How to Get the Most Realistic Efficiency Calculation for Gearboxes

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Introduction

In recent years the estimation of gearbox power loss is attracting more interest — especially in the wind turbine and automotive gearbox industry — but also in industrial gearboxes where heat dissipation is a consideration as well. As new transmissions concepts are being researched to meet both ecological and commercial demands, a quick and reliable estimation of overall efficiency becomes inevitable in designing the optimal gearbox.

Having a closer look at the efficiency calculations for gearboxes, the calculations are relatively well-defined for the gear mesh loss, and plunge or churning losses in the standards, such as ISO 14179. However, the efficiency calculations for the many other machine elements, i.e. — clutches or synchronizers — are relatively new concerns with no as yet established standards, although there exist several pioneering works. The research is still ongoing, and thus far the power losses can be approximated most exactly only by using data maps from measured power losses from a reference gearbox on test rigs. In short, the designer is faced with this task: achieving the most realistic efficiency calculation for gearboxes.

These demands present a major challenge for the software supplier. In response KISSsoft implemented a special template in *KISSsys* to automate the efficiency calculation and thermal rating of a whole gearbox — including gears, shafts, bearings, seal, discs, synchronizers and other machine elements. The template includes two parts; 1) the calculation of the power losses, and 2) the calculation of heat dissipation — both using calculations from standards set by ISO, AGMA, VDI, as well as from research works produced by academia and industry.

Along with the standards, other data sources are needed. So for gear losses the local contact analysis delivers very detailed results, including the microgeometry; as well, the interpolation using measured power loss maps is available. The template has been proven by the comparison with the actual measurement data from our customers in close cooperation with us.

In this paper the overview of the standards for the power loss calculation is shown and applications for an industrial and automotive gearbox are explained with the achieved results.

Application of Thermal Rating for Industrial Gearboxes

The development and production of industrial gear units are subject to considerable general cost pressure that requires gear manufacturers to design their products for maximum efficiency — especially from an economic viewpoint.

The factors involved in the conservation of resources and environmental protection are playing an increasingly significant role in the manufacture and operation of gear units. Interest in monitoring Total Life Cycle Costs is growing among machinery and industrial operators, and is a factor that must also be addressed by gearbox manufacturers. For this reason, gearbox manufacturers now need to conduct thorough investigations into all the relevant influencing factors, such as:

- Production processes (manufacturing costs)
- Gear unit usage (operating costs)
- Service life (operating costs)
- Maintenance (operating costs)

The need to reduce energy losses, and therefore minimize operating costs, is gaining in importance as one of the targets designers must meet when designing gear systems. Energy losses typically manifest themselves as increased operating temperatures that often limit the performance of fast-running, compact gear units. Gear units with low levels of energy loss are not only less expensive to run, but also have less impact on the environment. In addition, customers often ask for exact details about surface temperatures and efficiency as the specific values for a gear unit.

In order to meet the requirements described above, it must be possible, even at the design stage, to specify product characteristics accurately and effectively. The standards developed in the field of mechanical strength calculations provide a broad basis of data which the *KISSsoft* calculation platform, with the added functionalities provided in *KISSsys*, has implemented in a system that is not only comprehensive, but also very user-friendly.

For these reasons KISSsoft AG and ZAE-AntriebsSysteme GmbH & Co KG have been working together to develop a generally applicable calculation tool — within the *KISSsys* system — that can be implemented to determine the power loss and temperatures present in a gear transmission unit.

Calculation of power loss and thermal rating. ISO Technical Report 14179 (Ref. 3) can be used as the basis for a general calculation for determining temperature and power loss in complete gearbox systems. This report contains the basic data required to ascertain the specific losses for the various different machine elements, which can then be added together to determine total power loss. The newly developed calculation tool can also handle calculations defined in other current standards, such as ISO/TR 13593, AGMA 6123-B06, SKF 1994 and 2004, and VDI 2241.

