Forward-looking solutions for transmissions in electric vehicles

Transmission concepts for electric vehicles/potentials from system and component perspective

Dipl. Ing. (FH), MBA Matthias J. Derse, Chief Engineer, Neumayer
Tekfor Group, Offenburg;

1. Abstract

Electric mobility is an important development issue at the moment. Customer interest in electric vehicles is huge and all of the major vehicle manufacturers are working on developments in this area. The ranges of electric vehicles are still relatively modest due to the limited capacities of present-day batteries compared with conventionally powered vehicles. The development of a high-efficiency powertrain thus has to be the main objective, especially for electric vehicles.

Assuming a suitable electric engine has been chosen, the main focus of this paper concern the various transmission options available for electric vehicles. It discusses the advantages and disadvantages of the different concepts in terms of efficiency, space requirements and range of applications. The paper begins with a preferential transmission concept before identifying the lightweight design potential of the components and functional development potentials.

2. Introduction

After over 100 years of continuous development and success of the combustion engine in motor vehicles, a paradigm shift is now taking place in the automotive sector. Even if the combustion engine will continue to remain important for the foreseeable future, electric vehicles will assume greater importance in the future. A technological turning point is taking place in the automotive sector. The electrification of engines by means of battery- and fuel cells will be a key element in sustainable mobility as such technology provides 100% carbon-free driving. Supportive measures from policy-makers are evidence of the aim to move away from current CO_2-intensive electricity generation to one based on renewable energies. Electric vehicles thus offer the opportunity to reduce our dependence on oil, minimise vehicle emissions and to better integrate our vehicles within a multi-modal transport system.

Almost all major OEM's are working on 100% electrically powered vehicles. The biggest challenge comes from achieving a range acceptable to the customer. Companies are working intensely on the development of new batteries and alternative means of energy storage. At the same time, increasing the efficiency of the electric driveline is also very important. Issues of weight reduction and optimising efficiency are more important for electric drivelines than conventional engines. Only by fully exploiting all potentials in this field will it be possible to achieve ranges that are acceptable for customers in the foreseeable future.

3. Background: Do electric vehicles need a transmission?

Present-day concepts for full electric vehicles use synchronous permanent magnet machines (PSM) or asynchronous machines (ASM). PSM has a higher torque density, is rugged and thus offers greater benefits in terms of space requirements. The disadvantage of these motors is the complicated manufacturing process and the expected limited supply in magnetic materials for mass production. Current vehicle concepts therefore include both designs. However, the torque and efficiency characteristics of both types are similar to such an extent that, regardless of which machine is used, relatively high-revving electric engines are crucial for an efficient electric driveline. The diameter of the electric engine – for a specified overall length - defines the amount of torque that can be generated. It therefore makes sense to use small, high-revving electric motors and to increase the torque by reducing the speed. The use of high-revving electric motors reduces the weight and space requirement of the electric engine to a minimum. Possible maximum speeds are restricted by requirements on acoustics and bearing technology (including heat, sealing …). At present, electric motors with a maximum speed of 18,000 to 20,000 rpm represent a good compromise.

From these initial considerations, it is apparent how crucial transmissions are for electric vehicles. Based on a wheel speed below 1000 rpm with a vehicle speed of 65 mph, it can be shown that an efficient electric engine requires gear ratios in the range i = 10 to 14. According to Figure 1 however, the efficiency of an electric engine falls at higher

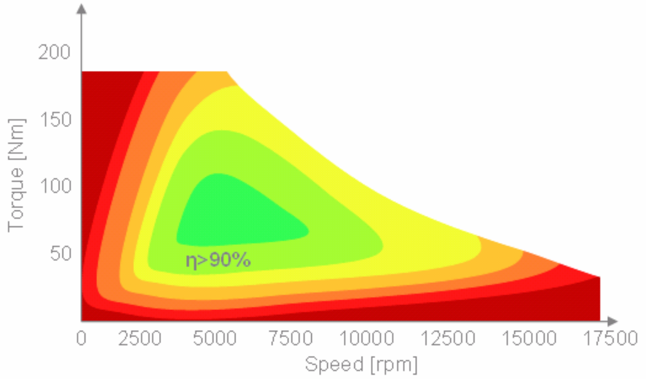


Figure 1: Efficiency of an electric engine [1]

speeds. Concepts with a single-speed gearbox make sense for city cars operating at maximum speeds of 50 mph. However, vehicles with a broader range of application favour a twin-speed gearbox. This is the only way to resolve the essential conflict - acceptable speed and decent efficiency versus high accelerations at lower speeds. According to calculations made by Neumayer Tekfor, using a second set of gears increases the efficiency of the driveline in new electric vehicles by 8 to 10%.

