Load-oriented Topology with reduced material-needs and costs for electric car drives

Bernhard Hoffmann / Dr. Andreas Gründl
eMoSys GmbH
D-82319 Starnberg, Germany

***Abstract*—This document commence with an overview over the electric machines and powertrain-configurations. Further, a new E- motor-design is explained, based on a comparison of the different types of electric machines and according to the typical requirement from car application. The favorable data of this design, in respect of high efficiency, low weight and small dimensions are shown.**

I. Requirements for Electric Vehicle Drives

Since several years electric driven automobiles are not only offered from small manufacturers and those where perceived as exotic vehicles. Now some of the big worldwide operating manufacturers are selling electric cars from series production. Those cars have a high standard and are well equipped. The handling performance of these E-models has reached such a high level of longitudinal- and lateral dynamics and comfort, like we know from combustion-engine driven cars.

This result is based on a professional development management which had to be used holistically for the entire vehicle also in respect of his employment in its real environment. Procedures and methods for "the development of car characteristics" are already introduced for combustion engine cars. An application for E-vehicles is described in the paper of *Wiedemann* [2]. To achieve the development goals for cars with a successful entrance to the market, all relevant drive components have to be designed in respect to these requirements, those who lead to the given goals of car characteristics.

It is well known, that for "pure" E-cars, working only with electric drive, the battery is the main obstacle to reach the goals for the costs and in particular to reach the range of combustion engine cars, due to its big weight and volume. This is without doubt the reason for the extreme slow rise of sales volume of pure E-cars, which can be changed now only by subvention or official privilege.

Although the battery design and –assemblage are the crucial factors for the achievement of the goals of car characteristics, a considerable influence remains possible by optimally adapting of the other drive components, the electrical machine and the power electronics:

- attenuation of restrictions and costs due to the battery by high exploitation of the available electric energy (*range*, *cost effectiveness*)
- evocation of additional E-car specific attractiveness by improved *longitudinal- and lateral dynamics*.

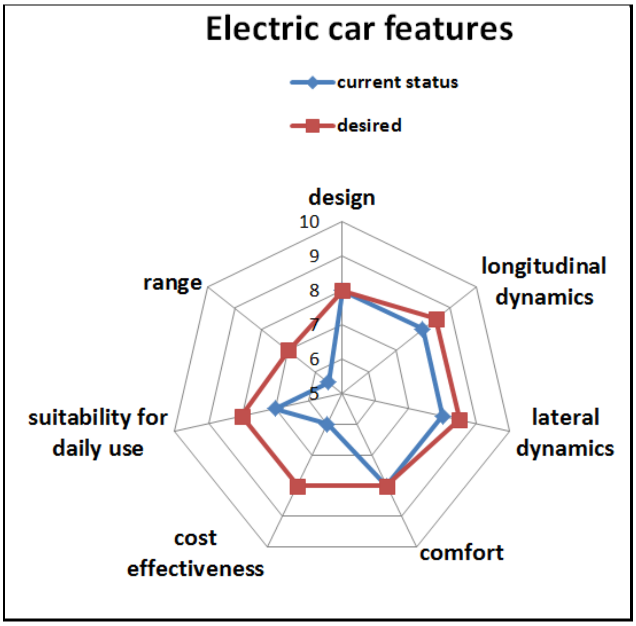

Fig. 1. Electric car features

This leads to the requirements for the features of the electrical machine(s). These features are specified below with their influence on the car characteristics:

A1: high efficiency under load close to reality according to the designated use
- range
- effective recuperation
- consumption of primary energy

A2: overload capability
- avoidance of disablement when designated load is exceptionally exceeded (thermal stability)

A3: good efficiency also with low load
- effective range extending when car is driven in economical manner
- satisfy formal requirements for power consumption (NEFZ-cycle)

A4: low costs

- costs of material
- manufacturing costs

A5: low weight

- directly: low weight of the machine and the power electronics (inverter)
- indirectly: that saves weight from unneeded mechanical parts because of changeover of functionality from powertrain (e.g. two single motors and omission of differential gear)

A6: small dimensions,
suitable for bad environmental conditions,
robustness (no magnets situated at the air gap)

- simplified integration

A7: low rate of necessary installed apparent power (kVA) of the inverter:
high level of installed inverter apparent power (kVAs) leads to:

- costs for power electronics proportional to kVSs
- weight and volume augments with the kVAs
- rising of absolute inverter loss with rising kVAs while inverter efficiency is kept constant
  → decreasing of total efficiency

A8: No annoying noise emission

II. Placement of E-Machine

It is well known, that electrical machines can be placed in many combinations and at several locations in a vehicle. There are possible solutions from single machines to drive one wheel individually till the replacement of the combustion engine at the entrance shaft of the conventional gearbox. Wheel hub motors, which are directly connected to the wheel or working via a fix gear ratio are not supposed for a use in serial manufactured cars, except military and utility vehicles.

