Electrical Motor in the Drive Train

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Preface

The idea of the electrical motor is not new – LuK was working in this field 15 years ago. However, the times were not yet ready for such a system. Nothing helped there, not even the indicator displays that LuK switched to force the inertia flywheel clutch, as the electrical motor was called then. This shows how much patience can be required with such developments.

Figure 1: Bosch - LuK – electrical motor (around 1990)

The term electrical motor usually evokes an image of an electrical machine whose rotor is secured directly on the crankshaft and which can work as a generator and a motor. As the name implies, it can replace the starter and the generator. This arrangement was developed as a result of sharply rising electrical power demands on the vehicle’s electrical system, due for example to the increased use of electrical components. In order to improve efficiency, for example for electrical value actuation, an increased voltage demand on the
vehicle electrical system is required. [1]. In addition, a start-stop function should be integrated that would allow the motor to be shut off when the vehicle is stopped and to be restarted quickly and quietly. However, the electrical system has to be large enough so that it could still be started reliably even at extremely low temperatures. Depending on the engine, even passenger cars can require momentarily more than 400 Nm torque.

Once such an expensive system is decided upon, car designers will attempt to integrate even more functions. The creativity of engineers here knows no bounds.

Figure 2 lists more requirements of the electrical system, which, depending on the case, could become even more important than the original motivation to combine a starter and a generator into a high-performance electrical engine.

- High generator performance with high efficiency
- Free choice of generator performance
- Start/stop function with quiet start (engine stops when vehicle coasts or stops)
- Direct start
- Pulse start
- Booster
- Energy recovery during coasting
- Active synchronization
- No interruption of the tractive force to the wheels with automatic shift transmissions
- Similar concept with all types of transmissions
- Torsional vibration damping

Figure 2: Possible requirements of the electrical engine in the drive train

As mentioned above, the nowadays widely discussed topic of electrical motors require minimal output from the electrical machine when starting at low temperatures. During a pulse start, only when the electrical machine is first up to speed and the clutch is disengaged, can the electrical machine alone be dimensioned to meet the power requirements.

If a relatively large electrical machine is used (with an output of up to 10 kW) it should also support the vehicle’s engine, at least briefly, and thus act as a booster.
Perhaps an even more interesting task for the future would be to recover the energy expended during the braking process. Therefore, in many designs the recovery of energy becomes the focal point.

Several times attempts have been made to use the electrical machine to synchronize the transmission. This is hardly possible since extremely high electrical power output is required to accelerate the inherent mass moment of inertia quickly enough to the new speed.

Attempts to eliminate the irregularities of the engine by means of an active counterbalancing coupling fall into the same category. This was a nice idea, but unfortunately it leads to a marked increase in fuel consumption [2].

Another clever idea is to combine the electrical machine with the automated shifted manual gearbox to compensate at least in part for interruptions that unfortunately occur in the tractive force during the shifting process. This idea appears to be interesting enough that an article is being prepared on it [3].

In deciding on a design, the question whether a similar design can be used for all types of transmissions arises.

Figure 3a: Normal arrangement of alternator and starter motor
Crankshaft

Between two clutches

Transmission input

Figure 3b: Coaxial arrangement of the electrical machine
Figure 3c: Non-coaxial arrangement of the electrical machine
The most important arrangements are illustrated schematically in Figure 3. A rough distinction was made between coaxial and non-coaxial arrangements. In principle, there are three possibilities for the coaxial arrangements. First, the usual arrangement with the electric machine on the crankshaft, then on the transmission input shaft and between two clutches (Figure 3b).

Initially, similar arrangements are possible with the non-coaxial solutions, whereby the electrical machine that is now mounted to the side must be somehow connected via a drive (Figure 3c). Other possible arrangements include using the electrical motor in the auxiliary drive (Figure 3d). Interesting solutions are anticipated for this as well.
Electric machine on the crankshaft

In the best known, and perhaps also the simplest arrangement, the rotor of the electrical machine is attached directly to the crankshaft and thus replaces the usual flywheel (Figure 4).