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The heat dissipation calculation covers the heat dissipated via the housing surface, through the base, and the rotating parts, such as shafts and couplings. In it, the user can input more detailed information, for example, about the properties and condition of the surfaces to improve the accuracy of the calculation. The heat dissipation calculation uses the results of the power loss and temperature measurements at the thermal equilibrium, together with data about the ability of the gearbox to absorb heat, to mathematically calculate the temperature progressions and equilibrium temperatures.

A central point in this calculation is the option for users to modify the approach used to calculate individual losses and heat dissipation in order to suit their own specific requirements. In future, the interdependency of the power loss during operation and the operating temperature this generates will also be taken into account. This requires an iterative process to be applied to the calculation of temperature and power loss.

Practical application. The power loss and temperature calculation was applied to a gearbox (Fig. 1, left) recently developed by the company ZAE. The gearbox in question is a three-stage cylindrical bevel gearbox from the latest series, which has a nominal torque of 1,200 Nm. At present this series is produced in four different sizes, with a transmission ratio that ranges from 10:1 to 200:1.

KISSsoft's newly developed calculation tool was then used to calculate the power loss and operating temperature. To achieve this, KISSsoft designed the required gearbox model (Fig. 1, right) and supplied it with the necessary parameters.

The cylindrical bevel gearboxes underwent numerous measuring tests that recorded the temperature of the oil sump and the surrounding environment (Fig. 2). The associated levels of gearbox efficiency were measured at the same time.

To analyze how the gearboxes reacted under load, the operating conditions for the test series were set up in such a way as to ensure that all influences on speed and torque could be clearly identified. The results of these tests were then used as the basis for scaling the calculation model (Fig. 1, left). The sophisticated approach applied here made it possible to modify the power loss and temperature calculations in *KISSsys* to accurately reflect the situation in reality.

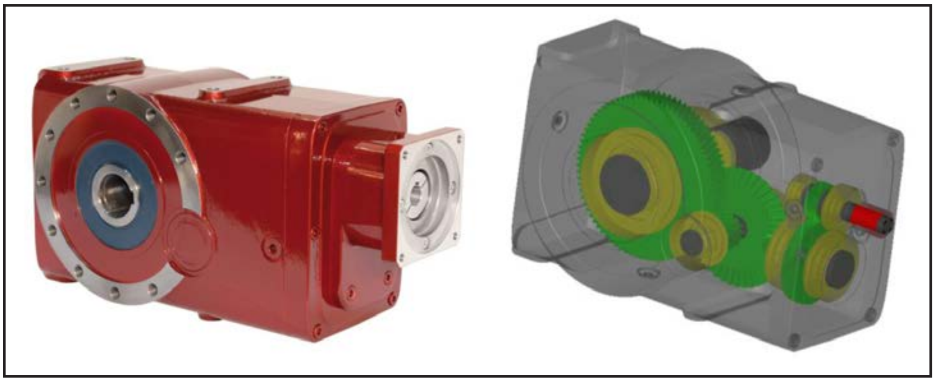

Figure 1 **ZAE cylindrical bevel gearbox and *KISSsoft* model.**

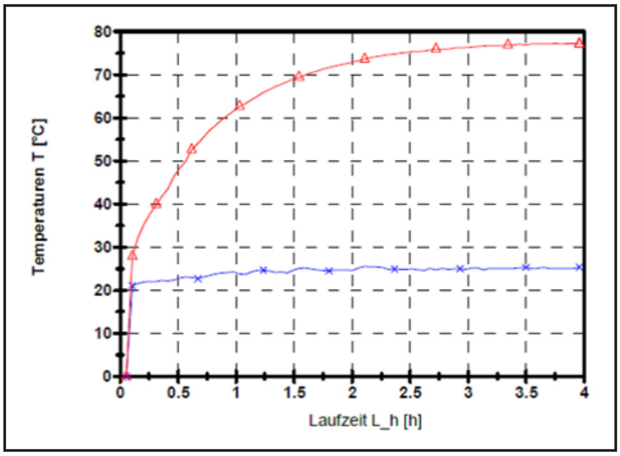

Figure 2 **Test result (temperature progression) of gearbox (red line) and ambient temperature (blue line).**

After being modified in this way, the calculation provided results that were very close to reality. These results then formed an excellent basis for the calculation module applied to other gear units. In future this calculation basis will also make it possible to size and optimize any type of gear unit.

