Integrating of the Auto Shift Gearbox with the electrical machine

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Introduction

Against all predictions, manual transmissions still have in Europe a market share of more than 80%. This can be attributed to the high efficiency and the small space required for installation together with low weight and low cost.

In the meantime, there are indications that the manual shift transmission can be successfully automated and thus additional advantages can be gained at very little expense.

The basis was the automatic clutch, as provided by LuK and Bosch for the Mercedes-Benz A-class. In the meantime, we have the first Auto Shift Gearbox (ASG), which is based on a manual shift transmission [1], [2]. Eliminating the interruption of the tractive force during shifts promises major potential for improvement.

As shown in other lectures, not only can the starter generator fulfill the demands of future on-board electrical systems, but major energy-related advantages can also be achieved. According to calculations by LuK, energy savings as high as approx. 20% can be achieved in comparison to the currently available manual shift transmission, thanks to the start-stop automatic system, and the recovery of braking and coast energy [3] to [7].

By combining the ASG and the starter generator in an intelligent manner, LuK is aiming to achieve more than just the sum of the advantages of these systems – the goal is also to eliminate the interruption in the tractive force. LuK calls such a transmission Electric Shift Gearbox (ESG).

Arrangements of the starter generator in the ASG

Figure 1 depicts an overview of the different possible arrangements for the electrical machine in the drive train with a manual transmission.

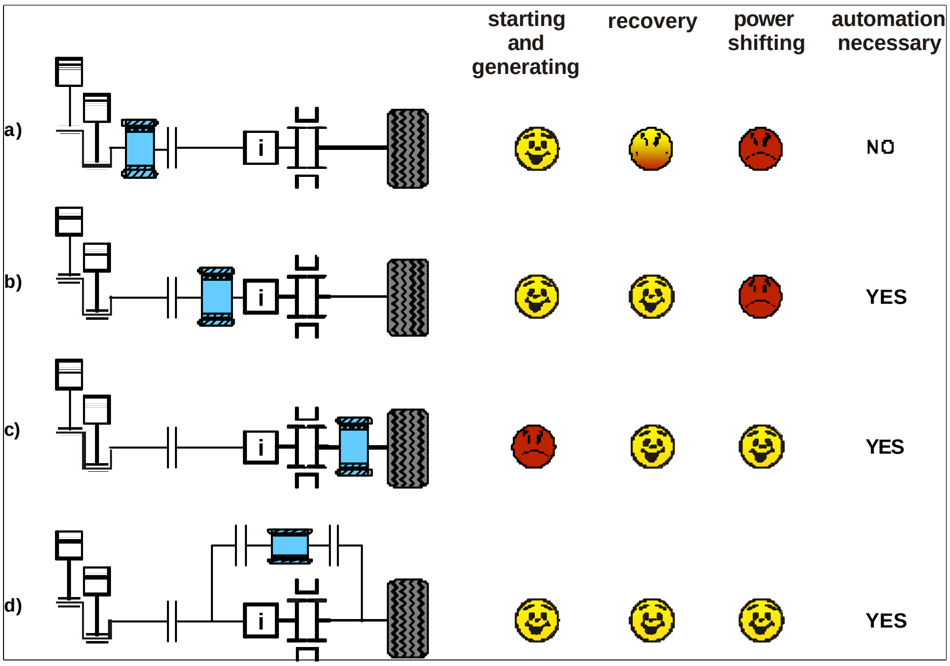


Figure 1: Arrangements of the starter generator in the drive train

In the first possibility, the **starter generator** can be attached **to the crankshaft** (Figure 1a). With this arrangement, starting and generating are possible. In principle, recovery is also possible, however, it does not utilize the full potential of the starter generator, since the internal combustion engine must always be rotated.

The electrical machine can be placed onto the **transmission-input shaft** (Figure 1b). To do so provides the advantage that the electrical machine can be disengaged from the engine, therefore allowing the full potential for recovery. In comparison to the previously mentioned solutions that were attached to the engine side, the potential saving is approx. 10% higher.

The internal combustion engine can be started either with an engaged clutch directly or with an impulse start, where the starter generator is accelerated first and the clutch is subsequently engaged. Thus, the electrical machine does not have to deliver the maximum drag torque at low temperatures, what allows the use of a smaller electrical machine.

For this solution it is necessary to automate the manual transmission, since to start the vehicle, it must be taken out of gear and the clutch has to be engaged; and to recover, the vehicle has to be put in gear and the clutch has to be disengaged.

By keeping the electrical machine on the input shaft, the weak point of the ASG – an interruption of the tractive force during the shifting process – is retained.

To change this, the **electrical machine must impinge on the power take-off train,** (Figure 1c). In this case, recovery is also possible. Here, too, a connection with an automated clutch or an Auto Shift Gearbox is required. With this arrangement, however, the internal combustion engine can no longer be started with the electrical machine, and a generating process is possible only during driving.

