The Electrical Variable Transmission

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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. The working principle of the EVT is explained and its losses are discussed.

I. Introduction

In this paper, a description is given of the Electrical Variable Transmission, which may replace the clutch, gearbox, starter, and generator in buses and light trucks. We can regard the set clutch, gearbox, starter, and generator as an electromechanical converter (figure 1) with two mechanical ports (to the engine and to the differential) and one electrical port (to the battery).

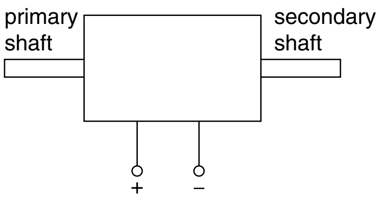

Fig. 1. The considered system

One of the disadvantages of the electrical part of the conventional 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], [3], or [4].

Furthermore, a conventional gearbox has a limited number of gear ratios, which is not optimal for the combustion engine. A continuously variable transmission allows the engine to work with better efficiency, which can result in a considerable reduction of the fuel consumption, especially if the over-drive region is large, see [5].

A proper electromechanic system can overcome the disadvantages of the conventional system mentioned above. Here, we will develop such an electromechanic system, resulting in the Electrical Variable Transmission (EVT). We will discuss some characteristic operation modes and the losses in the system. Finally, we will pay some attention to the proof of concept.

II. The basic idea

A. The cascade system

A better electromechanic system for a vehicle might be a cascade system of a DC generator (AC generator with rectifier) and a DC motor (inverter with AC motor), as shown in figure 2. In this case we use an unconventional generator in which the squirrel-cage winding is on the stator and the electric power is withdrawn from the rotor (the rotor of a wound-rotor induction machine with sliprings). This choice is made for the further development of the system.

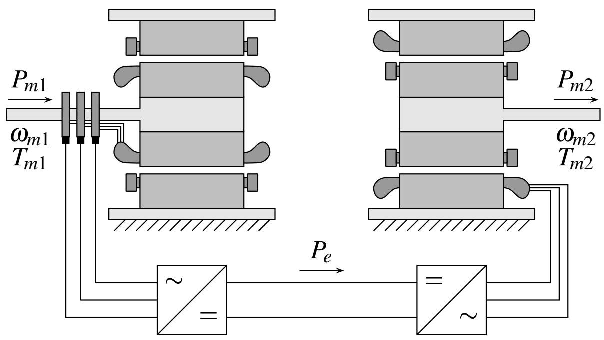

Fig. 2. A cascade system

We will have a look at this system for the case that it is 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).

The system is supplied by the primary-shaft power

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

where ω_{m1} is the rotational speed and T_{m1} is the (mechanical) torque. This power is converted into the electrical power P_e, which is converted to the secondary-shaft power $P_{m2} = \omega_{m2} T_{m2}$. In this case, the full power flow is through four convertors, resulting in a relatively low efficiency in reality.

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This efficiency can be increased significantly if we directly lead the stator torque of the primary machine to the rotor of the secondary machine, as is shown in figure 3.

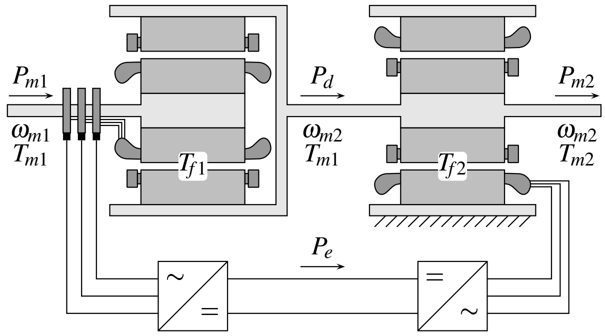

Fig. 3. The basic idea

In this case, the electrical power generated by the primary machine is

$$P_e = (\omega_{m1} - \omega_{m2})\, T_{f1} = (\omega_{m1} - \omega_{m2})\, T_{m1} \tag{2}$$

where T_{f1} is the electromagnetic (field) torque, which equals T_{m1}.

The electric power is one part of the power flow. The other part is directly passed to the secondary shaft, via the electromagnetic torque in the primary air gap:

$$P_d = \omega_{m2} T_{f1} = \omega_{m2} T_{m1} \tag{3}$$

So, the power balance of the primary machine is

$$P_{m1} = P_e + P_d \tag{4}$$

The power P_e still is the power flow through the power-electronic converters with relatively high losses (in reality). The power P_d is the power flow directly passed from the primary rotor to the secondary rotor with relatively low losses. The powers P_d and P_e as a function of the secondary rotational speed ω_{m2} are shown in the left graph of figure 4. The parts of the graphs for low values of ω_{m2} are dotted, because the assumption that the system is lossless is not reasonable in this region.

