changed by a software almost arbitrarily, no mechanical changes are necessary.

15.2 Designs of EPS Systems

15.2.1 EPSc: Column

The EPSc (Fig. 15.5) is the oldest EPS variety in regular use. It entered mass production as early as 1988, in a Suzuki Cervo (Stoll and Reimpell 1992). It was used at first only in minis and compact cars whose rack forces and steering powers are very low. Today, the EPSc is also used in middle-class vehicles. This became

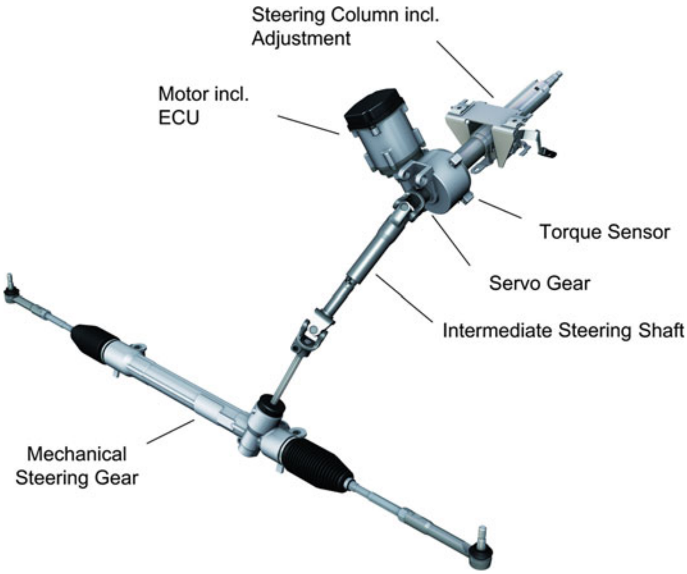


Fig. 15.5 Electric power-assisted steering with power-assist unit in the steering column (EPSc)

feasible due to the use of new materials for power-assisted gears, steering columns and pinions that permit transmitting higher torques.

The power-assist unit of the EPSc is accommodated in the interior of the vehicle. This is favourable with regard to the environmental requirements. In the interior, the power-assist unit does not need to be watertight, for example. A lower temperature range of −40 to 85 °C applies as well, while the engine compartment requires −40 to 125 °C. Especially the high temperatures are a challenge for the electronic parts of the power-assist unit. A shortcoming of the interior is that the power-assist unit is placed very close to the driver and can be heard more easily.

The power-assisted gear of an EPSc is not a self-locking worm gear. The screw is mounted at the engine shaft of the electric motor, and the accompanying worm wheel is connected to the steering column. Other gearbox varieties are known, e.g., a belt gearbox or a direct drive. However, these do not appear in significant numbers on the market so far.

The forces of the power-assist unit are transferred along steering column, intermediate steering shaft and pinion, setting limiting factors for the highest accessible steering forces. A longitudinal adjustment of steering columns, for example, requires sliding elements in the steering shaft (see Chap. 10). For higher torques, they have to be laid out more sturdy and, therefore, more expensive. The easiest configuration of such sliding elements is a simple plastic slider. Higher transmission torque make expensive metal bearings obligatory.

A particular problem is the crash response of the EPSc, because the power-assist unit is in the upper steering column, near the driver.

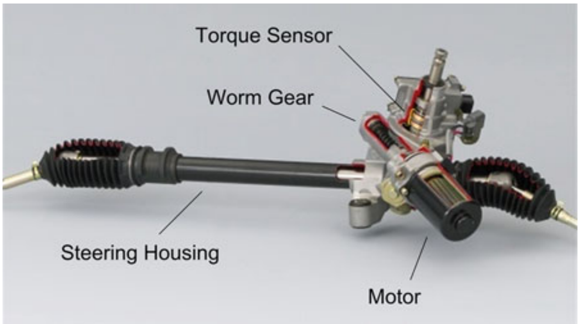


Fig. 15.6 EPSp by NSK company (*Source* Internet NSK Europe)

15.2.2 EPSp: Pinion

The power-assist unit of the EPSp is placed right at the steering pinion (Fig. 15.6).

The power-assist torque generated by the electric motor is transferred by a worm gear to the pinion and the rack. The system can achieve slightly higher steering powers than an EPSc, because the forces do not need to be transferred along steering column and intermediate steering shaft. Since the power-assist unit (engine and ECU) is near the EPSp in the engine compartment, it has to meet higher requirements for temperature, density and vibration than, e.g., an EPSc. These higher requirements also apply for the EPSdp, EPSapa and EPSrc systems (Sects. 15.2.3–15.2.5).

The package possibilities of this system are limited, because the power-assist unit can be turned only around the axis of the steering pinion. Another problem is that the power-assist unit is near the driver's legs. Therefore, it needs to be ensured that the power-assist unit cannot penetrate into the space of the legs during a crash.

15.2.3 EPSdp: Dual Pinion

The power-assist unit of the EPS Dual Pinion is mounted at a second pinion (Fig. 15.7). This steering is very well suited for medium or upper middle class vehicles. The first standard use of such a steering occurred on the VW GOLF Platform in 2002.

The installation of the power-assist unit at the second pinion permits separating sensor unit and drive unit. Since the main drive pinion gear ratio is independent from the steering ratio, a power-optimising layout is possible. The additional system power is 10–15 % higher than that of an EPSc or EPSp.

The power-assist unit can be positioned by an accordingly tuned worm gear, individually turning 360° radial to the rack and main drive pinion axis (Fig. 15.8). This quality allows adapting the steering to very difficult installation space. A very good crash safety can be achieved by careful exploitation of the installation space.

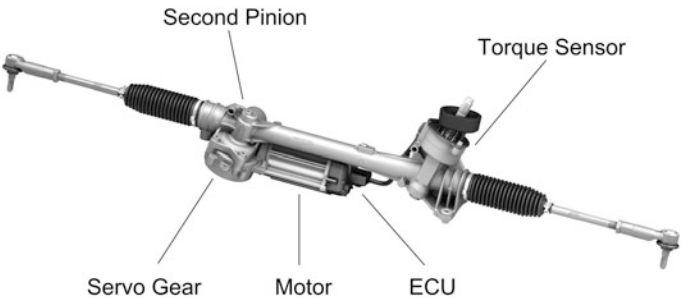


Fig. 15.7 EPSdp by ZF Steuersysteme

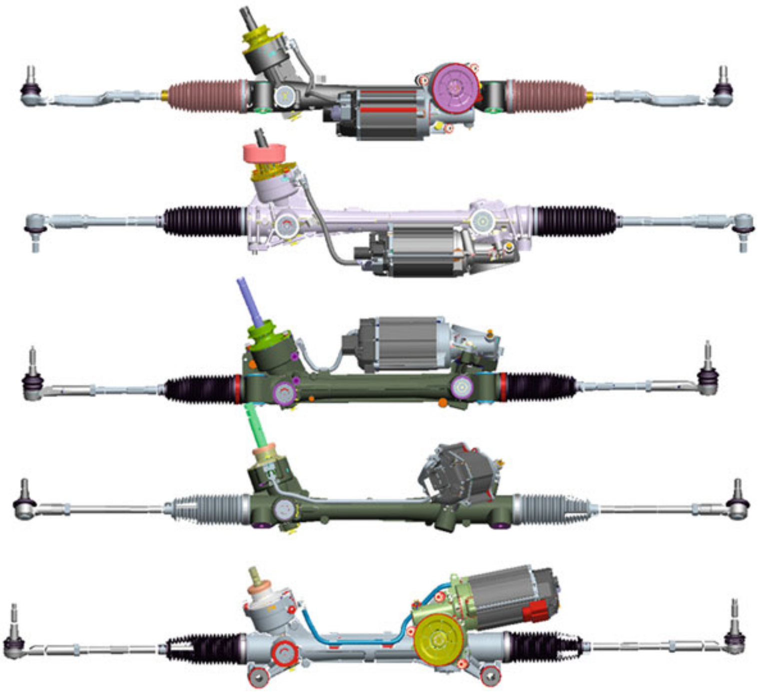


Fig. 15.8 Various examples of the EPSdp, the power-assist unit can be placed very flexibly. Therefore the steering can be best adapted to the available installation space

15.2.4 EPSapa: Axle Parallel

The EPSapa (Fig. 15.9) with an axle-parallel drive is marked by low system friction and high efficiency. This steering is applied in dynamic sports cars, upper middle class cars, even in high load vehicles, for example, in cross-country

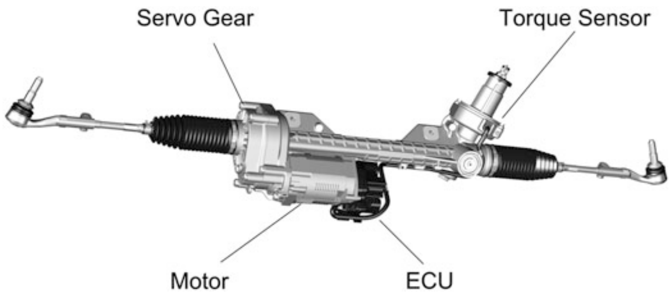


Fig. 15.9 EPSapa steering by ZF Steuersysteme

vehicles and transporters. The first standard model to use the EPSapa was the BMW 3 in 2007.

In this steering model, the power-assistance is generated by the electric motor and transferred to the rack by a combination of ball screw and timing belt gearbox. The ball screw converts the rotation of the engine into a translation of the rack.

This gearbox model requires that the engine is arranged in parallel with the rack. The power-assist unit can then be turned arbitrarily around the rack, so that the installation space on-board can be perfectly exploited.

15.2.5 EPSrc: Rack Concentric

The rack-concentric steering system uses a ball screw as a gear to convert the rotation of the engine into a translation of the rack. In contrast to the EPSapa, the ball screw is here directly driven by an electric motor. Therefore this steering system has one gearbox layer less than the EPSapa (cf. Sect. 15.2.4).

The concentric configuration requires a special servo motor with hollow shaft rotor, because the rack of the steering passes through the motor.

As mentioned above, the motor engages directly into the ball screw, and there is one gear ratio layer less. Since the multiplication is lower than that of the EPSapa, an electric motor that can produce higher torques is needed. If the power fed by the on-board wiring should stay the same, this can be achieved only by a larger motor. This means that in comparison to an EPSapa, the electric motor of an EPSrc has to produce a twice as high torque at the same output power level.

Due to the concentric arrangement, the EPSrc is very compact, yet this configuration has a disadvantage. All the previously discussed steering systems allow arranging the power- assist unit to some extent around the steering, enabling easier packaging. The motor of the EPSrc and its ball screw can be shifted only slightly axially along the rack (Fig. 15.10).

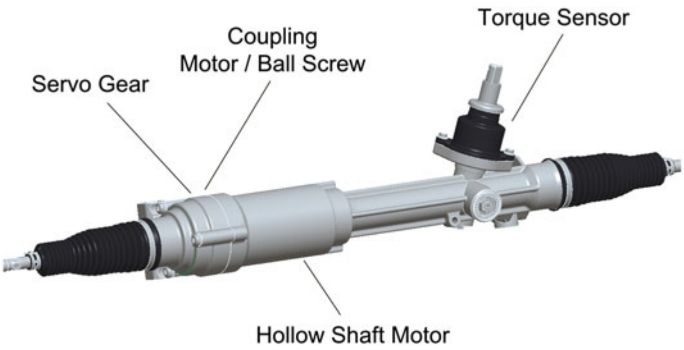


Fig. 15.10 EPSrc, the hollow shaft motor is arranged concentrically around the rack

15.3 Subassemblies of the EPS

15.3.1 Power-Assisted Gear

The power-assisted gear establishes the connection between drive unit, wheels and driver. Hence, it is active right in the power flow of the EPS. Because of vibration, friction or inertia effects, the gearbox parts have to be considered in an assessment of the static and dynamic qualities of the overall system. Combinations of screws, ball thread, timing belt and rack-and-pinion gears (cf. Chap. 11) are used for EPS applications, according to the system version. As the gearbox configurations are always form closed, every input movement is allocated a unique output movement.

Function The main function of the servo gear unit is the transmission of the power-assist torque to the rack when the electric motor has provided it on demand. The rotation of the power- assist drive is converted into a translation of the rack. The different characteristics of the necessary output power and the available drive power generate a necessity to adapt the torque or rev level by the power-assisted gear for power transmission. The drive torques have to be amplified by a gear ratio towards the slow end, to generate the necessary rack forces while meeting the requirements of the power-assist drive with regard to costs, space or power demand. Accordingly big transmission ratios can be achieved by a combination of two gearbox layers.

An essential secondary function of the servo gear unit is a change of the axis of rotation. This concerns the position of the drive and driven axles in space, which is essential for size and shape of the space the EPS is installed in. A general division of gearboxes with parallel, intersecting or oblique axes of rotation is possible.

Qualities of power transmission In view of the power transmission, the EPS gearbox layers are mainly determined by their transmission ratio and their efficiency. The transmission ratio i is the ratio of input and output rev, n_{in} and n_{out}.

$$i = \frac{n_{in}}{n_{out}} \tag{15.1}$$

The loss of power in a gearbox layer, *PV,* is represented by its efficiency η. It represents the ratio of usable power P_{use} and supplied power P_{sup}.

$$\eta = \frac{P_{use}}{P_{sup}} = 1 - \frac{P_V}{P_{sup}} \tag{15.2}$$

Technical requirements In the following, the most important technical requirements of the power-assisted gear for EPS are listed:

- high static and dynamic strength
- high safety against self-inhibition
- high loading capacity for operation and ambient conditions
- no servicing to maintain the effectiveness for the whole service life
- high efficiency to keep specified limit values for the input and output power of EPS systems
- low free travel to avoid an unstable steering torque curve during alternate steering or by dynamic rack force changes
- high stiffness and low moments of inertia as a basis for the best steering feel
- low weight, taking into account strength requirements and target costs
- low emission of structure-borne and airborne sound to avoid interfering noise and vibrations.

15.3.1.1 Worm Gear

Worm gears belong to the screw gears. The axes of screw and worm wheel do not intersect. The shape of the screw corresponds to a multi-stroke threaded bolt whose rotation drives the worm wheel, due to its screw-like shape, see Fig. 15.11. A big slip component is typical for the transmission of motion in comparison to spur gears, see also Niemann and Winter (2004). Noiseless and steady transmission of motion is possible. Nevertheless, the slip towards the contact line generates a higher loss of power. Therefore, the efficiency is lower in comparison to spur cut gears.

Worm gears are used in the EPSdp to transmit power between electric motor and main drive pinion. The steering column variety EPSc and the pinion variety EPSp apply a worm gear for power transmission as well. It is used to transfer the drive torques of the electric motor to the steering column. Worm gears allow for great gear ratios in a layer. For EPS applications, they are in the range of 15–30. The transmission ratio corresponds to the ratio of the number of worm wheel cogs to the number of thread gears at the screw.

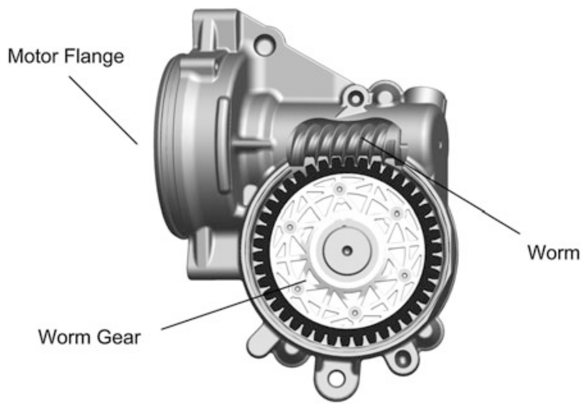


Fig. 15.11 Worm gear of an EPSdp. The variable arrangement of the screw in the perimeter of the worm wheel offers an additional degree of freedom to exploit the installation space in the best manner

A worm wheel with plastic gear rim is the most common tool to keep dovetailing noise and the wear of the cog flanks low for the whole service life. It cogs with a hardened steel screw. The gear rim, strongly loaded as a result of the high forces, is made out of high-performance plastics. To maintain a lasting zero backlash in the cog engagement, the screw can be put on to the worm wheel using a helical spring with a defined pretension.

15.3.1.2 Ball Screw Drive

Ball screws transform the rotation of the electric motor in an EPSapa or an EPSrc system into a translation of the rack and vice versa. The application of ball screws in steering technology traces back to the ball-with-nut steering gear. Essential parts of the ball screw (KGT) are, acc. to DIN 69051-1 (1989), the ball thread spindle, the balls as rolling elements and the ball thread nut including the runback system and the seal elements, see Fig. 15.12.

Ball screws are favourable for converting rotation and translation because of the high mechanical loading capacity, the big attainable transmission ratios and the highly efficient energy transmission with little loss. Efficiencies of more than 90 % can be achieved.

The ball thread spindle of modern EPS systems is a part of the rack. The ball thread nut also called steering nut, is supported by means of a ball bearing. This bearing accepts the radial and axial forces applying during the operation. The axes of steering nut and rack are overlaid. The drive comes either directly (EPSrc) or via a belt gearbox (EPSapa) from the electric motor. The drive torque is supported by the rack near the pinion dovetailing. To reduce the resulting load of the steering pinion, the rack can be Y-shaped.