In order to fulfill all requirements, i.e., starting, generating, recovering and power shifting, the **electrical machine must be able to either affect the input shaft or the power take-off** (Figure 1d).

Therefore, the desired consumption advantages and starter generator function can only be achieved if the electrical machine can affect the transmission input. Therefore, we will concentrate only on variations 1b and 1d.

Shifting gears using individual synchronizations

Having the electrical machine on the transmission input shaft, the challenge lies in the shifting process. To illustrate this, we will first describe the shifting process of an Auto Shift Gearbox (ASG).

On the right side, Figure 2 depicts (using symbols) the drive train with the manual shifting transmission, i.e., the ASG. The clutch connects the internal combustion engine and the input shaft. Between the input shaft and the output shaft two toothed gear pairs act with different ratios and a shiftable dog clutch. A single synchronization affects each dog clutch. A tire at the output shaft symbolizes the vehicle mass.

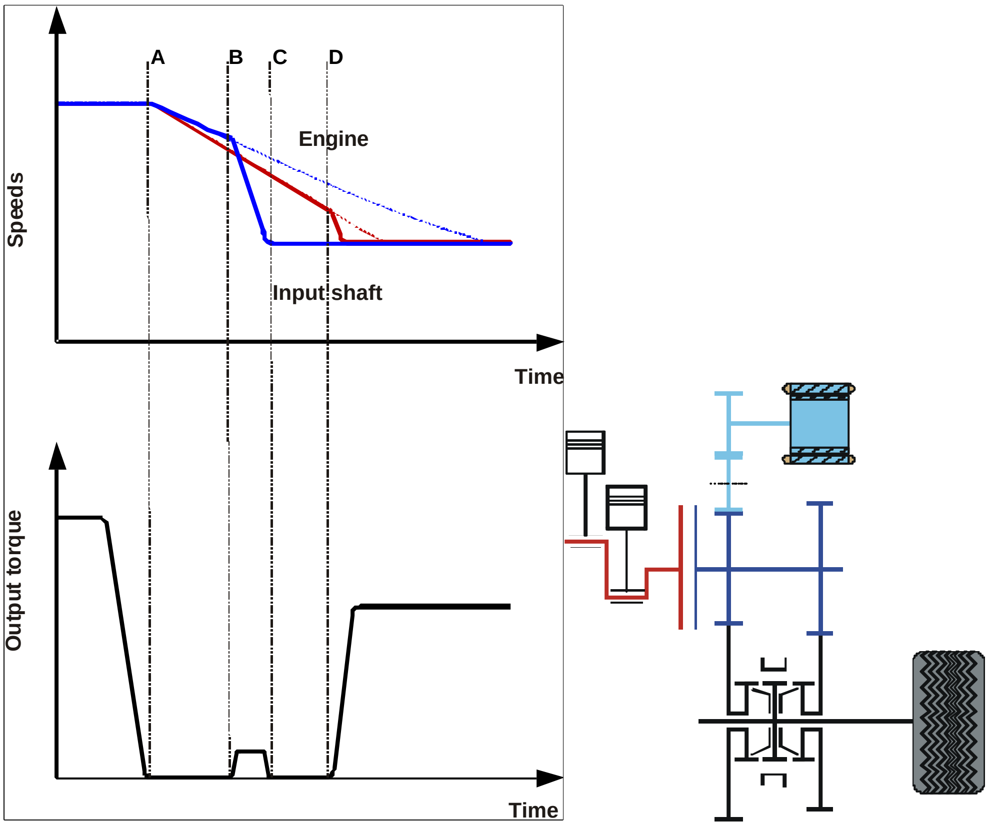


Figure 2: Up-shifting the ASG using individual synchronization

In the top diagram in figure 2, the speed characteristics of engine and the input shaft are depicted over time; and in the bottom diagram, the corresponding torque at the drive shaft.

What happens during the shifting of the gears? First, a look at the process without the starter generator.

In order to release the dog clutch of the old gear, the torque at the transmission input is reduced to zero (point-in-time A). To achieve this, the engine torque is decreased and the start-up clutch is disengaged, which has a direct effect on the output. The transmission input shaft and the internal combustion engine are decelerated very slowly. By synchronizing the process at the dog clutch of the new gear, the gear input shaft is very quickly brought to the speed level of the subsequent gear via the synchronization on the dog clutch of the new gear (range from B to C). Then the new dog clutch can be engaged (Point D). Finally, with the help of the start-up clutch, the speed is synchronized between the engine and the transmission input shaft. Afterwards the torque of the new gear acts on the transmission. The thin lines depict the speed curves that would result without adjusting by synchronizing and re-engaging the clutch.

If the starter generator is connected with the input shaft, then not only the rotating mass of the input shaft, but also that of the electrical machine must be accelerated during the synchronization phase (range from Point B to C). This would lengthen the phase and would stress the synchromesh more. To give support, the electrical machine could receive power. The power requirements are very high however, if the vehicle is to be shifted within the same time-frame as when no additional rotating mass is present. A few attempts to integrate the starter generator into the ASG were not successful due to this problem.