The secondary-shaft torque T_{m2} consists of the contribution of the primary air-gap (field) torque $T_{f1} = T_{m1}$ and the secondary air-gap torque

$$T_{f2} = \frac{P_e}{\omega_{m2}} = \frac{\omega_{m1} - \omega_{m2}}{\omega_{m2}} T_{m1} \tag{5}$$

where we used the power balance of the stator of the secondary machine and equation (2).

So, we found for the secondary-shaft torque (as expected):

$$T_{m2} = T_{f1} + T_{f2} = \frac{\omega_{m1}}{\omega_{m2}} T_{m1} \tag{6}$$

The torques as functions of the secondary rotational speed are shown in the right graph of figure 4.

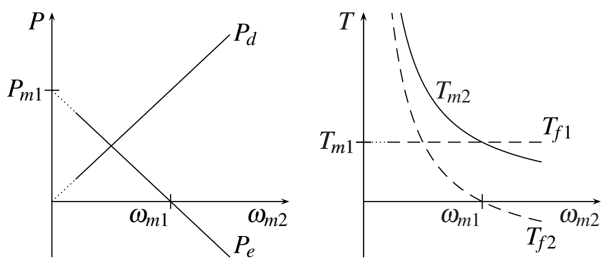

Fig. 4. Power and torque characteristics

As we can see in figure 4, P_e is relatively small in the region around $\omega_{m2} = \omega_{m1}$ (direct-drive). Thus, the losses are also relatively low in this region and it should be the favorite operation region. For low values of ω_{m2}, P_e is relatively high. In traction drive systems, this region corresponds with the acceleration, which normally doesn't take a long time. So, a good choice of the direct-drive speed can result in a relatively high efficiency for the application in traction-drive systems.

B. The system rating

As we have seen, the first advantage of the cascade system of figure 3 above the cascade system of figure 2 is its efficiency. In this subsection we will see that the second advantage is that the rating of the system components is lower.

Because a high secondary-shaft torque T_{m2} (at a low secondary speed ω_{m2} is mostly only necessary during a very short time, the continuous available (rated) torque $T_{m2,rat}$, can be much lower than that peak torque. Here, we use

$$T_{m2,rat} = n_{rat} T_{m1,rat} \tag{7}$$

where n_{rat} is the rated gear ratio. For example, in a city bus, n_{rat} is probably somewhere between 2 and 2.5, whereas the peak gear ratio can be around 5.

For the further explanation, we will use figure 5 and we assume that the primary-shaft torque equals its rated value $T_{m1,rat}$. For low values of ω_{m2} (and ω_{m1}), this is not possible in the case of a combustion engine. For that reason, the curves are dotted in that region.

The secondary-shaft torque for rated primary-shaft torque is the bold curve in figure 5a, which is derived from the right side of figure 4. Because there are no losses, the rated secondary-shaft speed follows from

$$\omega_{m2,rat} = \frac{1}{n_{rat}} \omega_{m1,rat} \tag{8}$$

The region on the right side of $\omega_{m2,rat}$, is the constant-power region (see figure 5b). Because T_{m1} is assumed to be constant ($T_{m1,rat}$), the primary speed is constant too in this region (figure 5c). In the region on the left side of $\omega_{m2,rat}$, the secondary torque is constant. So, the power (figure 5b) and the primary speed (figure 5c) are proportional to the secondary speed here.

For the rating of the primary machine, we look at figure 5c and remind that the primary torque equals $T_{m1,rat}$. When we neglect the magnetizing current and assume the flux to

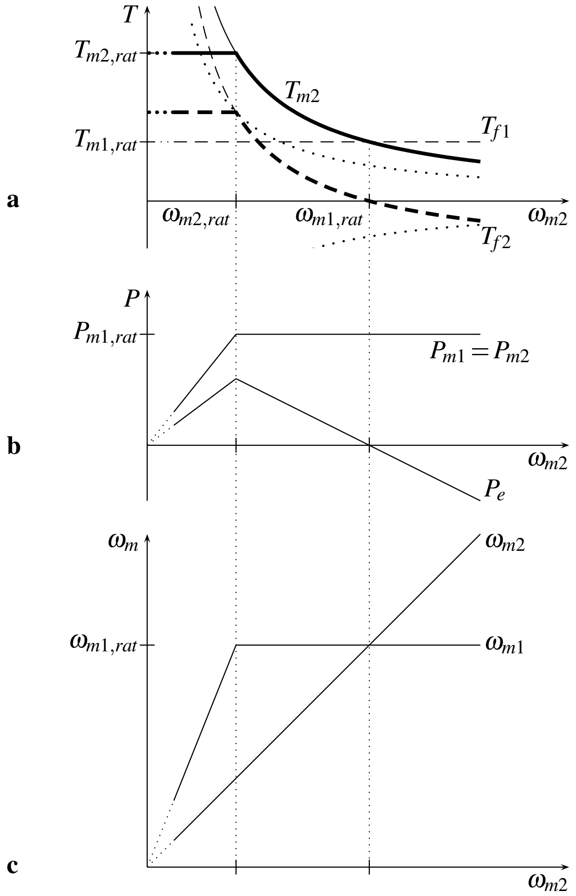

Fig. 5. The system rating

be constant, this torque corresponds with the current. With a constant flux, the voltage corresponds with the rotational speed seen by the primary machine $|\omega_{m1}-\omega_{m2}|$. The maximum of this difference occurs at $\omega_{m2}=\omega_{m2,rat}$. So, the rated electrical power for the primary machine is (using (8)):

$$P_{el,rat}=T_{m1,rat}(\omega_{m1,rat}-\omega_{m2,rat})=T_{m1,rat}\omega_{m1,rat}\frac{n_{rat}-1}{n_{rat}} \quad (9)$$

