Konzept und Funktionsweise des elektrischen variablen Getriebes

Concept and Functionalities of the Electric Variable Transmission

Dr. Ralf **Kruse**
Siemens AG, Bereich Siemens VDO Automotive

Salem **Mourad**, Darren **Foster**
TNO, Business Unit Automotive

Prof. Dr. Martin **Hoeijmakers**
Delft University of Technology

Zusammenfassung

Beim Elektrisch Variablen Getriebe (EVT) handelt es sich um einen elektromagnetischen Energiewandler mit zwei mechanischen und einer elektrischen Schnittstelle. Mechanisch ist das EVT wie ein herkömmliches Getriebe über die Eingangswelle mit dem Verbrennungsmotor verbunden und über die Ausgangswelle mit den Rädern. Elektrisch ist das EVT zusätzlich an eine Hochleistungsbatterie angeschlossen. Insgesamt stellt das EVT ein kompaktes, multifunktionales Gerät dar, das derzeit von Siemens in Kooperation mit TNO entwickelt wird. Durch sein kontinuierlich variables Übersetzungsverhältnis ersetzt das EVT das herkömmliche Automatikgetriebe. Gleichzeitig steht die volle Hybridfunktionalität zur Verfügung: Start-Stopp-Betrieb, regeneratives Bremsen und Boosten sind ebenso möglich wie rein elektrisches Fahren. Der Fahrspaß wird gesteigert durch die gleichmäßige, rüttelfreie Drehmomententfaltung auf der einen Seite und das zusätzliche Boostdrehmoment auf der anderen Seite. Simulationen zum neuen europäischen Fahrzyklus (NEDC) – durchgeführt für einen Mittelklasse-Pkw mit Otto-Motor – zeigen einen sehr niedrigen Benzinverbrauch von nur 4,3l auf 100km.

Summary

The Electric Variable Transmission (EVT) is an electromagnetic energy converter with three power interfaces currently under development by Siemens in cooperation with TNO. Two interfaces are mechanical like in a conventional transmission: the input shaft, which is connected to the engine, and the output shaft, which provides the torque to the wheels. The third power interface is electrical and connected to a high power battery. The EVT is a compact, multifunctional device. Its functionality of a continuously variable transmission replaces the standard automatic transmission. Furthermore the EVT enables the full hybrid functionality including start-stop, regenerative braking, boosting and pure electric driving. The smooth torque delivery and the additional boost torque result in high driving pleasure. The simulations of a mid-size gasoline passenger car equipped with EVT show a very low fuel consumption of 4.3l per 100km in the new European drive cycle (NEDC).

1 Introduction

The requirements to the automotive industry regarding emissions and fuel consumption are increasing from year to year. The association of European car manufacturers (ACEA) has voluntarily committed to reduce the fleet emissions of CO_2 to 140g/km until 2008. This is equivalent to fuel consumptions of approximately 5.3l per 100km for diesel engines and of 5.8l per 100km for gasoline engines. Currently it is under discussion to reduce the fleet emissions of European car manufacturers even to 120g/km for new vehicles in 2012. These targets are very challenging.

With vehicle cost in mind it seems to be advantageous to reach the emission reduction targets via optimization and improvement of existing components. For example the efficiency and the performance of gasoline engines are improved by gasoline direct injection. Diesel engines are equipped with common rail systems for high pressure injection. The supercharging of combustion engines is continuously improved. All these technologies enable the downsizing of the engine. To achieve further improvements regarding fuel consumption and emission reductions additional components are integrated within the vehicle. These additional components increase the cost. One example is the integration of a second turbocharger.

The hybrid technology, that means the combination of the combustion engine with one or two electric machines, enables additional improvements of fuel economy. The emission reductions reached by hybrid technology are additional reductions, which are independent from the results achieved by engine optimization and improvement of other existing components. Unfortunately the hybrid technology has the disadvantage of needing additional components and causing additional costs. Therefore it is very important that the added value reached by hybrid technology does not only affect fuel economy and emissions but driving pleasure as well.