The assembly of the electrical machine(s) to a package together with the power electronics for each axle is a preferred solution for 4x4 cars as well as vehicles with one driven axle. The drive configuration either with centrally mounted machine and differential gear or two single machines per axle is in both cases working over a fix gear ratio. A combination with a gearbox will not be used for serial manufactured electric cars.

The dimensions, this means also the weight, the volume and the costs of the electrical machine are crucially determined by the needed torque. So it is desirable, to push the speed as high as possible by the choice of the suitable gear ratio. The limits, which have to be respected on the other hand, are given by the more than proportionally augmenting losses due to aerodynamic and due to the remagnetizing included eddy current effects and also by the maximum allowable mechanical stress generated by centrifugal force in the rotor. Also the emission of noise of high speed machines has to be taken in account. Roughly, the value of the speed of the rotor surface at the air gap should not increase over 90 m/s.

Mostly the air gap between rotor and stator is tangentially orientated (drum-shape rotor). In special cases electrical machines are designed with an orientation of the air gap vertically to the axle of rotation (disc-shape rotor). This is favorable for motors with small axial length and big diameter, for high required torque but a limited speed. This makes sense essentially for direct drives, when an adaption of the rotor speed by a gear ratio is not possible. A use for electric serial cars is not expected.

The rotor in the usual drum-shape configuration is in-runner or out-runner. Machines with outer rotor allow a maximal possible radius for the air gap in relation to their outside radius, if the radial thickness of rotor is small, like with the open flat magnet configuration. Here a bandage is not necessary due to the centrifugal force in the right direction. But the bell shape of outer rotors leads often to problems because of their elevated risk of noise generation and finally there is a rather limited axial length because uncontrollable vibrations can occur.

Mostly machines with inner rotor can easier be integrated in the powertrain, so an outer rotor configuration is advantageous only with open flat magnets or direct wheel hub drives.

These compact machines with high power density are preferably cooled by a water-cooling jacket at the back of the stator, while the heat from the rotor can be transferred by air ventilation to the housing and the stator.

III. E-Machine Type

Hereafter (Fig. 2a – 2f) is a choice of machine types, which are used for electric car drives (all figures: Inst. für elektrische Energiewandlung, TU Darmstadt [1]):

TABLE I.:
COMPARISON MACHINE TYPES

	open flat magnets / buried magnets	single tooth stator winding / distributed winding	continuous-torque (force per square N/cm²)	overload factor torque	power density-augmentation by high speed possible	robustness	temperature-limitation rotor(°C max)	special design restrictions	required inverter reactive power / mechanical power (n_edge / n_max 1:3)	idle losses at high speed	costs [€/kW]	fig. 2 x
1: ASM	----	VW	1,8	3,5	yes	yes	200	-----	2	0	15	a
2: PM_OFM_VW	OFM	VW	2,4	3,0	limited	no	140	only outer rotor	2,6	med.	20	b,f
3: PM_OFM_EW	OFM	EW	3,1	2,5	limited	no	140	only outer rotor	2,6	med.	19	---
4: PM_VM_VW	VM	VW	2,1	3	yes	yes	170	-----	2	low	19	c
5: PM_VM_EZ	VM	EW	2,6	2,5	yes	yes	170	------	2	low	18	d
6: SR	-----	EW	2,2	2,5	yes	yes	200	------	2	0	13	e
7: PM_TV	OFM	----	4,5	1,2	limited	no	140	only outer rotor	1,5	high	15	g
8: PM_VM_SMM	VM	EW	6	1,7	yes	yes	140				chapt.	4