When we look at figure 5c, we can see that $|\omega_{m1}-\omega_{m2}|$ also becomes larger for relatively large values of ω_{m2}. We don't consider that case here.

For the rating of the secondary machine, we look at figure 5a. For $\omega_{m2}<\omega_{m2,rat}$, the torque contribution of the secondary air gap T_{f2} is maximum: $(n_{rat}-1)T_{m1,rat}$. In that region, the maximum power occurs at $\omega_{m2}=\omega_{m2,rat}$. So, the maximum power in that region is again $T_{m1,rat}\omega_{m1,rat}(n_{rat}-1)/n_{rat}$ (see (9)). For $\omega_{m2}>\omega_{m2,rat}$, we can use field weakening in the secondary machine, so that the flux is inversely proportional to the rotational speed. In that case, the voltage is constant. If the current is kept at a constant value, the torque is a hyperbolic function of the rotational speed. These are the dotted curves in figure 5a. As we may see T_{f2} is always between those curves, except for the case of higher values of ω_{m2}, which we don't consider here. So, the maximum again occurs at $\omega_{m2}=\omega_{m2,rat}$ and we may also use (9) for the secondary machine.

Because we considered the currents and the voltages of both machines, expression (9) for the power rating is also valid for the power-electronic converters. Furthermore, we can find the value from expression (9) in the maximum of P_e in figure 5b.

In the foregoing, we didn't consider a possible magnetizing current. An extra magnetizing current component (in an induction machine) results in a higher (apparent) power rating. When we consider the example of a city bus from [5], we find an apparent power rating for the (induction) machines and the power-electronic converters of about 65 % of the rated power of the combustion engine.

C. The practical implementation

For the practical implementation of a continuously variable transmission the secondary machine is concentrically arranged around the primary machine as shown in figure 6. The basic idea for this implementation is very old (1935, using DC machines [6]).

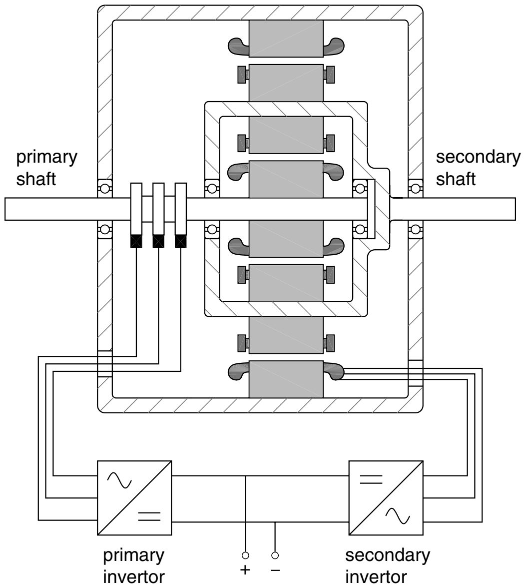

Fig. 6. Two concentric induction machines

We will again have a look at this system for the case that it is used as a continuously variable transmission. However, we will take the most important losses into account. Further, we replace primary by inner (the subscript 1 by i) and secondary by outer (the subscript 2 by o) on some places.

The system is supplied by the primary-shaft power $P_{m1}=\omega_{m1}T_{m1}$ (see figure 7). This power is split up into two parts. The part

$$P_{fi}=\omega_{fi}T_{m1} \quad (10)$$

(ω_{fi} is the rotational speed of the field in the inner air gap) is directly passed to the secondary shaft via the inner squirrel-cage winding ($T_{m1}=T_{fi}=T_{mci}$). However, we have the

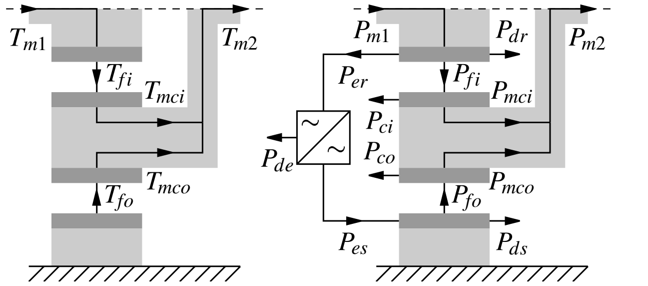

Fig. 7. The torque and power reference directions for two concentric induction machines

losses P_{ci} in the inner squirrel-cage winding:

$$P_{mci} = P_{fi} - P_{ci} = \left(\omega_{fi} - \frac{\omega_{slip,i}}{p}\right) T_{m1} \tag{11}$$

where we used

$$\omega_{slip,i} = p\left(\omega_{fi} - \omega_{m2}\right) \tag{12}$$

which is the slip angular frequency and where p is the number of pole pairs.