The electric power train of a compact car with single-speed transmission and 150 kW/ 220 Nm may be replaced by an electric engine with 45 kW/ 80 Nm using a two-speed transmission. In this example the acceleration from 0 to 62 mph was given with 8.8 s. This acceleration could be achieved with a peak power of 71.2 kW. To calculate the drive power to reach the maximum speed of approx. 90 mph the following formula leads to the result:

$P*\eta_T = Av + Cv^3$ (P: power, η_T: power train efficiency, A: roll resistance; C: drag coefficient)

The result is approx. 42 kW. In other words, a 45 kW electric engine joint with a two-speed gearbox with $i_1 = 16$ and $i_2 = 11$, can replace a power train using a bulky 150 kW engine and a single-speed transmission with $i = 7$.

Electric vehicles offer various ways of integrating the electric engine. Wheel hub engines allow for the realisation of interesting vehicle designs and modular systems. Integrating the drive in the wheels offers a lot of freedom in vehicle design. The wheels only need to be connected mechanically and electrically to the vehicle's electrical system. Acceleration, braking and recovery can be achieved independently in the wheel drive elements. Even if high-revving electric engines are used optimally, the resulting high undamped masses, represent a challenge in terms of ride comfort. In many applications therefore a single drive with central electrical engine will be the means of choice. The above configuration allows for the development of relatively small drive elements comprising an electric engine and a transmission. These can be positioned directly on the front or rear axle. The classic design with the engine at the front- and rear wheel drive will thus not be used in full electrical vehicles.

These space-saving, electric drive units allow for a variety of vehicle concepts. All-electric vehicles are driven by a single electrical drive module, whereas full hybrid vehicles have a traditional driveline on the second axle. This modular design makes it possible to standardise components, thus making it possible to produce them more economically.

4. Clutch, gearbox and synchronisation of gears in electric vehicles

From the above discussion, an efficient electric driveline needs a transmission. The electric engine is still linked to the transmission unit via a clutch as before, although this does not appear necessary for driving. Since the electric engine - unlike the combustion engine - provides its maximum torque (Figure 2) "from the off", the clutch no longer functions as a starting element. A rigid connection between the rotor shaft of the electric engine and the transmission is easily implemented and can be used in all driving conditions. The clutch, however, assumes a safety function in the event of a failure. In the event of a short-circuit, the PSM generates a braking torque which would have unmanageable effects during driving. Depending on the electric engine chosen and the safety strategy, it may make sense to use a pure isolating clutch [4].

For two-speed transmissions, the implementation of the gearbox and synchronisation in the vehicle needs to be taken into account. We already know from conventional drives that optimal efficiency is only achievable if the transmission shifts into the optimal gear automatically. Switching between two gears is very easy to accomplish with an actuator. Many mechanical components can be dispensed with so that a cost disadvantage should not arise compared to a cable- or rod based shifting mechanism. Based on preliminary investigations made by Neumayer Tekfor, the synchronisation of the rotational speed during shifting can be synchronised by the electric engine [5]. The downshift is the critical instance. Here, the gear and rotor assembly of the electric engine must be made to produce a higher rotational speed against the moment of inertia. Rough calculations for an electric engine with a rated output of approx. 50 kW and a rated torque of 100 Nm produce synchronisation times below 0.4 s. This seems acceptable when compared with conventional engines where the typical slip times of 0.15 to 0.25 s [6] must be added to the time required to engage and disengage the clutch. There are ways to optimise the system by reducing the inertia of the gear assembly and rotor shaft and by increasing the output of the electric engine over a short period of time. It is apparent that further development work is needed in this area. This also explains why some electric drive concepts still use conventional synchronisations. In the medium to long term, however, it is likely that a dog clutch adapted to this use will be used - combining lower costs with greater efficiency.