Efficiency Calculation of Automotive Transmissions

Parallel to the industrial gearboxes, the automotive branch needs to focus on fuel economy and emission reduction in automotive transmissions, for example through hybridization or a higher number of gears and larger gear spread. Finally then analyzing and optimizing the efficiency can make a major contribution to reaching future CO_2 limits. In cooperation with IAV GmbH, one of the leading development partners to the automotive industry, KISSsoft AG developed a tool for analyzing, evaluating and optimizing transmission losses.

This paper uses an IAV 7-speed dual-clutch transmission to explain the process for efficient calculation of the transmission's overall efficiency. The primary focus here is on the automated generation of speed- and load-dependent power loss maps which can be used in subsequent cycle simulation. The modular approach to calculating individual losses provides the capability of performing detailed analyses by loss drivers and of validating optimization measures in a simple way.

Based on *KISSsoft* and *KISSsys* software, this calculation method is therefore a helpful tool employed throughout the development process—from concept phase to production layout stage. Combining IAV's experience with calculation tools from KISSsoft resulted creates a toolbox that can be widely used for practical cases.

Dual-clutch transmission IAV 7DCT280. The seven-speed dual-clutch transmission IAV 7DCT280 is a structurally optimized modular transmission in front-transverse design for compact and mid-size vehicles. Compared with current six- and seven-speed transmissions the mechanical components can be reduced to just one main shaft and one countershaft to provide the seven forward speeds. The package for the otherwise conventional

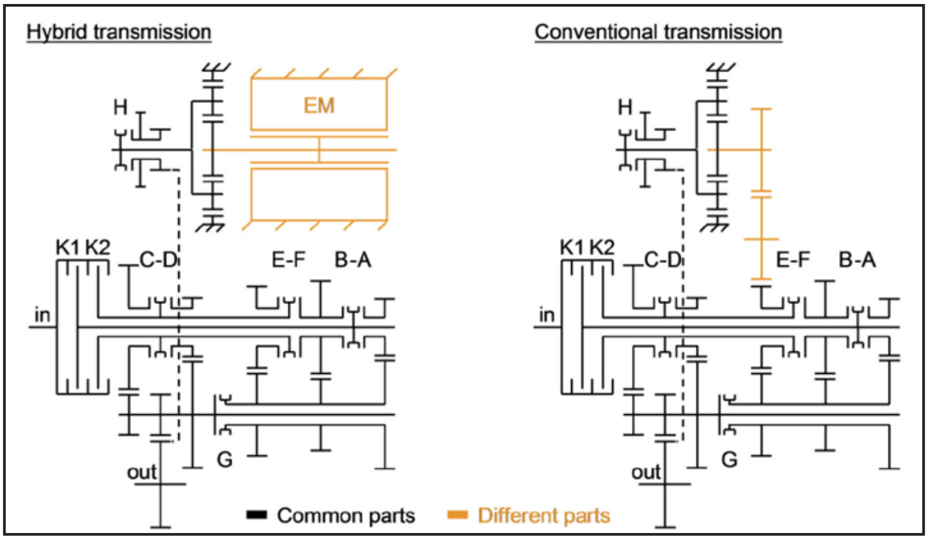

Figure 3 Modular transmission system of the 7-speed hybrid DCT (left) and the 7-speed DCT with mechanical reverse speed (right).

