The Electrical Variable Transmission in a city bus

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***Abstract*— First, an electromechanical converter with two mechanical ports and one electrical port (consisting of two concentric machines and two invertors) is considered. This converter works as a continuously variable transmission between the mechanical ports and may, for example, replace the clutch, gearbox, generator, and starter motor in a motor vehicle. The working principle of this converter is explained.**

Next, a new converter, the Electrical Variable Transmission (EVT), is presented. This converter has similar properties, but is smaller and lighter. The EVT may be seen as built up from two concentric induction machines with a combined, relatively thin yoke. So, we obtain one electromagnetic device instead of two magnetically separated devices.

For the explanation of the principle of the EVT, different operation modes are examined by means of analytical two-dimensional field computations and the losses are discussed.

The performance of the EVT in a city bus was simulated and compared with a bus with a conventional automatic transmission. The bus with the EVT uses less fuel because the combustion engine can operate with higher efficiency. The EVT is very well fit to be used in a hybrid configuration, which decreases the fuel consumption even more.

I. Introduction

On many places, mechanical energy is available from a rotating shaft and used through a shaft rotating with a different speed. In for example a motor vehicle, this conversion problem is solved by means of a gearbox. However, in a vehicle we also need a generator and a starter motor. The resulting system is shown in figure 1. In a vehicle, the electrical port of the system is connected to a battery.

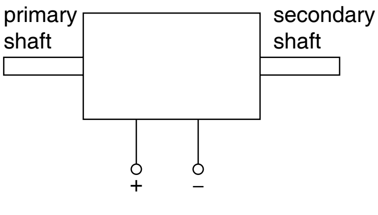

Fig. 1. The considered system

One of the disadvantages of the conventional electrical system is the wear of the starter. This limits the number of starter actions and is an important reason for city buses not to switch off their engines at bus stops (which would be more comfortable and reduce the fuel consumption). Another disadvantage is the belt-driven generator, which has a low efficiency and a low maximum power rating. These disadvantages are the reason for a big R&D interest in starter-generators, see for example [1], [2], [4], or [6].

A better electromechanic system for a vehicle might be a cascade system of a DC generator (synchronous generator with rectifier) and a DC motor (inverter with induction motor). However, in this case, the full power flow is through two (four) convertors, resulting in a low efficiency.

This efficiency can be increased significantly when a (larger) part of the power flow is converted directly. This may be realized by using two concentrically arranged electrical machines. The basic idea for this implementation is very old (1935, using DC machines [3]). A version with two concentrically arranged induction machines is shown in figure 2. The outer machine is a normal squirrel-cage machine. The inner machine has its squirrel-cage winding on its outer part and its three-phase winding on its inner part with sliprings (like the rotor of a wound-rotor induction machine).

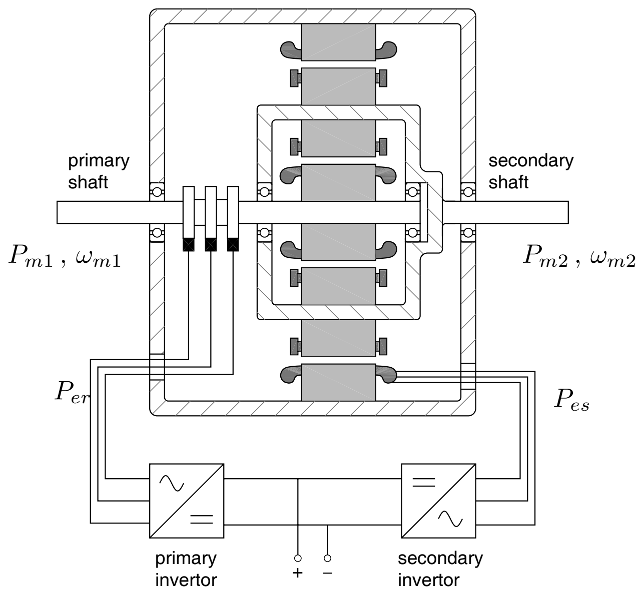

Fig. 2. Two concentric induction machines

We will have a look at this system for the case that it used as a continuously variable transmission (without a battery on the DC link). For the explanation, the system is assumed to be lossless (also no losses in the squirrel-cage windings).