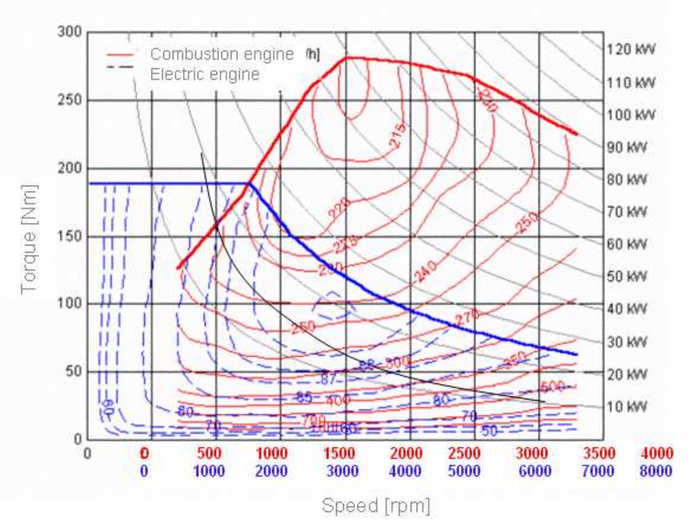


Figure 2: Torque diagram of an electric engine in comparison to a combustion engine [2]

5. Possible transmission types

A basic distinction can be drawn between drives where the engine and drive are arranged coaxially and those in which the engine and drive are arranged in parallel. The advantages and disadvantages of the different arrangements are considered below.

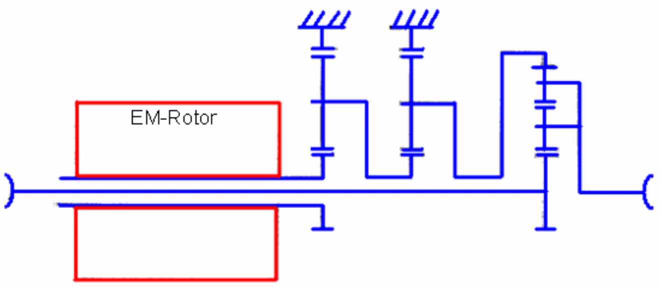


Figure 3: Gearbox pattern of a single speed gearbox with coaxial layout

In the coaxial layout, the drive shaft extends through the electric engine. One possible design is shown for a single-speed gearbox in Figure 3. The two-stage arrangement provides for the necessary gear ratios; the electric engine can be made small enough to eliminate potential ground clearance issues. The relatively large length of these units, however, leads to relatively short drive shafts and thus large bending angles, which works against optimal efficiency. A two-speed gearbox cannot be integrated in the longitudinal axis due to the additional space requirement [3]. Figure 4 shows the gearbox pattern for a spur gearbox with coaxial drive arrangement. The much simpler design is clear to see. The required increase in direction of the vehicle's longitudinal axis is offset by the reduced length. The load on the axle driveshaft joint is significantly reduced. A spur gear even allows for a two-speed gearbox (Figure 5), where the overall length is still less than that of single planetary gear set.

Considering efficiency, the spur gear set again has a slight advantage. Typically a loss of 1% is taken per tooth engagement. This leads to η=0.974% for the planetary single speed transmission and to η=0.98% for the spur gearbox.

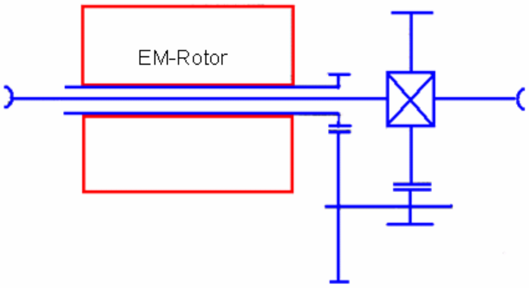


Figure 4: Gearbox pattern of a sinlge speed spurgearbox in coaxial layout

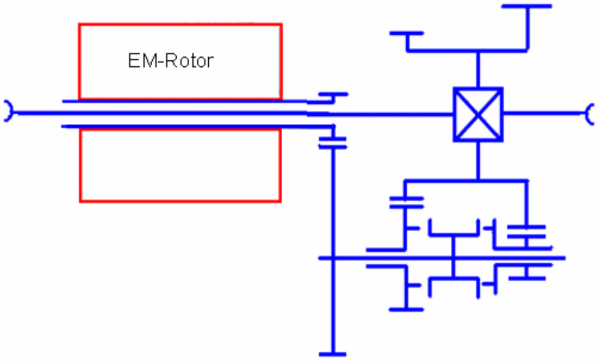


Figure 5: Gearbox pattern of a two speed spurgearbox in coaxial layout

The coaxial layout of electric engine and output has a small radial space requirement. In the concept described in the beginning with electric engine speeds of 18,000 rpm, 40 kW of continuous power can be achieved with an engine diameter of 200-220 mm. The length of these units and sealing the rotor shaft pose problems. Radial shaft seals cannot be used here due to the relatively large diameter of the hollow shaft and the high rotational speeds involved.