Today many concepts for hybridization are available, e.g. the parallel hybrid or the belt-driven starter-generator. Amongst others the solutions with transmission-integrated electric machines seem to be advantageous. These solutions enable reductions of size and weight for the electric machine and therefore comparatively low cost. In some cases the electromagnetic energy conversion enables a partial or complete abolition of the conventional transmission. The Electric Variable Transmission (EVT) presented in this paper consists of two electric drives, which are combined mechanically and magnetically to form a highly integrated and very compact system. The EVT replaces the conventional transmission completely, that means there are no gears any more. The EVT enables not only continuously variable transmission, but the full hybrid functionality also. Start-stop operation, regenerative braking and boosting are included as well as pure electric driving.

The following chapter 2 describes some examples of transmission-integrated hybrid electric drives. Based on the cognitions of this chapter within chapter 3 the EVT structure and functionality is described. Advantages of the EVT are presented. Chapter 4 shows the simulation conditions for a vehicle equipped with EVT. The vehicle simulation results for the new European drive cycle (NEDC) are presented in chapter 5. A short conclusion finalizes the paper.

2 Well-known transmission-integrated hybrid concepts

One of the discussed transmission-integrated hybrid concepts is the double-clutch-transmission (DCT) with side-mounted starter-generator (SSG) shown in figure 1 [1]. Like each hybrid electric drive the SSG consists of two components: the electric machine (EM) and the ECU (electronic control unit, inverter). The DCT has two concentric shafts, each with a clutch, enabling automatic shifting without torque interruption like a standard automatic transmission. Shaft 1 has the odd-numbered gears and the reverse gear, shaft 2 has the even-numbered gears. Furthermore the SSG is connected to shaft 2 via a gear ratio of typically 3:1. This gear ratio enables a reduction of the SSG torque rating by a factor of 3. Considering that the size of the electric machine depends on the torque it is obvious that the gear ratio of 3:1 enables a significant size reduction for the electric machine.

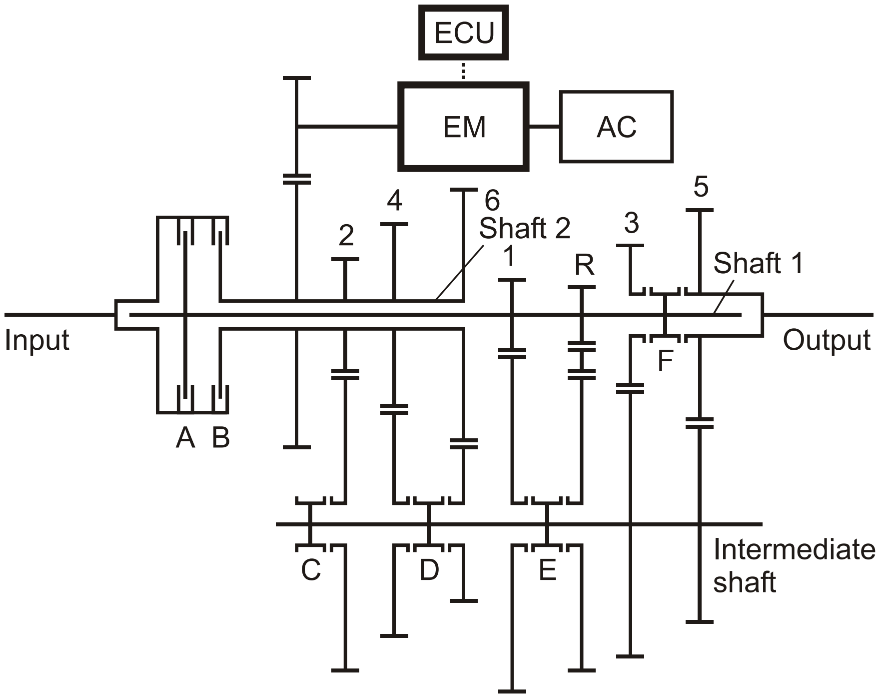

Fig. 1: DCT with SSG

The SSG starts the engine via clutch B. The launching process as well as other acceleration phases can be supported by the SSG. This boosting increases the driving pleasure. For even-numbered gears the boost possibility is obvious from figure 1. For odd-numbered gears it is possible also by closing clutch B. In total the configuration from figure 1 enables start-stop, regenerative braking and boosting resulting in higher fuel economy and lower emissions. Furthermore the SSG enables the electric drive of the air-conditioning compressor (AC) as can be seen from figure 1. This is important if the vehicle is stopped and the engine is turned off. In total the DCT with SSG enables not only a small size of the electric machine, but additional functionality as well.