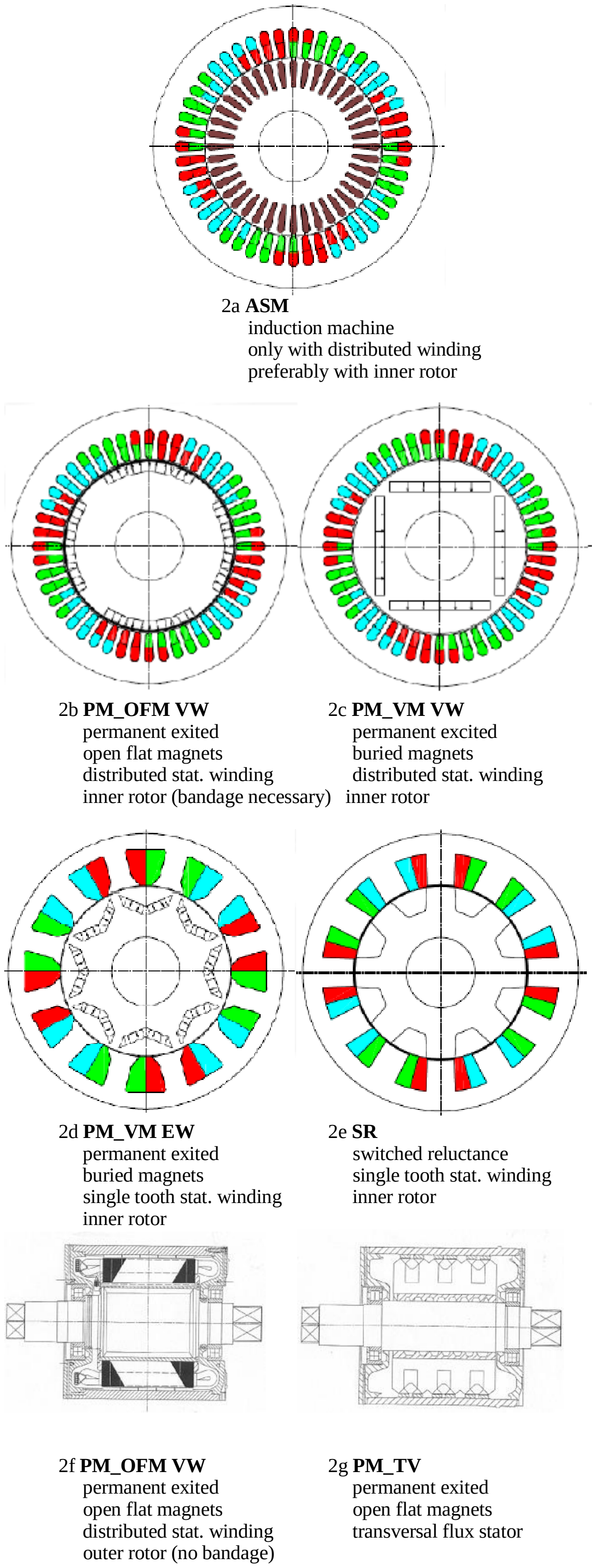

Fig. 2. Different types of electrical machines

Few and far between, dc commutator machines (no inverter is necessary) and synchronous machines with electrical excitation are used for E-vehicles. They are not regarded here because their application for serial use is not expected.

Several analyses, evaluations and comparisons where performed for the machine types and summarized in TABLE I.

A high specific torque leads fundamentally to a light and compact machine with finally favorable costs. The highest continuous torque, when dimensions and weight are determined, can be achieved with a transversal flux type (Nr.7, PM_TV). But its restraint to the outer rotor configuration, the not existing overload capability and the high drag losses at high speed makes the transversal flux machine often prohibitive. If the prognostics for low serial costs will become true, the use of this type makes sense for certain applications, e.g. city vehicles with low ratio of maximal- and characteristic-speed. Very positive is also the necessity of very low apparent power from the inverter.

The machines with permanent magnet excitation are without exception superior to the induction machine (TABLE I, Nr.1, ASM) and the switched reluctance machine (Nr. 6, SR) respective to the torque density. The advantage of ASM and SR are the practically not existing drag losses at zero torque, which become significant at high speed. But this advantage has a real impact only with hybrid cars, when the rotor speed is directly and fix coupled with the crankshaft- or wheel speed. With pure electric vehicles, having a fix ratio between vehicle speed and machine rotor speed, the maintenance of high rotor speed needs always a certain torque. A drag situation with speed but without torque occurs only exceptionally. So the moderate drag losses of the most permanent magnet machines are not relevant in E-car applications.