The principle of ball screws corresponds to that of a wedge which converts a translation through an inclined plane into a lateral movement and vice versa, see also Steinhilper and Sauer (2006). The sloped plane is a screwing line around the rack and inside of the steering nut. Balls are used as rolling elements to reduce the

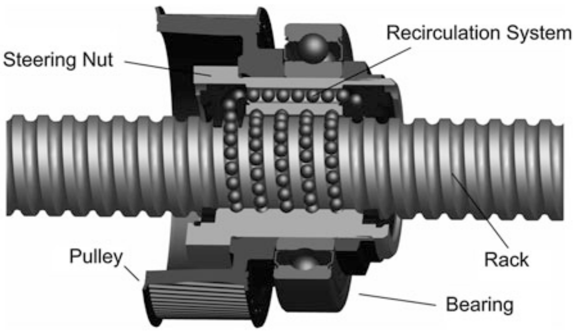


Fig. 15.12 Parts of the ball screw (EPSapa). This allows an efficiency-optimised power transmission also with the highest steering forces

friction and to transmit loads between the tracks of ball thread nut and ball thread spindle.

The slope h represents the distance by which the rack is shifted during one axial rotation of the ball thread nut. The slope of ball screws in modern electromechanical steering applications has a typical value of 5–10 mm. The slope helps to directly compute the transmission ratio of the ball screw:

$$i_{KGT} = \frac{2\pi}{h} \tag{15.3}$$

Layout and safety of ball screws are very demanding. Beside classical bench tests and strength computed by means of FEM analyses, NVH examinations are necessary as well, see Fig. 15.13.

15.3.1.3 Toothed Belt Drive

Toothed belt drives of the EPSapa transfer the assist power of the electric motor to the ball thread nut. The engine shaft (axle drive shaft) and the ball thread nut (driven shaft) are axle-parallel. The toothed belt drives for EPS applications consist of a

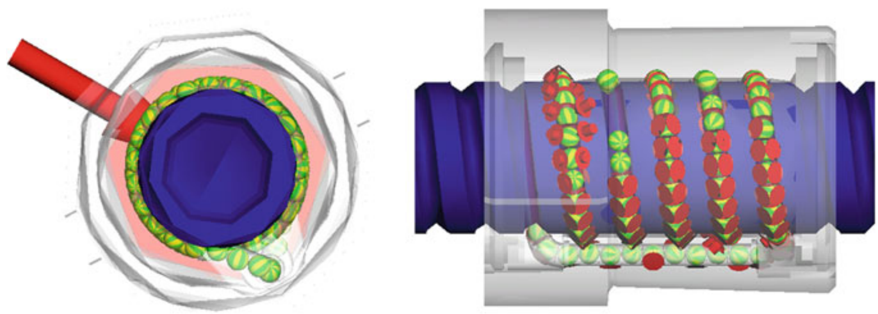


Fig. 15.13 Multi-body simulation of ball screws for the inquiry of internal motion sequences. The simulation results serve as an early functional safety check

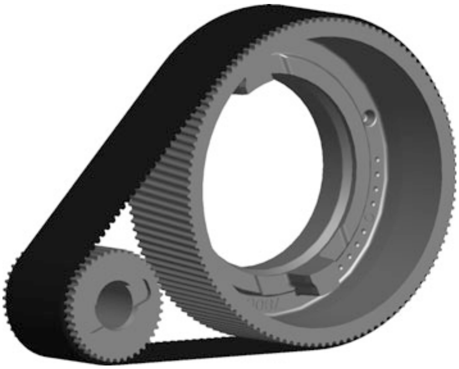


Fig. 15.14 Timing belt gearbox of an EPSapa. The use of high-capacity treads and diagonal dovetailing allow for a better noise response

belt and two serrated pulleys, Fig. 15.14. The transmission ratio corresponds to the ratio of the diameters of the driven pulley d_2 and driving pulley d_1:

$$i_{belt} = \frac{d_2}{d_1} \tag{15.4}$$

Current transmission ratios are in the range of 2–4.

Toothed belt drives belong to the shape-paired traction drives. The positive locking of the dovetailing between the belt and the serrated pulleys prevents slipping during the power transmission. At the same time, the necessary pretensions can be significantly reduced in comparison to other traction drives. Timing belts are also called synchronous belts, because of their synchronisation.

The free belt segments between the serrated pulleys are called empty span and tight span. The tension of the belt in the tight span is higher than its pretension when load is transmitted between the pulleys. At the same time, the belt tension in the empty span drops by the same amount. The belt always has to be loaded with a certain least tension, so that the belt is bedded trouble-free in the dovetailing of the serrated pulley. A correct belt pretension is vital for service life, noise response and good transmission of the belt. More noise can develop from amplified vibrations of the belt when its pretension is too low, see also Nagel (2008).

A basic sizing of toothed belt drives is stipulated by the standard ISO 5295 (1987). It can be used to approximately identify the required belt width for the safe transmission of the torque, as a function of the used belt tread, the power and the geometrical ratios of the gearbox. The detailed layouts that include the loading time as well, for example, have to be determined in close cooperation between belt and steering system manufacturers. The use of high-performance treads enables the highest power density, an energy-efficient transmission of motion and a better noise response. This can be further improved by diagonal dovetailing. The increased risk that, because of this, the timing belt might leave the serrated pulley has to be counteracted by means of flanged wheels.

High differences in temperature near the internal combustion engine and the resulting load of the timing belt may put tight constraints to the range of usable belt materials. The temperature range of −40° to +125 °C is a reason to use rubber elastomers as basis material of the timing belt. Fibreglass is used for the tensile member. It offers not only the best tensile strength but also low thermal expansion. Sinter materials are preferred for the serrated pulleys of modern standard EPS applications.

15.3.2 Electric Motor

15.3.2.1 Overview/Comparison/Working Area

The power assist is supplied by the electric motor of the electromechanical steering system. It converts electric energy, fed in by the on-board wiring, into mechanical energy on demand. Sufficient power assist in all driving situations has to be provided through a good choice of the motor type and size. The electric motor is crucial for the steering feel and the driver's perception because of the direct mechanical connection to the steering wheel.

Classification (Lindner et al. 1999; Fischer 2006; Stölting and Kallenbach 2006) Electric motors can be classified by the type of motion as rotational engines and translational engines (or linear motors). Only rotational engines are used for EPS applications, because of easy configuration, high power density and uncomplicated control. They consist of a stationary stator and a swivelling rotor, concentric to the stator. Depending on how stator and rotor are arranged, they are further classified as internal and external rotor motors. The type of power feed distinguishes DC, AC, 3-phase and pulse motors. The three-phase AC motors, or polyphase motors, can be differentiated by the rev response of the rotor to the magnetic field of the stator as asynchronous and synchronous motors.

Motor-power classes Brushed DC motors with permanent magnets were originally used in the first EPS systems. They can be operated by a very easy control at the DC wiring of automobiles. The rising power demand of middle and large vehicle classes and the rapid development of microprocessor and inverter technology made brushless AC motors feasible, driven by a rectifier and field-oriented actuation.

Operating range The choice of a motor has to include the notion that a steering system is not operated at a steady nominal working point, for example, a steady rev or torque (cf. Sect. 15.4). A typical parking procedure with high steering forces has to be fed with the highest assistance force, up to a defined steering speed. The steering forces are much lower when driving, but then, higher steering speeds are required, e.g., for evasive manoeuvres.

Simply said, the operating range of an electric motor for EPS can be divided into a speed range with constant torque and another speed range with almost

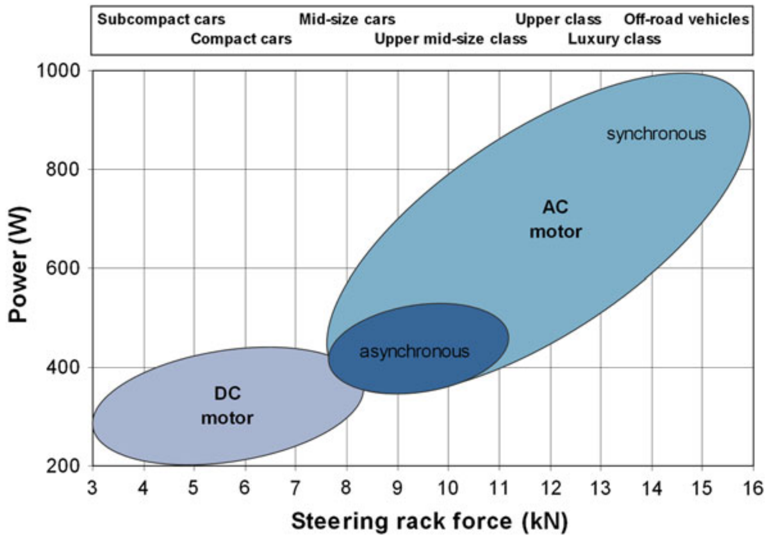


Fig. 15.15 Sketch of the power demand of electromechanical steering systems to the electric motor and typical characteristic curves of current EPS motors

constant output power (Fig. 15.15). Taking a limited supply voltage and the highest permissible power consumption of the electric motor into account, some typical characteristic curves of motors of currently used EPS motors are shown in Fig. 15.15.

A comparison of the power demand with typical characteristic curves of motors illustrates the advantage of the 3-phase motors for the use in EPS, due to their wider speed range, achieved by field weakening (Stölting and Kallenbach 2006). The field weakening enables operating the motor above the nominal speed without having to amplify the input voltage or input power of the drive. The lesser available motor torque in the field weakening mode does not limit applications in electric power-assisted steering, because the required steering forces are dropping much at high steering speed.

Externally excited DC motors, permitting field weakening as well, are not used for EPS systems, because of their more complicated configuration and the still limited output power.

Technical requirements The main technical requirements for an electric motor for EPS systems are listed in the following:

- highest output power between 150 and 1,000 W as a function of the vehicle class (Fig. 15.16) to cover the peak capacity during parking and evasive manoeuvres.

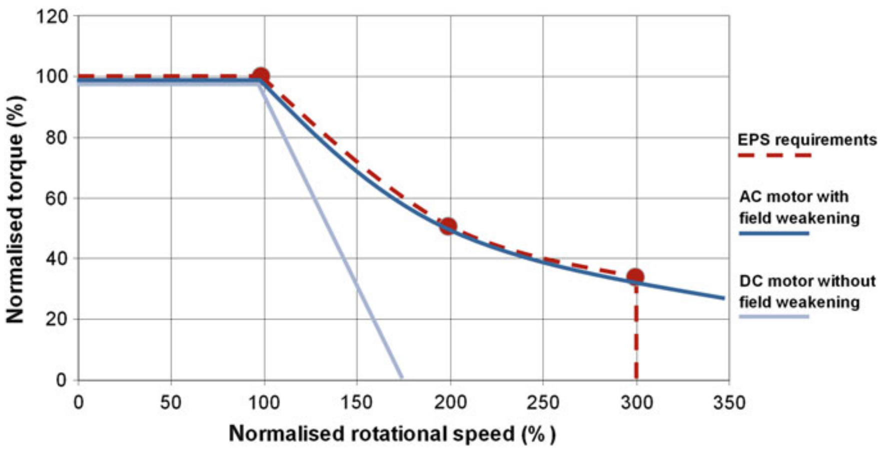


Fig. 15.16 Operation range of different electric motors for electromechanical steering systems

- The highest output power has to be made available only briefly, because on average, steering forces are low and steering events are rare, so the longterm required output power is fairly low.
- wide operating range (M/n characteristic curve) with steady output power to supply high steering forces for parking and high steering speeds for evasive manoeuvres.
- very high power density and good efficiency, because the available space is small and the power from the on-board wiring is low.
- very high torques in the operation mode and low cogging torque to achieve a constant uniform steering force power-assist.
- very high engine dynamics serving a stable steering control, i.e. low electric motor response time and inertia.
- when using a PME engine: Special winding connections to prevent inadmissibly high brake torques from short circuits in the motor winding.
- quiet motor for a good acoustic response of the steering.
- solid configuration for the whole service life, because the steering is laid out as a maintenance-free system for the service life and no exchange of the motor is intended.
- low EMC disturbances to maintain reliable service of all electric vehicle systems, most relevant for mechanically commuting motors, because of brush sparking.
- high ambient temperatures, between +85 and +125 ˚C, according to installation place.
- high mechanical strength with regard to accelerations and vibrations.

15.3.2.2 DC Motor with Mechanical Commutator (see also Stölting and Kallenbach 2006)

The stator of mechanically commuting motors (DC motor) serves to generate a stationary magnetic field. This magnetic field can be generated either by permanent magnets or by a field winding (externally excited motor, inverse-speed motor, shunt-wound motor). The rotor consists of a core with grooves that accept the rotor winding. The power is supplied by a commutator/brush system which impresses the current as a function of the relative position of rotor and stator in such a way that a continuous rotation is the result. Therefore a mechanically commuting engine can be operated with DC power.

PME engines are essential for EPS systems, as discussed in Sect. 15.3.2.1. They can be actuated by very simply power electronics with two lines only, because of the absent field winding. The lack of a field weakness range is a disadvantage of this motor, because the PME DC motor to reach high revs is rather big. Since the motor torque is directly proportional to the impressed motor current, the torque control that is typical for EPS systems can be implemented with little control effort.

The rather bad cooling of the rotor windings and the high inertia of the rotor limit its use to low-power steering systems. The accessible power density of DC motors is lower than that of AC motors because of the loss and space demanded by the commutator. In addition, sufficiently low wear of the mechanical commutator/brush system and electromagnetic tolerance with the engine needs to be ensured (Fig. 15.17).

The motor housing is usually deep-drawn out of a simply sheet steel and contains a support for the engine shaft. Cheap hard ferrite is used for permanent magnets. They do not achieve the power density of rare-earth magnets like samarium-cobalt (SmCo) or neodymium-iron- boron (NdFeB). The magnets are glued or clamped into the motor housing and mechanically protected by an

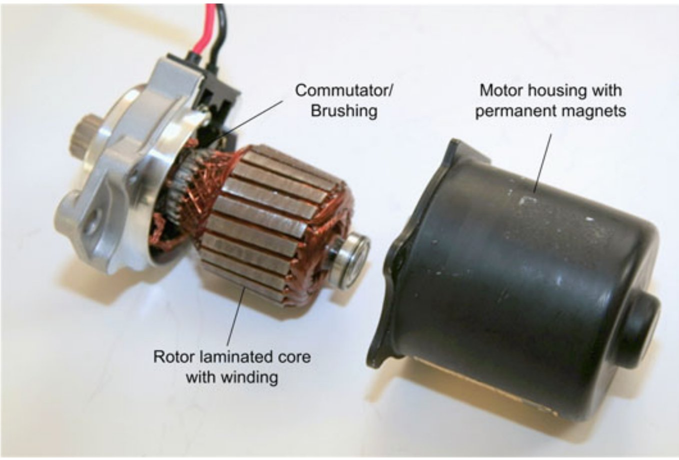


Fig. 15.17 Typical EPS DC motor with mechanical commutator

additional sheet-metal jacket. Motor housing and magnets represent the stator of the DC motor. The rotor consists of stacked and electrically isolated electric metal sheets to reduce iron loss from eddy currents and demagnetisation. To achieve low torque ripple and small cogging torques, the winding is distributed to as many grooves of a set rotor core as possible and connected to accordingly many commutator bars. The commutator is completed to a commutator/brush system with spring- supported carbon brush conductors. A cover bearing the brush system axially closes the motor housing. Typical DC motors for EPS systems are 4-pole engines with two or four carbon brush conductors and 22 commutator bars.

15.3.2.3 Asynchronous Motor

The asynchronous motor (ASM) is a three phase AC motor, distinguished by an extremely robust construction, high operational safety and high strain ability. This is achieved by the fact that the rotor is a squirrel-cage rotor, containing no additional parts like wire winding or magnets. A squirrel-cage rotor consists of conducting rods arranged in parallel with the shaft in a metal plate packet. They are short-circuited at the front by rings (squirrel-cage). The stator is usually equipped with a three-phase winding generating a rotating magnetic field. The rotating field induces currents in the squirrel-cage of the rotor which, obeying Lenz's law, counteract the source and therefore generate a torque on the rotor shaft (Fig. 15.18).

Due to the cooling of the stator winding and the ECU (piggyback ECU, cf. Sect. 15.3.4.1), a solid casting housing is used for the housing of the asynchronous motor shown above. The core with the stator winding is arranged inside. The three-phase winding is made of solid copper wire for a very robust motor construction, distributed across the perimeter of the motor. The rotor also contains a core, to reduce the eddy current loss. Aluminium moulded in its grooves make for the squirrel-cage. The air gap between stator and rotor has to be kept very small in this design, to achieve a low demand for a magnetisation current, hence, high

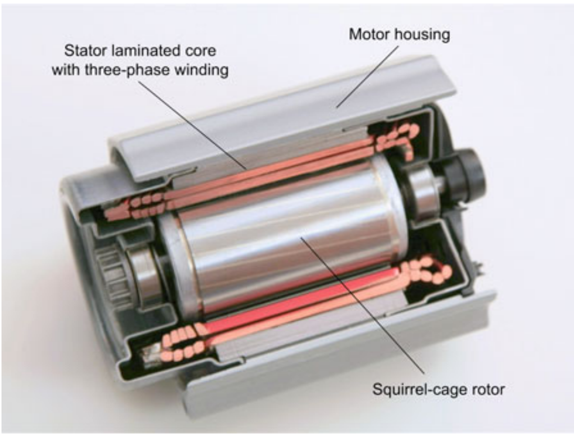


Fig. 15.18 Configuration of a robust asynchronous motor

efficiency. This often leads to narrow manufacturing and assembly tolerance margins.

Asynchronous motors with squirrel-cage rotors cannot operate as generators, because of the missing magnetic excitement from a stator's magnetic field. Hence, no additional safety measures to shut down the motor power have to be included into EPS systems. The safety concept is much easier. Lacking a magnet, the motor is also marked by low torque fluctuations and is very quiet. Compared to mechanically commuting DC motors, asynchronous motors with higher current and power have a higher power density. In contrast to DC motors with permanent magnets, asynchronous motors can be operated with field weakening.