Therefore, we are looking for a synchronization that takes into account the mass of the electrical machine. The following two sections show an approach and a solution.

Synchronization using the engine brake against the housing.

The principle introduced here is already being currently used in trucks (Figure 3).

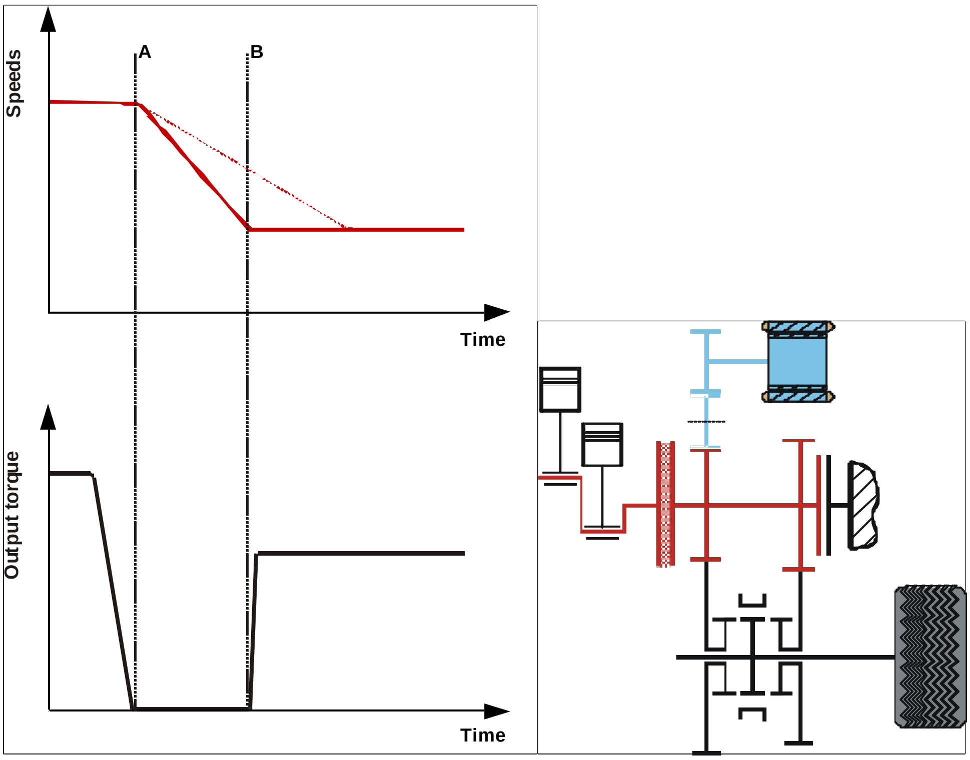


Figure 3: Synchronization using the engine brake against the housing

Synchronization of the speeds of the transmission input shaft, the internal combustion engine and the electrical machine is achieved by a powerful brake acting against the housing.

Therefore, it is not necessary to synchronize the individual dog clutches. An interruption in the tractive force, however, cannot be avoided even during this kind of synchronization.

Synchronization using the engine brake against the power take-off

In the above principle of the engine brake, the torque is supported at the housing. During the braking process, the kinetic energy of the internal combustion engine and the electrical machine is transformed into heat and is lost to the drive.