An alternative is to arrange the electric engine and transmission in parallel. The space requirement in the direction of the vehicle's longitudinal axis increases; accordingly, the length of the side shafts is the same as the dimensions known for conventional drives. As an example, Figures 6 and 7 show the gearbox pattern for a single- and two-speed gearbox.

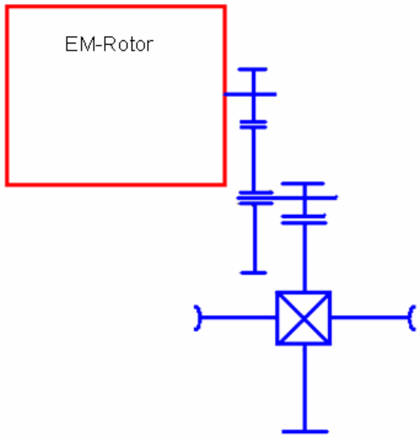


Figure 6: Gearbox pattern of a sinlge speed spurgearbox with parallel layout

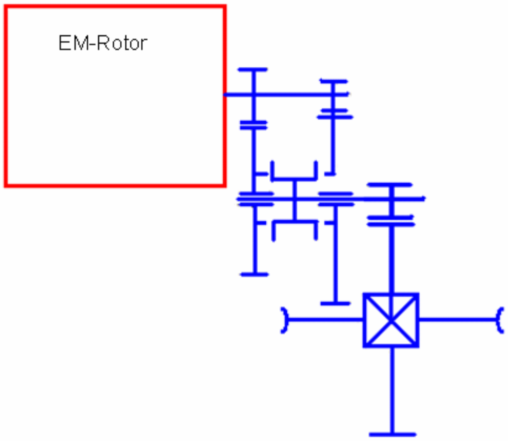
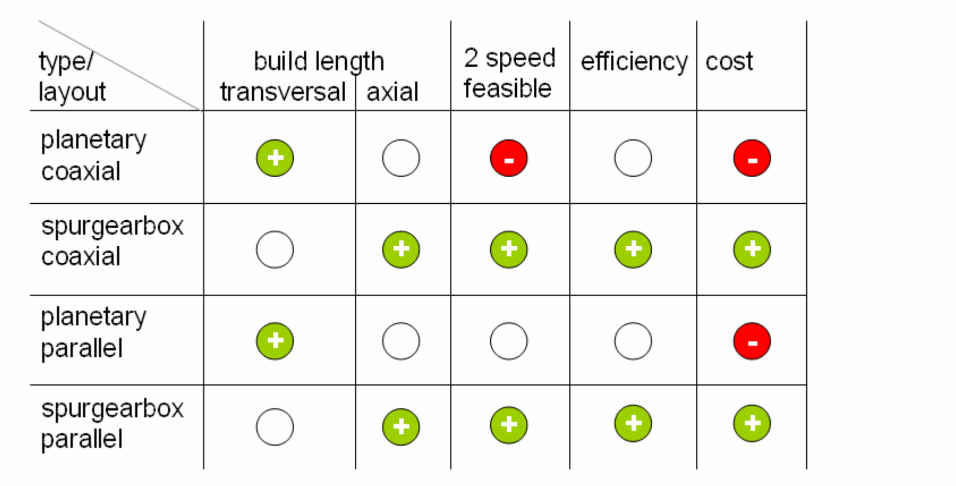


Figure 7: Gearbox pattern of a two speed spurgearbox with parallel layout

The chart in Table 1 illustrates the advantages and disadvantages of the various electric engine concepts. As long as one can dispense with the purely cylindrical dimensions of the electric engine, the spur gearbox offers the simpler solution for the coaxial layout. Based on these considerations, a 2-speed gearbox is only possible with a spur gearbox. The spur gearbox is also recommended for parallel coaxial layouts.



type/ layout	build length		2 speed feasible	efficiency	cost
	transversal	axial			
planetary coaxial	⊕	○	⊖	○	⊖
spurgearbox coaxial	○	⊕	⊕	⊕	⊕
planetary parallel	⊕	○	○	○	⊖
spurgearbox parallel	○	⊕	⊕	⊕	⊕

Table 1: Comparison of different gearbox types and layouts for electric cars

6. Optimising the components of an E-gearbox

Spur gearboxes for electric drives are similar to the gears in a conventional driveline. This has the advantage that existing and established technologies and existing capacity can be utilised, at least in gearbox development. However, some special features of them need to be taken into account. The input shafts reach high speeds, which increases the demands on the tooth system, runout and unbalance. The highest priority has to go to reducing the rotating mass and weight of the transmission in the E-gearbox and further increasing the overall efficiency.

