Chalmers University of Technology

Efficiency impact of motor type and motor size choice

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Abstract

Permanent magnet synchronous motors are often used in drive trains for electric and hybrid vehicles. At the Division of Electrical Engineering at Chalmers University of Technology several works on different machine types as traction motor have been done. Radial flux machines of different sizes , axial and transversal machines have been investigated. Together with the department of Environmental Systems Analysis, the different motors have also been objects for LCA calculations.

This report investigates high power cars that often use one machine per wheel axis. The radial flux machines with 8-poles and different sizes have been evaluated. As an alternative to two permanent magnet machines one of them are exchanged to a reluctance machine. With the reluctance machine it's possible to keep that machine rolling without iron core losses and only use it when needed for acceleration. The high speed performance is quite low but it can save a lot of losses during normal operation.

The losses over the WLTP drive cycle is halved, when using the reluctance and PM combination, compared to a solution with two permanent magnet machines and the same gain can be seen when compared to one big permanent magnet machine. The gain at highway speed seems to be lower but still there are efficiency gain to be done.

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Content

Innehållsförteckning

1. Introduction....6
2. Investigated motors....8
3. Car size....9
4. Drive cycles....11
4.1 WLTP....11
4.2 US06....12
4.3 'Kassel' hills....12
4.4 Highway speed....13
5. Results in terms of efficiency....15
5.1 Permanent magnet machine....15
5.2 Optimal motor size with respect to WLTP....15
5.3 Big permanent magnet motors....17
5.4 Reluctance machine....17
5.5 Sum of reluctance and permanent magnet machine....18
5.6 Fictive motor....19
....19
6. Results from drive cycle evaluations....21
7. Future work....23
8. Conclusion....25
9. References....26
Appendix A. Main machine data....30

1. Introduction

In order to lower the carbon dioxide emissions from the transportation sector it is suggested that the cars should be powered by electricity. Several cars can be bought today, but most of them are so called SUV's, i.e. a high and not so sleek construction. They are mostly powered with two powerful motors, and some different solutions exist. The aerodynamic drag is important especially at high speed, which limits long travels unless the battery is big and the charging power is high. Other cars such as Tesla have lower drag and frontal area, which makes it easier to make long travels. Tesla have been a forerunner in the electrification of cars and use high power motors in combination with an efficient system for control of the motors. Other car produceras haven't been able to compete with Tesla cars in terms of efficiency and range. Partly this is due to aerodynamik drag that is low for the Tesla cars but higher for European SUV's. Bigger cars will need more energy, battery, higher charge power and have higher impact on the electric grid.

Not only the shape of the car is important, also the efficiency of the propulsion system is important. This can be exemplified with the Kia eNiro, which has the same consumption as the Volkswagen ID3 although that the eNiro is a bigger car. The propulsion system has several parts as battery, inverter, motor, gears and finally the wheels with different size and bearings. All parts produce losses and are important. This report focus on the electric motor, i.e. just one part of the overall losses. One of the best electric cars in terms of efficiency is the Tesla Model 3 LR, which have not only a low drag coefficient but also a two motor system. Tesla uses one efficient PM motor and an induction motor on the other wheelpair.

At Elteknik Chalmers several projects have been done on the topic of electric propulsion of a vehicle. Ali Rabiei [2], have investigated different converter alternatives and how they can influence the efficiency of the drivetrain. Further on he have investigated how different control algorithms can influence the efficiency. Normally the so called MTPA (maximum torque per ampere) is used but this control mainly minimise the copper losses. The machine has iron core losses as well and this is normally not taken car of. Rabiei have investigated several methods where minimum losses of the propulsion system are achieved and this can lower the consumtion with as much as 5 % for low speed operation but over a whole drive cycle the gain isn't that high.

Emma Grunditz have thoroughly investigated different drive cycles and scaling of the propulsion system. The scaling have been done in one direction, i.e. the length of the machine is varied in different car setups. The overall energy consumption are clearly depending on the machine size, but for lower sizes the acceleration performance isn't achieved. The consumption can increase with as much as 5 % in some drive cycles if the propulsion system are over dimensioned.

Another work is done by Mademlis G. Et al[3], who have investigated a synchronous machine for more heavy duty use. The machine shows high efficiency over a large area of the speed-torque envelope and indicates that the flexibility of an separately magnetised machine can be useful in vehicle operations. The efficiency is high at low force/torque. An alternative motor is the synchronous reluctance machine and Ban et. al. [5] shows a way of optimising the reluctance machine.

In a bigger project the life cycle assessment of different solutions have been investigated for different motor types, [6]. One of the motors where of reluctance machine type but with inset magnets of ferrite material. Ferrites have rather low magnetic performance so the machine behaved more or less as a reluctance machine. The efficiency was good but the high speed torque was lower than for the machines with rare earth material.

In this work I will use bigger changes in machine size, and the smaller machine is used at high current density in order to follow the drive cycles. Not only the machine length is varied but still their is no optimisation of the machine inner parameters. Lamination radius and machine length is scaled linearly.

The reason for investigating bigger machines is that some car producers tend to have performance that is like 300 kW for a car that could as well have 100 kW as maximum power. The high power level is of course a selling argument but can result in poor performance at normal usage. This work will investigate how the high performance cars perform in normal usage, which is represented by the WLTP-cycle. A comparison is also done in high way speed US06 and with hills like the type around Kassel, which is renowned as a demanding part of German high ways with steep climbings of several 100 meters with a gradient of 8 %.