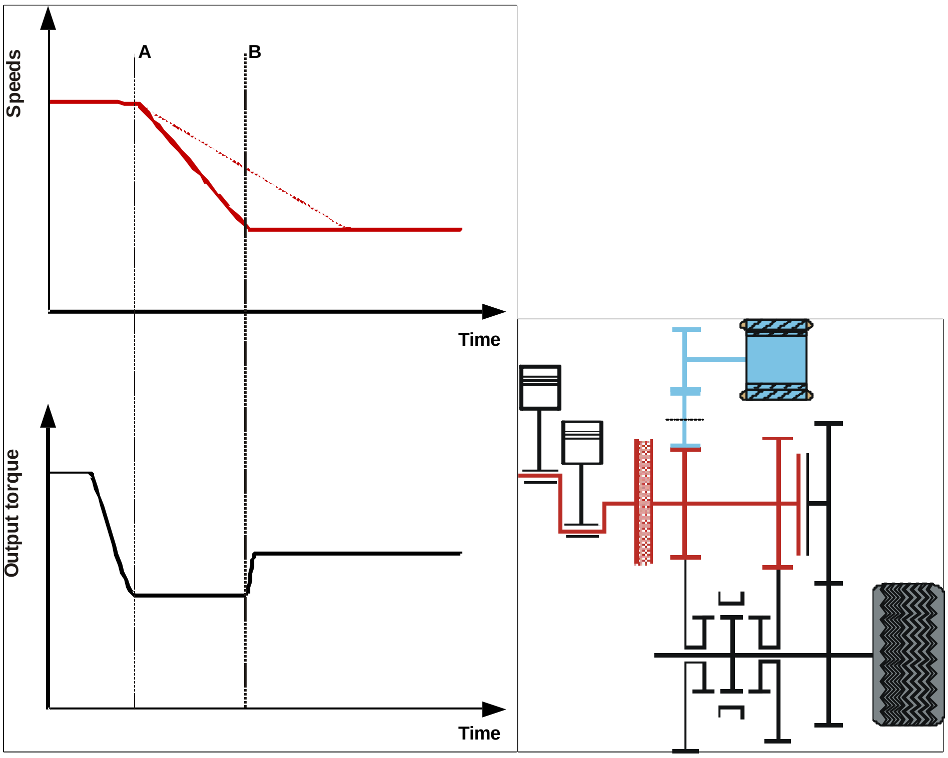


Figure 4: Synchronization using the engine brake against the power take-off

It is preferable to deliver this torque to the drive train, using a power shifting clutch and thus to transfer portions of the kinetic energy of the internal combustion engine and the electrical machine during the shifting process to the vehicle (Figure 4). **This is the basic principle of the Electric Shift Gearbox** (ESG).

Here, the power shift clutch fulfills two functions:

- Synchronizing the transmission input shaft, internal combustion engine and electrical machine
- Avoiding the interruption in the tractive force by delivering the torque to the drive train

In comparison to the ASG, using this principle to adjust the speed eliminates the delay times that occur between disengaging the dog clutch and beginning the synchronization process, as well as between the completion of the synchronization process and the re-engagement. The gear shifting elements move simultaneously in the interlocking phase and independently of the synchronization process by the power shift clutch. The gradient of the transmission input shaft speed during the synchronization process may now be less than that of the ASG (Figure 2), without it lengthening the time it takes to shift gears. This simplifies the demands on the electrical machine.

The thin line in Figure 4 again compares the speed curve, as it would be without synchronization by the power shift clutch.

The Electric Shift Gearbox – ESG

Design of the ESG

Figure 5 depicts how, in principle, an ESG could be designed.

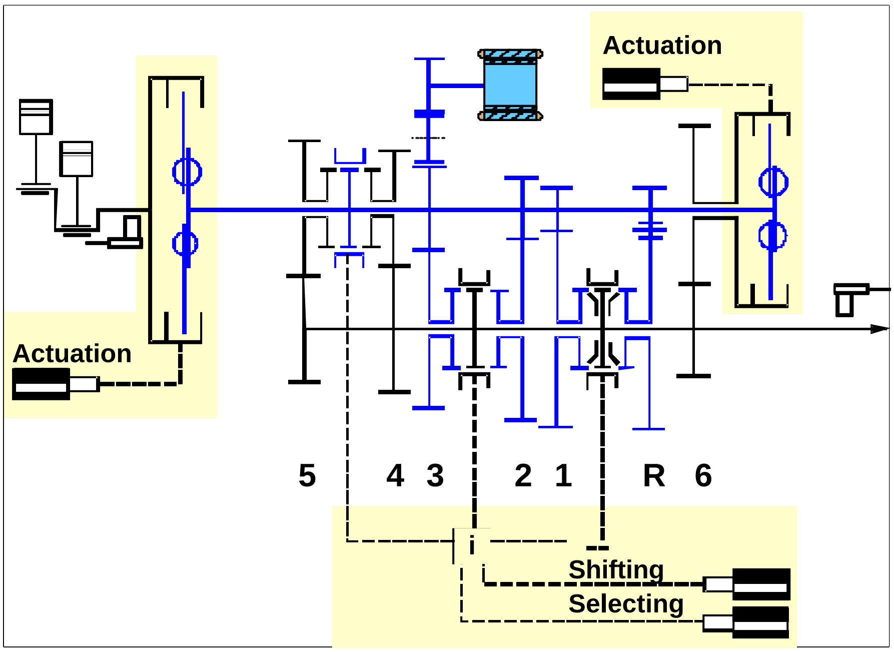


Figure 5: ESG design

Synchronizers are eliminated, and now an additional power shift clutch is added to the start-up clutch. This power shift clutch connects the input shaft with the output shaft via an auxiliary gear pair – here depicted for the sixth gear. The demands made on the power shift clutch regarding torque and performance are similar to those made on a start-up clutch. In addition to being used for power shifting, this clutch can also be used as a locking mechanism for parking, without any additional expense! To do this, the power shift clutch is engaged after a gear has been selected – this puts the drive train into a torque-lock condition.

As mentioned above, in order to transmit the inertia effect and the torque of the internal combustion engine to the transmission and thus via the power shift clutch to the vehicle, the start-up clutch remains engaged during the shifting processes.

This means that during the start-up only the start-up clutch is used and when the gears are shifted, only the power shift clutch is used. This is the basis of the idea to operate these two clutches with a common actuator and to design them as a combi clutch (Figure 6).