![Diagram of coaxial electrical motor with a clutch](image)

**Figure 4:** Coaxial electrical motor with a clutch. The rotor is secured directly onto the crankshaft.

Since the rotor plates themselves are not suited to act as counter friction surfaces for a clutch facing, a counter friction surface that is similar to the regular flywheel must first be attached with the rotor, to which the clutch is then screwed. It would seem reasonable to connect the two to one another via a torsion damper and thus achieve the function of a dual mass flywheel (Figure 5). The effect of the dual mass flywheel can thus be achieved for almost nothing.

Of course it is possible to try to arrange the clutch within the rotor. However, in this case there is no room available for a torsion damper, which can be compensated for by other measures, as illustrated below. In many cases, the clutch diameter is too small. The double disc clutch that would be required as a result would be somewhat critical with regard to axial installation space.
Regardless of the design selected, the electrical motor needs a great deal of additional axial space, which is not available in many vehicles. Therefore, the goal is to save space when installing the electrical motor on the side of the auxiliary drive and to run all auxiliary equipment electrically. With the exception of the air conditioning compressor, this poses no problems. Regarding the air conditioning compressor, there is still some controversy among the experts whether an electrical drive is conceivable at all, given its high power demands versus efficiency.

If the auxiliary drive is avoided completely, then the space required for the electrical motor is available. The engine can be moved accordingly. However, what has to be considered is that in the majority of engines a torsional vibration damper or absorber is integrated into the pulley drive, which dampens the critical natural frequencies of the crankshaft. Of course, then there is no space available for that. Therefore, LuK developed a special damper that is fastened on to the last crankweb of the crankshaft, which serves the same function as the customary dampers that are arranged in the pulley.
In order to best utilize the start-stop function, the control of the clutch should be taken away from the driver, and the clutch should be activated automatically. Only in this manner can a safe engine start be guaranteed without the vehicle starting off by accident. In this context, LuK revived the old idea to filter out the irregularity of the engine with a slipping clutch and thus keep the irregularity away from the transmission [4]. Figure 6 shows the effectiveness of such a clutch, which only needs a slip of below 100 rpm for this purpose. This idea was being worked on intensely 10 years ago. Worldwide, this development was stopped due to increased facing wear. In addition, the clutch slip also caused some increase in the fuel consumption.

Figure 6: Insulating the vibration with a slip clutch

For all these years, however, this problem continued to prey on the minds of the LuK engineers. Today, as a result of a series of individual improvements, a slipping clutch can be created without the disadvantages that caused the development to be previously abandoned.

By cleverly combining a torsion damper in the clutch disc with an ingenious slip strategy, using only as much slip as is necessary for the current condition of the vehicle, and having no slip at all at speeds over ~ 1,500 rpm, the increase in fuel consumption can be reduced to below 0.5 %. This of course, has a positive effect on wear. A further improvement in wear is achieved with modern clutch facings. And since this was still not enough, wear compensating, self-adjusting clutches (SAC) are added, thereby providing approximately twice as much facing
wear volume. Here, perseverance paid off. It produced a solution that is very interesting for all applications that use an automatic clutch.

- Combination with a special torsion damper minimizes the required slip range

![Graph showing consumption and wear minimizing measures in a slipping clutch](image)

- SAC permits higher wear reserves
- Wear-resistant clutch facings

Figure 7: Consumption and wear minimizing measures in a slipping clutch

**Electrical motor with two clutches between engine and transmission**

The arrangement introduced so far, with a rotor secured directly onto the crankshaft, does not allow for all of the desirable possibilities to be fully utilized. For example, it is only possible to recover energy in a very limited manner. In addition, not just any size electrical machine can be used, since a direct start must be possible even at the lowest of temperatures.

A second clutch circumvents these difficulties, such that, in principle, the electrical machine is mounted between these two clutches (Figure 8). This makes it possible to connect the electrical machine either with the internal combustion engine or with the transmission, as desired.
A direct start occurs when the engine is warm, i.e., with the first clutch engaged. If the temperatures are low, when the drag torque of the internal combustion engine is too great, while the clutch is disengaged, the rotor is first accelerated and then the first clutch is quickly engaged. The crankshaft is then pulled up and the engine starts immediately. For this reason, this is also called a pulse start. An additional measure of freedom was thus created; the size of the electrical machine is no longer determined by the highest drag torque of the internal combustion engine. Another effect of such quick starts is a marked reduction in emissions.