Usually the PM-machines with open flat magnets (TABLE I, Nr.1 and Nr.3) are regarded critically for series car application. The restraint to outer rotor configuration was already graded as disadvantageous and makes this type inappropriate for many applications. Open flat magnets at an inner rotor needs always a reinforcement bandage at the air gap. So the performance of the machine is deteriorated by the enlargement of the magnetic gap. The most series manufacturers decline bandaged rotors because of unreliability.

The rotor topology of permanent excited machines with buried magnets (TABLE I, Nr.4 and Nr.5) avoid theses disadvantages concerning robustness and restraints for integration. Single tooth windings (Nr.5) tend to achieve higher torque density compared with the distributed winding configuration, but then slightly higher rotor losses have to be taken in account. The operation with single tooth winding effectuates additional magneto mechanical stimulation, so it needs more engineering work and technical effort, to keep the noise emission under the tolerated level.

The soft magnetic parts of the rotor with buried magnets generate an angle dependent modulation of the reluctance, so that in addition to the permanent magnet based torque a second part, the reluctance torque, is contributed. So this motor configuration is also called "*hybrid machine*" this is a combination from permanent magnet motor and reluctance motor.

A result from this chapter is: permanent excited machines with buried magnets are the most appropriated for pure electric cars. But the arrangement of magnets buried in soft magnetic material, which is advantageous for the robustness, leads on the other hand to not desired magnetic bypasses, which weakens the flux density arriving at the air gap. So buried magnet machines have lower specific magnetic force density than those with open flat magnets and this becomes significant with high power design by more weight and volume. The machine topology, described in the following chapter, achieves a significant higher effective exciting flux density because the magnetic bypasses are avoided and due to the flux concentration directed to the air gap. This leads to essential higher force and power density.

IV. Machine Design for 120 kW-Electric Drive

Based on the longitudinally dynamic requirements for compact class cars with typical 1.5 t car's kerb weight an electric machine design will be given below. The electric drive train consists of one machine with fixed gear and differential gear on the axle of a one axle driven car.

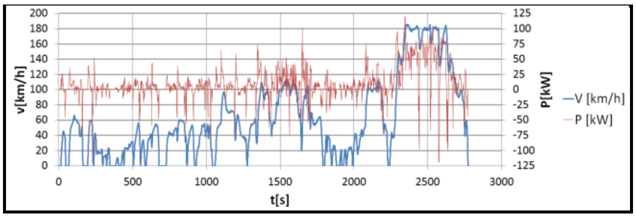

Fig. 3. real cycle for passenger cars of typ.1.500 t, Power of drivetrain

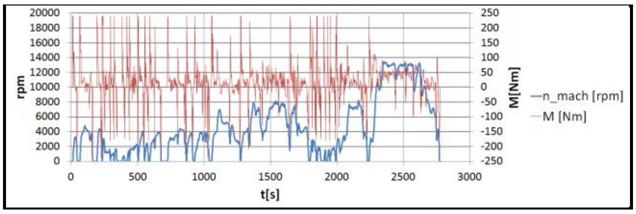

Fig. 4. real cycle for passenger cars of typ.1.500 t, Torque of electric machine

This cycle represents real drive conditions with urban and highway contents up to 185km/h. Therefore, the following requirements for the electric machine are necessary:

- M_max 240 Nm maximum torque
- M_dauer 140 Nm continuous torque
- n_max 13000 rpm maximum speed according to 185 km/h
- n_eck 4700 rpm characteristic speed with M = M_max
- P_max 120 kW rated power
- P_dauer 70 kW continuous power

Corresponding to the requirements described in the previous chapters with regard to compactness, high torque density and robust design we should choose a design with buried permanent magnets (machine type Nr. 5 from TABLE I). To achieve the desired high torque density a single-tooth winding is necessary