In the other power flow we have the rotor (copper and iron) losses P_{dr}. So, the electrical power obtained from the rotor (sliprings) is:

$$P_{er} = \left(\omega_{m1} - \omega_{fi}\right) T_{m1} - P_{dr} \tag{13}$$

This power is supplied to the power-electronic converters with the losses P_{de}. So, the electric power supplied to the stator is:

$$P_{es} = P_{er} - P_{de} \tag{14}$$

After subtraction of the stator losses P_{ds} (copper and iron), we get the air-gap (field) power, which is directly related to the air-gap torque:

$$P_{fo} = P_{es} - P_{ds} = \omega_{fo} T_{fo} \tag{15}$$

As in a normal squirrel-cage induction machine this power is converted into the mechanical power P_{mco} with the loss in the outer squirrel-cage winding P_{co}. This corresponds with the contribution $T_{mco} = T_{fo}$ to the secondary shaft torque T_{m2}.

The idea of two concentric machines has been implemented in various ways, see for example [7] and [8].

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 for the differential may be supplied by the engine as well as by the electrical source, see for example [9].

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 6 is its size and its weight. In this publication a new electromechanic conversion system with similar properties is presented, which is much smaller and lighter

III. 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 8. This system is named the Electrical Variable Transmission (EVT).

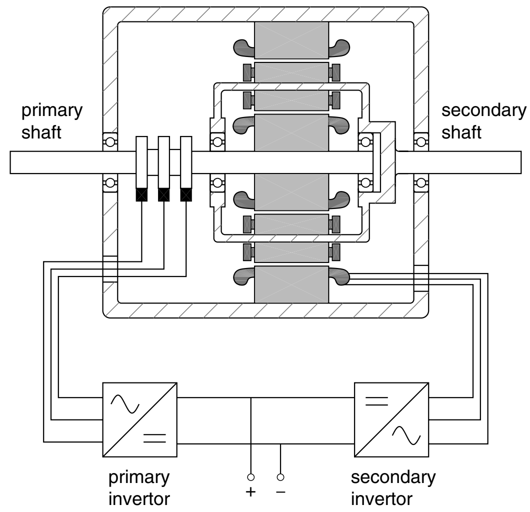

Fig. 8. The Electrical Variable Transmission

The rotor on the secondary shaft is named the interrotor: it rotates between the (primary) rotor and the stator. The interrotor shown in figure 8 is just one of the possible arrangements.

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 vector which has another direction than the rotor current vector, 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 7), is named T_{rs} (see figure 9). This torque leads to a kind of synchronous-machine behavior between the rotor and the stator through the interrotor. So, the air-gap torque of the inner machine consists of two components:

$$T_{fi} = T_{mci} - T_{rs} \tag{16}$$

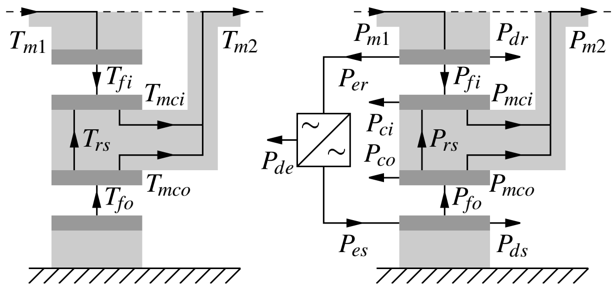

Fig. 9. The torque and power reference directions for the EVT

IV. A SIMPLE MODEL OF THE EVT

Because there is still no good, validated EVT model available, especially not for the interrotor-yoke saturation, we will derive a simple model based on well-known expressions for the induction machine. Later, we will only use this model to get an idea of the system losses.

First, we pay attention to angular frequencies and angular speeds. In the EVT, the angular speed of the field in the inner and in the outer part are the same ($\omega_{fi} = \omega_{fo} = \omega_f$). So, the slip frequencies in both squirrel-cage windings are equal too ($\omega_{slip,i} = \omega_{slip,o} = \omega_{slip}$) and the relations with the stator and the rotor angular frequency are:

$$\begin{aligned} \omega_s &= p\,\omega_f = p\,\omega_{m2} + \omega_{slip} \\ \omega_r &= p\,(\omega_f - \omega_{m1}) = p\,(\omega_{m2} - \omega_{m1}) + \omega_{slip} \end{aligned} \tag{17}$$