Another argument possibly carries even more weight. If the electrical machine is secured directly onto the crankshaft, then the only energy expended during braking that can be recovered is that amount that exceeds the energy that the engine consumes due to internal friction. Considerable output is converted into heat, during coast, particularly at higher speeds. Figure 9 illustrates this for a gasoline and a diesel engine.
Figure 9: Braking efficiency of engines with approx. 2.0 l piston displacement while in coast
The actual distribution of acceleration and deceleration that is measured in a vehicle indicates that most decelerations happen with a deceleration power of less than 10 kW (Figure 10). Under normal circumstances these are the decelerations where the driver only lets up on the gas and uses the engine to brake. With a generator that is connected directly to the crankshaft, this energy cannot be recovered. With an electrical motor with two clutches, however, the first clutch can be disengaged, which leads to an immediate engine stop. The deceleration power can be completely recovered, as long as it does not exceed the maximum output of the electrical machine.

![Distribution of acceleration and deceleration in the FTP75 cycle](image)

Figure 10: Distribution of acceleration and deceleration in the FTP75 cycle

Figure 11 illustrates that this is worthwhile for various driving cycles. The lower, green bar depicts the savings in gasoline consumption achieved by start-stop. In addition, the expected theoretical and real savings achieved by recovery are also shown. The real values already contain the efficiency from converting mechanical into electrical energy and vice versa. Despite these losses in the conversion process, it is worthwhile to consider recovering energy. Figure 11 proves this conclusively. In the entire vehicle, perhaps no single measure alone can result in consumption savings of this magnitude. It is for this reason that LuK believes that the real development goal with the electrical motor should be the recovery of the braking energy. This should then also be reflected in a new, yet to be discovered name.
If two clutches are used, then the question arises as to the arrangement of the masses on the engine and the rotor. Figure 12a again details the structure with a small flywheel inertia applied directly onto the crankshaft and, if desired, with a torsion damper in the clutch "KM". Depending on the presence of a torsion damper, the design must be based around the clutch "KM". Without a torsion damper and with a small $J_{\text{engine}}$, practically the full torque peaks arrive at the clutch. For this reason (particularly with diesel engines) the clutch must be able to transfer a maximum torque, which is a multiple of the engine torque (Figure 12b). To simplify the clutch design, the temptation would be to attach a suitable flywheel mass with a torsion damper to the crankshaft. Since the resonance speed should not exceed 600 rpm, however, the spring rate in the torsion damper should not exceed the limit curve shown in Figure 12c. The result is the full dual mass flywheel effect.

The larger $J_{\text{engine}}$ becomes, the more difficult the pulse start. The obvious concern is that there will be a detectable jerk in the vehicle if the internal combustion engine is started again by quickly engaging the clutch KM. This could be softened by lengthening the engagement time of the clutch (Figure 12d). This discussion illustrates the somewhat contradictory requirements that are imposed upon the flywheel mass and the torsion damper that are connected to the crankshaft. A good compromise will have to be sought for a concrete application.
Figure 12: Selection of the mass distribution between the engine and the rotor with an electrical motor using two clutches.
Figure 13 depicts a completed design. Both clutches are actuated automatically via a hydraulic clutch release system. In this case, clutch KM is released via a concentric release system from the engine side. Of course, this is not the most space-efficient solution. For this reason, double clutches were developed, where both clutches can be activated from the transmission side via a dual central release (Figure 14).

Figure 13: Electrical motor with two clutches. Both clutches are activated by separate hydraulic release systems.

A detailed analysis of the required clutch conditions shows that a sequential cycle is also possible. Therefore, both clutches can also be activated via a gear-selector drum with only one actor, without experiencing major restrictions regarding starting behavior (direct start or pulse start), drive-off behaviour or recovery.

LuK recognized that the success of the electrical motor depends in large part on the compactness of the clutches. Therefore, a great deal of effort is being expended on developing simpler and more compact solutions.
Figure 14: Electrical motor with two clutches and two concentric release bearings. The clutch on the engine side is engaged, the rotor is connected to the crankshaft.

**Electrical motor in automatic clutches with torque converters**

The demand for more available electrical power will increase, particularly in higher end vehicles, since numerous comfort features requiring electricity will be installed in these vehicles. Automatic clutches are already prevalent in this class of vehicles. Therefore, the demand for an electrical motor should be even greater in this sector. The simplest solution, but one that has only limited possibilities, is represented by an electrical motor that is attached directly onto the crankshaft.