Another well-known hybrid concept is the power-split solution of the Toyota Prius [2]. Figure 2 gives an overview of the drivetrain concept. It includes two electric drives, each consisting of electric machine plus inverter. The first electric machine (EM1) is connected to the sun gear of a planetary gear (PG), the second one (EM2) is connected to the ring gear. The internal-combustion engine (ICE) is connected to the planetary carrier. This concept with two electric machines enables dispensing of any transmission except of the simple planetary gear. Nevertheless it enables a continuously variable transmission ratio and includes therefore the functionality of automatic transmissions.

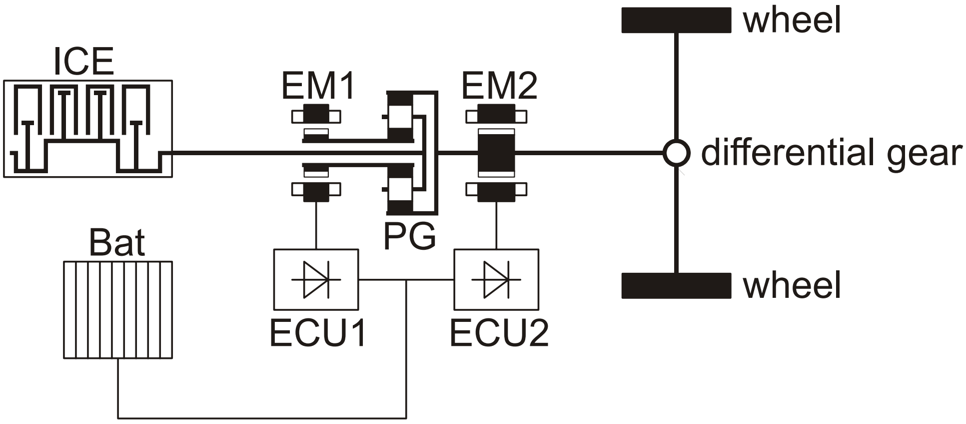

Fig. 2: Power-split hybrid solution of Toyota Prius

EM1 is a smaller fast-running machine with lower torque, which is mostly driven in generator mode. EM2 is a larger machine with higher torque driven mostly in motor mode. This electric machine enables pure electric driving, while the combustion engine is shut-off and EM 1 runs in no-load operation that means without any torque. If the engine shall be started during pure electric driving, the fast running EM1 has to be switched from no-load operation to generator mode. This means that EM1 supplies a braking torque to the sun gear. As the planetary carrier does not yet rotate, the ring gear has to supply the reaction torque. This reaction torque has to be additionally developed by EM2 to avoid any influence to the driving behavior. In the Prius the planetary gear has a gear ratio of 2.6:1 between sun gear and ring gear that means the reaction torque of EM2 is 2.6 times the original braking torque of EM1. The planetary carrier has to withstand the sum of both torques that means that the engine is started with the original braking torque of EM1 multiplied by a factor of 3.6.

In total the Prius system covers the functionality of a continuously variable transmission as well as the full hybrid functionality including start-stop, regenerative braking, boosting and pure electric driving. The technical efforts with two electric drives plus high power battery are comparatively high. On the other hand these efforts are reduced again by dispensing the standard automatic transmission.

During normal driving operation the Prius engine mostly runs faster than EM2. EM2 typically operates in motor mode, while EM1 operates in generator mode delivering the power for EM2. A part of the engine's power runs directly the mechanical path via planetary carrier and ring gear. The other part runs the electrical path via EM1 and EM2. The power is split into two paths. This is the reason, why the Prius system is characterized as a power-split hybrid system. It should be mentioned, that the EVT presented in next chapter is another kind of power-split system.

Another gear-integrated power-split solution is the so-called two-mode hybrid system [3]. This solution contains two smaller, fast-running electric machines combined with three planetary gear sets and three clutches. It also replaces the standard automatic transmission and enables the same functionality like the Prius concept.

As can be seen from the examples the smart integration of electric drives into the powertrain results in cost-effective combinations of transmission and hybrid functionality. Within the next chapter the EVT as another interesting variant of electric drive integration will be explained.

3 Structure and functionality of the Electric Variable Transmission (EVT)

The idea of the Electric Variable Transmission (EVT) is based on the standard series hybrid concept as shown in figure 3. The series hybrid contains two electric machines with inverters. The first machine EM1 works in generator mode and transforms the mechanic power of the combustion engine into electric power. The second machine EM2 retransforms the electric power into mechanic power and supplies this power to the wheels.