15.3.2.4 Synchronous Motor

Like asynchronous motors, synchronous motors belong to the group of three-phase motors, operated with sinoidally powered three-phase windings. The rotor consists of stratified electric metal sheet and serves to generate a magnetic field which is independent from the stator power. EPS motors apply permanent magnets for that (PME synchronous motor/PMSM). This permanent, non-inductive magnetic rotor causes the rotor to turn synchronously to the applying stator magnetic field, hence, the name synchronous motor.

Publications use the terms, brushless DC motor (BLDC) or electronically commutated motor (EC). This kind of motor is driven not by sinoidal but by block-shaped currents. Including integrated power electronics and power sensors, it is used, for example, as a self- controlled engine for actuator drives in the automotive industry. It can be operated with DC power. Since an ideal, rectangularly impressed current does not exist in reality and the distribution of the magnetic flux density would have to be very high, these motors have a rather high torque ripple. Hence, only PMSMs with sinoidally impressed current are used, for current electric power-assisted steering (Fig. 15.19).

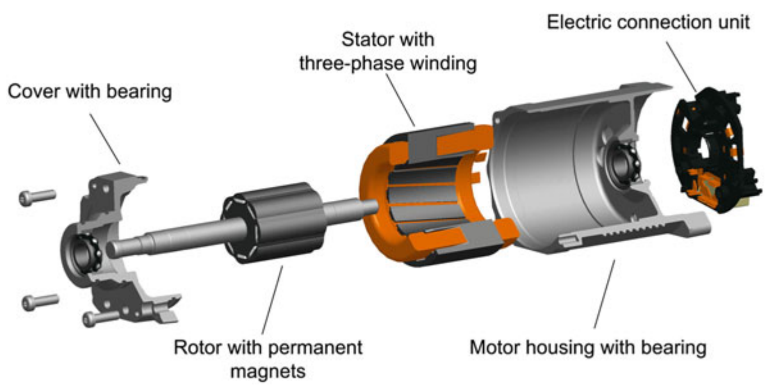


Fig. 15.19 Configuration of a synchronous PME motor (exploded view, cut in parts)

The stator of a synchronous motor is basically identical to that of the asynchronous motor. Instead of a distributed winding, a concentrated single-tooth winding is preferred for EPS systems. The spatial separation of different windings and corresponding connections help to avoid short circuits, reducing brake torques that might occur in the generator mode. Additional measures may be taken to disconnect the motor currents in a fault case, such as phase or star point separation, according to motor-power class and vehicle response.

Power drains and torque disturbances due to circular currents in the motor windings can be avoided by connecting synchronous motors in star-connections. The windings are distributed into different stator grooves. The stator grooves and the number of rotor poles define the motor topology. 6- , 8- and 10-pole engines with 9 to 12 stator grooves are often used for electric power-assisted steering.

Highly energetic rare-earth magnets of neodymium-iron-boron (NeFeB) are used as magnetic materials for the rotor. These are inserted in a very sturdy configuration as block magnets, either in individual bags of the core (embedded magnets) or on the surface of the rotor core as ring or segment magnets. Motors with surface magnets have an additional sleeve over the rotor to prevent the brittle magnets from splitting off (Fig. 15.20).

Because the motor torque of a synchronous motor depends on the strength of the stator and the rotor magnetic field and their enclosed angle, the machine is very well suited for field- oriented motor actuation. This allows driving the machine very precisely and dynamically. Modern synchronous motors can be operated in field weakening mode if the magnets are sufficiently powerful, hence, above the nominal speed. They supply the steady output power which is typical for steering applications across a very wide speed range (Sect. 15.3.2.1; Fig. 15.21).

Compared to the asynchronous motor, the PMSM is marked by a higher power density and better efficiency. A main source of losses are the ohmic stator losses which can be drained by the stator metal-sheet package and the motor housing. The synchronous motor has a lower rotor moment of inertia than DC and asynchronous motors. A chamfer of the rotor or stator helps to reduce the cogging torque to a level which is fitting for EPS systems.

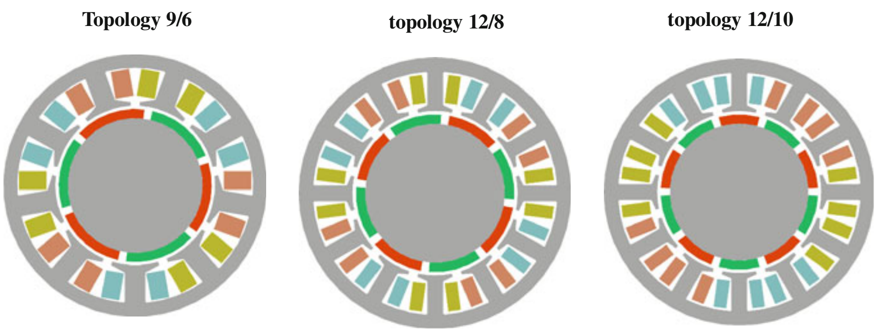


Fig. 15.20 Motor topologies of PMSMs

Rotor with embedded magnets **rotor with surface magnets**

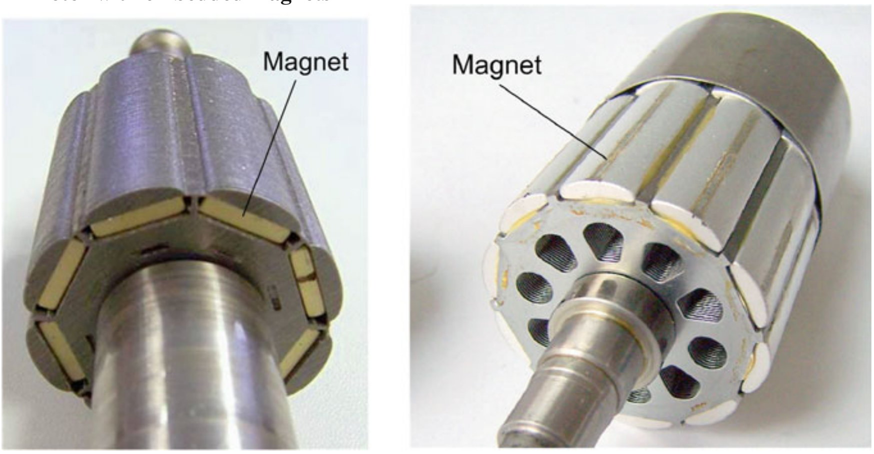


Fig. 15.21 Rotor configurations of PMSMs

15.3.2.5 Position and Rev Sensors

If a DC motor with a mechanical commutator is used, no position or rev sensors are required for the actuation, because the individual motor windings are fed by the commutator.

Field-oriented actuation of polyphase motors is common, as it permits a very dynamic motor operation in a wide speed range. It needs additional sensors for the proper impression of the stator's currents and its magnetic field. The rotor speed is used for the field-oriented actuation of the synchronous motor and the rotor angle for that of the asynchronous motor.

Technical requirements

- without servicing or wear, therefore, touch-free measuring principle
- high resolution and accuracy
- high temperature range of −40 to +85 ˚C (interior) or −40 to +125 ˚C (engine compartment)
- high serviceable life and service life
- high reliability/availability, hence, redundant electronics for diagnostics capacity are common
- small size, easy configuration and assembly
- sturdy measuring principle with regard to fouling, vibrations, EM compatibility

Two different sensor designs for the position and speed sensors of polyphase motors have prevailed.

Resolver A resolver consists of a field winding and usually two receiver windings, enabling measuring the angle of a swivelling shaft. Exciter and receiver coil are magnetically coupled by a swivelling structure. The measuring principle is based

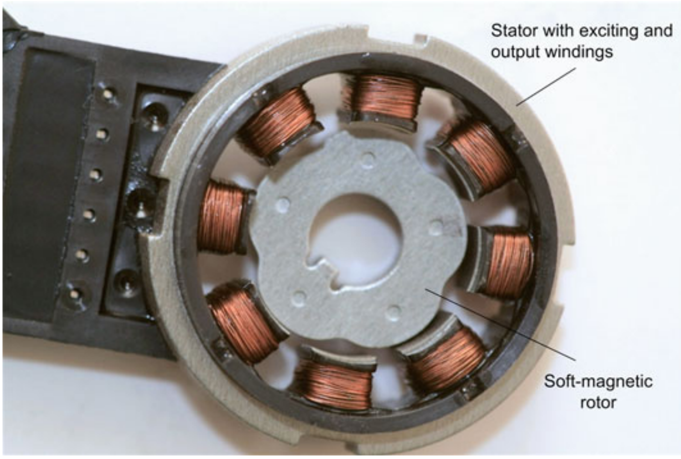


Fig. 15.22 Configuration of a reluctance resolver for EPS systems

on the induction law and consequently works with alternating voltages and currents for excitement and analysis. The classical resolver has a rotating field winding and is supplied with power by brushes and slip rings. The receiver coils are turned by 90° and fixed in the case.

Modern resolvers of steering applications have field winding and receiver windings arranged on the stator. This allows measuring angles contact free and without electric signals supplied to the resolver shaft. The magnetic coupling that can be changed by the rotary angle is generated by a special soft-magnetic rotor structure (reluctance resolver) (Fig. 15.22).

In contrast to magnetic measuring principles, the absolute measuring range of a resolver can be adapted by a suitable stator and rotor configuration. The sensors can be adapted to the number of terminals of the used motors so that there is a higher angular resolution serving as input signal of the field-oriented actuation. The inductive measuring principle makes the resolver resistant against interferences by external stationary magnetic fields. They are suited for transmitting signals across medium distances (standalone ECU) and need no magnet material. In a favourable configuration, the rotor is squeezed as a core onto the engine shaft. The rather complicated electronics and signal analysis is unfavourable, because the carrier-frequency method needs a special demodulation. The rather complicated configuration of resolvers with stator carrier, wire-wound coils and rotor core needs a rather wide space. They are often more expensive than magnetic measuring principles.

Magnetic angle sensors The basic principle of a magnetic sensor is based on a permanent magnet generating a stationary magnetic field. This magnetic field passes one or several parts that are dependent on a magnetic field. Angle sensors

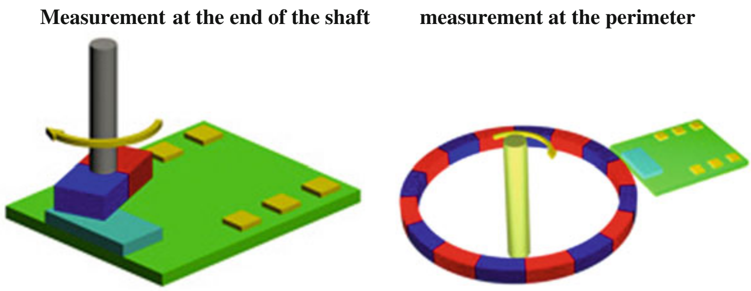


Fig. 15.23 Measuring arrangements of magnetic sensors for position and rev measurement (*Source* Internet Sensitec)

are made by setting a transducer magnet on the shaft to be measured, for example, on the engine shaft, and arranging magnetic field sensors axially or radially.

Two different plans for EPS systems are in use. For measuring at the end of the shaft, a 2-pole magnetic tablet is used, for the perimeter measurement, a magnet ring (Fig. 15.23) is applied.

A measurement at the end of the shaft is preferred if the ECU is axial to the engine (cf. Sect. 15.3.4.1). This arrangement is favourable due to its compact package, because the evaluation sensors can be integrated into the EPS-ECU. No other parts like sensor case or electric connections are required.

The transducer magnetic field is analysed by Hall or magneto-resistive sensors. From an application perspective, the most important difference is the physical quantity that is measured.

The Hall sensor is based on a magnetic flux density measurement, i.e. the intensity of the magnetic field is recorded. A magneto-resistive sensor, on the other hand, measures the magnetic field curve, i.e. the orientation of the magnetic lines of the flux (MR sensors, Zabler et al. 2001). This dependence on the direction of the magnetic transducer field often suggests the MR sensors as the favoured solution, because the measuring accuracy does not depend on the absolute magnetic field strength and, hence, is independent of many parameters like temperature, ageing and mechanical tolerance margins.

A disadvantage of the widespread anisotropic magneto-resistive angle sensors (AMR) is the unambiguous measuring range of only 180°, because only the position of the magnetic field can be measured, but not its orientation or polarity. Hall sensors provide an unambiguous measuring range of 360°, but compared to MR sensors, they need a more sophisticated signal analysis and compensation for a precise measurement of the angle, because the mentioned parameters affect the measurement result. In future EPS applications the Giant MR effect might substitute the current AMR sensors, as it allows measuring an unambiguous angle for the full range of 360°.

15.3.3 Torque Sensor

15.3.3.1 Requirements/Classification

One of the most important measured variables of EPS systems is the steering wheel torque initiated by the driver. It is measured at the input shaft of the steering system. Based on the measured steering torque, the required power assist is identified by the steering functions and control; the EPS motor supplies it to the driver. The quality of the steering torque measurement has an impact on the attainable steering feel, because the driver perceives it directly. Beside the functional requirements for measuring accuracy and resolution, the steering torque has to be measured with absolutely reliability. Otherwise, if the measurement was faulty, the EPS motor might be unintentionally actuated and initiate an uncontrollable steering event.

The most important technical requirements for torque sensors of modern EPS systems are listed in the following:

- utmost reliability
- active torque measuring range of approx. ±10 Nm
- high signal resolution and measuring accuracy
- high measuring dynamics and signal processing with little delay
- high serviceable life and service life
- interference-resistant, diagnostics-capable interface to the ECU
- temperature range −40 to +85 °C for interior applications (EPSc) and −40 to +125 °C for engine compartment applications
- Resistant to fouling, vibrations, wear.

The torque sensors can be classified by their mechanical configuration as sensors with or without mechanical torsion rod. The torsion rod of torsion-afflicted sensors convert the torque measurement into an angle measurement. The typical stiffness of a torsion rod in modern EPS systems is between 2 and 2.5 Nm per degree of torsion angle (2 –2.5 Nm/°). The highest torsion is limited by a mechanical entrainment to ±5° for the protection of the torsion bar.

Torque sensors can also be classified by the basic measuring effect, differentiating between measurement of the torsion angle, the surface strain and the torsion load.

Current EPS systems apply only sensors with torsion rod, because they permit high- precision and interference-resistant torque measuring. The following section will therefore discuss sensors with torsion rod first, then Sect. 15.3.3.3 will specify the motivation and limits of the torsion-resistant torque measurement.

15.3.3.2 Sensors with Torsion Rod

Figure 15.24 shows an extract of potential principles to measure the steering torque in EPS systems. Sensors with torsion rod apply a great number of potentiometric, inductive, magnetic and optical sensors.

Potentiometer measurement The first EPS applied only potentiometer sensors which are very cheap because of their widespread use in industrial products and their simple configuration. These sensors are used only for low-cost systems in the compact car segment now. The main reason is that the measurement value may be blurred by wear of the not contact-free measuring principle, the limited mechanical loading capacity and the sensitivity to dirt.

The measurement is based on a slider potentiometer establishing an electrically conductive track by a sliding contact. The 'measuring' and, therefore, the electric resistance change as a function of the slider's position on the resistance track. For safety reasons, torque sensor applications in EPS systems apply at least two resistance tracks and several parallel sliding contacts for the signal feed. The resistance tracks are made of conductive plastic and the sliders are shaped like brooms to reduce the wear.

A benefit of the potentiometer measurement is the ratiometric analysis. The measurement is independent of the absolute resistance value and temperature interferences. Moreover, the potentiometer measurement supplies a sufficiently big measuring effect, so that no additional amplification and processing of the signal is required. That's why the temperature requirements are unproblematic. Some potentiometer torque sensors for EPS systems include an angle measurement to identify the current steer-angle.

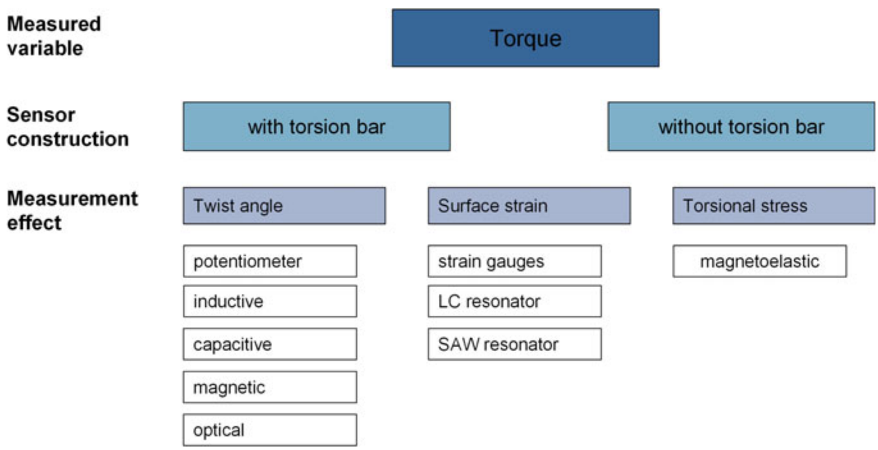


Fig. 15.24 Overview of fundamental measuring principles to measure the steering torque of EPS systems

Unavoidable wear and the resulting blur of the measurement values limit modern potentiometer torque sensors to an accuracy of ±3 % over their service life.

Inductive sensors Inductive sensors are a type of magneto-dynamic sensors, because the basic effect assumes an alternating magnetic field. The main advantage of the inductive measurement is its insensitivity against external media like dirt, oil and water. Inductive sensors can be reliably operated in adverse surroundings. That's why inductive sensors have chiefly prevailed for industrial measuring tasks, beside the potentiometer sensors. They are supplied in many different configurations and measuring arrangements (Zabler et al. 2001).