For the primary-shaft power, we can use

$$P_{m1} = \omega_{m1} T_{m1} \tag{1}$$

where ω_{m1} is the (mechanical) rotational speed and T_{m1} is the primary (mechanical) torque. In this case, T_{m1} is also the air-gap torque of the inner machine, and the electrical power generated by the inner machine is

$$P_{er} = (\omega_{m1} - \omega_{m2})\, T_{m1} \tag{2}$$

where ω_{m2} is the (mechanical) rotational speed of the secondary shaft.

The electric power P_{er} is one part of the power flow. The other part is transferred directly to the secondary shaft, via the electromagnetic torque in the inner air gap:

$$P_d = \omega_{m2} T_{m1} \tag{3}$$

Because we assumed the system to be lossless and there is no battery in the DC link, the rotor power equals the stator power (see figure 2):

$$P_{er} = P_{es} = P_e \tag{4}$$

In practice, this power flow P_e through the two invertors causes relatively high losses.

The electric power P_e results in a torque in the air gap of the outer machine:

$$T_{e2} = \frac{P_e}{\omega_{m2}} \tag{5}$$

Thus, the secondary-shaft torque is:

$$T_{m2} = T_{m1} + T_{e2} = T_{m1} + \frac{P_e}{\omega_{m2}} = \frac{\omega_{m1}}{\omega_{m2}} T_{m1} \tag{6}$$

as also directly results from the power balance.

The idea of two concentric machines has been implemented in various ways, see for example [8] and [9].

Because such a system is a continuously variable transmission, it allows a better use of the engine in a vehicle, in which it also works as a starter motor and a generator (with a high efficiency). Further, the electrical port may be used to connect an energy storage unit which is larger than a normal battery. Thus, we get a hybrid drive system: the mechanical energy to the wheels may be supplied by the engine as well as by the electrical source, see for example [7].

Of course, the idea can also be applied in other application than vehicles, for example dredgers or the combinations of an expander and a compressor, which exchange mechanical energy with supply or withdraw of electrical energy.

A big disadvantage of the machine in figure 2 is its size and its weight. In this paper, a new electromechanic conversion system with similar properties is presented, which is much smaller and lighter

II. The Electrical Variable Transmission

If the inner and the outer machine have the same slip frequency (including the direction), the fields of both machines rotate with the same speed and we can strongly reduce the height of the yokes attached to the rotor of the secondary shaft. In this way we get the machine in figure 3. This system is named the Electrical Variable Transmission (EVT).

The rotor on the secondary shaft is named the interrotor: it rotates between the (primary) rotor and the stator. The interrotor shown in figure 3 is just one of the possible arrangements.

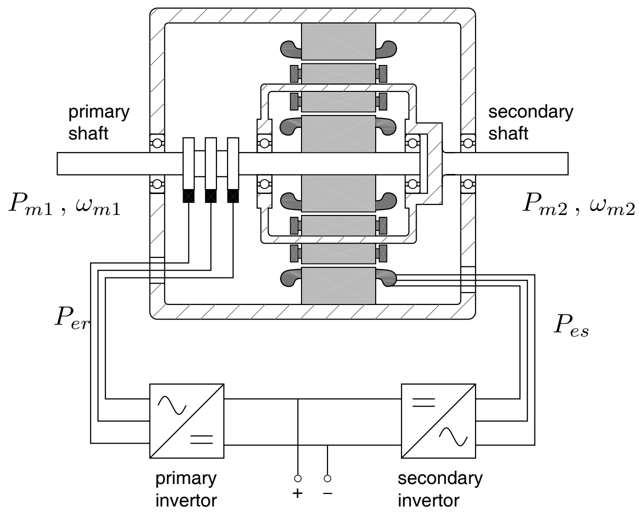

Fig. 3. The Electrical Variable Transmission

The electromagnetic behavior of the EVT is totally different from two separate induction machines.