Most European car producers use permanent magnet machines, which can be worse than using other types of electric motors when there is a demand for high power. For instance Tesla use one permanent motor on one axis and an induction motor on the other. BMW will use synchronous machines in the coming vehicles and both of the non-permanent motors have the possibility to lower the flux density in the motors at not so demanding operating points. This is especially useful when the machine is powerful and used with low utilisation. Another advantage is of course that the use of rare-earth magnets can be avoided.

This work investigates the difference between having high power with permanent magnet motors and a use of an extra machine for acceleration performance together with a smaller motor that is used for 'normal' operation. The reluctance machine are chosen as extra machine and it can be controlled to have no magnetic flux without current and the losses in the rotor are low. Compared to machines with current in the rotor the cooling arrangement can be simplified.

The efficiency of the propulsion system is important of several reasons. The energy losses during driving is perhaps not the biggest issue, renewable energy is fairly cheap today, and a high consumption doesn't show in the money spent. However low efficiency put high demand on battery size and charging infrastructure. An efficient use of produced batteries and infrastructure makes it easier the coming decades when the transportation sector have to transform to zero carbon dioxide.

2. Investigated motors.

The base for this work is a variant of the Toyota Prius machine from 2004. Smaller alterations to the Prius solution are made and it is called the reference machine. It is used as reference machine in many types of studies at the Division of Electric Power Engineering. An illustration of the machine is shown in Figure 1. The main data can be seen in Appendix A.

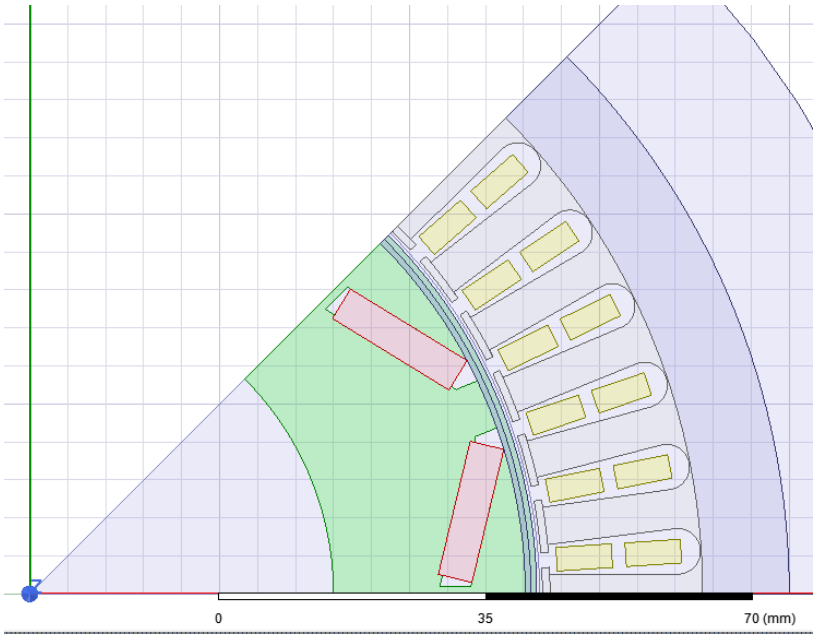

Figure 1. Reference motor. Outer diameter 200 mm.

In order to find alternative motor sizes the reference motor is scaled linearly both in radial and axial direction.

The other motortype is a synchronous reluctance machine with the same stator as in the reference machine. The rotor is changed to a rotor with no magnets but with voids in the lamination. The voids are made in order to achieve different magnetic reluctance in different directions of the rotor. The difference of reluctance is the basis of this machine type and is used for torque production.

There are many ways to create the voids, in this case they are made of constant radius segments. A more realistic variant can be seen in [5], where the reluctance difference is made up of four voids.

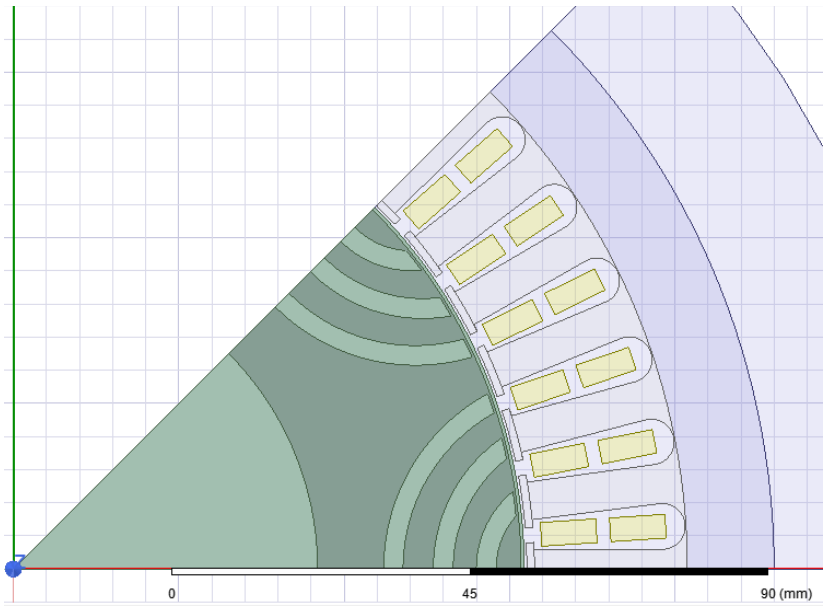

Figure 2. Reluctance motor

3. Car size

Why are producers using motors with power ratings of 300 or 400 kW? It's obvious an idea that high performance cars should have high acceleration capability. In Table 1 some high profile cars are listed and also three main stream cars, the Leaf, ID3 and Kia eNiro.