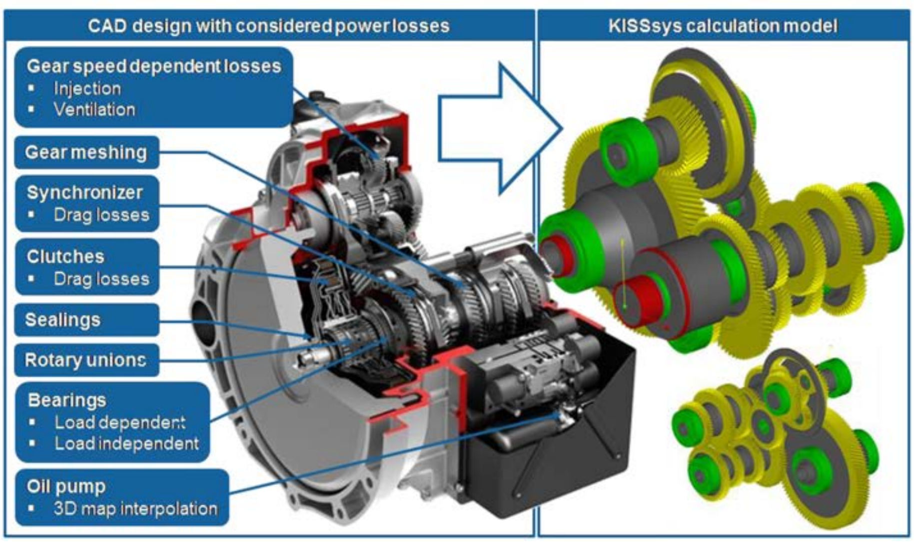

Figure 4 Considered power losses (left) and KISSsys calculation model (right).

second countershaft can be used on a modular basis to integrate an electric traction motor for various hybrid functions, or the mechanical components of a classic reverse speed (Fig. 3).

In the hybrid variant the electric motor is linked to the differential gear via a second output stage (Fig. 3, left). A planetary gear set serves as a booster stage for the electric motor, supplying the hybrid system with high levels of wheel torque — even at low vehicle speeds — and also helping to achieve better efficiency ranges. Synchronizer H provides the optional capability of disengaging the electric motor from the rest of the powertrain to protect the motor at higher vehicle speeds or in the event of a fault in the electric system.

In the conventional transmission variant these elements can be carried over in support of the commonality concept that is aimed for. The mechanical reverse speed is provided merely by replacing the electric motor with a set of spur gears connecting the main shaft's center gearwheel with the sun gear shaft of the planetary transmission (Fig. 3, right). This transmission structure is also shown to provide a high level of flexibility in its ratios, gear steps and spacing in return for slight modifications to the gear set ratio steps (Ref. 1).

Further investigations regarding power losses will be done on the basis of the conventional variant with reverse speed and without hybrid functions.

Model set-up and power loss maps. A calculation model under *KISSsys* (Fig. 4, right) is used to compute transmission power losses. At this system level all kinematic and kinetic interactions between the individual machine elements in the overall transmission are taken into consideration. This means that the most important prerequisite for automated generation of gear-dependent power loss maps is already fulfilled. In addition, the *KISSsys* model is complemented to include the loss modules. As in many cases a *KISSsys* model is already available for dimensioning of the machine elements, power losses can thus be calculated without major extra modeling work.

The analysis claims to be able to calculate the overall transmission efficiency in an integrated way; this is why all relevant loss sources are factored in. These are losses produced by gear meshing; churning and ventilation; drag torque at the synchronizer units and disengaged multi-disk clutches; by radial shaft sealing rings; rotary unions; and bearings as well as by the oil pump's power consumption (Fig. 4, left). The calculation methods to ascertain the different types of losses are based on relevant standards and dissertations or publications. Furthermore, there is great flexibility to choose different approaches for calculating individual loss sources.

The load-dependent losses caused by gear meshing are calculated on the basis of the proposal presented by Niemann/Winter (Ref. 2). In addition, contact analysis can be used to define the optimum microgeometry using profile and tooth trace modifications. A multitude of calculation methods is available for load-independent churning, squeezing and ventilation losses. The rules defined in standard ISO/TR 14179-2 (Ref. 3) are used to determine the losses occurring in the injection lubrication implemented in the dual-clutch transmission. The injection volume flows at the tooth contacts are assumed to be 1 l/min for the gear pairings and 2 l/min for the constant gear ratios respectively.