An example of torque measurement in steering systems is given by the measuring arrangement in Fig. 15.25.

The sensor is based on a system of coils which is driven by an oscillator. The voltage induced in a coil changes as a function of the torsion angle of the torsion rod. A first coil is arranged over two soft magnetic rings. Each ring is mechanically connected to an end of the torsion rod (Fig. 15.25 Detecting coil). Both rings have distinctive cogs along their perimeters. The effective air gap between both rings changes as a function of the turning of the cogs against each other. This alters the impedance of the coil and changes the voltage induced in the coil. A second coil (Fig. 15.25 Compensating coil) is used because the coil impedance depends on other parameters which are in turn dependent on temperature, for example. The compensating coil is arranged over a magnetic circle that is independent of the torsion angle and supplies a reference voltage which is subject only to ambient conditions and facilitates a compensation of various parameters.

The sensor configuration with wire-wound coils discussed above is complemented by inductive measuring systems with planar coils (Fig. 15.26). Suitable conducting paths on a board create transmitter and receiver coil. The rotor consists of an electrically conductive material and provides the magnetic coupling between transmitter and receiver coil.

An alternating current generates an alternating magnetic field in the transmitter coil which passes the rotor, inducing an alternating current. This rotor current leads

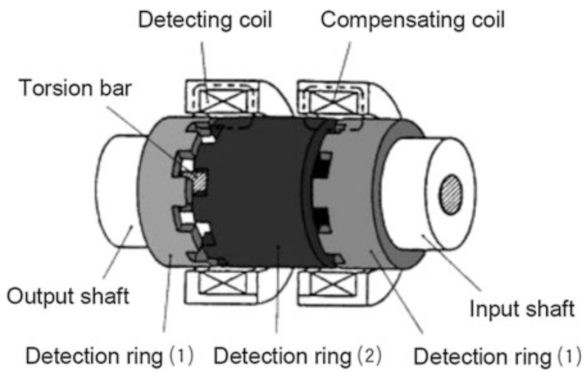


Fig. 15.25 Example configuration of an inductive torque sensor for EPS systems [*Source* Internet Koyo (Yoshida 2002)]

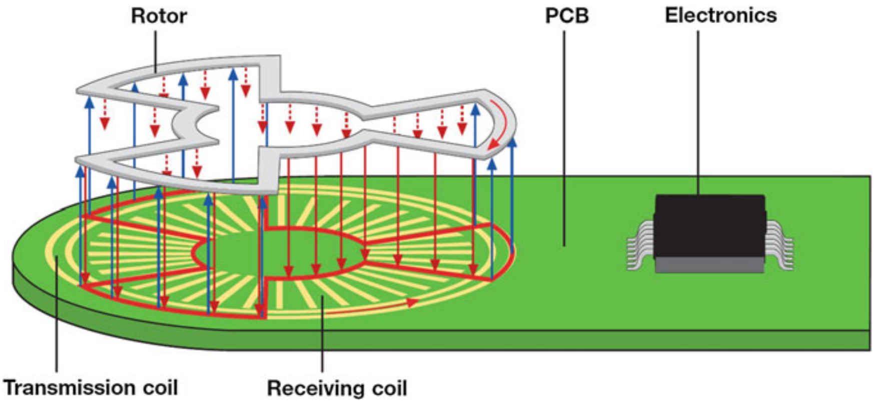


Fig. 15.26 Example configuration of an inductive measuring principle with coils made of conducting paths (*Source* Internet Hella 2014)

to another electromagnetic field which induces a voltage in the receiver coil. The special shape and position of transmitter coil, rotor and receiver coil make the electromagnetic coupling between transmitter and rotor independent of the rotor's position, while the feedback from rotor to receiver depends on the rotor's position.

One transmitter and two receiver coils are commonly needed. If the voltage induced in the reception coils is compared to the source voltage (ratiometric signal analysis), the measurement is mostly independent of temperature and insensitive to mechanical tolerances. Such processes need no separate compensation coil and distinguish themselves by an easy configuration.

Magnetic sensors Unlike inductive sensors, magnetic sensors apply a static magnetic field which is generated by a permanent magnet and passes one or several sensor elements that are dependent on the magnetic field. As discussed in Sect. 15.3.3.1, the torque of sensors with torsion rod is determined by an angle measurement, hence, the same measuring effects can be exploited as in the magnetic angle measurement (cf. Sect. 15.3.2.5). The same qualities and choice criteria apply for useful magnetic sensors as for the magnetic angle measurement. For this reason, Hall and MR sensors have prevailed on the market for magnetic torque sensors.

The lower absolute angle measuring range of the MR technology (180°) in comparison to Hall measuring (360°) is no restriction for the application as a torque sensor, because for the applied torsion bars only a small torsion angle range has to be measured.

When a torsion bar with 2 Nm/° and a measuring range of ±10 Nm is used, an angle measuring range of ±5° is required, for example. The torque measuring range may be modified by the applied torsion bar or by the number of poles of the transducer magnet.

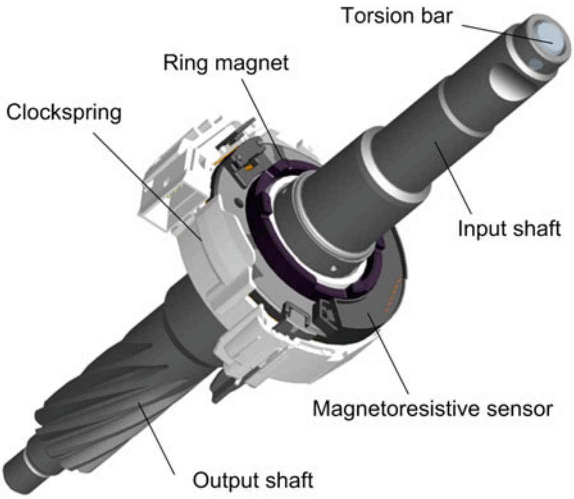


Fig. 15.27 Magnetic torque sensor with direct difference angle measurement by ZF Steuersysteme

In EPS applications, two basic measuring arrangements of magnetic sensors are currently used. The first configuration measures the torque directly via the difference angle of input and output shaft. Figure 15.27 shows that a multipolar magnet ring is set on one side of the torsion bar, and a magneto-resistive sensor is placed opposite of it and connected to the other end of the torsion bar.

This arrangement is favourable because of the immediate measurement by sensors in the torsion rod. Mechanical parts and assembly tolerances that might affect the measurement result are reduced to a minimum. If magneto-resistive sensors are used to measure the magnetic field, high-resolution and high-precision torque sensors can be built because of the typical field direction measurement (cf. Sect. 15.3.2.5) and ratiometric signal analysis. This depends very little on extraneous factors like temperature and ageing. The electric contacts of the sensor element, that is rotating in a steering event, is established by a clockspring whose length depends on the steer-angle range. During assembly, attention is paid so that the clockspring cassette remains in neutral position until the steer-angle is limited by the steering system to avoid any damage or tear. For that reason, a different configuration of a magnetic torque sensor without clockspring has been established.

The magnetic torque sensor without clockspring uses a magnet ring as a transducer magnet as well. However, the sensor elements for measuring the magnetic field are fixed in the case. A soft magnetic flow conductor couples transducer magnet and sensor element (cf. Fig. 15.28).

The flow conductor consists of two parts which are concentrically arranged over the transducer magnet and connected to one end of the torsion bar. The transducer magnet is right on the other end of the torsion bar. The position of the flow conductor relative to the transducer magnet and, therefore, the magnetic flux density in the flow conductor changes as a function of the applying torsion bar

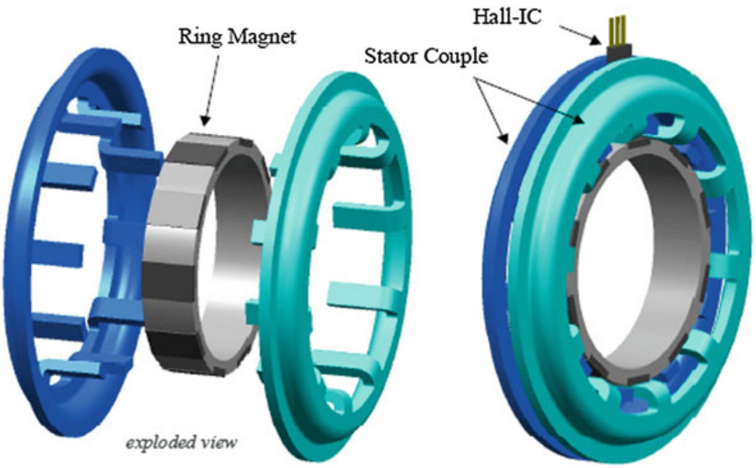


Fig. 15.28 Magnetic torque sensor without clockspring for electric contacts (Jerems et al. 2004) (*Source* Valeo 2004)

torque. The flux density is measured by Hall sensors which are arranged at the perimeter between both parts of the flow conductor.

The process is based on an absolute measurement of field strength or flux density. Hall sensors and transducer magnets that can be calibrated and compensated for ambient temperatures are therefore required. The influence of parts and assembly tolerances on the measurement result can be reduced because the concentric magnetic field is accepted by the flow conductors across the full perimeter of the transducer magnet (integrating measurement). By comparison, the MR technology discussed before is a measurement of the magnetic field at a specific point. A high measuring accuracy with low hysteresis is achieved when during the design of the magnet circle close attention is paid to the choice of a soft magnetic material with low remanence and to a precise adjustment of the transducer magnet when the sensor is assembled.

Optical sensors Optical sensors consist of a light-emitting and a photosensitive component. Both parts are separated by a suitably structured component. The luminous flux from transmitter to receiver is influenced by the torsion angle of a torsion bar. A common configuration of optical sensors are incremental encoders, often used in automation for high-precision positioning tasks.

The optical measuring principle means that the sensors are very insensitive against electromagnetic disturbances (EMC). Filigree code disks and optical structures help to gain very high resolution. However, due to the very harsh conditions, and because of their sensitivity to dirt and limited mechanical load capacity, these sensors can only be used in limited circumstances. Moreover, such sensors supply only pulses for source signals which may be added up to a relative information on the angle. Such incremental sensors are not suitable as torque sensor,

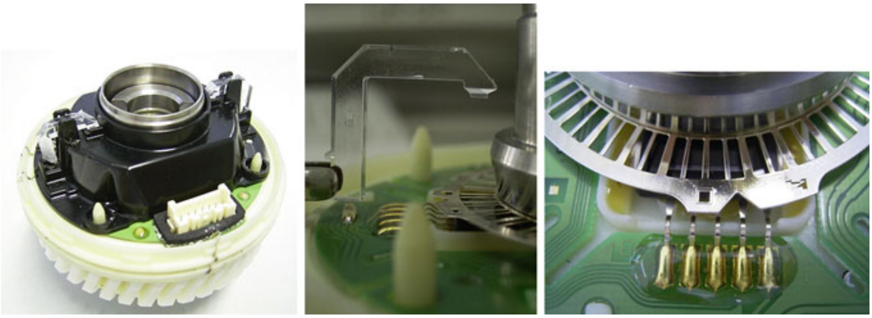


Fig. 15.29 Optical torque sensor for EPSc systems (TRW)

because the angle difference of the torsion bar across the desired torsion range has to be unambiguously identified. Hence, the light intensity between transmitter and receiver is varied and evaluated with absolutely measuring sensors by one or more code disks. The following series of figures shows such a sensor (cf. 15.29).

The luminous flux generated by an LED is conducted by a fibre-optic light guide and two lead-frame plates, arranged over a torsion rod to an integrated photo-diode array.

The sensor in Fig. 15.29 is partially redundant, it has two independent optical measurement modules. Optical torque sensors are used only for EPSc systems at the moment because of the limited temperature range of optical semiconductor parts and the general sensitivity to dirt.

15.3.3.3 Torsion-Resistant Sensors

An important factor for a good steering feel is the stiffness of the complete steering driveline, between steering wheel and the guided wheels (cf. Chap. 3). A too low stiffness is often perceived by the driver as an inert and imprecise steering response, leading to frequent steering corrections. A too high stiffness may mean that impacts at the wheels, for example from bumps on the road, can be transferred undamped to the steering wheel. EPS systems currently tend towards a torsion bar stiffness of above 2 Nm/°. Assuming a constant measuring range for the torque measurement, this leads to lower torsion angles and, hence, to higher requirements for the absolute resolution and accuracy of the used sensor measuring principle (angle measurement by torsion rod). For these reasons, many concepts and patents deal with the torsion-resistant torque measurement for EPS.

Classical strain gauges, as they are used in industrial measurement for measuring torques, are no option for EPS systems. Due to the fact that the filigree resistance foils are glued on the measurement shaft, which is unsuitable for large series production, and the often troublesome calibration needed, other solutions are researched.

A measuring system which is also based on a surface strain of the measurement shaft is called Surface Acoustic Wave (SAW). The basis of the measuring principle are SAW resonators. One such resonator consists of metal electrodes on a piezoelectric substrate (quartz). Operated with an alternating voltage of suitable frequency, the piezoelectric substrate generates a mechanical vibration which spreads out along the material surface. External forces, e.g., from strain and compression lead to a change of the resonator frequency. The frequency change is therefore a direct measure of the applying torque. This process is sometimes used to control the tyre pressure of cars (Fig. 15.30).

A measuring principle which measures not the surface strain, but the mechanical load at the measurement shaft, is based on the magneto-elastic or magneto-strictive measuring principle. The altering magnetic field of a ferromagnetic shaft is measured here under torsional load (Fig. 15.31).

The magneto-elastic measuring sensitivity of common steels is very small. A sufficiently amplified measuring sensitivity can be achieved in some processes by also permanently magnetising the measurement shaft. Yet the sensitivity of a steering torque measurement is much lower than that of current torsion-afflicted sensors and requires additional insulation.

Another big challenge is to achieve a high measuring accuracy, in particular following the overload torque specified in Sect. 15.3.3.1. That is because overload protection by mechanical limitation of the torsion angle is not available. Hence, both described torsion- resistant processes suffer currently a wide hysteresis following an overload torque, which results from the measuring principle.

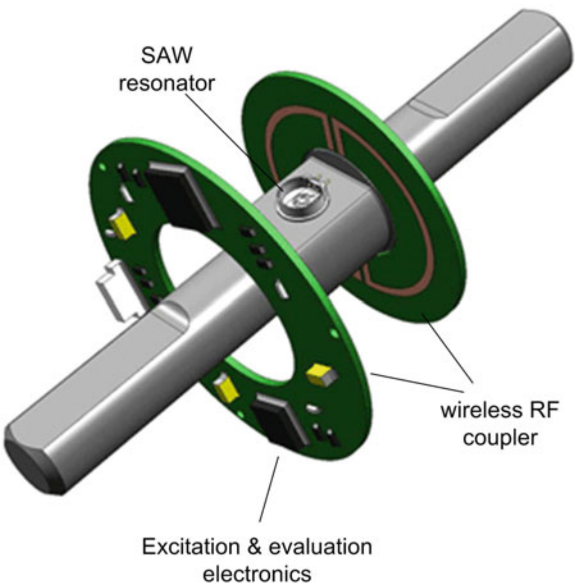


Fig. 15.30 Design of an EPS- torque sensor based on a surface strain (*Source* Internet Transense Technologies)

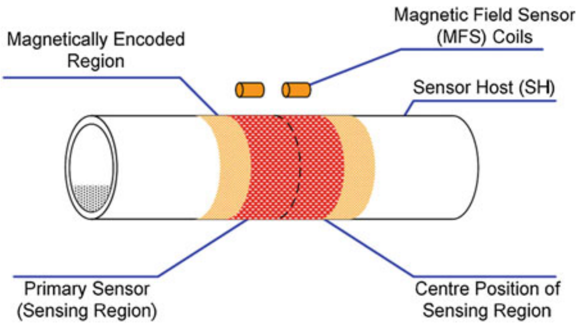


Fig. 15.31 Simplified measuring configuration of a magneto-elastic torque sensor (*Source* Internet NCT Engineering)

15.3.4 ECU

ECUs for EPS basically include signal-processing electronics, to compute the currently required power assist, and power electronics, to feed the electric motor accordingly (Fig. 15.32).

Interior and engine compartment ECUs are distinguished by their location on-board. The following table lists the most important requirements for EPS-ECUs (Table 15.1).