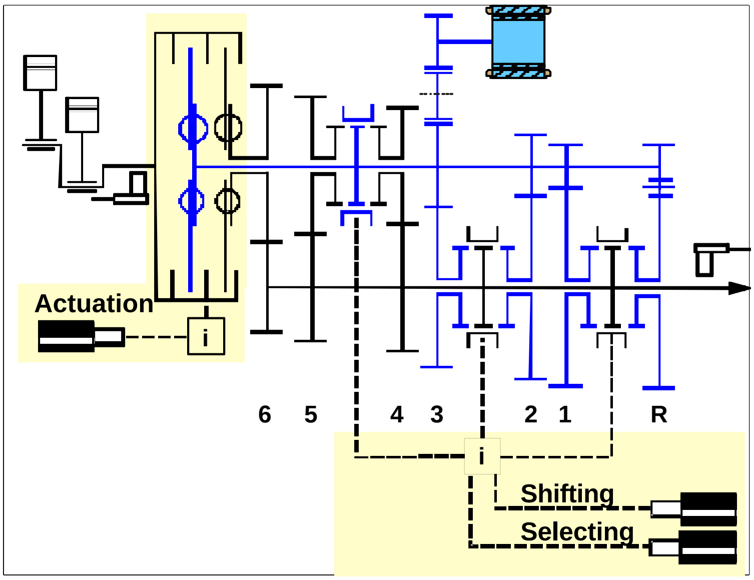


Figure 6: ESG with one actuator for the start-up and power shift clutch

The corresponding characteristic curves for torque are depicted in Figure 7.

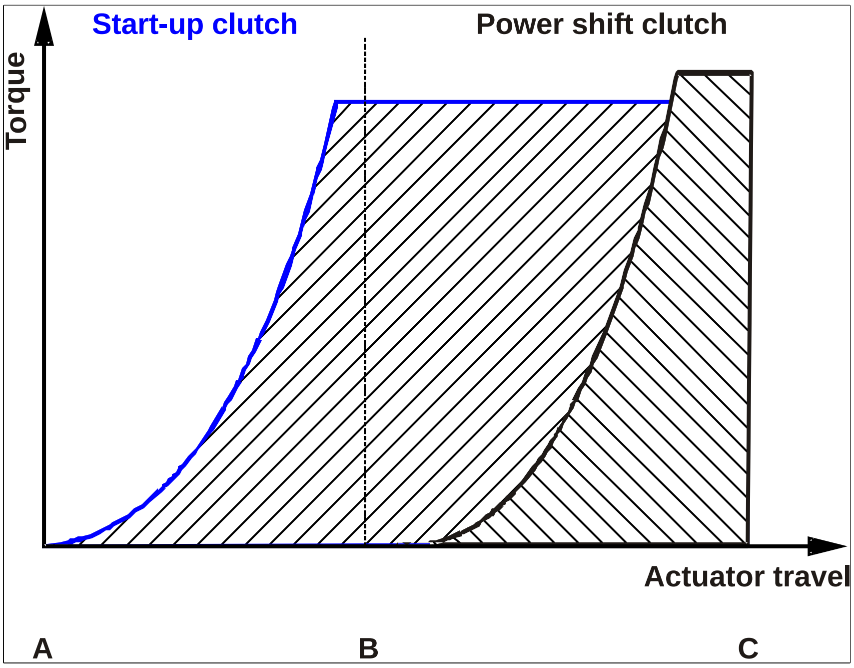


Figure 7:The torques of the start-up clutch and power shift clutch versus actuator travel

If the actuator is located at *Point A*, then both clutches are disengaged. On the way from *Point A* to *Point B* the start-up clutch will be engaged and the vehicle starts to move. If the actor is at *Point B*, it can either move left and disengage the start-up clutch and it can realize the torque follow up strategy or it can move to the right *(in the direction of Point C)* and then initiate the shifting process by activating the power shift clutch, whereby the start-up clutch remains completely engaged.

Cost comparison of ESG to ASG

As many components as possible were used from the ASG during the design of the ESG. They have the same number of the following components:

- Start-up clutch
- Shifting actuators
- Input shaft
- Gear sets
- Housing
- Clutch actuator
- Interior shifting mechanism
- Output shaft
- Dog clutches
- Release bearing

No additional actuator is required, despite power shifting and the electrical machine. **In addition, the following components are required**:

- Connection to the transmission
- Larger battery
- Power shift clutch
- Electrical machine / Electronics
- Wiring

To compensate, the following components are eliminated:

- Synchronizers
- Starter
- Generator
- Belt drive

ESG system requirements

Controls

With ESG, triggering the system, in particular the clutches, is a considerable challenge.

In order to fulfill the synchronization function, the power shift clutch, the internal combustion engine and the electrical machine must be controlled in a coordinated manner. In addition to the shifting strategies the additional functions of the electrical equipment (starting, supplying power to the on-board net) must be guaranteed.

The power shift clutch slips during the shifting phase and thus dominates the power torque. This requires very sensitive control.