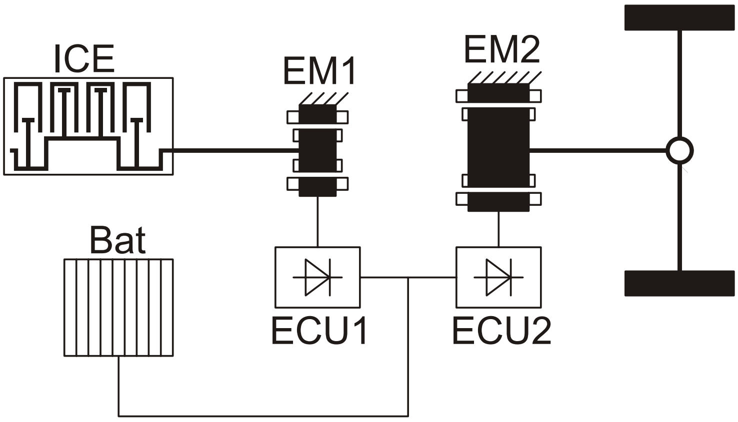

Fig. 3: Series hybrid concept

The series hybrid has the disadvantage that both electric machines and both inverters have to be designed for the complete power of the drivetrain. Furthermore EM2 has to be designed for the maximum torque, which has to be supplied to the wheels. In consequence the effort for the electric drives is very high resulting in comparatively large size and weight. In consequence the series hybrid concept is interesting only for bus applications, but not for passenger car applications.

To reduce the size of the components it is necessary to split the power similar to the Prius concept. This is reached by the interim solution shown in figure 4. As can be seen both parts of EM1 are rotating. The "stator" (the inner part) of EM1 is connected to ECU1 via slip rings. EM1 has to withstand the torque of the combustion engine like in the series hybrid concept. But this torque is provided directly to the wheels, because the rotors of both electric machines are mechanically coupled. In consequence EM2 has to develop a smaller torque than in the series hybrid concept. Therefore the size of EM2 can be reduced.

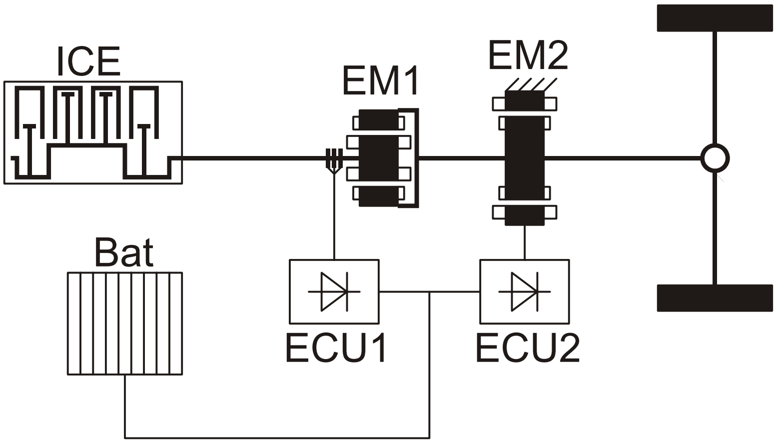

Fig. 4: Interim solution between series hybrid and EVT

In general EM1 works in generator mode and provides the power for EM2. The power is split. One part takes the mechanic path directly to the wheels via the stator and rotor of EM1. The other part takes the electric path via both inverters. The inverters have to be designed only for this part of the power and can be strongly reduced in size and weight.

The concepts from the figures 3 and 4 can be realized using permanent magnet synchronous machines [4] as well as induction machines [5, 6]. In the following the solution with induction machines is considered because of its advantages regarding costs.

The disadvantage of the interim solution from figure 4 is that two full-size squirrel cage rotors are necessary, even though both rotors are mechanically coupled and have the same speed. If both rotors could be integrated into one part, this would reduce size, weight and costs. This integration was done resulting in the EVT shown in figure 5. Both induction machines are integrated concentrically to one compact device. Therefore the squirrel cage rotors are combined to one so-called interrotor having two squirrel cages and a common yoke between. This common interrotor yoke is very thin, even thinner than each rotor yoke of the interim solution. The result is a comparatively low mass and a small packaging of the EVT. The thin interrotor yoke causes a magnetic coupling between both machines. Therefore the control of the EVT is a special challenge. The magnetic circuit of the EVT was optimized using the finite element method (FEM). A special control scheme was implemented enabling mathematically the electromagnetic decoupling of both machines. Based on these developments the EVT seems to be a very compact and cost-effective solution for a power-split hybrid electric drive.