Table 1. Car data mainly gathered from ev-database.org

	Acceleration (s) 0-100 km/h	Power (kW)	Motor 1/2	Weight (kg)	Cd	Consumption WLTP (Wh/km)	Consumption at 120 km/h (Wh/km)
Tesla Model 3	5,6	202	PM	1825	0.23	148	188
Tesla Model 3 LR	4,4	324	PM/ Induction	1919	0.23	148	
Audi e-tron 55	5,7	300	Induction/ Induction	2595	0.28	224	310
Audi e-tron 55	4,6	370	Induction/ Induction	2695	0.28	268	
Audi e-tron 55 Sport	5,7	300	Induction/ Induction	2595	0.25	219	250
ID3	7,3	100	PM	1625	0.26	166	201-210
ID3	10	150	PM	1794	0.26	161	
ID4	8,5	150	PM	2124	0.28	193	250-260
Kia eNiro	7,8	150	PM?	1812	0.29	159	Appr 200
Nissan Leaf	7,9	110	PM	1580	0.28	164	
Nissan Leaf e+	7,3	160	PM	1756	0.28	172**	Appr 250
Lightyear One	10	100	Direct drive	1300	0.19	83	

* Measured by enthuiastic amateur reporters on Youtube (Nyland et.al)

** EVDB-value

The last column should be taken as an indication, the tests aren't done in a systematic way and could even be done on different locations and weather/ traffic situations.

From the table it's hard to find how much influence the electric motor can have on the total efficiency. It's quite clear that the big SUV's have higher and in some cases very much higher consumption per km than the more sleek and aerodynamic cars. If we compare the two e-tron models the bigger motors variant results in a 14 % increase of the consumption when motorpower is scaled up. The variants of Nissan Leaf differs 5%, but there is also a weight difference. The two Volkswagen models have a lesser difference of 3 % and the one with lower rating has also smaller battery and weight which could be an explanation. The difference of 3% is iterated when comparing the Tesla Model 3 Long range and the standard range. In this case the motor choice is the one that we investigate in this report and it can be interesting to see how much difference there is between the PM/PM-configuration and a configuration with PM and a motor that is used for acceleration.

Normal driving doesn't need high power but high acceleration at high speed implicates high power rating. One test that the news paper Auto Motor Sport uses is the constant start stop test. Audi for instance claim that the motor is cooled in a way that makes it possible to make up to 10 full acceleration/deceleration. It's important when you are on the race track but perhaps not in normal traffic.

At which acceleration do we need a power of 200 kW? Considering an acceleration to 100 km/h car weight m=1700 kg and we look for the 0-100 km/h (v_{100}) time at different peak power values (at 100 km/h).

$$
\begin{aligned}
F &= ma \\
\frac{dv}{dt} &= a \\
v_{100} &= 27.8\, m/s \\
P_{100} &= F * v_{100} = 200\, kW \\
F &= 7194\, N = m\frac{dv}{dt} = m\left(\frac{v_{100}}{T}\right) \\
T: acceleration\, time\; T &= m\frac{v_{100}}{7194} = 6.6\, s
\end{aligned}
\qquad (1)
$$

a is the acceleration and *m* vehicle mass. I.e. 200 kW could result in an acceleration tim 0-100 km/h in 6.6 s if we assume that the force is constant. Normally the motors start to field weak at a lower speed, meaning the the power level is reached earlier during the acceleration.

In the report the motors are set to field weak over 2/3 of the speed interval. The car are investigated for two gearing ratios we set the top speed to 140 and as an alternative 200 km/h and we assume that the motor can produce full torque to 47 and 67 km/h. The motor maxsped is 12000 rpm and it is assumed that the machine is controlled in field weakening from 4000 rpm.

The main car data are shown in Table 2.

Table. 2 Car data

Car mass (kg)	1700
C_d value	0.29
Front area (m^2)	1,9
Top speed (km/h)	140 / 200
Gearing motor to speed	12000 / 140 (200) (rpm/km/h)
DC-link voltage (V)	430

4. Drive cycles

Several drive cycles are at hand for evaluation, see [1]. In this report I've limited the evaluation to two drive cycles and one invented. The losses during pure high way use is also evaluated.

4.1 WLTP

WLTP is the certifying drivecycle of European cars and an important measure for new vehicles. The acceleration is fairly low and the torque demand implies a motor power of 60-75 kW for a normal car. The high speed part of the drive cycle increases this figure, but overall the power is fairly low and represents every day travelling with normal driving.

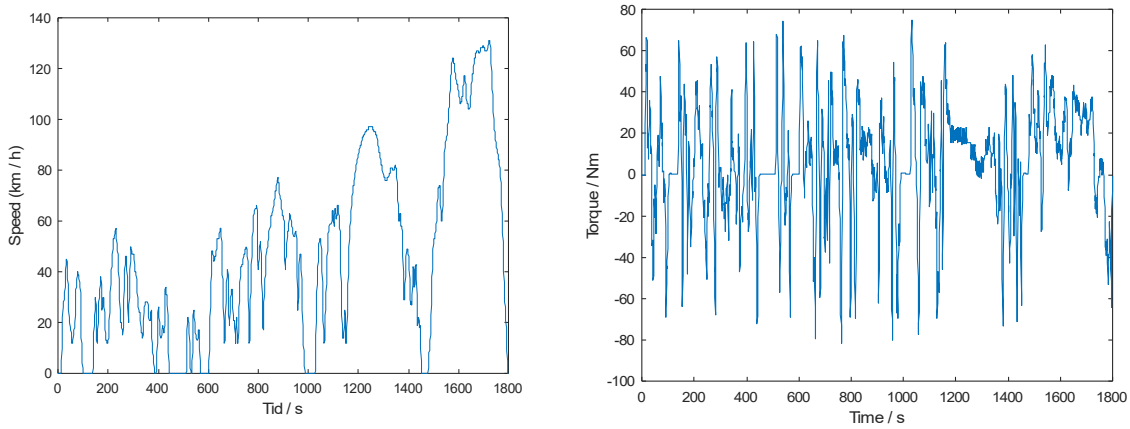

Figure 3.a. WLTP speed vs time. b. Force vs time

Figure 3.b shows the resulting Force on the vehicle.