If a double clutch is decided on for a manual shift transmission, which allows for a full recovery in addition to a pulse start, then it is likely that this option will be carried over to automatic transmissions. As Figure 15 shows, there is even a particularly elegant solution for this. A second clutch merely has to be integrated in the space of the current lock-up clutch, which can separate the engine from the pump housing. This results in a particularly space-saving design. Both clutches are actuated hydraulically. If the first clutch is disengaged, the engine can be turned off and the electrical machine can still be running. With this
configuration, all conditions can be realized that were described in the previous chapter under the dual clutch solution.

Figure 15: Electrical motor with two clutches for automatic transmissions. The left clutch can connect the crankshaft with the rotor, the right one represents the regular lock-up clutch.

**Electrical motor in the CVT transmission**

The electrical motor can also be attached directly to the crankshaft (Figure 16 top). Special effects can be achieved, however, through a clever arrangement, particularly in the CVT. Figure 16, middle and bottom, shows a clutch attached in front of and behind the electrical machine. The electrical machine can be arranged coaxiallly or offset to the side. It is clear that all of the cases discussed thus far, including direct start, pulse start, booster and recovery can be realized with this arrangement. The conditions are particularly favorable for recovery, since energy storage can now be realized not only electrically, but also mechanically via the flywheel mass of the rotor.
Figure 16: Arrangements of an electrical machine in a CVT transmission
The clutch KM is disengaged during a mechanical recovery, then the variable speed mechanism is adjusted in the direction of the underdrive, causing the rotor to turn faster. By doing this, it draws kinetic energy from the drive train and the vehicle decelerates. During the next acceleration, the variable speed mechanism is readjusted in the direction of overdrive and the vehicle accelerates again. The short-term storage of mechanical energy will be effected with markedly fewer losses than using electric storage. Therefore, the theoretical savings in consumption depicted in Figure 11, i.e., a more than 20% savings in fuel consumption, will be approached.

A comparison of the inertial energy of a moving vehicle to a rotating flywheel mass shows that it is really possible to store considerable energy mechanically.

Figure 17, top, depicts the kinetic energy as a function of speed for a vehicle with a mass of 1,500 kg. In addition, the bottom figure shows the kinetic energy of a flywheel mass with $J = 0.3 \text{ kgm}^2$ as a function of speed. If a maximum speed of 10,000 rpm for the rotor of the electrical machine is assumed, a flywheel mass at these speeds has as much kinetic energy as in a vehicle moving at 50 km/h. This shows that many of the decelerations that occur in everyday driving can be recovered mechanically.

There is another advantage: If the internal combustion engine is to be started again after the recovery phase, the suitable speed of the rotor can be chosen. It makes sense to utilize a large portion of the flywheel effect to accelerate the vehicle first and then quickly engage the clutch KM at a low rotor speed. At the same time, to avoid a deceleration jerk on the vehicle, the variable speed mechanism is quickly adjusted slightly toward overdrive, which leads to a small acceleration jerk, which can balance the deceleration jerk. In addition, the electrical machine can interfere briefly to compensate. Therefore, it should be possible to reliably avoid a jerk while starting the engine.

The promise of an almost ideal behavior can be gained by combining a CVT transmission with an electrical machine. The somewhat lesser efficiency of a variable speed mechanism is more than compensated for by the improved energy recovery that is the result of combining it with mechanical recovery. The total efficiency and comfort level should be unsurpassed.
Figure 17: Kinetic energy in a vehicle (top) and in a rotating flywheel mass (bottom)
Electrical motor in the auxiliary drive

The concepts introduced thus far require major changes to the drive train (i.e., lengthening the transmission). If this appears to be too great a step, there is another solution that has hardly received any attention up to now. This solution would replace the alternator with a somewhat larger electrical motor that needs only slightly more space for installation. In order to guarantee a sure start of the internal combustion engine, a dual-stage transmission would be advantageous allowing it to engage either directly with the pulley at the crankshaft or at the electrical motor. Figure 18 shows the possible arrangements, which have advantages and disadvantages. In these arrangements, the transmissions are designed such that they are either dependent on the torque direction, which changes between the operation of the generator and the starter, or they can be actuated from outside between the two operating stages.