The torque corresponding with a squirrel-cage winding is supposed to be proportional to the slip frequency and the square of the flux linkage. So, we can write the torque contributions of the squirrel-cage windings as:

$$T_{mci} = \frac{\omega_{slip}}{\omega_{slip,i,rat}} \lambda_i'^2 T_{i,rat} \quad ; \quad T_{mco} = \frac{\omega_{slip}}{\omega_{slip,o,rat}} \lambda_o'^2 T_{o,rat} \tag{18}$$

where $\omega_{slip,i,rat}$ and $\omega_{slip,o,rat}$ are the rated values of the slip angular frequencies and λ_i' and λ_o' are the relative (per unit) values of the flux linkages (corresponding with the field weakening):

$$\lambda_i' = \frac{\lambda_i}{\lambda_{i,rat}} \quad ; \quad \lambda_o' = \frac{\lambda_o}{\lambda_{o,rat}} \tag{19}$$

The power dissipated in the squirrel-cage windings is

$$P_{ci} = \frac{\omega_{slip}}{p} T_{mci} \quad ; \quad P_{co} = \frac{\omega_{slip}}{p} T_{mco} \tag{20}$$

In the rated point, this is (using (18))

$$P_{ci,rat} = \frac{\omega_{slip,i,rat}}{p} T_{i,rat} \quad ; \quad P_{co,rat} = \frac{\omega_{slip,o,rat}}{p} T_{o,rat} \tag{21}$$

We can easily give reasonable estimations for these rated values in the case of induction machines. If we assume that the rated-torque values are known, we can use these equations to find the rated values of ω_{slip}. Further, we neglect the iron losses in the interrotor.

The losses in the rotor and the stator consist of the iron and the copper losses:

$$P_{dr} = P_{Fe,r} + P_{Cu,r} \quad ; \quad P_{ds} = P_{Fe,s} + P_{Cu,s} \tag{22}$$

The iron losses are supposed to be proportional to the square of the flux density and the square of the frequency:

$$P_{Fe,r} = \frac{\omega_r^2}{\omega_{r,rat}^2} \lambda_i'^2 P_{Fe,r,rat} \quad ; \quad P_{Fe,s} = \frac{\omega_s^2}{\omega_{s,rat}^2} \lambda_o'^2 P_{Fe,s,rat} \tag{23}$$

The copper losses are split up in a part corresponding with the air-gap torque (subscript T):

$$P_{Cu,T,r} = \frac{T_{fi}^2}{T_{i,rat}^2} \frac{P_{Cu,T,r,rat}}{\lambda_o'^2} \quad ; \quad P_{Cu,T,s} = \frac{T_{fo}^2}{T_{o,rat}^2} \frac{P_{Cu,T,s,rat}}{\lambda_o'^2} \tag{24}$$

and a part corresponding with the magnetizing current (subscript λ):

$$P_{Cu,\lambda,r} = \lambda_i'^2 P_{Cu,\lambda,r,rat} \quad ; \quad P_{Cu,\lambda,s} = \lambda_o'^2 P_{Cu,\lambda,s,rat} \tag{25}$$

where we neglected the non-linearity of the relation between flux en current.

For the relations between torques and between powers, we can use figure 9. The relation between an air-gap torque and the corresponding power can be found by multiplying the torque by the angular speed of the field $\omega_f = \omega_s/p$.

The loss behavior of power-electronic converters is usually unknown. For that reason, we use an estimated relation between the power P_{es} on the AC side of the secondary invertor and the power P_{er} on the AC side of the primary invertor as shown in figure 10 (exaggerated). The dashed lines in this figure correspond with a constant efficiency η_e. The no-load loss of both invertors together is P_{de0}. We can find the loss in the power-electronic converters by:

$$P_{de} = |P_{es} - P_{er}| \tag{26}$$

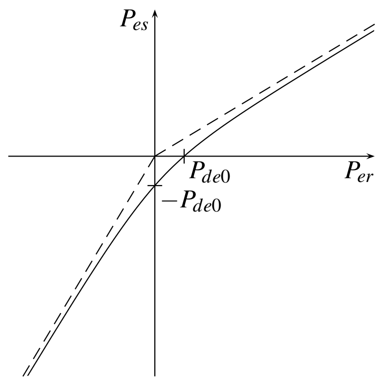

Fig. 10. The power P_{es} as a function of the power P_{er}

V. Some characteristic operation points

In this section, we will look at some characteristic operation points for the EVT. For this purpose, we use as an example a traction drive system with a combustion engine with a maximum torque of 850 Nm and a maximum power of 160 kW. These are typical values for a Dutch city bus. Because a combustion engine is never used continuously at its maximum torque, we choose the rated input torque of the EVT as 750 Nm. Further, we choose for this example the same value for the rated outer field torque ($n_{rat}=2$):

$$T_{i,rat} = T_{o,rat} = 750 \text{ Nm} \tag{27}$$

The rated frequency for both three-phase windings is 50 Hz and the number of pole pairs is 3:

$$\omega_{r,rat} = \omega_{s,rat} = 2\pi \ 50 \text{ rad/s} \quad ; \quad p = 3 \tag{28}$$

For the losses in both machine parts, we use some estimates for normal induction-machine losses:

$$\begin{aligned} P_{Fe,r,rat} &= P_{Fe,s,rat} = 0.5 \text{ kW} \\ P_{Cu,T,r,rat} &= P_{Cu,T,s,rat} = 1.7 \text{ kW} \\ P_{Cu,\lambda,r,rat} &= P_{Cu,\lambda,s,rat} = 0.3 \text{ kW} \\ P_{ci,rat} &= P_{co,rat} = 2 \text{ kW} \end{aligned} \tag{29}$$

It should be noted that a good quality magnetic material is used.