The drive cycle covers a distance of 23.2 km and the cycle is divided in four parts, LOW, MEDIUM, HIGH and EXTRA HIGH, [7].

The peak acceleration is approximately 1.5 m/s^2.

4.2 US06

The drive cycle US06 is a highway cycle with rather high acceleration. Figure 4 shows the speed during the cycle.

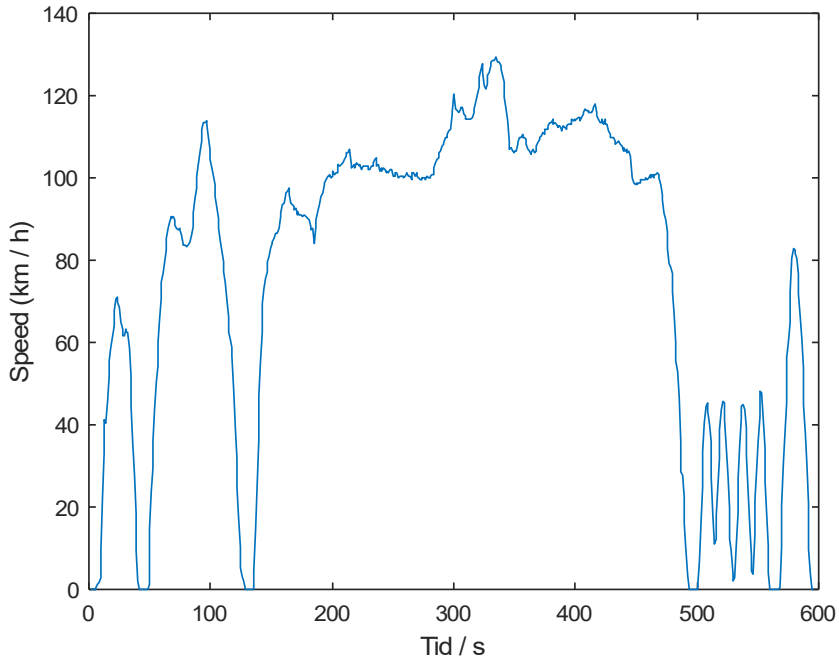

Figure 4. US06 speed in km/h.

The drive cycle covers a distance of 12.9 km and the cycle ends with repeated accelerations.

4.3 'Kassel' hills

This drive cyle is invented partly because of own experience when travelling with my -09 Prius in 140 km/h. I found that the battery was empty at the top of the hills. Colleagues at VCC told me that the part of highways is extra demanding. It consists of repeated up and downs and when travelling at high speed the power is high. I've assumed a slope of 8 % and an elevation of 300 m. It's worth noting that hardly no parts of Swedish interregional ways exceeds 6 %.

I've assumed a constant speed of 120 km/h and then the slope changes resulting in a varying torque, see Figure 5. The drive cycle covers a distance of 49.9 km and starts with an acceleration up to 120 km/h.

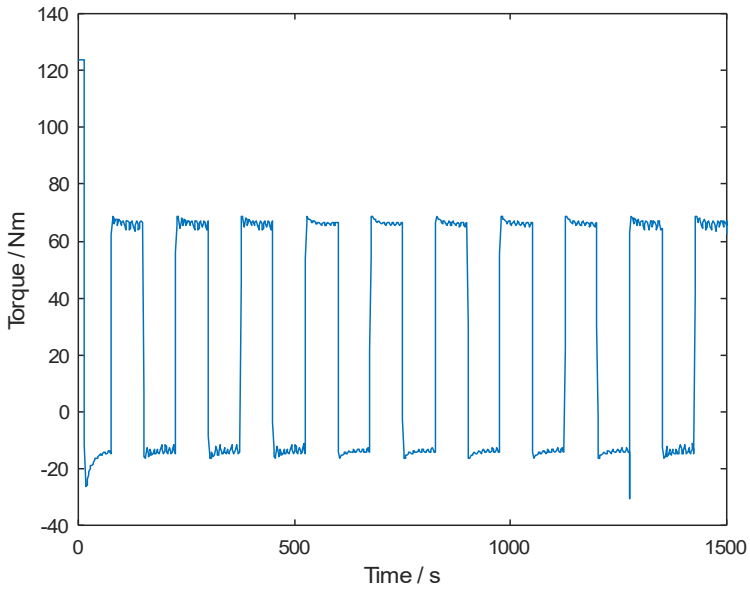

Figure 5. Torque when max speed is 140 km/h.

4.4 Highway speed

My opinion is that the efficiency at highway speed is important. If you buy a modern electric vehicle and intend to use it for more than city-driving the behaviour at highway speed is important. The major route in Sweden have the speed limit of 110 km/h and 120 km/h. Interregional ways have a lower tempo between 80-100 km/h so one could discuss which speed is the most relevant. I think 120 is a good point for investigation for two reasons.