When the magnetic reluctance of the interrotor yoke is very small, the EVT works as two concentric induction machines. However, the interrotor-yoke height is much smaller than the rotor-yoke or the stator-yoke height. As a result, the interrotor yoke is saturated and the inner and the outer machine are not magnetically separated anymore. In fact, we now get one electromagnetic device instead of two, in which there is also a direct interaction between the (slipring-armature) rotor and the stator.

An easy way to see this direct interaction is to consider the case that there is no stator current and that the slip frequency seen by the squirrel-cage windings is zero (so, there is also no current in the squirrel-cage windings). We increase the rotor current from zero. First, the rotor flux will pass the interrotor yoke tangentially. When the interrotor yoke saturates, a part of the rotor flux will cross the outer air gap and pass the stator yoke. When we next apply a stator current which has another direction than the rotor current, we get a direct torque between the stator and the rotor. This torque, which is not in the system with two concentric induction machines (figure 2), is named T_{rs}. This torque leads to a kind of synchronous-machine behavior between the rotor and the stator through the interrotor.

III. Some characteristic operation modes

For the explanation of the principle of the EVT, we will look at some characteristic operation modes. These operation modes can be examined by means of field plots. To obtain an impression of the magnetic field in the EVT, we use analytical two-dimensional field computations. In this method, the slot regions of the machine are represented by a homogeneous, anisotropic magnetic medium [5]. When we look at figure 4 as an example, we may distinguish the following cylindrical regions (starting from the center):

- the inner region, in the used model air;
- the rotor yoke;
- the rotor winding;
- the inner air gap;
- the inner squirrel-cage winding;
- the interrotor yoke;
- the outer squirrel-cage winding;
- the outer air gap;
- the stator winding;
- the stator yoke;
- the outer region, in the used model air.

The sinusoidally distributed current densities may be identified by the color densities.

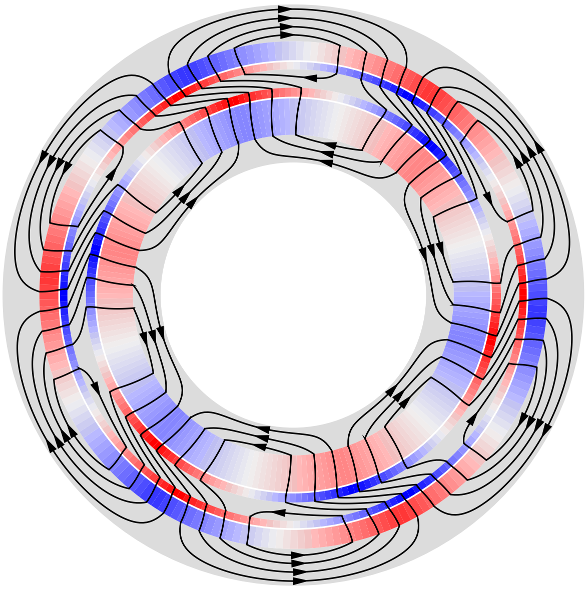

Fig. 4. Very-low-speed operation

The example in figure 4 is for the case that the secondary-shaft speed is very low. The input torque is 600 Nm and the output torque 1800 Nm. Here, the directly converted power P_d ((3)) is very low, because the output speed is very low. The main power flow is through the invertors from the rotor to the stator ((2): $P_{er} > 0$).

The currents in the four windings are relatively high and the flux densities are high too. As a result, we have high copper losses and high iron losses in the rotor (the rotor frequency is proportional to $\omega_{m1} - \omega_{m2}$, which is relatively high). The stator iron losses are low because the frequency is low.