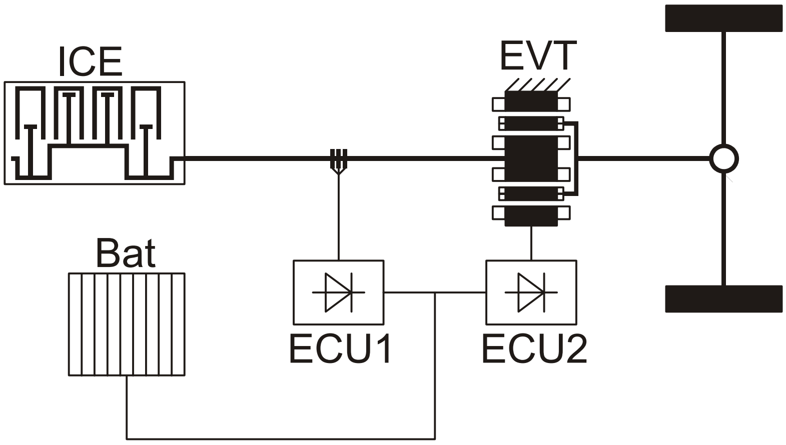

Fig. 5: Structure of the EVT

The EVT contains the functionality of a continuously variable transmission. Like in the Prius there is no conventional automatic transmission any more. Regarding mechanic complexity the EVT is even simpler than the Prius. The EVT has only two rotating parts. There are absolutely no gears any more. The induction machine technology enables a robust and cost-effective solution.

The EVT enables full hybrid functionality by using the battery as energy storage device. Regenerative braking and boosting are possible with the outer machine by charging or discharging the battery. Pure electric driving can be realized with the outer machine also. The start-stop function and the pure electric drive function require the starting of the engine via EVT. This is done with the inner machine. The impact of starting torque to the interrotor is compensated by the outer machine resulting in a smooth torque at the wheels. In total the EVT is a multifunctional, compact device. Especially the smooth torque delivery on the one hand and the additional boost torque on the other hand increase the driving pleasure.

The EVT is a scalable concept that may be applied to a wide range of vehicle classes, from passenger cars to heavy duty vehicles. Initial application studies were focused on city bus applications [6]. In the following chapters the results from the first passenger car investigations will be presented.

4 Powertrain Integration

4.1 Specifications for the application

In order to determine the performance and characteristics of the EVT in a passenger vehicle, a simulation study was performed. For this, an analytical model for the EVT was developed and integrated into TNO’s vehicle simulation tool ADVANCE [7]. This model was validated with FEM analyses. Special tools were developed to enable dimensioning and optimizing the EVT in the powertrain system.

A mid-size passenger vehicle was selected for the application. Vehicle and EVT specifications are shown in table 1 and table 2.

Inertia Class	1470 kg
Vehicle Class	CD segment
Battery	NiMH, 6.5Ah
Engine	1.5L 4 cylinder MPFI, 57 kW @ 5000 rpm
Final Drive	3.29:1

Tab. 1: Hybrid Vehicle Specifications

Rated Input Torque	115 Nm
Maximum Output Torque	610 Nm
Voltage	500 V DC

Tab. 2: EVT Specifications

4.2 Powertrain control

For the EVT, a power-based control structure was adapted (based on the system described in [8]) and the calibration optimized for this application. Engine control was based on a system-optimal workline based on power request (figure 6).

Additionally, an optimized charge algorithm was implemented that reacts to drive power and battery SOC, which depends on the efficiency characteristics of the system. This allows more extensive use of electric driving, increasing the fuel consumption reduction achieved by the hybrid functions. An overview of the hybrid functions used is shown in table 3.