In the same way as for the gear teeth, a distinction is made for load-dependent and load-independent losses caused by the bearings. These are taken into account on the basis of the information provided in the SKF bearing catalog 1994 (Ref. 4). Alternatively, the new SKF 2004 method (Ref. 5) can be used, which attributes frictional components in relation to their cause.

The losses of the elements as non-actuated synchronizer units, radial shaft sealing rings and open multi-disk clutches are determined by individual literature sources, as i.e. Rao (6).

The power consumption of the oil pump depends to a large degree on the hydraulic concept implemented. This is why it is expedient to describe the pump's power consumption with the help of a map. The map can be defined using interpolation points and saved to *KISSsys*. Linear interpolation serves to ascertain power consumption at individual operating points.

After reading in maps up to the third dimension, proprietary analytical approaches can be defined as well. The first step consists of analyzing a concept with a constant-feed pump connected on the drive side to secure actuating pressure, lubrication and cooling oil demand. Although the IAV 7DCT280 uses a more efficient system, the following section will outline the potential improvement that can be achieved, starting from this basic version often used.

After incorporating all relevant losses in the computation model, automated generation of power loss maps can start for all gears, as well as for the individual components. The maps are generated incrementally based on a grid and a predefined engine speed and torque range for the internal combustion engine. Figure 5 shows the maps for the seventh gear of the dual-clutch transmission investigated here.

The maximum efficiency is 94.1% in seventh gear at low intake engine speeds and high torque. With rising speed and decreasing torque, efficiency drops, as was to be expected. On the one hand, this trend can be explained by the progressive development of speed-dependent losses due, for example, to bearing- and injection-related losses as well power consumption of the oil pump. The drop in efficiency at low intake torque is attributable to load-independent losses that constitute a constant variable at a defined engine speed.