The example in figure 5 is for the special case that the flux is crossing the interrotor merely radially. So there is no direct torque between the stator and the rotor ($T_{rs} = 0$). The input torque is 400 Nm and the output torque 900 Nm. In this case, the directly converted power P_d is larger than in the case of figure 4 and the power flow through the invertors is smaller.

The copper losses are much less than in the case of figure 4, but the iron losses have about the same magnitude.

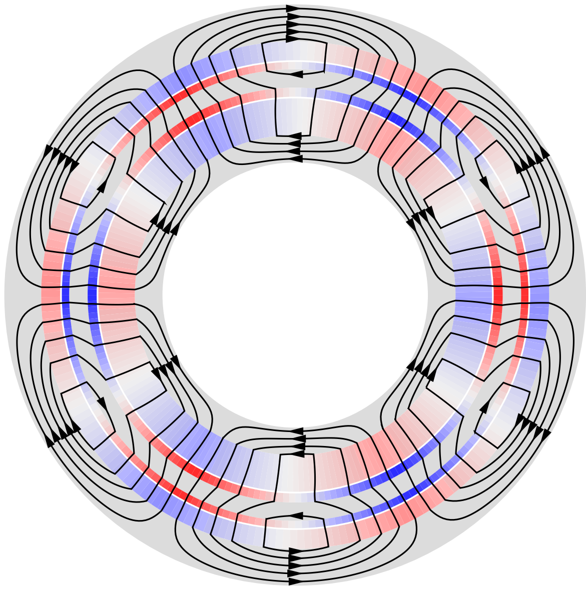

Fig. 5. Low-speed operation (flux crossing the interrotor merely radially)

Figure 6 is for the case of direct drive with a torque of 800 Nm. In this example, there is no stator current. As may be seen, the outer squirrel-cage is still active. In this case, all power is converted directly ($P_d = P_{m1}$) and the power flow through the invertors is zero ($P_e = 0$).

Here, we have relatively high copper losses (no losses in the stator) and low iron losses because the frequency in the

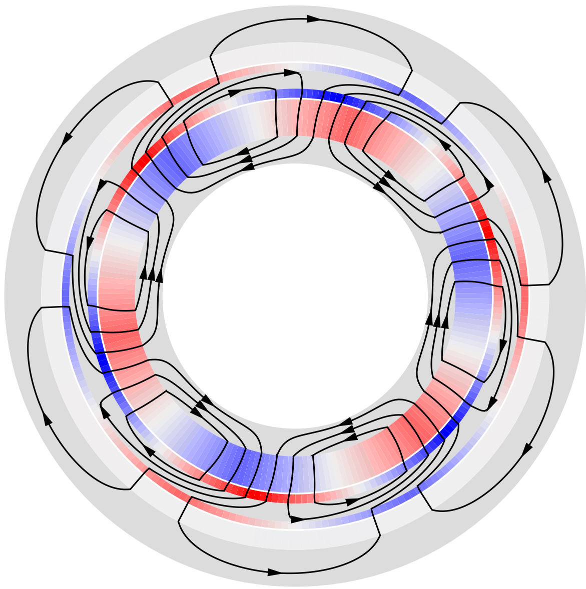

Fig. 6. Direct-drive operation

rotor (slip-ring armature) is very low (slip frequency) and the flux density in the stator is low too. In fact, we used field weakening in the stator. Because of this field weakening, the stator voltage is limited. This also results in a limitation for the rating of the secondary invertor. In a city bus, for example, the power rating of both inverters is about 65 % of the engine power rating.

The example in figure 7 is for the case of over-drive. The input torque is 800 Nm and the output torque 600 Nm. Here, the stator delivers electric power (works as generator) to the rotor via the secondary and the primary invertor ((2): $P_{er} < 0$). The larger part of the input is still converted directly.