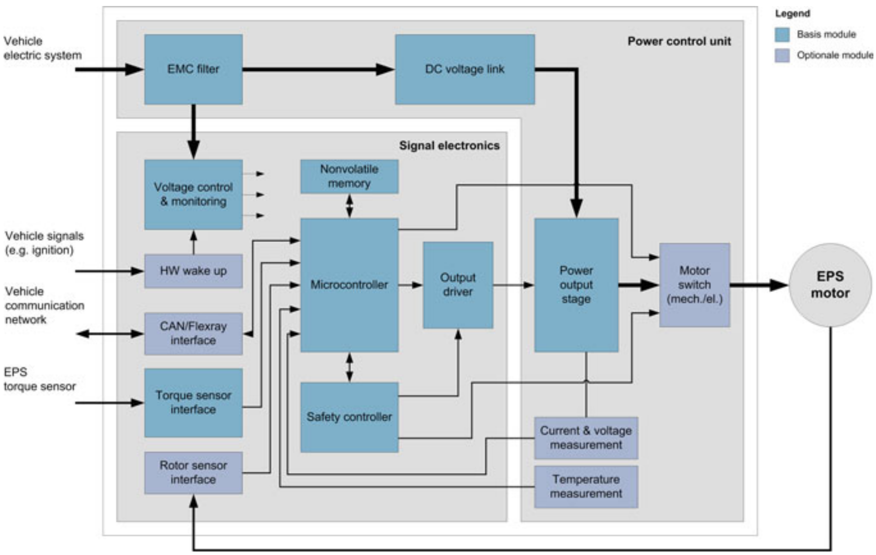


Fig. 15.32 Simplified block diagram of an EPS-ECU consisting of signal electronics and power electronics

Table 15.1 Requirements for EPS-ECUs for interior and engine compartment

On-board location	Interior	Engine compartment
Typical supply voltage	9–16 V	
Maximum closed-circuit power consumption	<250 μA	
Typical operating temperature	−40 to 85 °C	−40 to 125 °C
Thermo shock with flood water	No	Yes
Sealing requirements	IP5K0 dust-proof, no water protection	IP6K9 K dust-proof, jetting-resistant
Ambient resistance	Damp heat	Salt spray
Media resistance	No, only in special cases	Yes, different reagents
Mechanical vibrations	10–20 m/s^2 for body-mounted parts	
Mechanical shock	300–500 m/s^2 for body-mounted parts	
Electromagnetic tolerance	Immune against disturbances/irradiation. No interfering electromagnetic radiation Applied standards (excerpt): • Conduction disturbances ISO 7637 • Irradiated disturbances ISO 11452 • Radio disturbances IEC CISPR25	

15.3.4.1 Designs

ECUs are preferably arranged close to the EPS motor, to keep electric loss as low as possible (piggyback ECU). Internal loss develops in the connecting lines between the ECU and the electric motor of the EPS, they rise with increasing length of the line. The number and configuration of the electric contacts, as for example the plug-in connectors, have to be considered in computing the distribution loss as well.

The low level of distribution loss renders the piggyback ECU the common solution for any medium or high power rack-and-pinion power steering.

EPSc systems of the compact car segment may also apply standalone ECUs because of low power demand and limited space for installation. They are not arranged right at the steering but connected to the electric motor by lines of about 1 m in length.

Another drawback of standalone ECUs beside the mentioned distribution loss is the often too complex wiring of the motor and sensor connections. Additional parts like plugs and cable connections have to be used. Sometimes, additional measures are necessary to electromagnetically insulate the motor lines.

Figure 15.33 shows a piggyback ECU with axial mounting at the electric motor and internal electric connection.

High-current connections between electric motor and ECU can be made because of the axial mounting of the ECU, either by plugging, insulation-displacement connectors or welding. The position and rev sensors required in three-phase motors (cf. Sect. 15.3.2.5) can be integrated on the circuit board of the signal electronics, to achieve a measurement that is highly precise, immune to

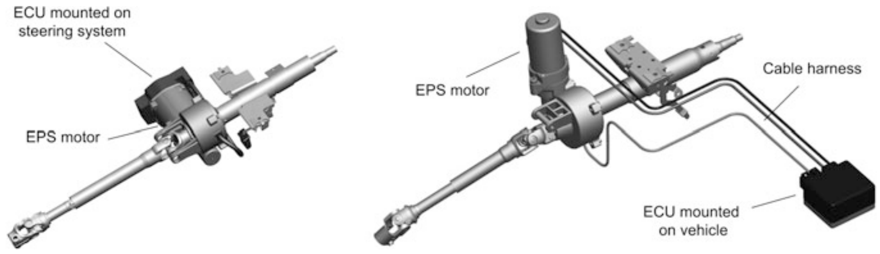


Fig. 15.33 Typical configurations of an EPS-ECU as piggyback (*left*) or standalone version (*right*)

Table 15.2 Current circuit boards for EPS-ECUs and their qualities

	Printed circuit board (PCB)	Thick film copper (TFC)	Isolated metal substrate (IMS)	Directly bonded copper (DBC)
Carrier material	Epoxide resin	Ceramics	Aluminium	Ceramics
Conducting material	Copper	Copper/silver paste	Copper	Copper
Conducting thickness (μm)	35–400	15–200	35–300	200–400
Electric conductivity	High	Low	High	High
Thermal conductivity	Low	Very High	High	Very High
Coefficient of expansion	High	Low	High	Low
Current load capacity	Medium	Medium	High	Very High
Mounting varieties	SMD, THC, on both sides	SMD 'bare-die'	SMD	SMD, bare-die
Integration density	Medium	High	Medium	High

SMD Surface Mounted Device
TFC Thick Film Copper
THC Through Hole Component
bare-die Semiconductor component without case/unpackaged chip

interference and cheap. The axial mounting of electric motor and ECU is complemented with a radial mounting, common for EPS piggyback ECUs (Table 15.2).

Ceramic carrier materials and metal substrates are used as circuit boards of modern EPS systems, beside the conventional printed circuit technology on the basis of epoxy resin (e.g., FR4). Individual circuit boards and external ECU connections are usually connected by punched copper rails (lead-frames), moulded in plastic. Wire-bonding or laser welding establish the contacts between lead-frame and circuit board.

15.3.4.2 Signal Electronics

The signal electronics compute the power assist required in the current driving situation. The required sensor signals are read, made plausible and used to compute the power-assist torque of the EPS motor by means of control algorithms discussed in Sect. 15.6. A motor control generates the actuating signals of the power electronics from the requested power-assist torque.

Recent EPS-ECUs communicate with other vehicle control systems, like the Electronic Stability Programme (ESP) or the vehicle diagnostics, by bus systems. The CAN-bus, used in chassis applications most often with transmission rates of 500 kBit/s, is complemented with the Flexray bus, enabling transfer rates of up to 10 MBit/s. This interface helps to read data on the driving condition, as, for example, vehicle speed and steering wheel angle, and external steering interventions are set, for example, by the driver assistance systems.

The core of the signal electronics are modern micro-controllers with CPU, RAM, ROM and additional periphery like AD converters, timer unit and serial and parallel interfaces (Beierlein and Hagenbruch 2004; Table 15.3).

The micro-controllers are programmed in C, including some special program directives for automotive applications (MISRA-C Rules 2004). Real-time operating systems acc. to the OSEK/VDX standard may be used for the sequence control of functions, also providing services for network management and communication.

The power electronics are actuated by highly integrated electric switching circuits (ICs). They convert the pulse-width modulated signals (PWM) of the micro-controller into voltages that may serve to control the power semiconductor. Moreover, they provide all the required supply voltages and often include signal amplifiers to measure the motor power and functions to protect the power semiconductors.

Beside the steering functions, various fault detection and shutdown measures are implemented in the signal electronics. They monitor the correct function of all the subassemblies, and in the event of a fault, the system is set into a safety mode (see Sect. 15.5). The state-of-the-art is to monitor the correct programme processing of the micro-controller by the second independent safety controller. It can be either another micro-controller (mostly 8 bits) or an application-specific

Table 15.3 Recent micro-controller characteristics of EPS

	Low performance EPS	High performance EPS
Architecture	Single μC with 8/16 bits	Single μC with 16/32 bits
Stroke (MHz)	16–32	32–128
Arithmetics	Integer	Integer and floating point
ROM (kByte)	16–32	256–1,024
RAM (kByte)	0,5–2	10–60
A/D converter (bit)	8	10/12
Interfaces	No	CAN or Flexray

integrated circuit (ASIC). Continuous monitoring checks the main computer for its time response and the contents of its arithmetic results. Other safety measures in the ECU are, for example, the monitoring of all the internal supply voltages and sensor signals and the issued actuation signals of the power output stage. In a fault event, the main controller and the safety controller can operate the electric switch-off channels (see Sect. 15.5.2.4). A switch-off channel can be a motor relay, for example. Upon a fault event, the power flow can be interrupted in the power electronics or in the e-motor to avoid unintentional brake torques by PME motors.

A fault management integrated into the software controls the registering, processing and storage of fault events. Any registered irregularities are identified and evaluated and suitable remedies are initiated. The remedies depend on the severity of the fault and may range from switching to redundant signals via switching off individual functions to shutdown of the complete power-assistance. The registered events are stored in a non-brief data memory, including a unique designator, for the subsequent vehicle diagnostics.

15.3.4.3 Power Electronics

The task of the power electronics is the control of the energy flow between on-board wiring and EPS motor. According to the motor-power class, modern EPS systems may feature amps of up to 170 A. The DC wiring makes voltage DC-links obligatory. First, the input voltage and the input current are filtered by inductances and condensers are filtered to meet the strict EMC requirements. The DC-link is made of several high-capacity electrolytic capacitors. Typical capacity values of the DC-link are 1,000 to 10,000 μF, according to the EPS motor-power class.

The actuation signals, provided by the signal electronics, are converted by a power output stage into suitable power for the EPS motor. The output stage consists of several power transistors in bridge connection. DC motors apply a h-bridge and three-phase motors a three-phase bridge connection.

Self-locking field-effect transistors (MOSFETs) are the only kind of transistors applied, marked by low-power control and low-impedance resistance in the switched-on state. IGBT transistors, as they are used in electric drives of hybrid vehicles, are not suitable for a 12 V on-board wiring because of their higher on-state power dissipation.

Modern power semiconductors can be operated at a chip temperature of 175 °C. At ambient temperature, they may conduct long-term currents of up to 200 A across a chip surface of 35 mm^2. In EPS systems, these transistors are implemented either as housed parts on printed circuits or metal substrates or they are mounted on ceramic circuit boards without housing (bare-die). Sometimes, the complete bridge connection is one subassembly, moulded in plastic (Fig. 15.34).

The heat of power semiconductors is commonly dissipated by a metallic backplate connected to the steering case or the electric motor. The layout of the transistor cooling has to include on-state power dissipation as well as losses from switching, because a very high power dissipation can occur briefly. The dissipation

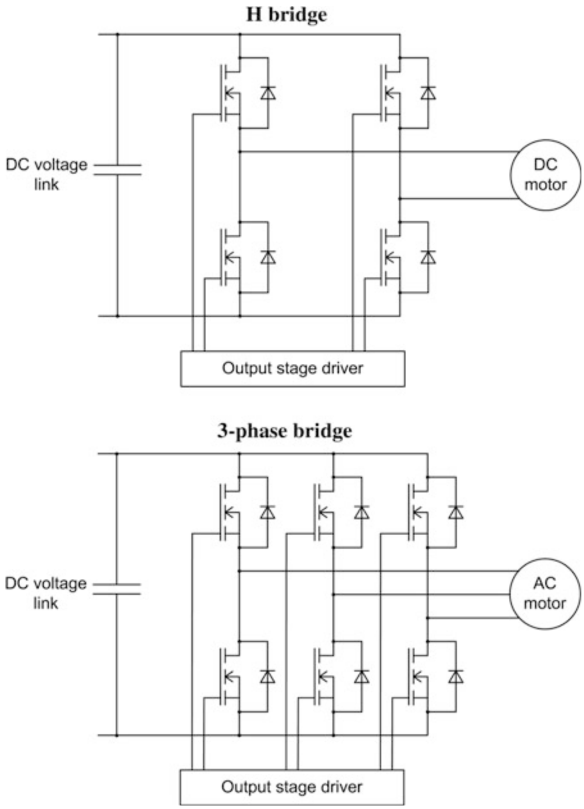


Fig. 15.34 EPS power output stage for DC and three phase AC motors

may be reduced and the EMC requirements met by a compact assembly of all parts in the power flow, low-impedance mounting and connection, and a symmetrical assembly and layout of the components that should feature low inductance (Fig. 15.35).

15.4 System Design

15.4.1 General System Requirements

This chapter discusses the essential technical requirements of electromechanical steering (EPS) that have to be included into the system layout (see Chap. 3).

Mechanical interfaces The steering is connected on-board with the steering shaft and the wheel by the input shaft of the torque sensor. On the output side, the tie rods connect the mechanical interface to the guided wheels via the hub carriers. The steering is screwed to the axle carrier of the vehicle. The structure-borne

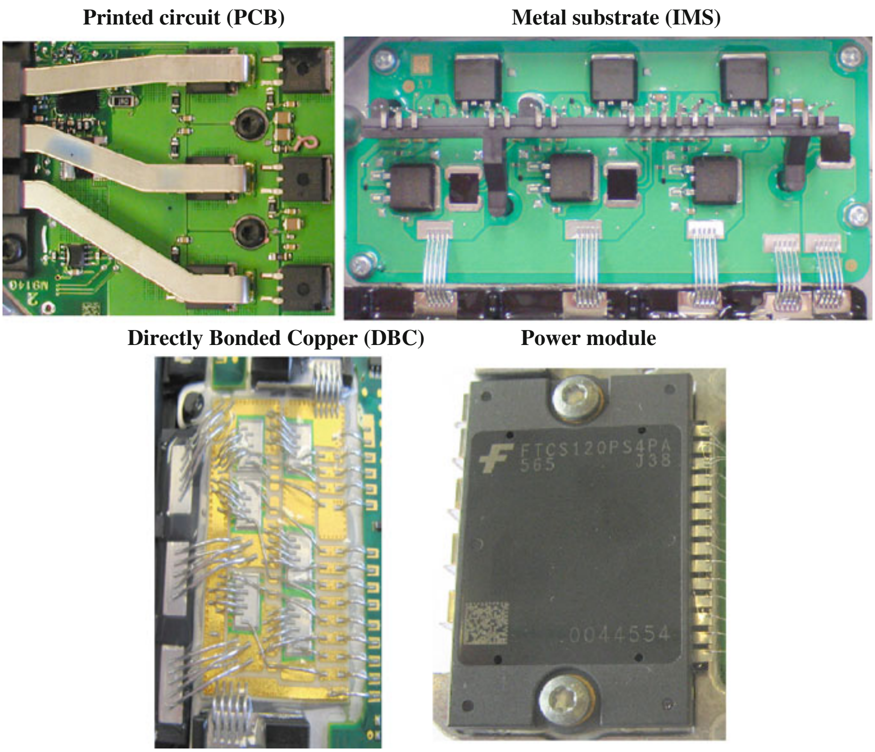


Fig. 15.35 Configurations of EPS power output stage (PCB, IMS, DBC, module)

sound transfer may be reduced by supporting the axle carrier on elastic bearings (silent jacks).

Electric interfaces High-current plugs connect the steering system to the on-board wiring. Modern steering systems add a connection to the communication wiring of the vehicle. The ECUs dispose of another hardware input to activate the steering (terminal 15). Activation by the communication network (software Wake Up) is also possible. The supply voltage and the highest possible power consumption are specified by the vehicle manufacturer (Fig. 15.36).

Power demand The output power of the EPS system is defined by several working points. A working point is defined by the total tie rod force, the steering speed and the steering torque. At least three working points are usually specified (parking, slow travel, evasive manoeuvre). An important aspect of the power demand is its basic constraints, like design temperature and voltage and the number of repetitions (load group).

Functional requirements The essential function of an EPS system is the supply of power-assist on demand. Other functional requirements are described in Sect. 15.6.

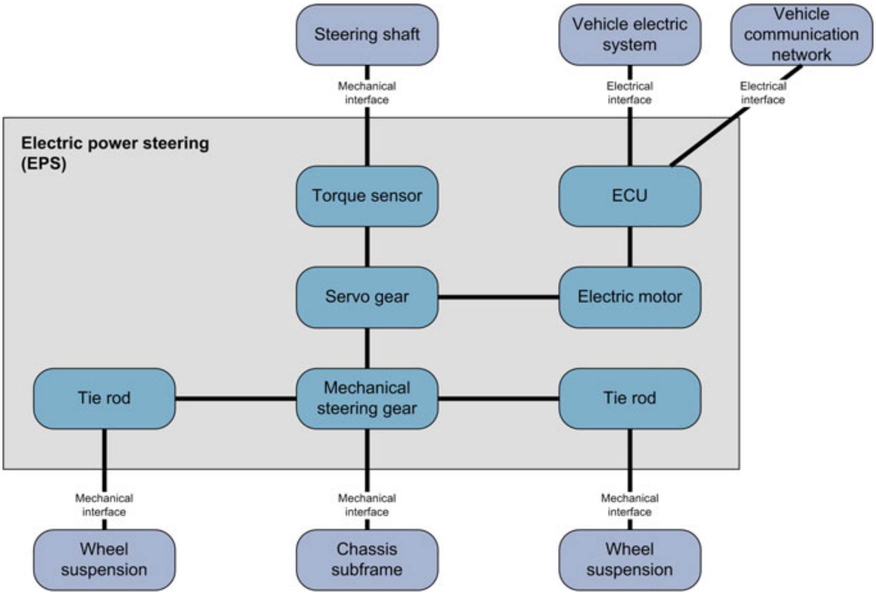


Fig. 15.36 Interfaces and parts of an EPS system

Safety requirements The electric power-assisted steering has to be laid out in such a way that a safety-critical state of the steering can be excluded during the serviceable life according to the state of the art. A safety-critical state is present when the vehicle response deviates from the normal state so much that the driver cannot keep control of the vehicle and a risk for body and life or real values develops (see Sect. 15.5).

Environmental requirements Environmental requirements are the whole structure of mechanical, electric, thermal, chemical, acoustic and other demands for the steering which are raised because of the on-board operation of the steering system (Table 15.4).

15.4.2 Design Parameters

The power of electric power-assisted steering is laid out along the power flow. The demanded output power and the available installation space of the steering serve to deduce the requirements for steering parts like rack, gearbox, electric motor, ECU and torque sensor. Depending on whether the EPS engagement is at the steering column or the rack, different kinematic relationships and degrees of freedom result in the system layout. All the following discussions assume stationary working points (uniform, not accelerated motion) and lossless parts.