1. If it's not clear for the costumer an electric car behaves different to ICE cars. The latter increase efficiency when speed and torque increase, which disguise the vehicle consumption. The difference between 90 km/h and 120 km/h can be as high as 100 % in an electric vehicle. There is a clear risk for disappointed costumers that buy an expensive big car with big battery but the resulting range at highway speed is 250-300 km, when the WLTP range is over 450 km. If that is paired with low charge power the result is not good.
2. The second reason is of course energy use. Electric energy is not so costly but when the number of vehicles grow the demand on electric grid and energy production will grow as well. So an overall awareness of the consumption is nice especially the coming decades when the number of electric vehicles will grow and we have to increase the output from battery manufacturers, charging infrastructure and electric grid.

5. Results in terms of efficiency

5.1 Permanent magnet machine

The size of the electric machine influence the overall efficiency of the electric car. In Figure 6 a typical efficiency curve of an electrical machine is shown.

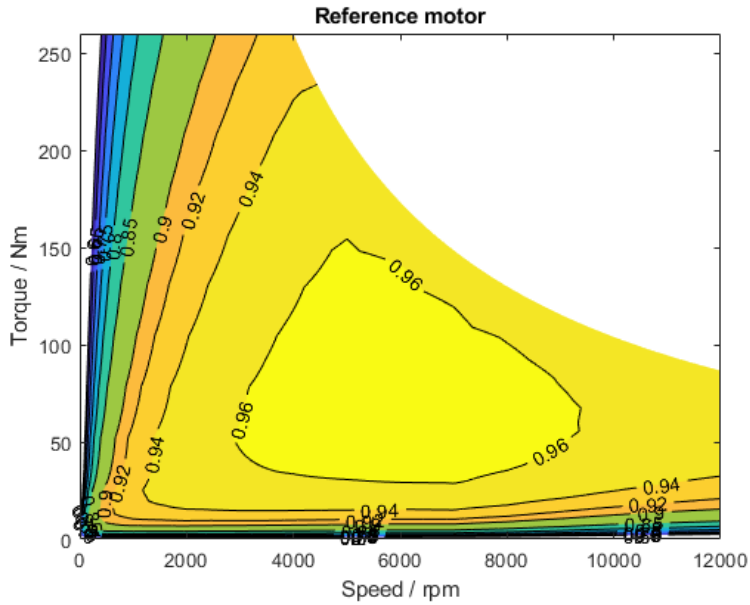

Figure 6. Efficiency at different speed and torque of an PM-machine. Reference motor

The machine is the same used in [1], the so called reference motor that is used frequently at the Electric Department on Chalmer University, but with higher current density resulting in a hotter winding. The data is according to Appendix A. In this work 120 degC is used for the winding temperature and 70 degC for the magnets. The MTPA-method is used for finding an operational point.

5.2 Optimal motor size with respect to WLTP

What happens if we scale the machine to higher and bigger geometrical size? The line correspondning to 96 % will be pushed towards higher torque when the machine size increase. For instance if the machine geometry are increased with 15 % both in length and radius the overall volume will increase with 52 % and the torque will also increase with 52 %. This means that the machine is 'equal' but for 52 % higher torque. I.e. 0.96-line that is parallell to 25 Nm will in the bigger machine be parallell to 38 Nm. The efficiency of the bigger machine is shown in Figure 7. The operational at constant speed is shown in the latter figure and as can be seen the torque is very low compared to the available torque from a 150 kW-machine.

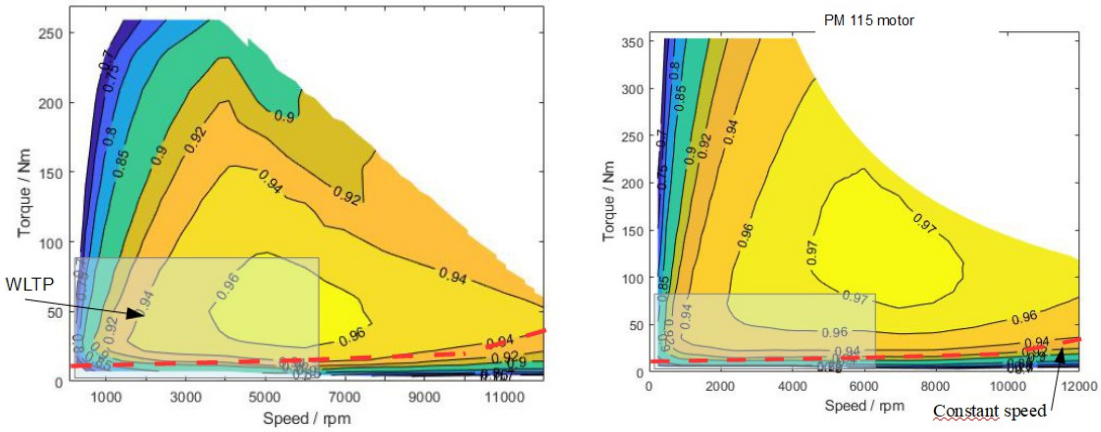

Figure 7. Efficiency when motor are scaled down and up. a. Small motor b. Big motor

As can be seen in Figure 8 the peak efficiency of the big motor don't coincide with the drive cycle data of WLTP. At constant speed and level road the load is far from the optimal regions. More analysis of this has been done in [1].