Further, there will be no field weakening in the rotor (λ_i'=1).

When we use soft-switched converters, we can get a high efficiency:

$$P_{de0} = 300 \text{ W} \quad ; \quad \eta_e = 0.97 \tag{30}$$

The considered operating points are given in table I. In the figures 11 up to 17 the torque and the power balance are also given for some points. The line width in these figures corresponds with the size of the flow.

The aim of this survey is just to get an impression of the distribution of the losses in the system. As mentioned before, we don't have a good, validated model of the interrotor saturation yet. This means that the computation of the magnetization currents is not reliable. Further, no extra (mechanical, ventilation) losses have been taken into account.

The first row (a) in table I corresponds with standstill (figure 11). Because, the direct contribution of the input torque (T_{m1}= 270 Nm) to the output torque (T_{m2}= 2250 Nm) is small, the stator air-gap torque and the corresponding copper losses are very high. Because there is no field weakening, the losses in the squirrel-cage windings are equal (and relatively high).

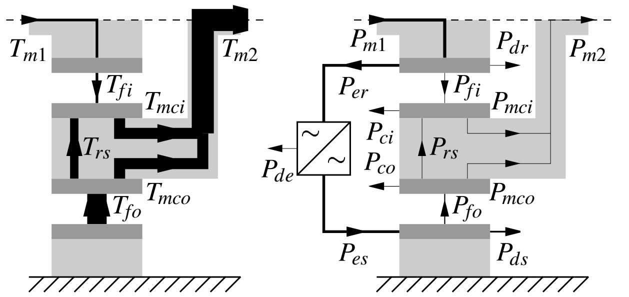

Fig. 11. The standstill mode with high output torque (row a in table I)

The rows b up to d in table I are for the case of an acceleration in which the inner and the outer air-gap torque are equal to their rated values (figure 12). There is no large change in the copper losses and the iron losses are still low.

Row d in table I (figure 13) is for the case of an acceleration with maximum electrical power (expression (9)). The losses are about their rated values. Further, it can be seen that the torque T_{rs} is reversed (from row c).

The rows d up to g in table I are for the case of an acceleration with high power. In this case, the stator field is weakened ($\lambda_o' < 1$; figure 14).

TABLE I

Some characteristic operating points

	ω_{m1}	T_{m1}	P_{m1}	ω_r	$P_{Cu,r}$	$P_{Fe,r}$	P_{er}	P_{de}	P_{es}	ω_s	λ_o'	$P_{Cu,s}$	$P_{Fe,s}$	T_{rs}	P_{ci}	P_{co}	ω_{m2}	T_{m2}	P_{m2}	η
	n_1			f_r						f_s							n_2			
	rpm	Nm	kW	Hz	kW	kW	kW	kW	kW	Hz	-	kW	kW	Nm	kW	kW	rpm	Nm	kW	-
a	800	270	22.7	-38	0.5	0.3	20.8	0.7	20.0	2	1.0	12.1	0.0	855	4.5	4.5	0	2250	0	0
b	800	489	40.9	-29	1.0	0.2	28.2	0.9	27.3	11	1.0	3.4	0.0	261	2.0	2.0	200	1500	31.4	0.77
c	1300	766	104.3	-34	2.1	0.2	51.8	1.6	50.2	31	1.0	1.9	0.2	-16	2.0	2.0	600	1500	94.3	0.90
d	1900	767	152.6	-49	2.1	0.5	75.7	2.3	73.4	46	1.0	1.9	0.4	-17	2.0	2.0	900	1500	141.4	0.93
e	1900	771	153.3	-24	2.1	0.1	36.3	1.1	35.2	71	0.7	0.5	0.5	-99	1.6	0.8	1400	1000	146.6	0.96
f	1900	773	153.8	1	2.1	0.0	-3.8	0.3	-4.1	96	0.5	0.1	0.4	-173	1.3	0.3	1900	750	149.2	0.97
g	1900	779	154.9	16	2.1	0.1	-28.2	0.9	-29.1	111	0.4	0.4	0.4	-218	1.1	0.2	2200	650	149.8	0.97
h	1200	397	49.9	30	0.8	0.2	-26.2	0.9	-27.1	90	0.5	0.3	0.4	-197	0.1	0.0	1800	250	47.1	0.95
i	800	372	31.2	-51	0.7	0.5	38.4	1.2	37.2	-11	1.0	6.0	0.0	-872	0.9	0.9	-200	-1000	20.9	0.67