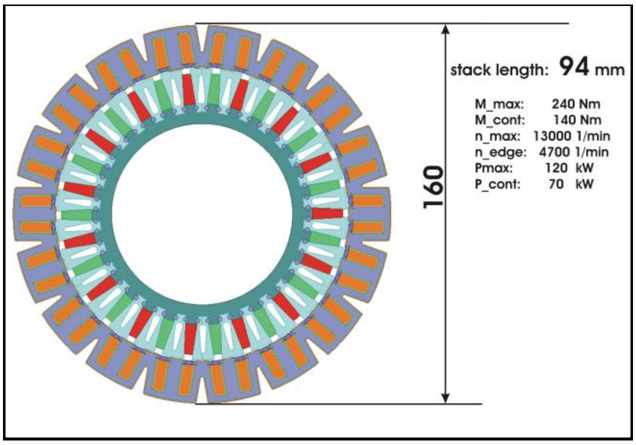

Fig. 5. 120 kW-machine with buried magnets in concentrating layout and single-tooth winding

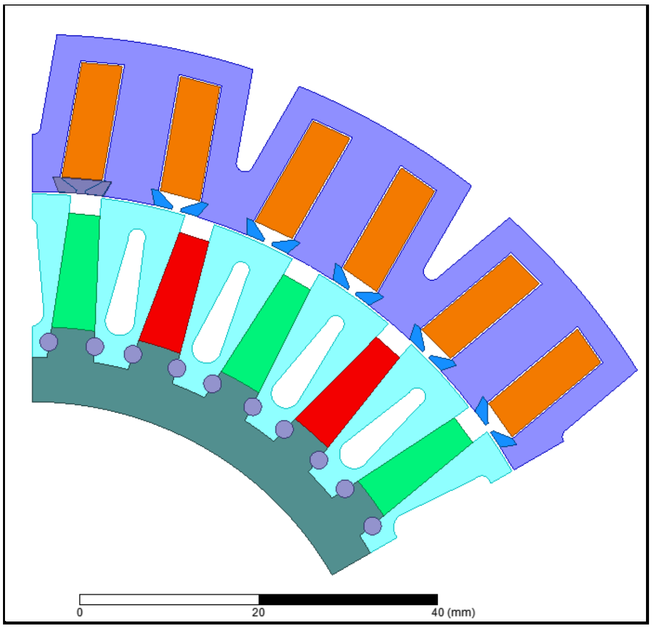

Fig. 6. 120 kW-machine with buried magnets in concentrating layout and single-tooth winding, section

The stator consists of 36 teeth, whereof each second stator tooth shows parallel flanked nuts. Therefore, it is possible to insert 18 prefabricated coils over each second tooth, filling the total nut volume. The remaining 18 tooth serve exclusively for magnetic flux return. The part opposite to the air gap of these unwounded teeth is v-shaped cut out. The remaining cross section is enough for magnetic flux conduction (Fig. 7). That way the stator weight lowers and the cooling surface on the outside of the stator, i.e. the contact face to the cooler, increases by the factor of 1.7.

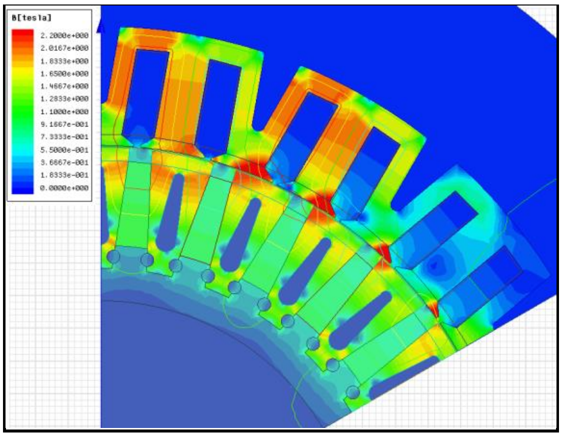

Fig. 7. 120 kW-machine with buried magnets in concentrating layout and single-tooth winding, level of magnetic flux by maximum torque

By the insertion of fully prefabricated stator coils, a high copper filling factor of nut is possible. Thus it is achievable to reach typical 50% copper in the cross section of the nut. This process is doable if there is no jump out of tooth crest.

Otherwise, tooth crests accordingly to the previous Figures are essential for forming the magnetic flux to reach the desired low rotor losses especially under low torque and high-speed condition. The solution is the integration of the tooth crest in the slot closure which is inserted after coil assembly (Fig. 6).

The interconnection of 18 stator coils to 3-phase winding generates a system with six coils each phase. By feeding with 3-phase inverter, the time dependent phase shift between two adjacent stator coils is 60°. Accordingly, the rotor pole pitch must enlarged and lead to 30 rotor poles. Thus, the magnetic behavior in the air gap replicates periodically with 60° i.e. six times for the whole machine.