Another challenge lies in disengaging and engaging the dog clutches. During the disengagement process the precise point in time must be found where the dog clutch is torque-free. During the engagement process the speed must be synchronized, however, at the same time the speed gradients should be as equally high as possible.

Comprehensive total system knowledge is necessary to coordinate engine, clutches and transmission. LuK already has gained expertise in this area from developing the ASG.

Power shift clutch design

High friction performance and good modulation capability is demanded from the start-up clutch as well as from the power shift clutch. The energy savings could be even higher than that of the start-up clutch, which would make wear-adjustment a sensible idea. If the clutches are designed as a combi clutch – start-up clutch and power shift clutch in one module – then this poses a particularly big challenge. In addition, both clutches must be reduced in force in order to use a small clutch actuator. Certainly that would be the right task for the clutch development departments at LuK.

On the road to ESG:
The Uninterrupted Shifted Gearbox – USG

In the revolution of the vehicle on-board system, with the EMST introduced here, we can offer a totally optimized transmission system.

In preparation, partial aspects of this technology can already be introduced without much additional expense. The introduced concept of the power shift clutch can already be used as an independent alternative to the manual transmission, i.e., the ASG, without integrating the electrical machine. LuK calls this system the Uninterrupted Shifted Gearbox (USG).

Design of an USG

Figure 8 depicts the design of an USG with a combination clutch that is activated with only one actuator.

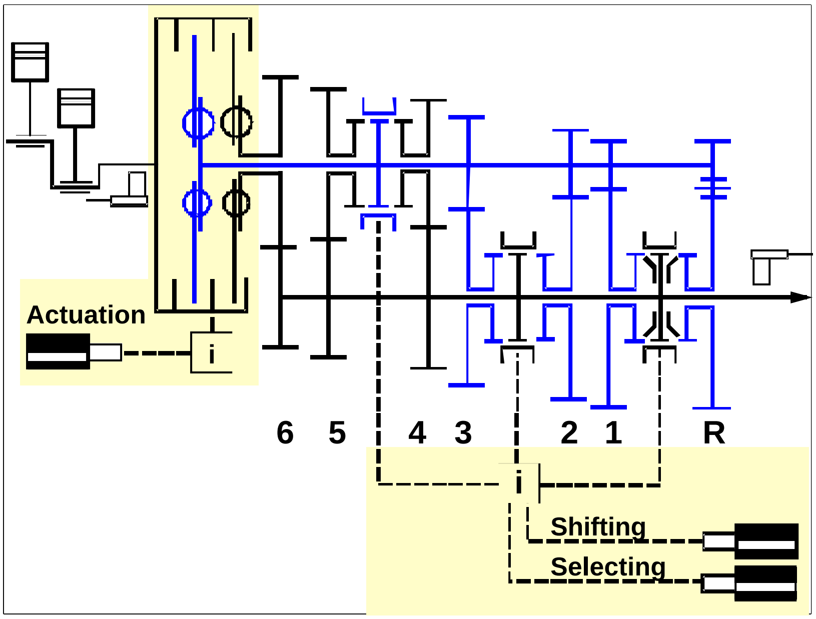


Figure 8: Design of the USG

LuK took the first step with the prototype illustrated in Figure 9. Here, the power shift clutch is attached to the fifth gear in an existing ASG. Only in the next development step are the two clutches to be united into a combination clutch.