The smaller motor has a smaller area with efficiency above 96% and higher load that corresponds to other drive cycles may result in poor efficiency.

$$\eta=\frac{P_{out}}{P_{¿}}=\frac{P_{out}}{(P_{out}+P_{cu}+P_{eddy}+P_{hyst}+P_{mag})}$$
$$P_{cu}=k_{scale}R_s I_s^2 \quad ,$$
$$I_s=k_T T/k_{scale}$$
$$P_x=k_{scale}P_{x0}$$

where P_{eddy}, P_{hyst}, P_{mag} are the eddy current losses, hysteresis losses and losses in the magnet material. The iron core is normally underestimated when evaluated due to the origin of material data. During the production process tensions are built into the material that increase the hysteresis losses. All losses for a certain torque and speed increase with increased motor size, k_{scale} except for the copper loss, P_{cu} . This is a simplified assumption because a smaller machine size will have higher impedance of the winding and more flux produced by the stator which has the implication that the core losses also depends on the current density.

$$\eta(T)=\frac{P_{out}}{(P_{out}+R_s k_T^2 T^2/k_{scale}+k_{scale}P_{eddy0}+k_{scale}P_{hyst0}+k_{scale}P_{mag00})}$$

Table 3 shows the losses over the WLTP-cycle and how it varies for different motor sizes.

Table 3. Energy losses when geared for 140 km/h

kWh/100 km	PM 90	PM 95	Ref Motor	PM 115	PM 126
WLTP	1.604	1.111	1.191	1.426	2.347

The bigger motors have increased iron core losses and have higher losses in WLTP, which have rather low torque level. This can of course be improved by using a finer iron core material. Lowering the motor size to much will increase the losses again and that is also seen in, [1]. The smaller machines have higher copper losses which will start to dominate and increase the WLTP-losses.

The 'PM 95' motor is used for more analysis and the efficiency map is shown in Figure 8.

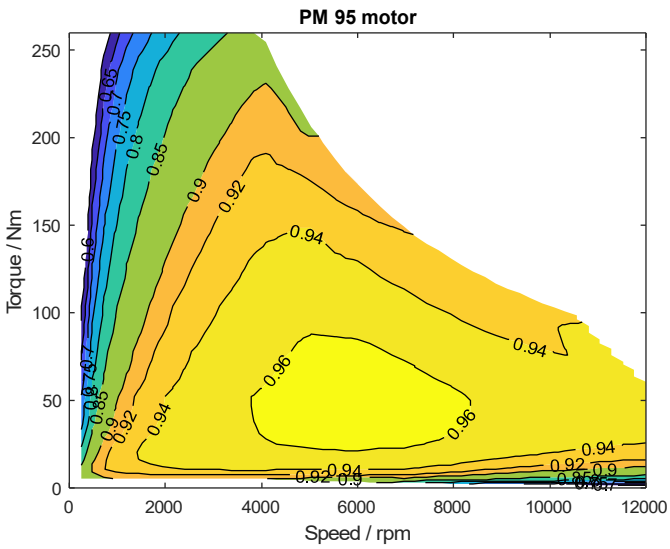

Figure 8. Motor scaled to 95 %.

5.3 Big permanent magnet motors

Several machines have been evaluated with Ansys Maxwell and common for all machines is the DC-link voltage of 430 V. The number of turns have been adjusted in according to the voltage. The current level differs of course and in some cases the normal field weakening cannot be achieved, which can be seen in Figure 9.a, where the slope betweeen 4000 - 5000 rpm isn't the usual field weakening behaviour. Above 10000 rpm the torque level isn't reached and that can be seen more prudent in the reluctance machine.

Scaling the machine to 115 % increases the power level to 150 kW and the biggest size is scaled by 126 %. The machine in Figure 9. a have problems to achieve the constant power trajectory and especially at high speed the torque drops off. Beside thermal issues this is a limit for what can be taken out of the machine.

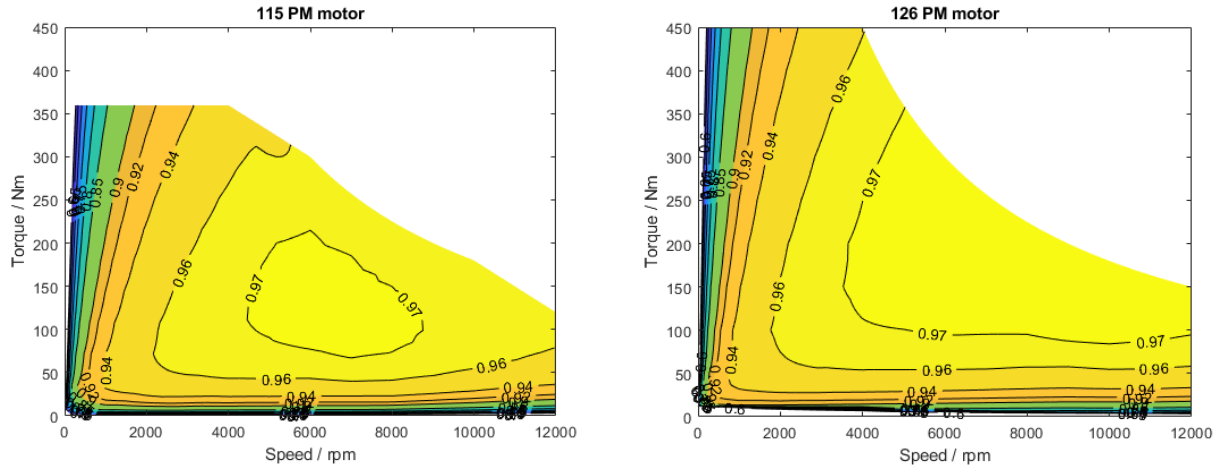

Figure 9. Efficiency of the two bigger machines. a. 115 % and b. 126 %

The biggest machine are used as the big PM-machine, the power level is 188 kW and the machine is not so stressed by high power in this case.