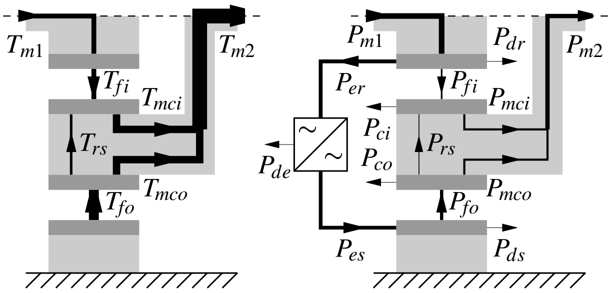

Fig. 12. Normal acceleration mode for very low speed (row b in table I)

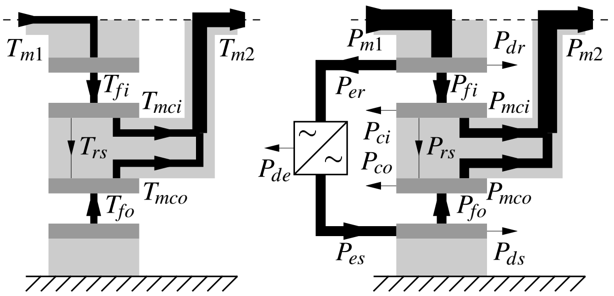

Fig. 13. Acceleration mode with maximum electric power (row d in table I)

Row f is for the case of direct drive (figure 15). In this case, it is very clear that the outer squirrel-cage winding contributes to the output torque while the stator torque is very small and even counteracts the input torque (the stator works as a generator). The contribution of the outer squirrel-cage winding results in a lower loading of the inner squirrel-cage winding and thus lower losses. Further, we can see that the electric power flow is reversed.

These phenomena are much clearer with the further acceleration with high power in over-drive mode (row g; figure 16).

An important advantage of the EVT is the possibility of a relatively strong over-drive in case of partial load. This is shown in row h. In this case, the efficiency of the EVT is smaller, but the combustion engine can be operated in a more efficient operating point, which results in a reduction of the fuel consumption [5].

If the output speed is reversed (row i; figure I), we get very high copper losses in the stator because the stator torque has to oppose the rotor torque.

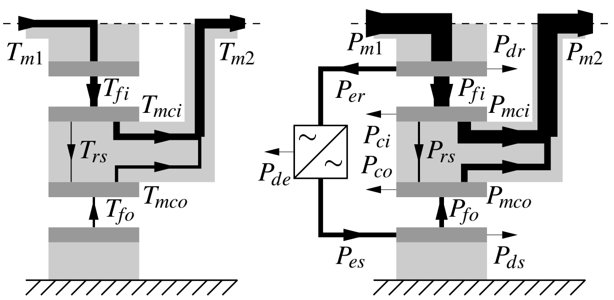

Fig. 14. Acceleration mode with high power (row e in table I)

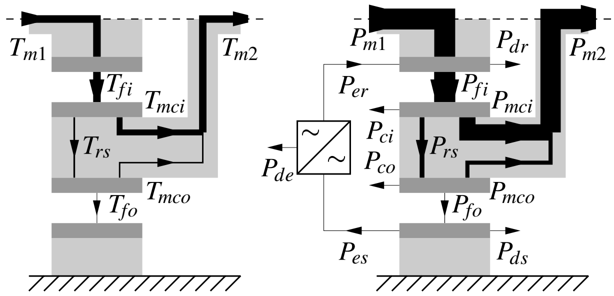

Fig. 15. Direct-drive mode (row f in table I)

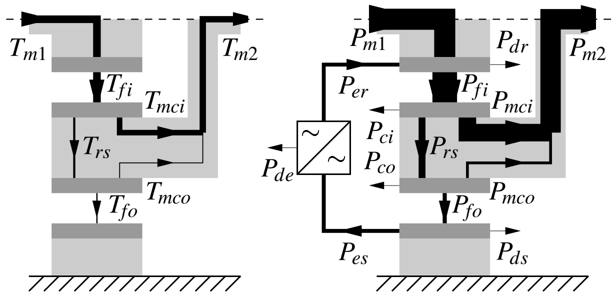

Fig. 16. Over-drive mode (row g in table I)

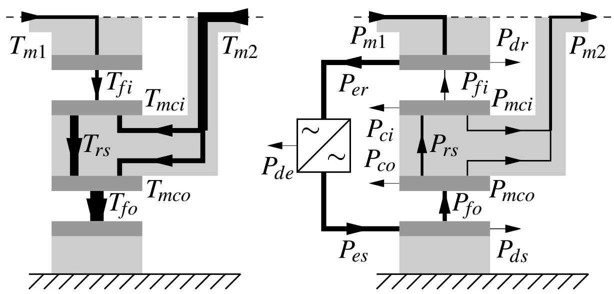

Fig. 17. Reverse mode (row i in table I)

We may conclude from table I that the efficiency of the EVT is very good in a large operating area. For a large part, this is caused by the fact that the contribution of the outer air-gap torque to the secondary-shaft torque is small in a large operating area. This results in low stator copper losses and low stator iron losses (because we may reduce the stator flux). Further, because the frequency in the (primary) rotor is relatively low in a large operating area, the iron losses in the rotor are low too. Only the copper losses in the rotor and in the inner squirrel-cage winding are significant.