Table 15.4 Excerpt from the system requirements of current EPS systems

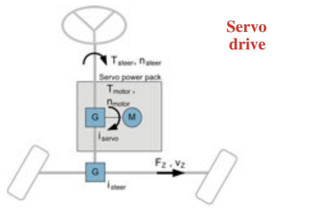
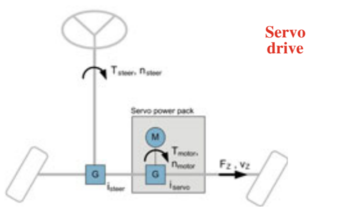
	Value range
Steering wheel angle range	±450 to ±650°
Steering wheel torque range with power-assistance	±3 to ±8 Nm
Steering wheel torque range upon abuse	±200 to ±300 Nm
Steering ratio (rack path per steering wheel rotation)	44–60 mm/rev
Peak tie rod force parking	±3 to ±16 kN
Minimum steering wheel speed parking	100–360°/s
Supply voltage	9–16 V
Maximum current bearing	<120 A
Temperature range	−40 to +85 °C for vehicle interior
	−40 to +125 °C for engine compartment
Serviceable life	15–20 years
	5,000–12,000 active hours of operation
	200,000–300,000 km of vehicle endurance
Acoustics	Sufficiently low noise generation has to be proved by objective test bench measurements at the complete steering system. The tests are coordinated between car and steering system manufacturer

Specification of the output power The output power (P_Z) of an EPS system is fully described by information on the required tie rod or rack force (F_Z) and the rack speed (v_Z) according to Eq. (15.1). Vehicle manufacturers usually specify not the rack speed, but the steering speed at the wheel (n_{steer}) and the gear ratio (i_{steer}) (Eq. 15.2). A separate description of the power demand for different driving manoeuvres is favourable (Table 15.5).

Choice of the steering system gear ratio The gear ratio is defined as a ratio between rack path and steering wheel angle. The gear ratio is specified by the vehicle manufacturer, because together with the axle kinematics, it determines the steering characteristics of the vehicle (see Chap. 4). A direct gear ration of, say, 58 mm per rotation of the steering wheel, reduces the effort that the driver has to invest into steering. With a gear ratio of 44 mm/rotation, the required steer-angle for the same rack path would be higher by a factor 1.3. Direct gear ratios are preferred in order to reduce the effort for parking and to get a very agile steering response from the vehicle. Nevertheless, direct steering ratios cause appreciable lateral movements of the vehicle from small steering movements at high speed. That's why VGRs are sometimes used, because they allow perfecting the effort for parking, taking into account the driving stability at high speed.

Choice of the servo ratio The working point of the electric motor (M_{motor}, n_{motor}) is defined by Eqs. (15.2), (15.3) and (15.4) for a given output power at the rack

Table 15.5 Kinematic connections of the different EPSEPS

Steering column EPS system (EPSc, EPSp)	**Rack EPS system (EPSdp, EPSapa, EPSrack)**
	
$P_Z = F_Z \cdot v_Z$ (1) $v_Z = i_{steer} \cdot n_{steer}$ (2) $F_Z = 2\pi \frac{M_{steer} + i_{servo} \cdot M_{motor}}{i_{steer}}$ (3) $n_{motor} = i_{servo} \cdot n_{steer}$ (4)	$P_Z = F_Z \cdot v_Z$ (1) $v_Z = i_{steer} \cdot n_{steer}$ (2) $F_Z = 2\pi \frac{M_{steer}}{i_{steer}} + i_{servo} \cdot M_{motor}$ (3) $n_{motor} = i_{servo} \cdot v_Z$ (4)

δ_H [rad] Steering wheel angle
δ_H* [rad] Pinion angle
M_A [Nm] power assistance torque
M_H [Nm] steering wheel torque
M_S [Nm] kingpin torque (sum of)
s_r [m] rack displacement
i_S [-] overall steering ratio

(F_Z, v_Z) and a given input power by the driver (M_{steer}, n_{steer}) over the servo gear unit. The symbol M represents the torque and the symbol n represents the rev.

The servo gear ration is selected in the tension zone between motor torque (M_{motor}) and motor speed (n_{motor}). The best system layout is found by varying the servo ratio with regard to positioning force or actuator speed. For example, for a given electric motor (M_{motor}, n_{motor}), a reduction of the servo gear ratio implies a lower rack force (Eq. 15.3) and a higher steering speed (Eq. 15.4; Figs. 15.37, and 15.38).

Layout of electric motors and power electronics The demanded working points (M_{motor} x, n_{motor} x) suggest the layout of the EPS motor. The power demand helps to define whether a DC or an AC motor is used (Sect. 15.3.2). This affects the requirements for power electronics (Sect. 15.3.4.3) and control engineering (Sect. 15.6). Then the electromagnetic motor design and the winding layout are defined, yielding the overall size and power input of the electric motor.

Essential layout criteria for the power electronics are the current load capacity and the cooling of parts. After possible power semiconductors and parts of the DC-link have been chosen, they are evaluated together with various mounting and connecting systems. The load of the high-power electronic parts with regard to voltage, current and thermal absorption is evaluated by simulating circuits and

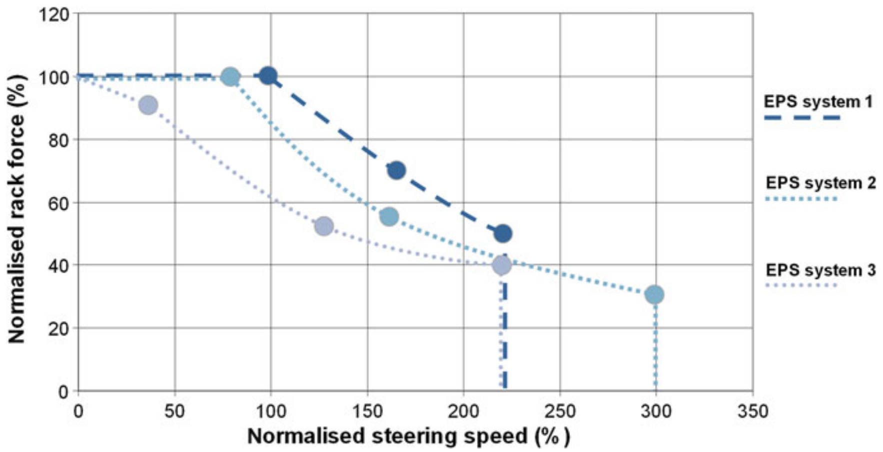


Fig. 15.37 Typical power demand of current EPS systems

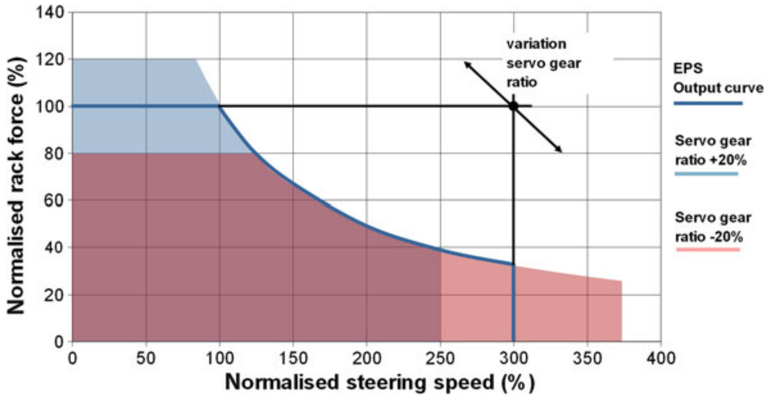


Fig. 15.38 Adaptation of the EPS operating range by varying the servo gear ratio

thermal response for different steering manoeuvres. The power consumption from the on-board wiring is verified.

Constraints for the system layout As mentioned before, the choice of the servo ratio defines the requirements for torque and rev of the electric motor. The servo ratio can be selected only within certain limits. For example, the permissible peak forces on the mechanical parts are limited because of their strength. This gives the least possible servo ratio. On the other hand, the servo ratio cannot be increased arbitrarily, because the engine speed will increase as well. Higher actuator speeds produce more noise in the mechanical parts, for example during the cog engagement of the servo gear units.

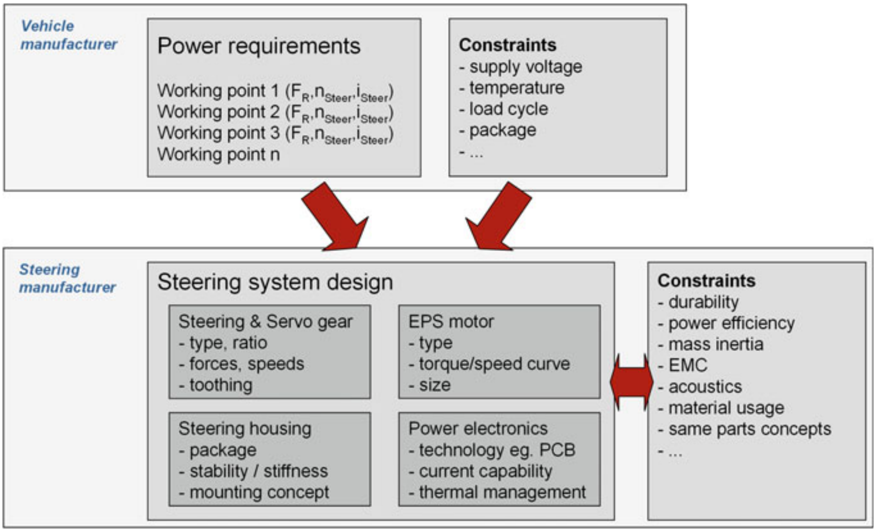


Fig. 15.39 Graphic representation of the power layout of EPS systems

The inevitable power dissipation of the parts, which also depends on their working points, has to be considered in the system layout as well. The overall efficiency of the steering has to be considered, as well as other technical functions as installation space, inertia and EMC, or even economic factors like material use and same-parts plans (Fig. 15.39).

15.4.3 Requirements for the Wiring System

The requirements for the electric on-board wiring can be taken from the mean power demand and the appearing power peaks.

Mean and peak power demand The power demand describes the electric power required from the on-board wiring as a product of supply power and consumed voltage.

Classical long-term consumers, for example, ignition control and fuel injection, have a higher mean power input then Power-on-demand systems, including electric power-assisted steering. An electric power-assisted steering needs an input power of less than 10 W in everyday travel. This comes mainly the power consumption of the signal electronics. This is opposed by brief power peaks of 1,000 W or more during parking and turning manoeuvres.

Hence, only the peak power demand is relevant for on-board wiring requirements of EPS (Fig. 15.40).

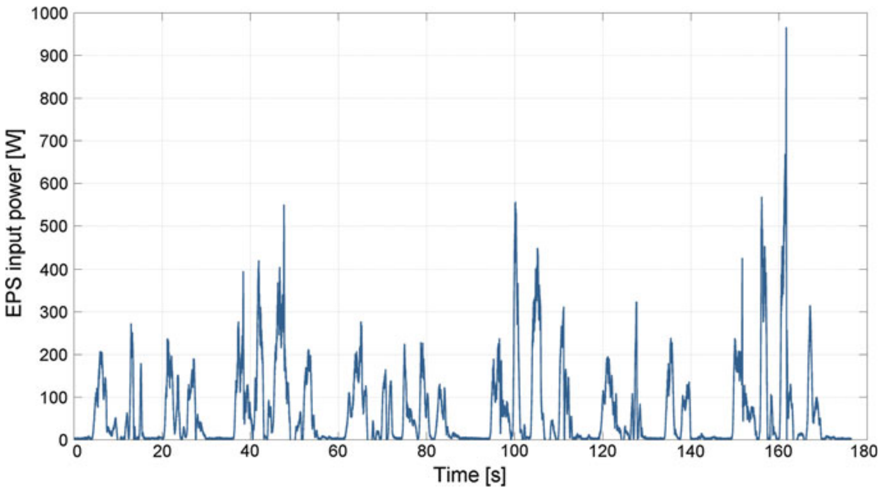


Fig. 15.40 Measured input power of EPS during parking of a middle class vehicle

Dynamic power demand The mentioned absolute power and the need of the consumers for power over time are crucial for sizing the on-board wiring. Brief power peaks have to be covered by the battery, for example, because of the delay in generator control. That's why the upward current slope is relevant for electric high-power consumers, as is the peak current for the stability of the supply power (Bordnetzrückwirkung).

On-board current repercussions The on-board wiring of a car consists in principle of a generator for energy conversion, a battery for storage, lines for distribution and the attached consumers (Bosch 2002). State-of-the-art is still the conventional 12-V on-board wiring, often called 14-V on-board wiring. The generally advancing electrification of cars pushes the conventional on-board wiring to its limits with regard to power load and dissipation. Rising demand by the electric consumers and measures to reduce consumption and emissions further burden the components of the on-board wiring. For example, voltage fluctuations and power load in the on-board wiring are rising due to start/stop function and the recuperation of braking energy.

A pure 42-V on-board wiring, as it has been stipulated for a long time in ISO 21848, has not been introduced to the mass market till now. One reason is the huge investment that a conversion of all the on-board wiring parts and consumers would entail. Beside the known parts, like generator and battery, all the ECUs would have to be adapted to the new voltage, for example, including sensors and actuators.

Energy management If several electric consumers briefly need energy at the same time, a safe power supply of the consumers has to be maintained even in the worst case, when the generator rev is low or the battery is partially discharged. For example, a very high and brief power demand may occur during an evasive manoeuvre with electric power-assisted steering and ESP intervention. Thus intelligent energy management systems are implemented in many modern vehicles. They coordinate the response of the involved on-board wiring components. Hence, an essential task of the energy management is to compare the power demand of the consumers to the power supply of the on-board wiring and to maintain balance. The battery charge is monitored as well as the energy distribution by demand and priority of consumers. For example, various standby and closed-circuit consumers are switched off when the vehicle is parked and the battery is low, so that the vehicle may be ignited again.

15.5 System Safety

15.5.1 Normative Code

15.5.1.1 IEC 61508

The IEC 61508 is an international standard for the development of electric, electronic and programmable electronic (E/E/PE) systems (Bosch 2002). This standard developed in the field of process engineering or mechanical engineering, but it is not restricted to certain application areas, it may rather be considered a 'fundamental standard' for the development of systems relevant for safety. The standard was published with the title 'Functional safety of electrical/electronic/programmable electronic safety-related systems' and was divided into seven sections.

The whole safety life cycle is considered, including the concept phase, planning, development, conversion, introduction, maintenance, change and disposal/scrapping.

Systems are relevant for safety when their failure indicates a considerable risk for persons or the environment.

The systems are arranged in safety integrity levels, or SIL. The range reaches from SIL1 to SIL4, with SIL4 making the highest demands to the systems. In the automotive industry, SIL4 is not relevant, the highest classification being SIL3. It has to be proved before mass production that the product meets the SIL requirements.

15.5.1.2 ISO 26262

ISO 26262 ('Road vehicles—Functional safety') is a standard of electric/electronic systems relevant for safety, especially for the range of application in automobiles.

The standard was necessary because the IEC 61508 originated in facility building, made in small or very small numbers. Their potential dangers for persons and environment were reduced by integrating external safety measures, such as protective screens or emergency shutdown strategies. Therefore, no detailed default requirements for the car industry could be taken from it.

The safety of automobiles has to be maintained by the correct configuration of the function, i.e. safety has to be an integral component of the product. In addition, specific features, such as mass production, which distributed development etc., have to be considered. Therefore, ISO 26262 was written on the basis of IEC61508. The first edition of ISO DIS 26262 is published on Nov 11, 2011.

There is a public draft, the ISO DIS 26262, in the process of coordination since 2009, the final international publication had been intended for 2011.

The safety **i**ntegrity **l**evels are divided by ASIL A to ASIL D (**A**utomotive **S**afety **I**ntegrity **l**evel), ASIL D corresponds to the highest requirement level and is comparable with SIL3 acc. to IEC 61508. Requirements which are not relevant for safety are marked QM (quality measure) and are not addressed by ISO 26262 activities. Instead, they have to be treated by the processes of quality maintenance.

15.5.2 Safety in EPS Applications

15.5.2.1 Task of the Safety Concept

The system has to be laid out in such a way that faults are safely controlled. The following options are conceivable:

- fault exclusion according to the state of the art, e.g., by suitable mechanical design
- exclusion of safety-critical fault consequences, e.g., by proving that the driver is not or only slightly affected
- fault detection by a suitable safety concept and taking down the system into a safe state sufficiently quickly (fail-safe principle).

The system risk or the safety integrity level (ASIL) is identified by a danger and risk analysis, first without considering safety measures. Then the system risk is reduced by developing a safety concept. The task of the safety concept is to implement safety measures to reduce the present systemic risk to a calculable, potential rest risk. The effectiveness of the safety concept is documented by a safety proof, see Fig. 15.41. The scope of proof is given by the safety integrity level (ASIL).