- Start-stop
- Electric drive with engine decoupling
- Regenerative braking with engine decoupling
- Boost
- Optimal charge

Tab. 3: Hybrid modes used in simulation

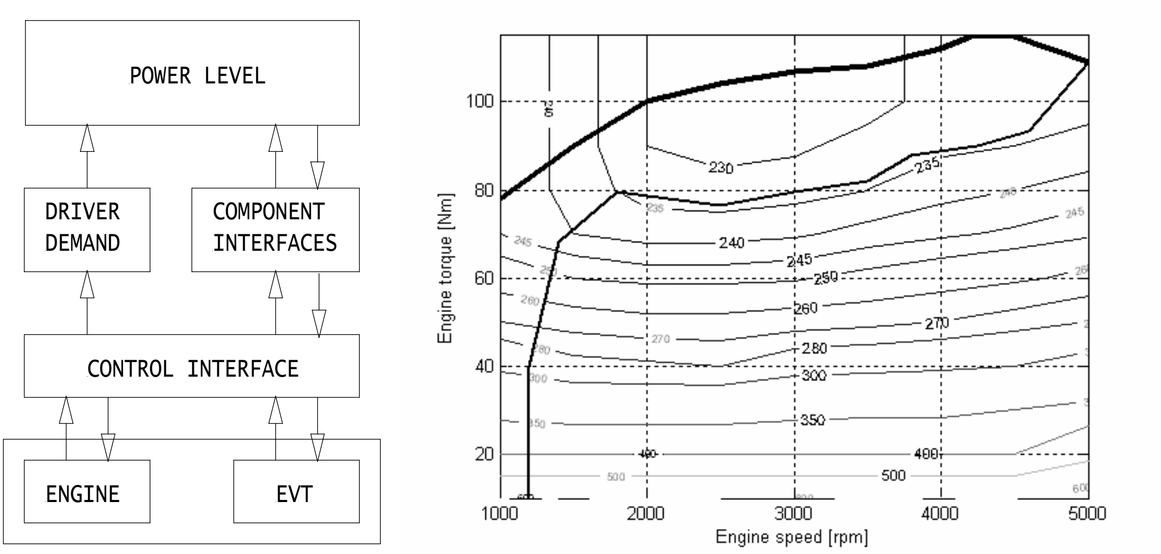

Fig. 6: Hybrid control structure and system-optimal engine workline

5 Performance and fuel consumption

Vehicle simulations were used to determine system performance and fuel consumption on the NEDC drive cycle. These results were compared with similar production hybrid vehicles.

Results show that the simulated EVT achieves very good fuel economy and acceleration performance when compared to current production hybrid vehicles (figure 7). The EVT vehicle reaches a fuel consumption of 4.3 l/100km and an acceleration time (0-100 km/h) of 10.8s. The very low fuel consumption is due to the EVT enabling full exploitation of hybrid modes 2 and 3 (see table 3). Additionally, the EVT's high charge efficiency (mode 5) allows extending the use of electric driving, providing a further significant improvement in fuel consumption.

The behavior of the EVT on a part of the NEDC cycle can be seen in figure 8. Phases of regenerative braking and pure electric driving can be clearly seen. The torque multiplication due to power split behavior in normal drive mode is apparent from the engine torque (equivalent to the inner machine torque) and the output torque (sum of the torques from inner and outer machine). As 100% of the engine torque is transferred directly to the output shaft, the outer machine has a lower torque rating than similar designs. This allows higher efficiency of regenerative braking.

As electric driving is possible to above 50 km/h, very good comfort levels and almost silent operation can be achieved in a city environment.