VI. Proof of Concept

Some experiments were carried out in the laboratory (see the figures 18 and 19). The system has operated in all important operation areas (reverse, under-drive and over-drive). Some

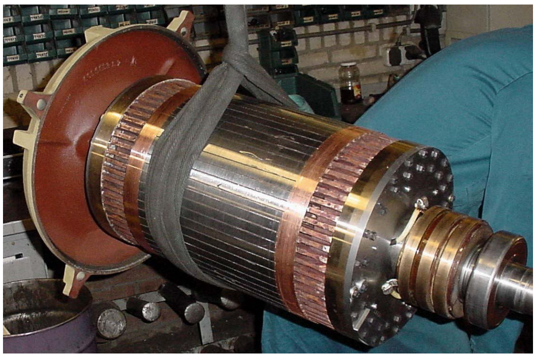

Fig. 18. The rotor/interrotor set

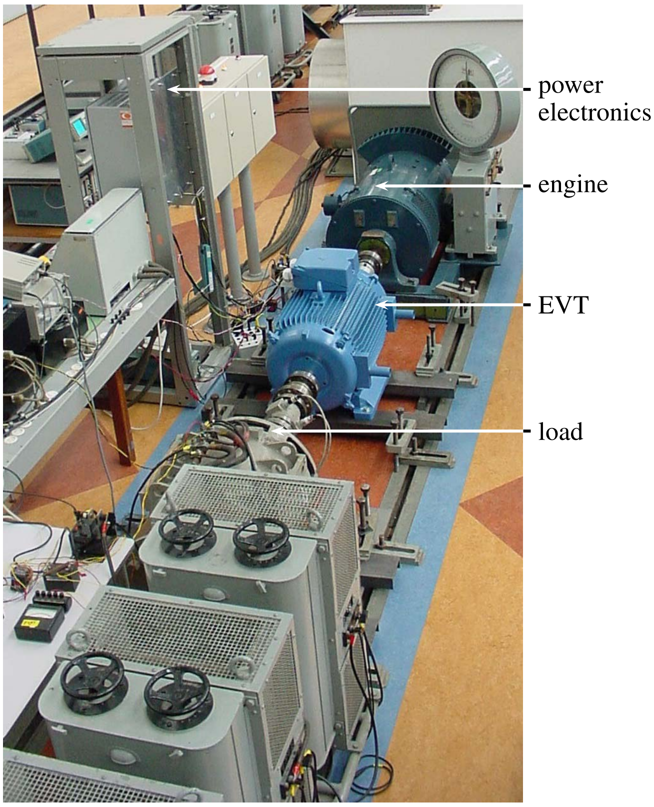

Fig. 19. The experimental set-up

results are shown in figure 20. However, because the machine made for the proof of concept had some serious mechanical imperfections, no efficiency measurements could be carried out.

VII. Conclusion

The Electrical Variable Transmission (EVT) is an electromechanical system which 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.

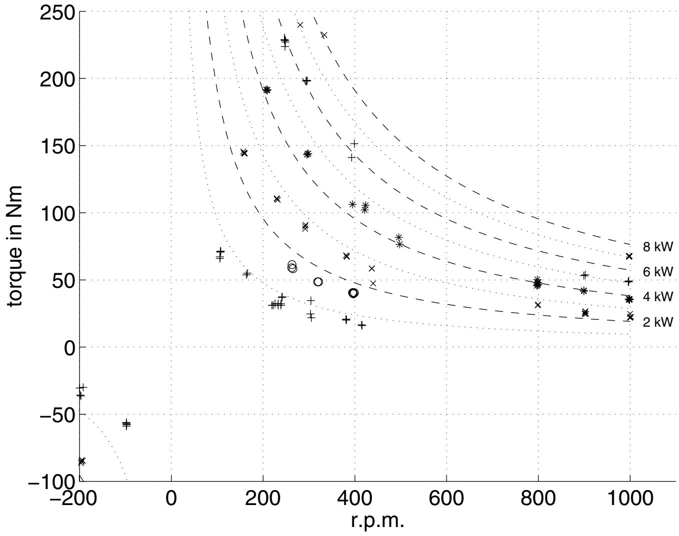

Fig. 20. Output torque-speed characteristics for 700 r.p.m. input speed

Further, it may be used in other applications, such as hybrid vehicles.

It was shown that the rating of the system components can be considerably smaller than the main power flow.

The EVT 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 has a very high efficiency in an important operation area.

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