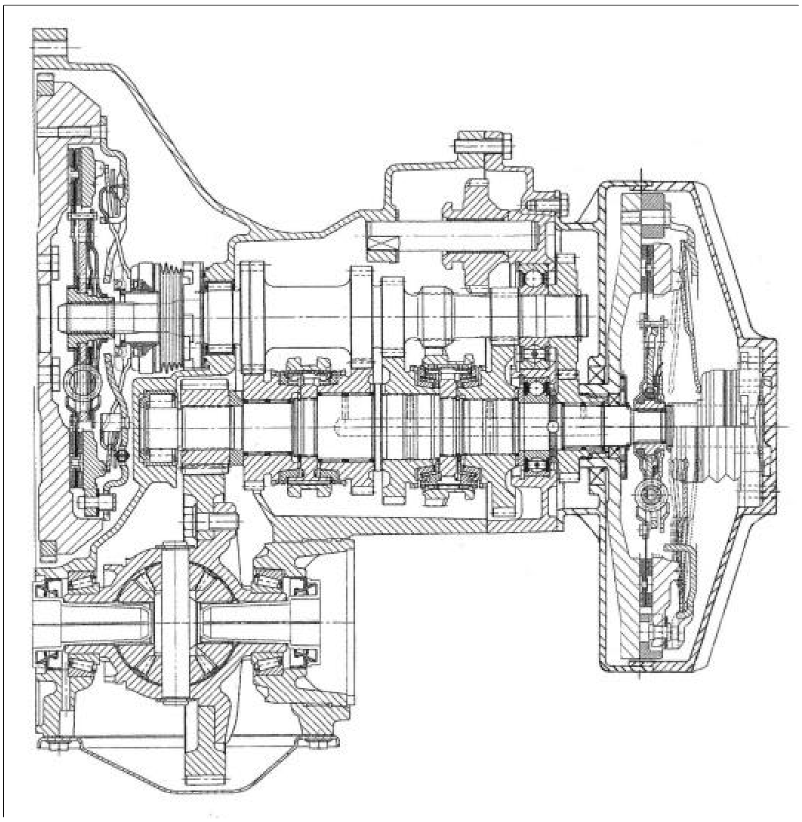


Figure 9: LuK prototype for the USG

Cost comparison of the USG to the ASG

ASG and USG **have the same number of the following components:**

- Start-up clutch
- Clutch actuator
- Shifting actuators
- Internal shifting mechanism
- Input shaft
- Output shaft
- Gear sets
- Dog clutches
- Housing
- Release bearing

Despite increasing the ASG function to that of the USG, no additional actuator is required. Only one **additional component** is required, whereby it can be made cost-efficiently by integrating it into the existing clutch:

- Power shift clutch

The **following components are eliminated:**

- Synchronizers

This comparison shows that despite the advantages, the USG does not have to be more costly than the ASG. Upgrading the USG to an ESG is possible without major effort.

We see an additional advantage by having the transmission manufacturers retaining the existing investments, which is made possible by the majority of the parts being the same.

Summary of the characteristics

In many ways, the ASG is the best in its class. Highest efficiency and lowest manufacturing costs, combined with lowest weight in the smallest space, which lead to lowest consumption and promise a long life for the ASG and thus the investments made in the manual transmissions (Figure 10).

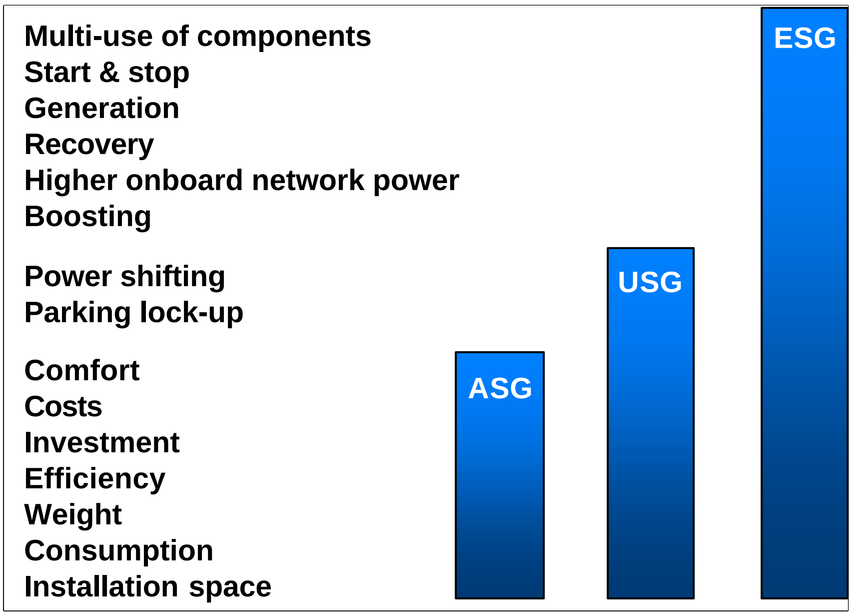


Figure 10: Characteristics of ASG, USG and ESG

For the USG, all these advantages are preserved. It offers additional functions, however, such as power shift and parking lock-up at no additional cost. Therefore, the USG is a stand alone system.

The USG, in turn, is the optimum basis for expansion with the starter generator to the ESG. The ESG is a turnkey concept that retains all the advantages of the ASG and USG and that fully utilizes the potential offered by the starter generator at start-stop and with recovery. All the additional functions of the starter generator, such as energy conversion, higher on-board network, performance and boosting are possible.

In the ESG the electrical machine supports the power shift clutch of the USG, making the shifting process even more comfortable and quicker (see Figure 11).