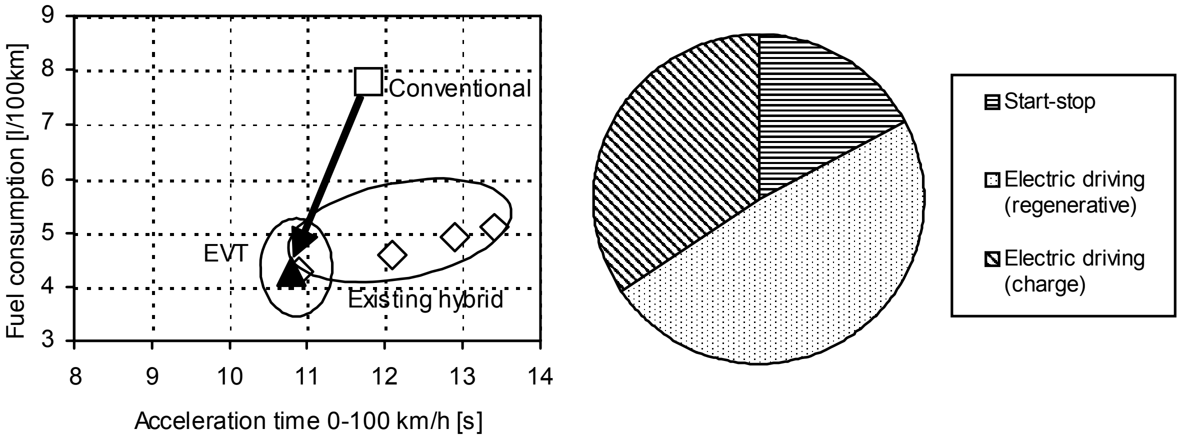

Fig. 7: Simulation results (left: acceleration and fuel consumption, right: relative fuel savings per hybrid function for the EVT)

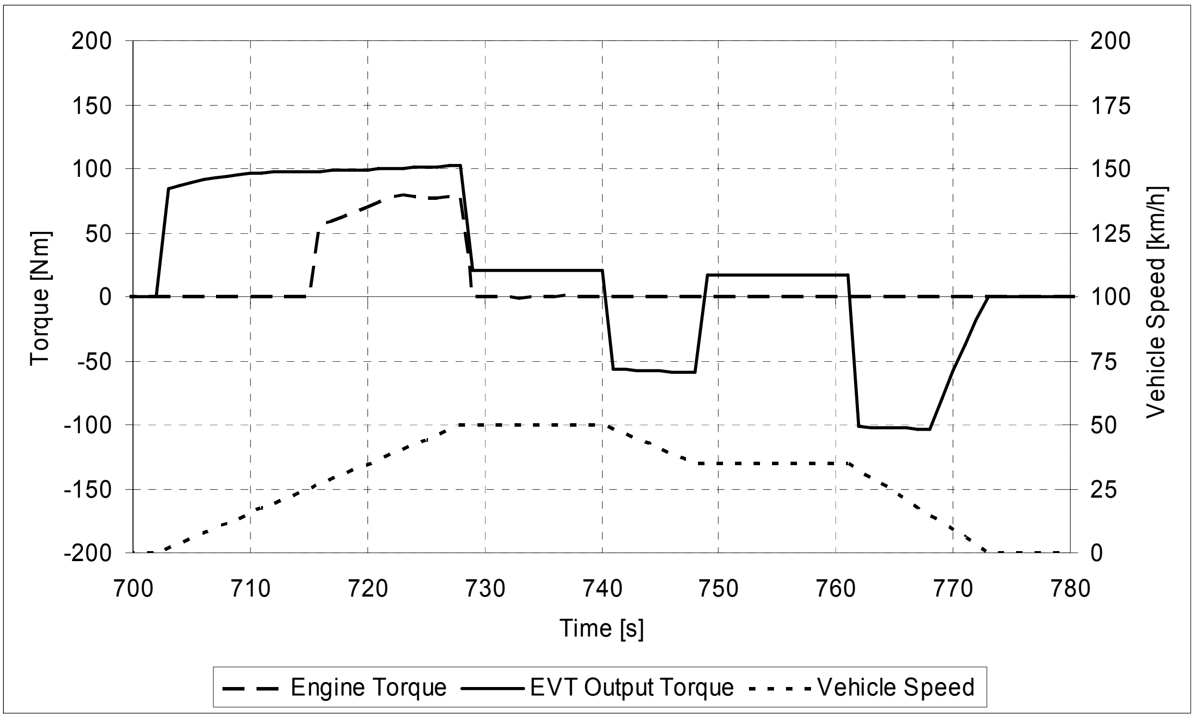

Fig. 8: EVT torques on part of the NEDC simulation

6 Conclusion

The EVT is a compact, multifunctional system. It replaces the standard automatic transmission and enables a continuously variable transmission ratio. Furthermore the EVT enables the full hybrid functionality including pure electric driving. The power-split results in a high degree of integration: both electric machines have reduced size and are magnetically coupled via a thin interrotor. The inverters also have reduced size due to the power-split. The mechanical structure of the EVT is very simple with only two rotating parts. The high efficiency of the EVT enables low fuel consumption of only 4.3l per 100km in the NEDC for a mid-size passenger car. The acceleration time from 0 to 100km/h is 10.8s for the same vehicle. The driving pleasure is further increased by the smooth torque delivery of the EVT.

7 Literature

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