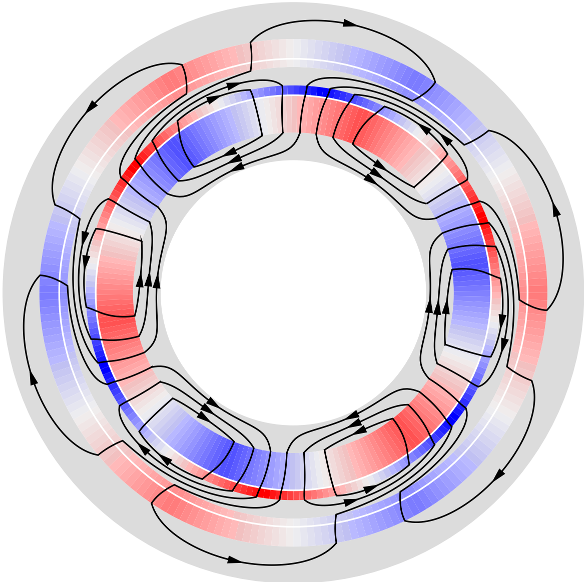

Fig. 7. High-speed operation

The copper losses are somewhat higher than in the case of figure 6, because the stator winding is active too. The stator flux level may be relatively low, because the contribution of the outer air-gap torque to the secondary-shaft torque is relatively low. Although the rotor frequency (proportional to $\omega_{m1} - \omega_{m2}$) is higher than in the case of figure 6, it still is relatively low in practice. So, the iron losses are still low.

IV. Proof of concept

Some experiments were carried out in the laboratory (see the figures 8 and 9). The system has operated in all important operation areas (backwards, underdrive and overdrive). However, because the machine made for the proof of concept had some serious mechanical imperfections, no efficiency measurements could be carried out.

V. The Electrical Variable Transmission in a city bus

The performance of the EVT as a transmission for a city bus has been simulated. A city bus was modelled, using a common bus diesel engine and the EVT. The EVT was controlled to get minimum fuel consumption. To make a comparison possible, a conventional city bus with the same engine and a four-speed automatic transmission (AT) was also simulated. Four different vehicle masses were used in the simulations.