An interesting way of increasing the power level of machines is found in Aquaviva and Skoog, [4,8], where they have dimensioned the motor for 25 A/mm^2 continous operation. This is a possibility for lowering machine size and minimise use of copper but the machine design has to be done with this in mind. The machine studied in this report needs some major changes in order to handle such a high current level. The cooling must be considered and also the high impedance of the winding.

5.4 Reluctance machine

The reluctance machine is relatively big in order to produce 260 Nm, see appendix A. The outer diameter is 230 mm and the eficiency is shown in Figure 10.

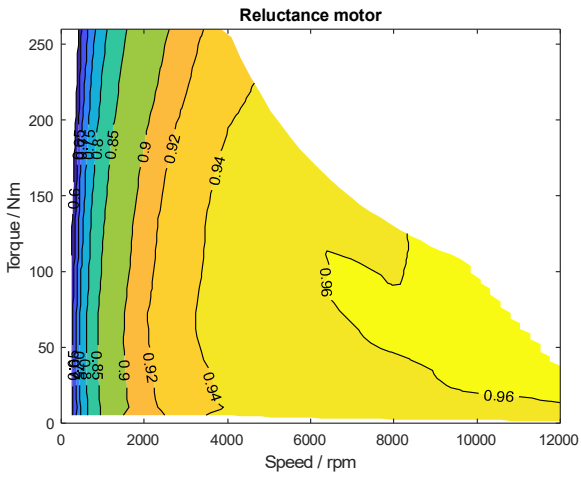

Figure 10. Efficiency of reluctance machine.

5.5 Sum of reluctance and permanent magnet machine

When using the two-motor solution two version of control are investigated. The first one is to just sum the torque from the two motors resulting in the efficiency map of Figure 11.a. In Figure 11.b the losses are minimised using the most efficient motor at the acual operating point.

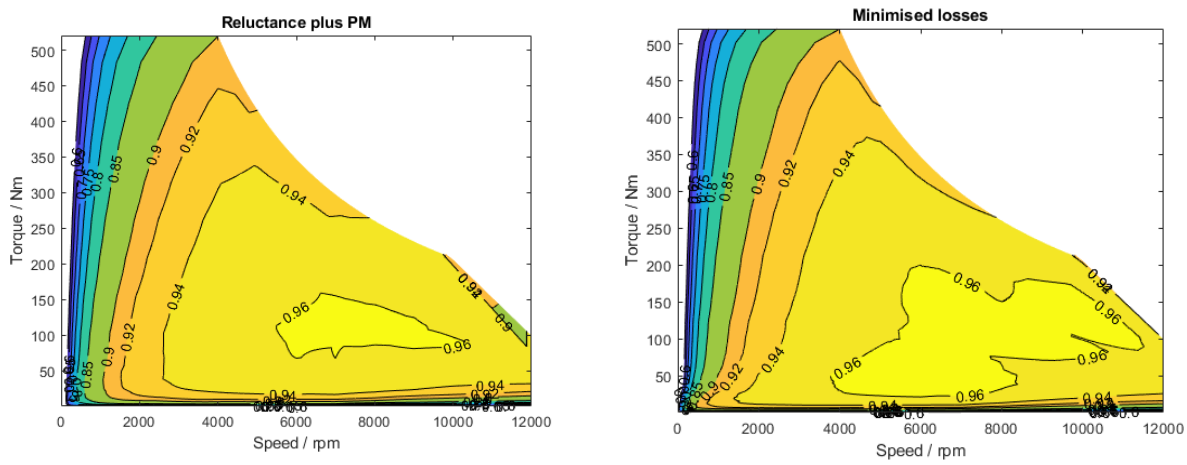

Figure 11. a. Efficiency of summing the two motors. b. Lowest losses

$$
\begin{aligned}
&T = T_{pm} k_{opt} + (1 - k_{opt}) T_{rel} \\
&\quad find\ k_{opt}\ so\ that \\
&\quad P_{pm} + P_{rel} \rightarrow P_{min}
\end{aligned}
\qquad (3)
$$

T is the torque reference, i.e. the total output from the machines and k_{opt} is a value that refers to how much of the output that is produced from the PM-machine. The solution is quite obvious, the PM-machine is used at low torque and the reluctance machine is shut down, but for higher torque the reluctance machine is gradually more involved. Approximately above 100 Nm, the reluctance machine starts to produce torque.

When minimising the losses the efficiency is improved especially low torque, which we shall see is important when calculating the losses.

5.6 Fictive motor

A fictive motor is realised with known copper losses and iron core losses and used for checking the evaluation process.

$$P_{cu} = k_{culoss} * T^2$$
$$P_{fe} = k_{feloss} * N$$

T is the torque and N rotational speed in rpm. The constants are chosen according to:

$$k_{culoss} = 0.1$$
$$k_{feloss} = 0.1$$

This results in the efficiency map shown in Figure 12.

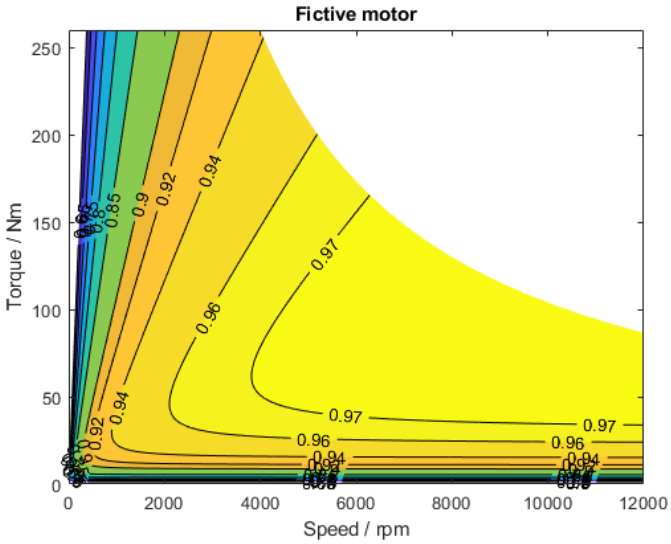

Figure 12. Fictive motor

The calculated energy loss in WLTP and US06 is according to Table 4.