15.5.2.2 EPS Risk Classification

The assessment of the systemic risk has to consider the range of application and the motor-power class of the EPS. Assessing the current steering systems for

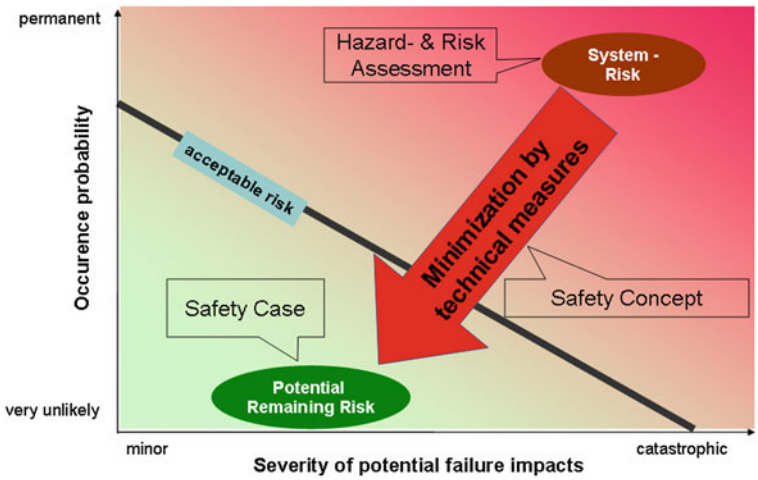


Fig. 15.41 Safety concept to minimise the system risk

medium and superclass vehicles yields the following classification (risk graph from ISO/DIS 26262-3, rev. 2009-06-28):

- undesirable actuation of the servo motor → ASIL D
- heavy running of the steering system, e.g., by false actuation of the servo motor (not mechanical causes) → ASIL D
- sudden supply of the power assist, e.g., by unintentional relaunch → ASIL A
- failure of the power assist → QM.

The above classification classifies EPS systems as ASIL D. The protective purposes can be deduced directly:

- The steering system has to recognise faults that trigger an undesirable actuator function and change into a safe state according to the ASIL D requirements.
- The steering system has to recognise the faults that lead to heavy running of the steering system and change into a safe state according to the ASIL D requirements.
- The steering system has to prevent unintentional relaunch of the power-assist according to the ASIL A requirements.

There can be no safety integrity function for mechanical parts, therefore, faults have to be excluded from the mechanical design. This is ensured by the processes of mechanical development.

Constructive design has to exclude, e.g.:

- loss of the mechanical contact between steering wheel and tyres
- heavy running of the steering due to mechanical causes.

15.5.2.3 Qualities of the Safe State

The safe state of an EPS steering can be defined by the following qualities:

- The steering system may not generate a power-assist.
- The safe state can be left only by switching off and on and successful initialisation of the ECU (see Fig. 15.42).
- The electric motor may not generate any torques above a safety-critical value (depending on vehicle and steering layout).
- The mechanical steering ability has to be maintained according to ECE R79 (UNECE 2005).

A power-assistance (state 'EPS active') may be generated only after successful, perfect initialisation. If a critical fault appears, the state 'EPS system fault' is immediately entered. The states 'EPS off' and 'EPS system fault' set the steering system into safe state. The switch-off channels (cf. Sect. 15.5.2.4) ensure that the safe state is reliably entered.

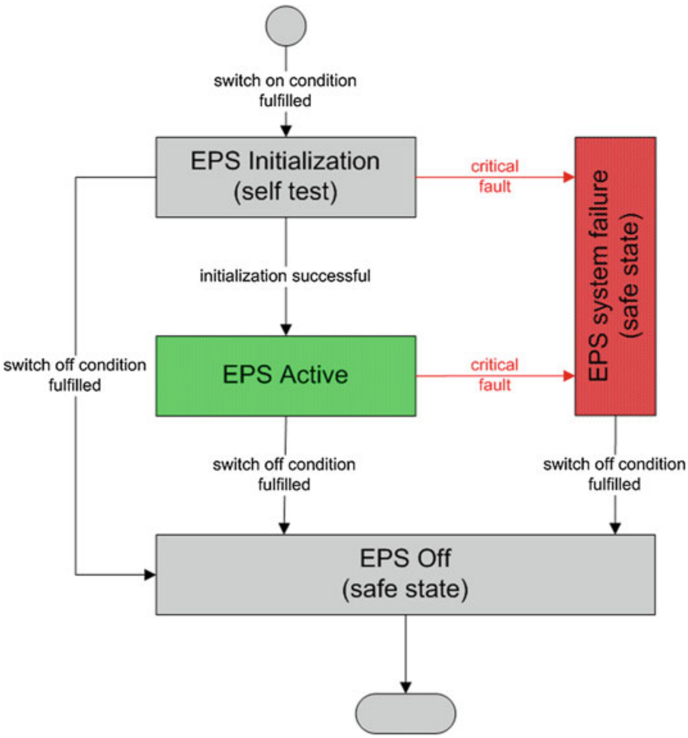
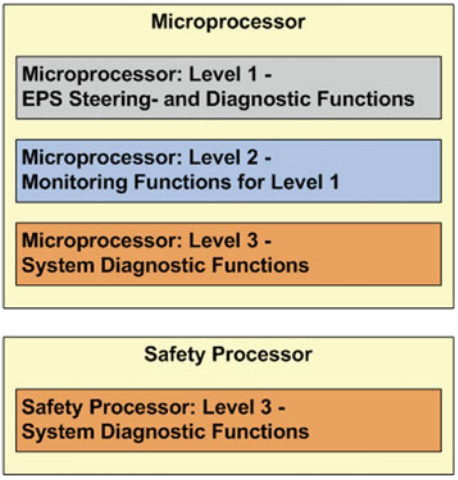


Fig. 15.42 System states of the EPS system

Fig. 15.43 3-level plan



15.5.2.4 Switch-Off Channels

When a safety-critical fault is recognised, the system has to enter the safe state with the help of the switch-off channels within a fault tolerance time. The fault tolerance time is the time during which the system may accept faulty signals without entering a dangerous condition. This time is required for fault detection and the subsequent fault reaction. It depends on the layout of car and steering.

A reliable fault reaction needs switch-off channels that can be activated by diverse and independent ways.

The switch-off channels are activated by the microprocessor unit and additional hardware parts. These parts have to be selected in such a way that they supervise each other all the time. This ensures that the system can be transferred into a safe state. EPS applications use the power electronics as a switch-off channel. The control to deactivate the switch-off of the power electronics can for example look like in Fig. 15.44.

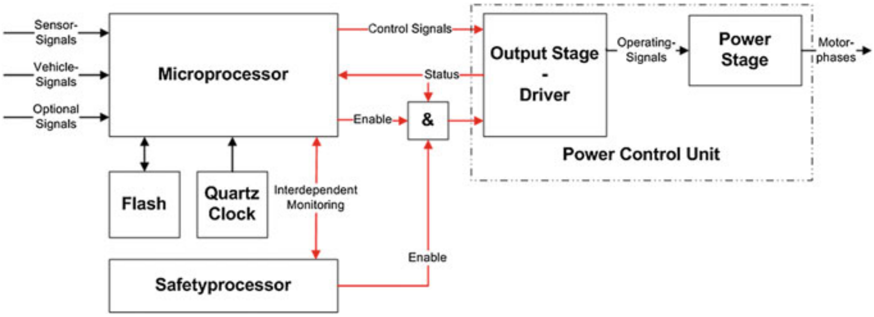


Fig. 15.44 Block diagram of the EPS ECU with switch-off channel

In order to exclude undetected faults in the operation of the switch-off channels their effectiveness needs to be checked individually before activating the steering functions. Therefore, test routines are run before the initialisation phase. Only if the test result was positive, the system is released and enters the state 'EPS active' (cf. Fig. 15.42).

The ECU is designed in such a way that the EPS remains in the safe state when powerless.

The safety requirement to switch off the fault-afflicted system immediately and to transfer it in the safe state has to be compatible with the demands on quality. An essential quality characteristic is the availability of the power-assistance, i.e. the amount of time when the power-assistance is present, relative to the serviceable life for the whole service life.

$$v = \frac{(n - a)}{n} \cdot 100 \tag{15.5}$$

v Availability [%]
a Failure time [h]
n Serviceable life for service life [h]

This means that from the quality point of view, it does not make sense to transfer the system immediately into the safe state after any fault event because not all faults are safety-critical to the same extent. Therefore, it is common to categorise the faults and to differentiate the system response. The following fault reaction strategies may apply:

- Limit EPS operation e.g., switch-off partial functions (restriction of the comfort) e.g., reduce the EPS assist power
- Switch to signal substitute values
- Transfer the system softly into the safe state, e.g., slowly reduce the power-assistance, then switch to the safe state.

15.5.2.5 Safety Measures for Subcomponents of the System

To analyse potential fault sources, it is sensible to decompose the system into its parts. The following subsystems can lead to undesirable actuation of the servo motor:

- fault in the external signals
- fault in the sensors
- fault in the microprocessor
- fault in the ECU (including power electronics and software)
- fault in the actuation.

Faults in the following subsystems can lead to a heavy steering

- fault in the engine (e.g., short circuits)
- fault in the ECU (including power output stage and software)
- fault in the actuation.

The fault consequences are classified as ASIL D with regard to 'undesirable actuation of the servo motor' and 'heavy steering'. High requirements to the subsystems are the result, i.e. the necessary safety measures have to achieve an accordingly high diagnostic coverage.

Monitoring of External Signals

The safety integrity of external signals depends on the respective vehicle manufacturer and the model varieties of the vehicles. The safety relevance of the signals read by the vehicle bus is evaluated by a systematic analysis.

If possible, the EPS functions are laid out so that no received signals may impair the safety. If this is not possible, then the steering manufacturer has to define suitable safety requirements for the concerning signals.

In addition, one or more of the following safety measures for external signals are common:

- monitoring time-out
- monitoring message counter
- monitoring check sum
- monitoring value range
- gap monitoring.

To improve the availability (see Sect. 15.5.2.4) of the power-assistance, it makes sense to switch external signals to signal substitute values upon a detected fault event, if possible. Although this can diminish convenience, for example through a higher required steering force, it entails no effects that are relevant for safety.

Monitoring Sensors

The calculation of the desired power-assistance and the control of the servo motor need sensors (see Sects. 15.3.2.5 and 15.3.3). Malfunctions of the sensors immediately affect the resulting power-assistance, hence, a failure to meet the protective targets cannot be excluded if no additional safety measures are taken (see Sect. 15.5.2.2). Monitoring with accordingly high diagnostic coverage has to be installed, matching the sensor design and their signal transmission.

Monitoring Plan of the Computer System

Generally, the EPS functions are computed on a microprocessor with a computer core. The high diagnostic coverage demanded by the SIL classification is often achieved by a 3-level plan to monitor this microprocessor. This plan has proved itself in E-gas and ESP applications. An intelligent hardware unit, called 'safety controller' in the following, is added as a further monitoring level. The implemented software functions are distributed on 3 levels (see Fig. 15.43).

The following functions are executed on **level 1**:

- the steering functions (e.g., sensor read, calculating output values, control of the steering actuators)
- the diagnostic functions for steering (monitoring and testing of system inputs, system outputs, sensors and actuators for specific steering functions)
- the comparison of level 2 and level 1 results (output values have to stay within a permissible tolerance range).

The following functions are executed on **level 2**:

- the diverse algorithms (significantly different algorithms to calculate the output values) for monitoring level 1 steering functions that are relevant for safety
- the comparison of level 2 and level 1 results (output values have to stay within a permissible tolerance range).

Level 1 and level 2 are installed on the microprocessor. The software of these levels can use different calculation resources of the microprocessor (integer unit or floating point unit).

The permissible tolerance range between the level 1 and level 2 results depends on the vehicle and steering layout and has to be gained from road trials in the target vehicle. Faults are purposefully set to identify the requirements and the effectiveness of the level 2 functions. The worst deviation of the output values computed from level 1 and tested on level 2 may only lead to a response of the steering system which can be safely controlled by the driver.

The system diagnostic functions are computed on **level 3**. These safety measures for software and hardware parts to maintain the system integrity are independent from the application. They include, e.g.:

- monitoring the storage areas
- operating the safety controller
- logical and temporal programming flowchart monitoring
- monitoring the operating system
- monitoring the software comparative algorithm (comparing the results from level 1 and level 2)
- testing the microprocessor core
- monitoring the microprocessor and the safety controller by means of a question/answer game.

Level 3 is split in two. One part is installed on the microprocessor and the other part on a separate safety controller. The results of the program parts are exchanged between microprocessor and safety controller by an interface.

If any of the three levels detects a fault relevant for safety, the system enters the safe state.

Monitoring Power Electronics/Actuator

The electric motor to generate the power-assistance for EPS applications differs by power demand and cost requirements (see Sect. 15.3.2).

Malfunctions of the electric motor can immediately lead to the identified system risks (cf. Sect. 15.5.2.2), hence, monitoring with accordingly high diagnostic coverage needs to be provided.

To control the effects of undesirable actuations of the servo motor, the system has to be able to deactivate the power electronics fast enough. The deactivation of the power output stage is intended as a switch-off channel.

All electric motor concepts have to meet the requirements of the safe state (cf. Sect. 15.5.2.3) to prevent heavy steering.

The switch-off of the power output stage may not be sufficient for some electric motor concepts, because a fault event, e.g., a short circuit in the electric motor or in the power electronics may unintentionally induce voltages producing a current. This unintentional current generates motor torques opposing the steering purpose of the driver. In other words, unintentionally braking motor torques can be generated which can cause a heavy steering for some gear ratios of the electric motor to the steering wheel. Without safety measures for these situations, the mechanical steering ability may not be available any more.

The potential unintentional current has to be prevented either by the electric motor used or by additional measures. Some safety measures are:

- exclude motor and inlet short circuits in the design
- avoid currents in the fault case by additional parts (engine/power electronics)
- monitor power electronics/actuator.

Safety-Related ECU Block Diagram

The ECU is responsible for executing the steering functions and all the safety functions of the EPS. The following parts are necessary:

- microprocessor, the core of the ECU
- safety controller for microprocessor monitoring (watchdog function) and for monitoring supply voltages
- non-volatile RAM to store non-volatile data
- quartz clock generation for the microprocessor

- output stage driver to control the parts of the power electronics of the output stage
- output stage to control the motor phases.

A block diagram of this configuration is shown in Fig. 15.44.

From the safety perspective, the hardware architecture is an enabled single-channel system which is controlled by a microprocessor. This unit is monitored by an independent safety controller, allowing good diagnostic coverage. The necessary means for the fault response are provided by the redundant control of the switch-off channels (release signal of the power electronics) which can be operated by the microprocessor, the safety controller or the output stage driver.

15.6 Steering Functions and Control

As discussed in the preceding sections, EPS disposes of an electric motor that feeds mechanical energy into the system. Now it is the task of the steering functions to feed this energy into the system on demand. On-demand means that the energy has to be fed in such a way that the driver's function of driving the vehicle is power-assisted in the best way possible. To meet this claim, the steering functions have to respond appropriately to the driver's intent and to the current movement of the steering system. The driver's intent is registered by the torque sensor. It measures the torque that the driver applies to the input shaft of the steering gear (see Sect. 15.3.3).

The movement state of the steering system is registered by an angle sensor. This signal can be measured by a steer-angle sensor at the steering column, or it can be computed by the rotor position sensor in the steering. The signal of this sensor is notably an absolute steering wheel angle.

The tasks of the steering functions in on-demand supply of mechanical energy can be classified as follows:

- actual steering functions
- control for the steering feel
- control of the electric motor

The torque is defined by the actual steering functions that the driver has to maintain or perform to guide the steering wheel. The response of the free steering wheel can be influenced by steering functions, too.

The control provides the proper supply of mechanical energy. As discussed above, it can be divided into two subclasses: the control for the steering feel and the control of the electric motor. The control for the steering feel assumes essential stabilisation tasks, so that the torque demanded by the steering functions is free of undesirable vibrations and other disturbances.

The control of the electric motor, on the other hand, is responsible for highly dynamic and precise supply of mechanical energy. The stabilisation and high dynamics tasks are closely connected to haptics and acoustics of a steering system, so that any shortcomings significantly affect the system performance in these areas. Too low dynamics of the actuation may cause a too tough response, leading to inert handling of the whole vehicle. Insufficient stabilisation can be the cause of bad haptics, whether slight vibrations in the wheel or an audible system response. For the control of the electric motor, see the standard textbooks, such as Schröder (2009) or Stölting and Kallenbach (2006).

15.6.1 Steering Functions

Based on the control of the steering, it is the task of the steering functions to define the force that the driver perceives while guiding the steering wheel. This includes the static hold of the steering wheel and dynamic situations like steering in and out of a corner. In addition, the response of the free steering wheel is defined by the steering functions, up to functions like automatic steering for parking.

The steering functions have to cover many aspects, so that understanding is improved by a structuring of the steering functions according to their main purpose. The following distinction can be made:

- basic steering functions
- extended steering functions
- functions at vehicle level.

The basic steering functions are those functions which represent the familiar response of a HPS in an EPS. This response is complemented with the extended steering functions that use the specific possibilities of EPS. Finally, in a group with other vehicle systems, like sensors for measuring parking spots or a lane detection camera, functions at vehicle level can be implemented into an EPS.

15.6.1.1 Basic Steering Functions

Within the scope of the basic steering functions, there are four essential functions:

- power-assistance
- friction compensation
- inertia compensation
- damping.

These basic steering functions may be made parametrisable according to speed. In the following, the impact of these functions is outlined and complemented with notes on the parametrisation as a function of speed.

Power-Assistance

The most elementary and most important basic steering function is the power-assistance. Its task is to ensure that the driver does not have to support all the forces applying at the rack by the steering wheel, but that the EPS motor supports an essential part of these forces. How such a function is made and parametrised decides how the relative strengths at the rack are presenting themselves at the steering wheel and, hence, to the driver.

The impact of this function is obvious from the notion that, in a first approximation, there is a quasi-stationary force balance at the rack:

Rack force = i_{steer} torsion bar torque + i_{servo} motor torque (see Fig. 15.45). Here, i_{steer} is the conversion of torsion bar torque into rack force. The corresponding conversion of the motor torque is i_{servo}.

The torsion bar torque is the torque which the driver has to support at the steering wheel, the motor torque is the share of the power-assistance function.