If the dual-stage transmission is attached to the crankshaft, favourable loads result for the belt drive. With regard to the generator, nothing changes from the present situation, since the dual-stage transmission is switched to direct transmission mode. During the start, the belt drive has to transfer only relatively little torque, since the high torque required for the start is produced only in the dual-stage transmission with a gear ratio of approx. 3-4.

However, if the transmission is run from the electrical motor during start-up, there is first a step-up to high torque and a subsequent transfer via the belt drive. Therefore, higher demands are placed on the belt drive. Based on current knowledge, this would only be possible for relatively small vehicles that have the regular ribbed V-belt. If a larger starting torque is required, toothed belts might have to be used, which could cause a critical situation with regard to noise. Of course, it would be advantageous if, due to the higher speed, the transmission on the electrical motor could be designed for substantially smaller torques than with a transmission on the crankshaft.

Figure 19 depicts such a two-stage transmission that can be attached to the crankshaft. In the case of a generator, an integrated, switchable planetary gear transmission permits a direct transmission, and in the case of the starter a transmission by a factor of approx. 4. The gear change depends on the torque direction. To achieve this, the planetary gear transmission is helical with a large helix angle. For this reason, depending on the torque direction, axial forces have a counter-directional effect on the ring gear. The ring gear can be moved axially. In the left position (upper part of Figure) a direct transmission is depicted; all parts of the planetary gear turn at the same speed. In the right position (lower part of Figure) the ring gear is connected with the stationary engine block. This results in the step-up into higher torque ranges, necessary for the starting process.
Figure 18a: Electrical motor in the auxiliary drive

Figure 18b: Electrical motor with dual-stage transmission on the crankshaft

Figure 18c: Electrical motor with dual-stage transmission on the electrical machine
attached to the engine block

generator operation \(i = 1\)

starting process \(i = 4\)

crankshaft

Figure 19: Dual-stage transmission on the crankshaft
During driving, the direct ratio should always remain switched on. Changes in torque also occur if the internal combustion engine is braked quickly. A centrifugal lockout system then prevents the gear shift.

A similar design, however, intended for lower torques, is possible in front of the electrical machine. Figure 20 depicts a variation in which the gears are changed via a magnetic clutch. This would allow for the gears to be changed according to requirements possible. This would only affect the electrical machine, however, since all auxiliary equipment is integrated into the belt drive with a set ratio.

![Electromagnetically actuated clutch switches between ratio \( i = 2.5 \) and \( i = 1 \)](image)

**Figure 20:** Dual-stage transmission on the electrical motor

An electrical machine in the auxiliary drive replaces the starter motor and the alternator. Therefore, a start-stop operation is possible, without any restrictions. Even a booster operation is conceivable, as long as the electrical machine generates sufficient output. To operate the electrical motor in the auxiliary drive thus represents a viable alternative. A study group made up of engineers from Bosch, ContiTech and LuK are working together to find solutions. Hopefully, this group will provide additional convincing proposals.
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<th>Feature</th>
<th>Auxiliary drive</th>
<th>Crankshaft</th>
<th>Between engine and transmission 2 clutches</th>
<th>Transmission input ASG</th>
<th>Transmission input automatic transmission</th>
<th>Transmission input CVT 2 clutches</th>
<th>Transmission input ESG [3]</th>
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<td>High generator output with good efficiency</td>
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<td>+</td>
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Summary

It was shown that there is more than just one kind of electrical motor. Those who develop drive trains today can select from among many variations. Depending on the development goal, the decision will be made for one solution. Figure 21 should be of help. The most important arguments in connection with using the electrical machine in the drive train have been evaluated for use in the various designs. Unfortunately, at this time there is still no reliable data available regarding the costs. Therefore, it is still a bit too premature to make reliable predictions regarding which systems will prevail in the end.

The electrical motor appears interesting in the auxiliary drive, since that arrangement requires the fewest changes to the vehicle. If the focus is shifted to recovery, the decision will be for the solution featuring the dual-stage clutch. A particularly advantageous transmission structure can be achieved with the CVT transmission drive, by offering a combination of mechanical and electrical recovery.
Literature