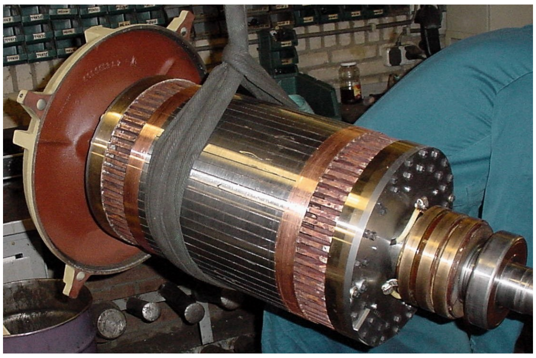

Fig. 8. The rotor/interrotor set

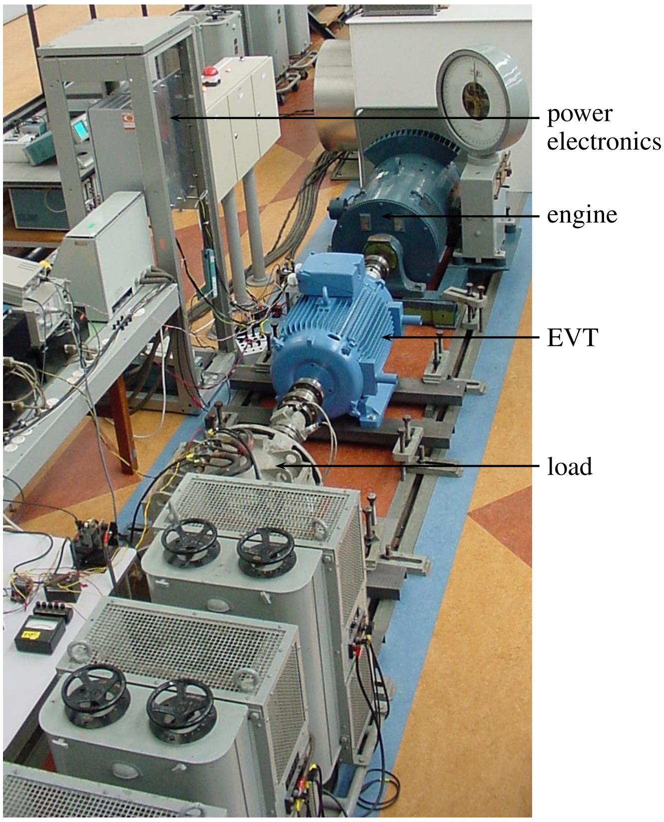

Fig. 9. The experimental set-up

The efficiency plot of the modelled diesel engine is shown in figure 10. The engine is more efficient at high torque output. Therefore the same mechanical power output can best be realized at low engine speed and high torque, rather than at high engine speed and low torque. In other words: the vehicle should drive in the highest possible gear.

The actual engine operating points for constant driving speed are shown in figure 11. The speed is in the range from 5 to 95 km/h in steps of 5 km/h. The figure shows that

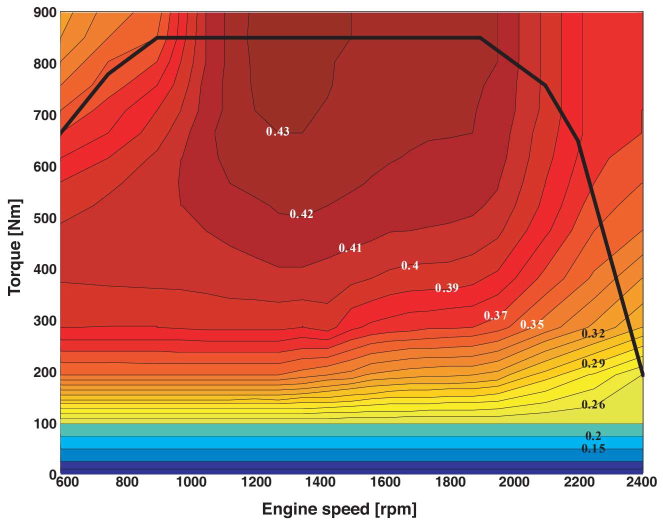

Fig. 10. The engine efficiency plot. Highest efficiency is 43%. The black line shows maximum torque.

for the same speed, the engine operates with less rotations per minute and more torque if the bus is equipped with an EVT. Left in the figure it can be seen that at a constant speed up to 30 km/h, the engine maintains its idle speed and only increases the torque, while with the automatic transmission the engine speed has to increase even to drive 10 km/h.

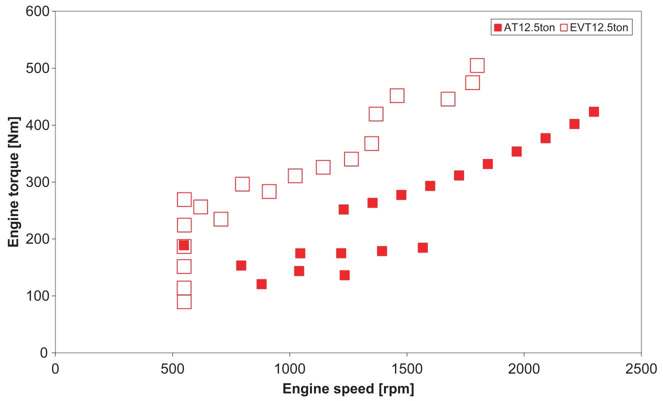

Fig. 11. Comparison of engine operating points at constant vehicle speed

The effect of the more efficient operating points can be seen in figure 12 in which the mileage at constant speed is compared for the bus with the EVT and the one with the conventional automatic transmission. The latter can only choose from 4 gear ratios while the EVT has an infinite number of ratios.

Since the EVT works as a continuously variable transmission, it allows a better use of the engine power. This results in a faster acceleration as well, because the acceleration will be performed with continuous maximum engine power. The results of the simulation are shown in table I.