A given value of the rack force can be offset by any combination of torsion bar torque and motor torque (see Fig. 15.46).

The choice of the distribution of torsion bar torque and motor torque decides how the steering feel is perceived by the driver and how much information about force changes can be resolved in the rack. The illustration shows one possible version. Plotting the motor torque over the torsion bar torque according to this diagram yields the power-assist characteristic curve known from hydraulics, see Fig. 15.47.

Information about the expectable feedback quality is gained from plotting the torsion bar torque over the rack force. A steep slope implies that minor changes of the rack force cause major changes of the torsion bar torque. This is perceived by the driver as a good feedback on road condition and bumpiness.

At low speed, especially at rest, the rack forces are highest. At such speed, a differentiated feedback about the road is unnecessary, hence, the power-assistance

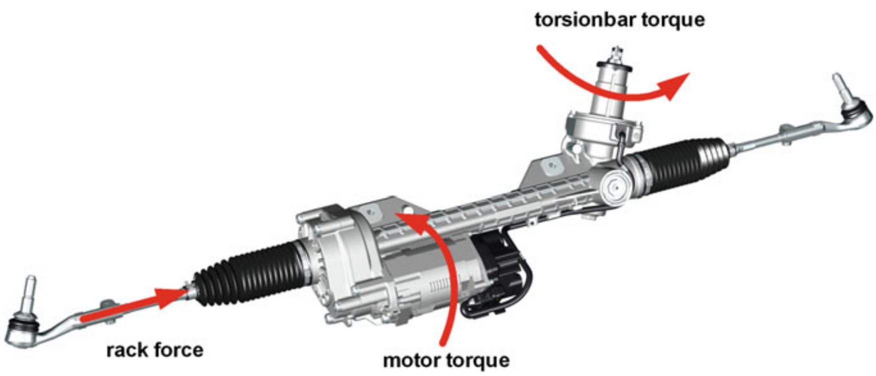


Fig. 15.45 EPS with essential forces acting on the steering system. These forces keep a quasi-statical balance

Fig. 15.46 Balance of rack force and the sum of motor torque and torsion bar torque. The share of the torsion bar torque is enlarged for clarity

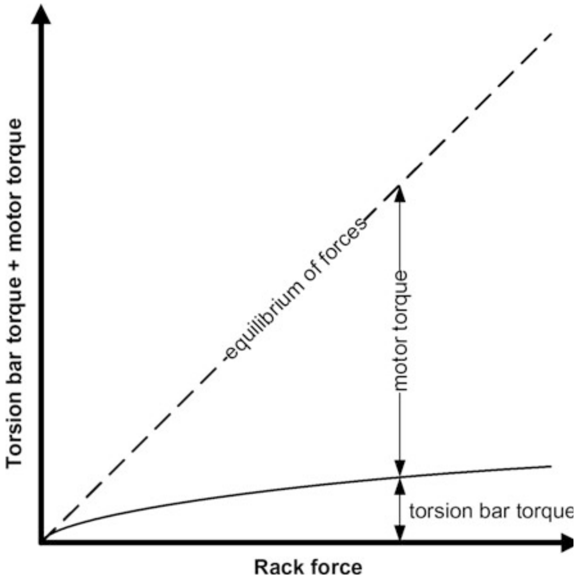
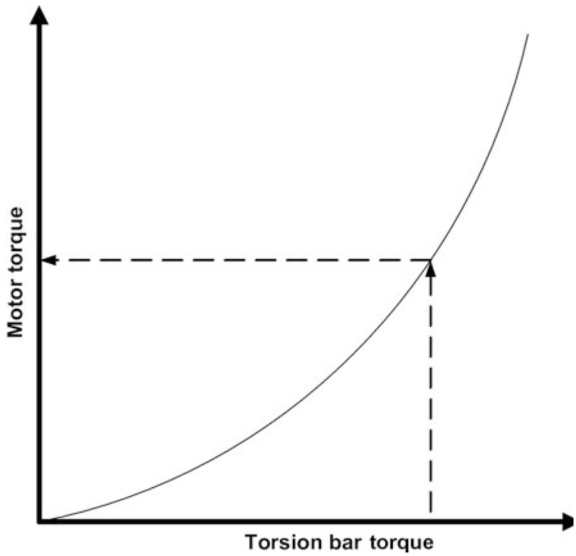


Fig. 15.47 The power-assist characteristic curve shows the motor torque as a function of the torsion bar torque



can be applied in such a way that comfortable steering, end-stop-to-end-stop, is possible. Nevertheless, beyond the low speed range, attention is devoted to the representation of the lateral acceleration or the rack forces in the steering torque, so that the power-assistance has to be applied very differently. One challenge for the application is to create a harmonious transition between both requirements.

Returning to the force balance outlined above, one may notice that this model only applies under the assumption that the steering system is without friction or inertia. Any support of the movable parts of a steering is subject to friction, though, and the movable parts, esp. the rotor of the EPS, have an inertia. Thus the force balance does not fully apply as described. To match the assumptions as closely as possible, the effects of friction and inertia needs to be compensated.

Friction Compensation

The task of a function for friction compensation is to reduce the effects of frictions in the steering with regard to the above-mentioned force balance. This can be achieved by supplying a suitable compensation torque as a function of the current movement state and the torque requested by the power-assistance.

A very simple friction compensation can be acquired by assuming a fixed amount of overall friction. This hypothetical friction moment is always applied in parallel with the current movement or, if the steering system is at rest, in the direction of the torque requested by the power-assistance.

Such a simple way of friction compensation is not very practical, though, because it is very susceptible to measuring noise and does not take changing friction into account. Frictions change esp. from ageing and, even more, because of varying temperatures.

The physical causes for friction in the steering system imply that friction compensation should not be parametrised as a function of vehicle speed.

Inertia Compensation

Typical EPS gear ratios yield an inert mass of several hundred kilogrammes for the movable parts in the steering, relative to the rack. The force balance discussed above does not consider these inertia effects. This entails that dynamic excitations in the rack do not affect the torsion bar torque, and steering movements initiated by the driver always have to operate against this inert mass. A function for inertia compensation has the task to reduce these negative effects of inertia on the steering feel.

Again, a very simple inertia compensation is conceivable. The rotor acceleration can be gained from a differential quotient, based on a measurement of the rotor position or rotor speed of the EPS motor. The current rotor acceleration gained this way can be offset against the overall inertia to yield a corresponding compensation torque. Then it can be requested from the EPS motor in addition to the torque from power-assistance and friction compensation. Such a simple way of compensation is not very practical, though, because it is very susceptible to measuring noise.

The physical causes for friction in the steering system imply again that inertia compensation should not be parametrised as a function of vehicle speed, either.

Active Damping

A friction- and inertia-compensated steering system responds very sensitively to disturbances in the force balance. Excitations from the road lead immediately to a violent acceleration of the system which is perceived by the driver as a kickback. Smallest changes of the moment that the driver applies to support the steering wheel produce powerful movements of the system and, hence, a very nervous steering response.

These undesirable qualities may be reduced by damping the steering system. In an EPS this is realised by a suitable steering function.

A simple way of a damping function requests from the EPS motor a torque that is oriented against the steering direction and proportional to the current steering speed. This way of damping contradicts the notion, though, that the driver's steering manoeuvres should be supported, so that a high-quality damping function has to be much more sophisticated.

A damping function should be parametrised as a function of vehicle speed. At rest, only the righting and the post-pulse oscillation of the steering wheel have to be suitably controlled. At high speed, adequate damping is necessary to prevent the steering wheel from overshooting and the car from fishtailing when the wheel is released in a corner.

15.6.1.2 Extended Steering Functions

Based on the already described basic steering functions, power-assistance, friction compensation, inertia compensation and damping, the EPS displays a steering response that is comparable to that of a classical HPS. Extended EPS functions are not included yet. This is achieved by extended steering functions.

Active Return

The design of modern front axles generates a runback response which is often unsatisfactory, primarily in the low, in the low speed range. Sometimes the axle designs are laid out in such a way that the forces revert well before the mechanical end stop, pulling the steering further towards the end stop.

The task of the active runback function is to improve this response. The basic idea is that the EPS motor adds torques in the straight-ahead direction as a function of the steering wheel angle or the steering movement. Such a function has to guide the free wheel as well as the driver-controlled wheel into the straight-ahead position as desired.

A very efficient variety of such a function can be a wheel rate control, with the nominal steering speed being defined as a function of the steering wheel angle and the vehicle speed. If the peak torque that the function may feed is reduced as a function of the applying hand torque, then the transition from free to guided steering wheel can be purposefully shaped.

Directional Stability Correction

The always present slope of the road towards one side means that the steering wheel is typically not free of torques when it is running straight. The driver has to actively correct to prevent a drift of the vehicle down the slope, i.e. the steering wheel is turned around a small angle when driving straight. Directional stability functions can be applied to relieve the driver from such routine tasks.

If an active runback function is already present, it is obvious that its straight-ahead course could be slightly shifted. Ideally, the straight-ahead course should be shifted by an offset angle until the course-keeping driver can hold the steering wheel free of torques. The setting of the offset angle is crucial for such a function. Note that the offset angle is a dynamic variable. If the slope changes, the offset angle has to follow.

15.6.1.3 Functions at Vehicle Level

A very specific steering feel, matching car and target group, can be achieved with an EPS by the basic and extended steering functions. In addition, the EPS can be integrated as an intelligent and integrated actuator into the context of functions at vehicle level. The role of the steering in the context of some functions at vehicle level will be discussed next.

Park Steering Assistant

The park steering assistant is a function that does not expect the driver to steer, esp. during reverse parking in the kerbs (parallel parking). The driver's task is focussing on throttling and braking, while the vehicle electronics steer the vehicle accordingly. The necessary steering movements are gained from ambient sensors, e.g., ultrasonic sensors, identifying the parking spot and the position of the car relative to the parking spot and other obstacles.

The task of the EPS is to perform the requested steering movements. An internal steer-angle control may be used to achieve this, but not only the steer-angle proper has to be controlled by the EPS. A suitable interface to the involved functional units has to be provided, too. Then this interface and the control have to be secured by a whole series of monitoring functions. It has to be ensured that the interface cannot be accessed during a motorway journey, and an injury of the driver from intervention into the turning steering wheel has to be excluded, to mention only two examples.

Driver Warning/Lane Departure Warning

A frequent cause for accidents on motorways is the unintentional departure from the lane. Often, tiredness or too little attention of the driver is the reason. To attain the attention of the driver when the road is unintentionally left, a vibration of the steering wheel, the driver warning, can be generated by the EPS.

Such functions survey the relative position of the car in the lane using an on-board integrated camera. If departure is imminent, the EPS receives the request to activate the driver warning function. Then the driver warning proper is generated by the EPS applying additional steering torques with suitable frequency and amplitude.

Tracking/Lane Keeping System

A logical advancement of the driver warning function is continuous tracking. Tracking has the purpose not only to warn the driver, but to keep the vehicle in the lane by an active steering control.

Current legal stipulations have to be observed which do not permit autonomous tracking. As a result, the tracking function may assist only if the driver actually controls the steering wheel.

An important aspect is the design of the additional torques. Account has to be taken of the fact that the function should reliably guide the driver in the lane without appearing irritating or even patronising. The tracking function implies that the EPS has an interface to actively control the steering torque. Ideally, an additional torque is directly applied to the steering wheel by this interface.

The application of any additional torques can provoke safety-critical situations. Hence, this interface has to be limited and monitored properly. The limiting has to be made in a way that enables the driver to override the additional torques requested by the tracking at any time.

Dynamic Steering Torque Recommendation

The functions of the dynamic steering torque recommendation is to try to motivate the driver to a specific steering movement by applying an additional torque. When braking on μ-split, the driver can be animated by a short torque impulse to correct on time. The structure of the torque impulse is subject to the same stipulations as the additional torques of the tracking. The impulses are limited so that the driver can override them at any time and no safety-critical situations can develop.

15.6.2 Control Plans for the Steering Feel

The preceding section presented many different steering functions. All of them are based on an underlaid control for the steering feel, by whose help the steering torque that these functions requested is adjusted. Two basic approaches for this basic control of the steering shall now be discussed. The steering control approaches discussed in Sect. 15.6.2.1 convey the principle of the HPS to the EPS. The group of control plans described in Sect. 15.6.2.2 has given up this idea and perceives the EPS as a mechatronic overall system focussing on controlling the torque which the driver feels at the steering wheel.

15.6.2.1 Classical Control Plans

All classical control plans for the EPS have in common that they emulate the functions of an HPS. The basic functional principle of the HPS can be described as follows: a suitable assistance force is applied by the steering as a function of the force applied by the driver. There is no simple linear connection between the assistance force and the driver's force but a progressive connection, see Fig. 15.47. The force applied by the driver corresponds to the torsion bar torque.

From the point of view of control engineering, this structure may be interpreted as a P controller with variable gain and a set point of 0 Nm (see Fig. 15.48). The shape of the classical power-assist characteristic curves implies that the gain factor increases with rising deviation.

A stability analysis reveals that the closed control circuit is unstable. As a consequence, the P controller has to be extended by a stabilising component. How this stabilisation should be made and parametrised is know-how of the steering manufacturer. Two basic approaches are conceivable. The first approach is based on the idea to make the stabilisation so solid that the variable gain can be compensated by the power-assist characteristic curve. The second approach exploits the fact that the current gain is known. Thus the parameters of the stabilisation can be guided, e.g., by tables of the current gain. The resulting control circuit is shown in Fig. 15.48.

It is interesting that the steering feel is not the set point for the control but rather the resulting residual deviation of the P controller, i.e. the power-assist

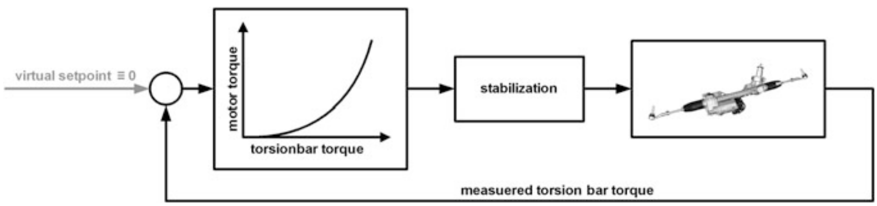


Fig. 15.48 Control circuit with classical EPS control plan

characteristic curve. The control or stabilisation of the steering in these control plans is very closely related to the steering feel. An adaptation of the steering feel always means an intervention into the steering control. Examining the steering functions on vehicle level, that try to impress additional torques at the steering wheel, will show that the context of classical control plans does not contain a direct way of doing so. These qualities of the classical control plans have led to new control plans being developed, these allowed giving the driver's torque as a set point.

15.6.2.2 Control of the Driver's Torque

Considering the task to provide a control for the steering feel will quickly yield the following structure: The variable perceived by the driver, the torsion bar torque, is the control variable, the EPS motor torque is the set variable. The forces acting by tie rods and rack on the steering are interferences, just like the torques applied by the driver to the steering wheel.

Thus the task of the steering control disintegrates into two parts. The first task is the determination of the set point for the torsion bar torque, in other words, the application of the steering feel. The second task is the identification of the EPS motor torque required to adjust this torsion bar torque, i.e. the control of the torsion bar torque. There is thus a distinct separation between steering feel and steering control, with little interaction. This distinct separation of tasks and the structure of the control circuit are shown in Fig. 15.49.

Such a structure demonstrates that additional torques at the steering wheel can be added to the set point for the torsion bar torque (see Fig. 15.49) and then really set.

The design of the torsion bar torque control can exploit the full range of known control unit design methods. The control unit design with LQG/LTR by Henrichfreise and Jusseit (2003) may serve as an example. The most important requirements for the control are performance and robustness. The necessary robustness is profoundly defined by the standard dispersion of production, ageing and ambient influences, such as the ambient temperature.

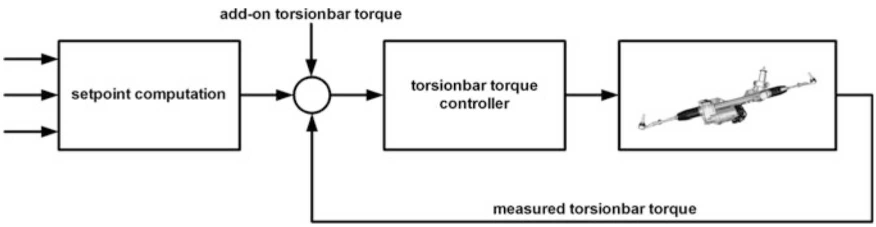


Fig. 15.49 Control circuit of current EPS control plans based on the control of the driver's torque

A main problem of the set point calculation is how to illustrate the basic steering function of the power-assistance in these new control plans. A part of the answer is given by the basic force balance of the steering. Classical control plans define by the power-assist characteristics in what way the power-assist of the rack force should be distributed to motor torque and torsion bar torque. Now it is possible to directly set the torsion bar torque that is supposed to apply at a given rack force. However, the answer is incomplete, because the question how the rack force can be computed is still unsolved.

Immediate computing of the rack force on the basis of the basic force balance is not promising, because this addition of forces always includes friction and inertia effects as well. They lead to rack forces being computed either too high or too low. A potential method for direct computing of the relevant forces is found in Grassmann et al. (2003). Alternative approaches try to interpret the rack force as a lateral force or acceleration (Pfeffer and Harrer 2007), originating in the field of driving dynamics.

The friction and inertia compensation functions are basic steering functions which are no longer needed, because the control adjusts the set point right at the torsion bar, so that intervening frictions and inertia are automatically compensated. The other steering functions can be made as discussed in the section on steering functions. However, the torsion bar torque will replace the motor torque here, so that these functions draw closer to the driver, so to speak.

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