Optimization measures for gears. After the cycle simulation (here the

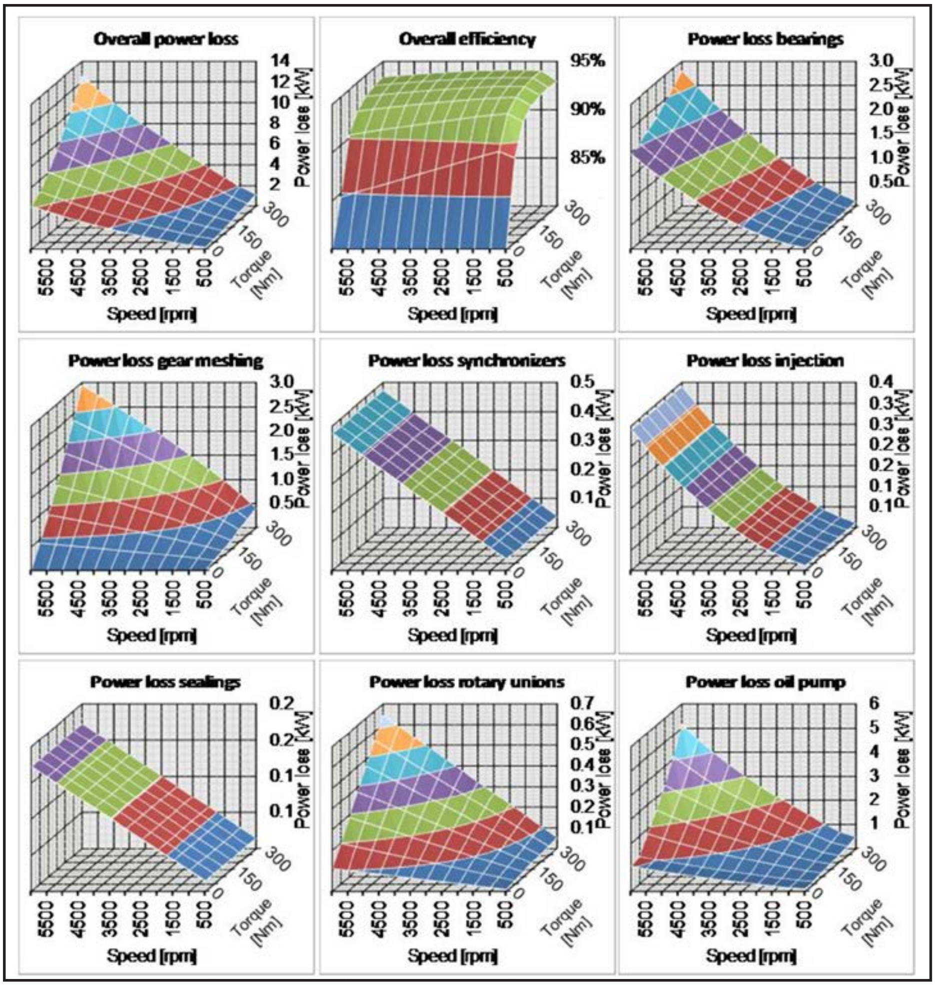

Figure 5 Power losses and efficiency maps of IAV 7DCT280 in 7th gear at 60° Coil temperature.

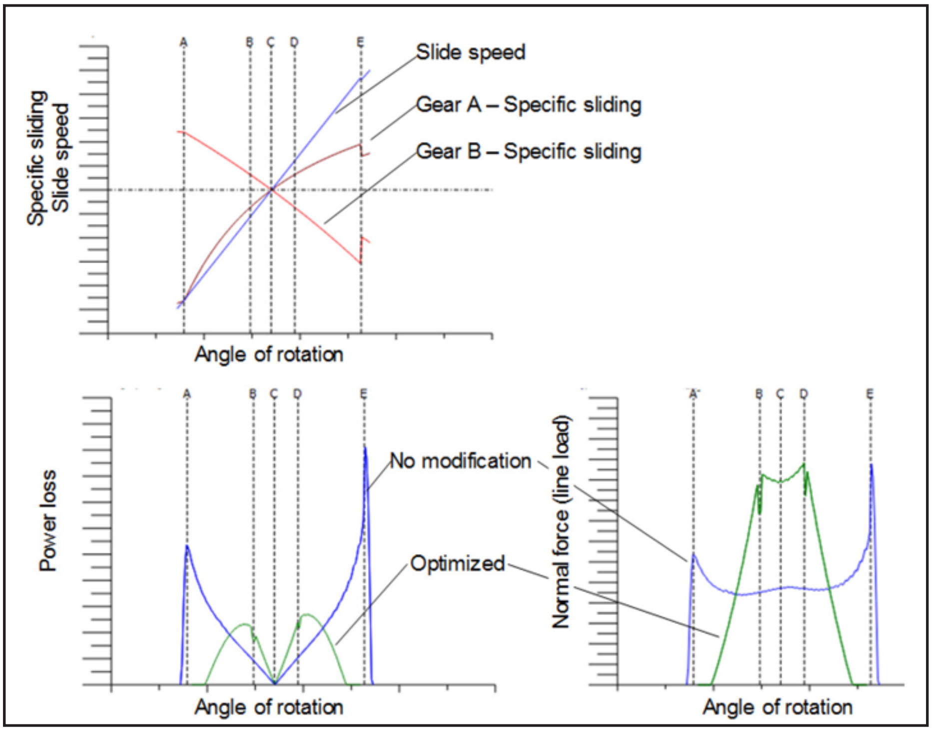

Figure 6 Sliding speed, local power loss, and normal force.

NEDC was applied) and analyzing the distribution of transmission losses, it was found that the actuating concept, the gear teeth, bearings and synchronizers harbor the greatest optimization potential for reducing CO_2 emission.

With a view to reducing gear meshing losses, the goal is to modify the design philosophy. The basic design exhibits a distribution between contact and overlap ratio of $\varepsilon\alpha = 2$ and $\varepsilon\beta = 1$ in order to meet the acoustic requirements. As the power loss mainly depends on the contact ratio, a new design with a distribution of $\varepsilon\alpha = 1.5$ and $\varepsilon\beta = 1.5$ is produced. With the same overlap ratio, a noticeable increase in efficiency is to be expected at the cost of acceptable acoustic disadvantages.