The rotor poles are of soft magnetic trapeze-shaped pieces. The permanent magnets between the soft magnetic poles (Fig7) are orientated in tangential direction with alternating clockwise and anticlockwise direction. The advantage of this well-known concentrating permanent magnet layout is that the magnetic excitation in the air gap increases with the ratio from radial magnet length to the tangential width of the rotor poles To that effect the magnetic induction is concentrated in the air gap.

The back of the rotor consists of non-magnetic steel such as austenitic steel in order that nearly the total flux of the permanent magnets reaches the air gap. Compared with the common layout of buried magnets no considerable portion of the magnetic flux drops away by a soft-magnetic „short circuit". The result of this consequent optimized rotor excitation is an unusual high magnetic induction in the air gap for permanent magnet motors and lead to very high force densities with corresponding high torques.

The soft magnetic rotor poles consist for low losses from thin plate non grain-oriented electric steel (NO10) as well as the stator stack. Even the non-magnetic back of the rotor consists of laminated steel to avoid eddy currents. Fig. 5-7 shows a high strength fixture between the soft magnetic rotor poles and the back iron of the rotor for a special high-speed application. The finished rotor poles and the finished rotor back iron are joined by the insertion of pins in the remaining holes. A more simple process is used in case of typical application with air gap velocities < 90m/s and accordingly low centrifugal forces. The total cross section for the rotor is made by joining thin plates of electrical and austenitic steel concentric together. These hybrid sheets are processed as usual by stamping and laminating

The neodymium-iron-boron magnets are made from 2mm isolated slices stacked in axial direction and assembled in axial direction with the rotor. By this layout, only negligible eddy current losses arise in the magnets.

A. Powertrain Data

Fig. 8 shows the speed torque characteristic. The intermediate circuit voltage (DC) and the number of winding turns is so adapted that for the maximum power of 120kW at speed higher than nominal speed of 4700 rpm a field weakening component of current must be applied.

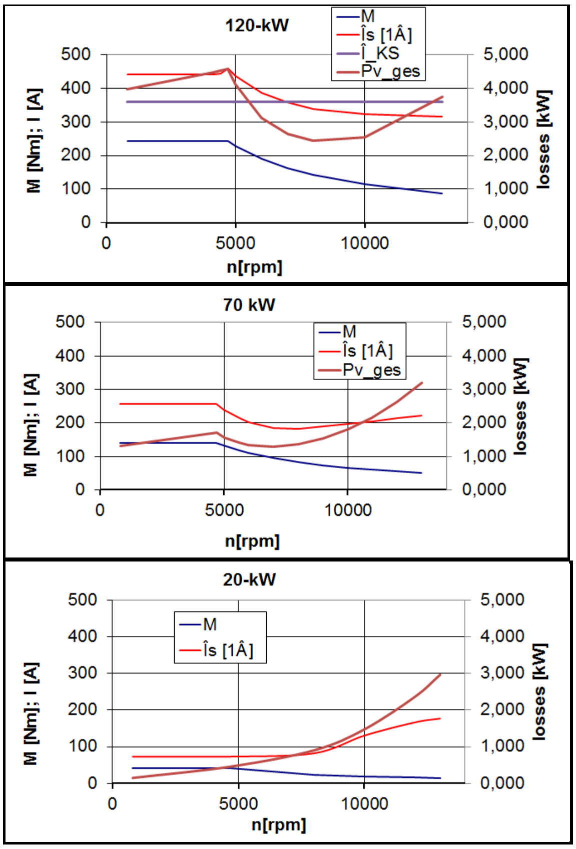

Fig. 8. effective stator current, torque and losses at 400VDC operation for different power

This shows the slight increase of the stator current at this point (Fig. 8a). Accordingly, the induced voltage Ui by the rotor is far above the maximal output voltage of the inverter. Fig. 9 shows the situation at 13000 rpm. Consequently, a negative (-Id) current appears for field weakening in this example about 180A. Through this adaption above the nominal speed always a field weakening portion of current (-Id) occurs.