In particular, the input shafts in E-gearboxes differ from conventional gearboxes on account of their higher rotational speeds and lower torques. FEM-optimised shafts have relatively small wall thicknesses (Figure 8). The high rotational speeds place high demands on the unbalance which requires high accuracy in the arrangement of splines to the running gears - for linkage to the electric engine. A method that lends itself to meeting these requirements economically is to precision-forge these components with

Figure 8: Inputshaft for a single speed gearbox of an electric car

rotary swaging and axial forming, followed by turning. By combining the rotor shaft and input shaft in the transmission, there is the additional potential to lower system costs while improving quality.

As noted above, there is a particular potential in reducing the rotating masses. With the gear wheels, it is possible to use a reduced weight spoke design, such as those used in a similar form in modern dual-clutch transmissions. The weight can be reduced by up to 25% compared to conventional designs (Figure 9).

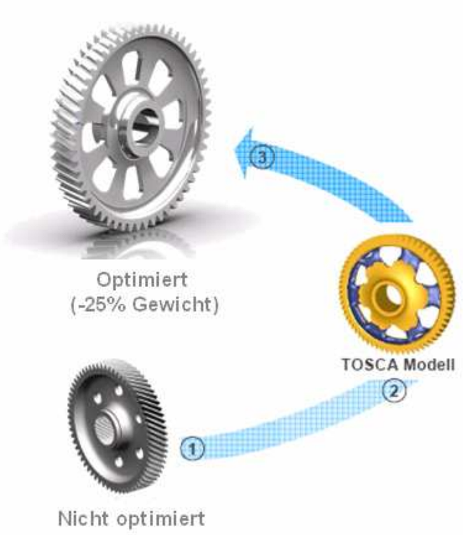


Figure 9: Optimisation of gears of an E-gearbox

The TEKMOUNT® process patented by Neumayer Tekfor provides an optimal component joining. The gear wheels are joined to the shaft using a longitudinal press fit. A spline can be dispensed with due to the efficiency of the process, significantly improving the runout of the assembly as a result. In many cases, the teeth can be machined for immediate fitting prior to mounting. The special feature of this process lies in the specially developed separator liquid which allows the components to be assembled at room temperature. Since the torque that can be transmitted in the longitudinal press fit is directly proportional to the mounting force, there is 100% supervision in the process. Unlike shrink fit joins, no costly post-process inspections are necessary. The process has already been tested in continuous test runs and has demonstrated its efficiency with torques up to 3000 Nm.

Another interesting solution is the caseless differential, N$^{\text{T®}}$ LightDiff [7]. Its special design enables very convenient, space-saving integration into a transmission for electric vehicles (Figure 10). As these transmissions are currently being designed from scratch, a central alignment of the set of bevel gears in the ring gear can be achieved from the outset. The weight of the differential is reduced by around 1.5 kg and the space requirement by around 20%. Neumayer Tekfor is currently testing the differential and it is likely to be available for shared customer development projects in 2011.

Figure 10: Gearset for an E-gearbox with N$^{\text{T®}}$ LightDiff

7. Summary and Outlook

The electric engine will become more important in the future. A modular vehicle design allows all-electric and hybrid vehicles to be realised using standardised systems. Using transmissions in electric engines will be essential to achieve optimal efficiency. The decision to go for single-speed or two-speed concepts will depend on how the vehicles are used; in most cases spur gearboxes represent the simpler and more flexible solution. These spur gearboxes will have a simpler design compared with conventional transmissions; although the specific requirements for the E-gearbox will still need to be taken into account. It is important to develop lightweight, cost-effective components with small space requirements. Lightweight gear wheels, hollow shafts and TEKMOUNT® joining process provide optimised gearsets. The N$^{\text{T®}}$ LightDiff offers additional potential for reducing the weight and space requirement of the transmission.

One development approach involves the design of special dog clutches that provides for shifting in two-speed gearboxes together with an optimised control unit. This means the traditional method of synchronisation using friction surfaces can be dispensed with, further reducing the weight and increasing efficiency.

There is research potential in the use of composite component solutions for gear wheels and shafts. Together with the University of Technology Munich, Neumayer Tekfor is looking at the possibilities of using gear wheels in a hybrid design made of plastic and steel. These wheels offer a further reduction in the rotating mass and the potential for noise reduction, especially in high-rev E-gearboxes. Neumayer Tekfor plans to present the initial results of this work next year.

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