The reviewed gear teeth layout with a contact ratio of $\varepsilon\alpha = 1.5$ allows gear meshing losses to be reduced by 28 W. As axial forces increase as a result of the simultaneous rise in the helix angle, the benefit is partly offset by the bearing-related losses that are 5 W higher.

A possible next step in reducing the gear meshing losses consists in elaborating an alternative distribution between gearwheel transmission ratios and final drive transmission ratio. Using the transmission variant generator in *KISSsys*, a solution with lower, final drive transmission ratio and hence higher gearwheel ratio can be identified for the IAV 7DCT280.

Above and beyond the optimization measures described above, gear meshing losses can be further reduced by appropriate gear teeth modifications, using the load-dependent contact analysis in *KISSsoft*. Among others, the analysis ascertains friction torque at each meshing position based on contact simulation. As local losses depend on sliding speed and friction force, profile modifications and a resulting redistribution of meshing forces can reduce friction losses.

KISSsoft provides a specific sizing function for the gear modification. This function varies modifications within predefined limits, ascertains all possible combinations of up to three sets of modifications and carries out a contact analysis for each variant. At the same time it is possible to vary load as contact behavior strongly depends on load.

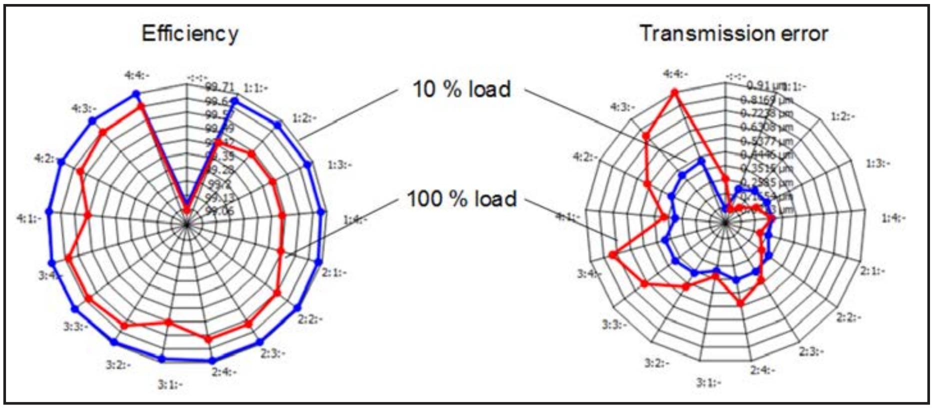

Figure 7 Radar charts for efficiency (left) and transmission error (right).

The results are visualized in clear form in radar charts, allowing several parameters to be reviewed simultaneously. This enables the engineer to determine the optimum combination of modifications for the case at hand. Figure 7 shows two radar charts, the left-hand one depicting efficiency, the right-hand one the transmission error. Here, variant 3:2 would constitute a good compromise exhibiting high efficiency (99.6% instead of 99.06%) and moderate transmission error.

Summary

The applications shown above represent the various but also different demands in efficiency and thermal rating calculation for gearboxes.

Whereas the industrial gearboxes include mainly machine elements for which the calculation methods already established and focus on thermal rating finally, the vehicle industry needs to meet the demands on CO_2 reduction targets and hence the efficiency calculation is important. However for many machine elements in automotive gearboxes no calculation methods are provided yet.

The calculation of the transmission power losses is based on a *KISSsys* model. On this system level all kinematic and kinetic interactions between the individual machine elements are taken into consideration. Beside many calculation standards the *KISSsoft* tools allow the possibility to check also about other criteria as gear strength (as, i.e., in case of changing oil viscosity for lower plunging losses) or noise (as, i.e., evaluating the transmission error in parallel to the efficiency of gears).

The process chain presented in this paper is suitable for both efficient evaluation of different transmission concepts and detailed optimization studies on existing transmissions. The calculation method based on KISSsoft and KISSsys is a helpful tool which is employed in the entire development process from the concept phase right through to the production layout stage. **PTE**

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