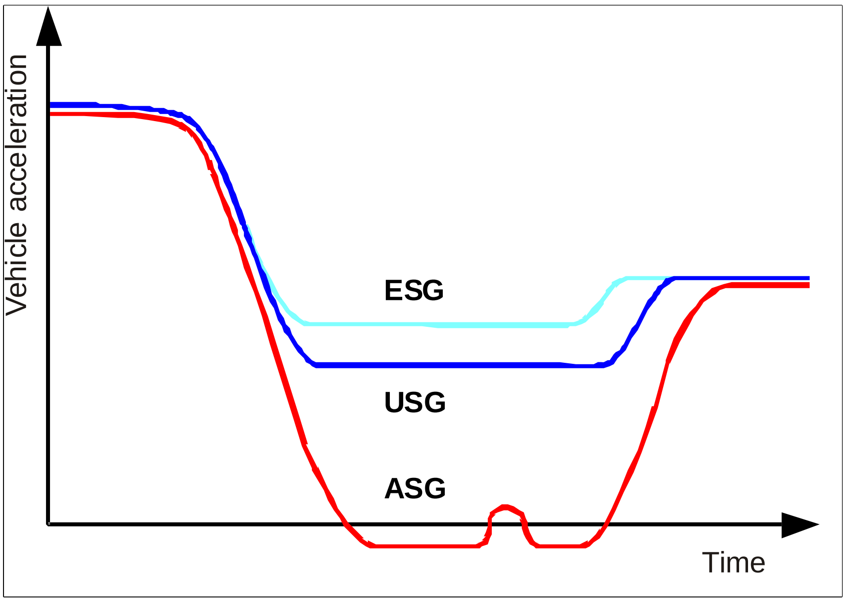
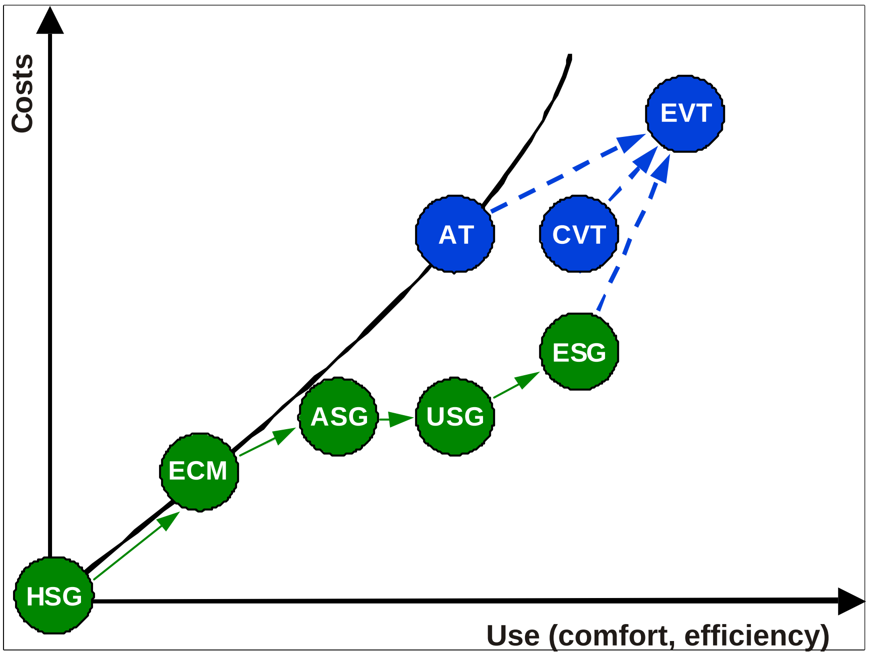


Figure 11: Vehicle acceleration during shifting with ASG, USG and ESG

System classification

In this lecture we dealt with the Uninterrupted Shifted Gearbox (USG) and the Electric Shift Gearbox (ESG) as a further development of the Auto Shift Gearbox (ASG). How do these systems relate to each other and how do they relate in comparison to other transmission systems?

In Figure 12 we attempted to depict a cost-benefit evaluation, whereby the good comfort and good performance level represent the benefit for the client.



ESG	= Electric Shift Gearbox	EVT	= Electrically variable transmission
USG	= Uninterrupted Shifted Gearbox	CVT	= Continuously variable transmission
ASG	= Auto Shift Gearbox	AT	= Automatic transmission
ECM	= Electronic clutch management		
MT	= Manual transmission		

Figure 12: Cost-benefit analysis of various drive train automatic systems

Currently, the manual transmission, the most cost-efficient transmission available today, is taken as the basis. The other known reliable cornerstone is represented by the automatic transmission (AT), with greater benefits, but also at higher costs. According to our estimates, the electronic clutch management (ECM) is at about one-third between the two systems mentioned above with regard to the benefits and costs.

With the ASG the benefit increases markedly in relation to the ECM, without markedly higher costs.

The USG is most likely as reasonable in cost as the ASG. However, the comfort level continues to increase, since the interruption in the tractive force is eliminated. LuK estimates the benefit of the USG to be equal to that of the automatic transmission, the focus being, however, on other classes of vehicles. With the USG not quite approaching the shifting comfort of the automatic transmission, the consumption nevertheless is much lower.

The ESG is the further development of the USG. The additional costs for the electrical machine and the performance electronics may not be assigned exclusively to the transmission, since the many advantages of a starter generator must be evaluated, in part, independently of the drive train. We see the major advantage in the potential for savings in fuel consumption.

The CVT costs approximately as much as an automatic transmission, however, it offers decidedly more comfort.

If comfort is the focal point during the development, then successors have been considered for the automatic transmission and the CVT. Systems will be used as have been introduced by, amongst others, Prof. Tenberge in his lecture [8]. As can be seen in Figure 12, however, this addresses a completely different market segment than ESG does.

ASG, USG and ESG are further developments of the manual transmission. LuK is working on it!

Literature

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