Table 4. Energy losses when geared for 140 km/h

kWh/100 km	Ficitive	Semi analytic
WLTP	1.017	1.016
US06	1.181	1.181

It seems like the handling of motor efficiency matrix and then converted to a loss figure over a drive cycle is correct. There is of course errors in the matrix produced by Ansys Maxwell but this is rather wellknown problems representing the lamination data. Another problem is how well the calculations converge and it's notable that the curves in Figure 12 are completely continous and smooth while there are some not so smooth lines in the other figures.

6. Results from drive cycle evaluations

The energy used is calculated over of the cycles and the energy use of the vehicle over the distance is calculated as well as the lost energy over the distance. Only the losses of the motor is investigated. The two last evaluations with constant acceleration and retardation and hills is done 10 times. The last two columns in Table 5 and 6 shows energy spent over 100 km for the vehicle. Positive figure is consumed and the negative values means that the car is braking and the energy can be fed back to the battery. It is assumed that the battery always can absorb a braking event.

Table 5. Energy losses when geared for 140 km/h

Kwh/100 km	Ref Motor	Two PM	One small PM	One big PM	PM+Reluctance	Optimal Choice	Vehicle	
WLTP	1.191	2.217	1.111	2.347	1.955	1.130	14.53	-4.62
US06	1.524	2.223	1.558	1.994	2.076	1.482	20.15	-5.35
Hills 8%	2.003	2.516	2.177	1.929	1.980	1.842	29.91	-6.33
120 km/h	1.534	2.225	1.431	1.830	1.730	1.444	25.44	0

In a case where the power is as high as 200 kW it's likely that the maximum speed of the car is 200 km/h. Table 6, shows the result from this gearing.

Table 6. Energy losses when geared for 200 km/h

Kwh/100 km	Ref Motor	Two PM	One small PM	One big PM	PM+Reluctance	Optimal Choice	Vehicle	
WLTP	1.021	1.854	1.119	1.784	2.182	1.103	14.53	-4.62
US06	1.391	1.755	1.699	1.558	1.971	1.378	20.15	-5.35
Hills 8%	1.458	1.570	1.877	1.520	1.624	1.511	29.91	-6.33
120 km/h	0.915	1.288	1.005	1.362	1.271	1.044	25.44	0

7. Future work

The induction machine and electrically magnetised synchronous machine should be investigated in this type of application. Both produce losses in the rotor which may result in a cooling circuit for the rotor.

The rotor voids of the reluctance machine can be investigated to see if better torque production can be achieved, especially at high speed.

The optimisation control should be scrutinised for improvements. It is now a simple search process in the loss-matrix.

8. Conclusion

Several PM motors are investigated in order to find out how the size impacts the losses over some chosen drive-cycles. The size matters in this case and using permanent magnet machines for high power vehicles is not recommended. The losses over WLTP can be doubled when doubling the motor size. This can be explained by the double amount of iron core that has to be magnetised and the copper losses are of lesser importance in the low power drive cycles.

A better case is to use one optimised permanent magnet motor and driving the other wheels can be done with a reluctance machine. The reluctance machine can be demagnetised without losses and the power losses of the motor may be 50 % over the WLTP-cycle. The more demanding US06 can also be operated with lower losses, but the gain is lower. Still a 10-25 % decrease of the losses may be observed.

The highway performance doesn't differ so much but there might be some 20-25 % lowering of the losses when using the reluctance machine.

9. References

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Appendix A. Main machine data

			PM 100	PM 95	PM115	PM 126	Reluctance
D_y	Outer diameter	mm	200	186	230	252	230
D_i	Inner diameter,	mm	135	126,2	155,2	170,1	155,2
r_d	Rotor radius	mm	133,5	124,8	153,5	168,2	153,5
D	Air gap	mm	0,75	0,7	0,85	0,95	0,85
b_{th}	Width of tooth	mm	5	4,75	5,75	6,3	5,75
h_l	Slot depth	mm	17	16,1	19,6	21,4	19,6
b_0	Slot opening	mm	2	1,9	2,3	2,5	2,3
b_m	Magnet thickness	mm	4,55	4,32	5,23	5,73	5,23
N_q	Number of turns		7	9	5	3	6
d	Air gap length	mm	0.75	0,7	0,86	0.95	0.86
l_{st}	Stator length	mm	127	114	146	160	167
P	Number of pole pairs		4	4	4	4	4
Q	Number of slots		48	48	48	48	48
l_{ma}	Winding length	mm	291,00	262,00	335,00	367,00	356,00
m_{fer}	Rotor core weight	kg	7,4	5,8	11,3	15,4	14,5
m_{fes}	Stator core weight	kg	5,1	4	7,8	10,6	8.49
m_{cu}	Copper weight	kg	7,2	5,6	10,9	15	11,6
m_{Nd}	Magnet weight	kg	1,25	0.98	1,9	2,53	0
Mass	Total weight of active material	kg	21	16,4	31,9	43,5	34,6

Iron core material: Cogent NO30
Magnet materiel NMX 37F 70 ºC
Conductor Copper 120 ºC

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