To calculate the fuel consumption of a vehicle, a driving cycle, which describes the vehicle's speed against time, is necessary. In this case the Dutch Urban Bus Cycle was used, see figure 13. It is a driving cycle that is based on real world measurements in urban buses in several Dutch cities.

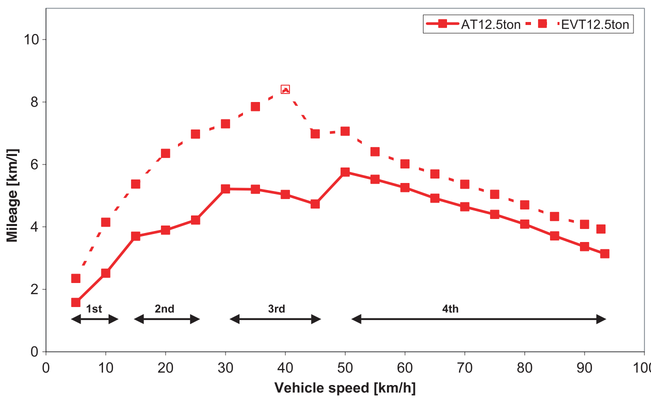

Fig. 12. Comparison of the mileage at constant vehicle speed

TABLE I
ACCELERATION TIME FROM 0 TO 50 KM/H

mass (tonnes)	AT accel. time (s)	EVT accel. time (s)
7.5	9.3	8.5
10	11.8	10.9
12.5	14.3	13.4
15	16.9	16.0

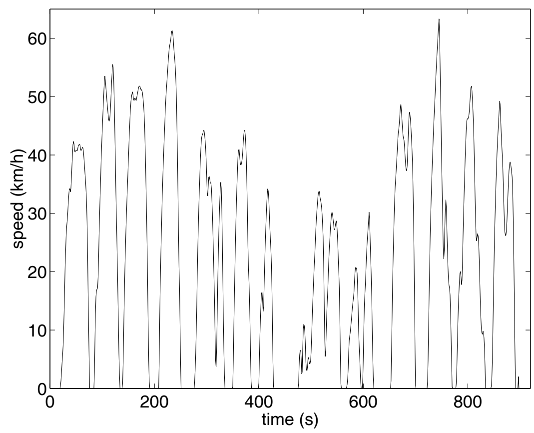

Fig. 13. The Dutch Urban Bus Cycle

The calculated mileages on the Dutch Urban Driving Cycle are shown in table II.

The reduction of fuel consumption is for the major part realized because the EVT allows the engine to work in more efficient operating points during partial load. For a heavier bus, less partial load occurs, especially during acceleration. That is why the advantage of the EVT decreases with increasing mass of the bus for the chosen engine.

The electrical port (see figure 3) may be used to connect an energy storage unit, like a battery or supercapacitors. It allows to shut off the engine at standstill and start again for

TABLE II
MILEAGE ON THE DUTCH URBAN BUS CYCLE

mass (tonnes)	AT mileage (km/l)	EVT mileage (km/l)
7.5	2.7	3.4 (+26%)
10	2.3	2.8 (+22%)
12.5	2.0	2.3 (+15%)
15	1.8	2.0 (+11%)

acceleration. This will give an extra reduction in fuel consumption of approximately 1.3 l/100 km, which corresponds to 3 %. If the storage system is large enough, we get a hybrid drive system which gives other possibilities to save fuel. The mechanical energy to the wheels can be supplied by the combustion engine as well as by the electrical storage. The brake energy can be stored, and used again for acceleration. Also, when the power requested from the engine is very low, it is possible to drive on energy from the storage and avoid that the engine has to operate in a low efficiency area.

VI. CONCLUSION

The Electrical Variable Transmission differs from similar designs because of the thin interrotor. This reduces the mass and gives rise to an additional synchronous torque between rotor and stator. The EVT can be useful as a continuously variable transmission in a motor vehicle, in which it also works as a starter motor and a generator. It allows the engine to work with better efficiency which can increase the fuel efficiency over 25 %. The EVT is very well fit for use in a hybrid system.

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