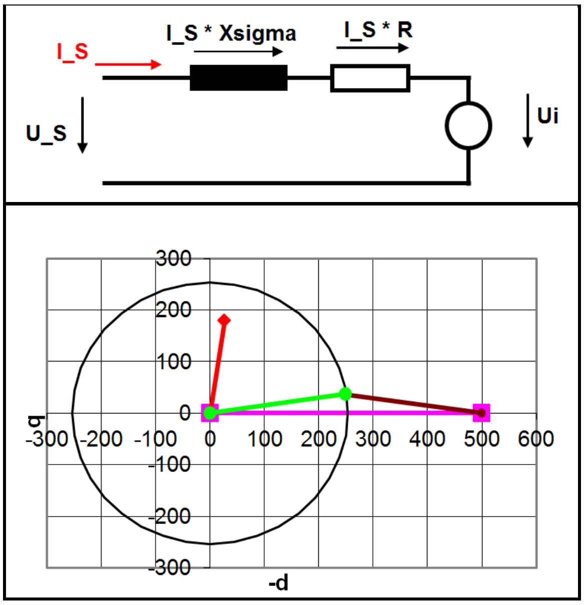

Fig. 9. Voltages and current d-q-notation (units: V, A) at n= 13000 rpm and P= 20 kW

- circle diagram — maximum inverter string voltage at 400VDC
- pointer-magenta — rotor induced voltage
- pointer-brown — voltage drop across longitudinal inductance Xsigma
- pointer-green: — stator voltage U_S
- pointer-red: — stator current I_S

This increasing portion of the field weakening current by increasing speed is the main reason for the increasing losses with speed.

The effective longitudinal inductance is designed such that the arising losses with field weakening have no considerable negative influence on the loss collectives of the real drive cycles.

For electric drives operating at torque zero and normal speed for longer times - say hybrid cars without separate clutch - the drag losses by field weakening become bad for the overall efficiency. In these cases, the intermediate circuit voltage must be designed much higher but this leads to much more installed inverter power.

The actual layout needs despite the ratio n_max / n_eck=2.7 only an apparent power of 174kVA for 120kW output power.

Security against overvoltage's by short circuit is possible continuous because the current in case of terminal short circuit is lower than the maximal thermal continuous current (Fig. 8a, I_KS).

The losses shown in Fig. 8 can be dissipated continuously at a coolant temperature of 65°C. The rotor losses exceed only at maximum speed the value of 100W (TABLE II) because of deep buried magnets, the optimized tooth geometry and the low-loss core material and are in a wide range of the cycles below 50W. Despite a maximal temperature of 150°C typically defined by the magnets, the dissipation of losses is possible trough air circulation in the housing.

TABLE II.: ROTOR LOSSES

		Rotor losses[kW]								
		speed[rpm]								
		1000	2500	4000	5500	7000	8500	10000	11500	13000
torque[Nm]	0	0,000	0,003	**0,009**	0,019	0,032	0,051	0,074	0,102	**0,135**
	50	0,000	0,004	0,011	0,023	0,041	0,064	0,092	0,127	0,169
	100	0,001	0,006	0,018	0,037	0,065	0,102	0,148	0,204	**0,271**
	150	0,001	0,010	0,029	0,061	0,106				
	200	0,002	0,015	0,045	0,094					
	250	0,003	0,022	**0,065**						

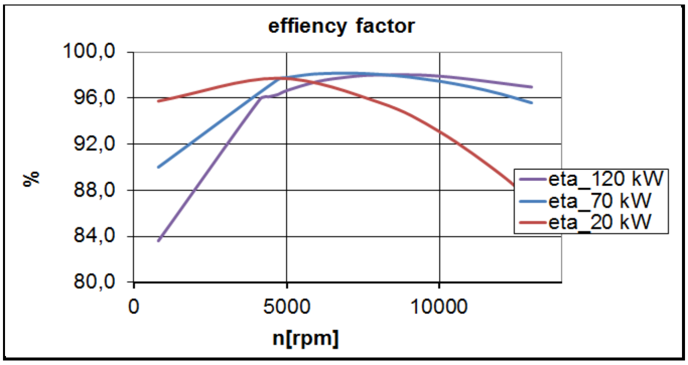

Fig. 10. efficiency

The efficiency characteristics for different power are given in fig. 10.

The rating of drives by efficiency is based on the NEFZ cycle by legal regulations. Usually a comparison is made on base of this unrealistic cycle but cycles that are more realistic are in discussion.

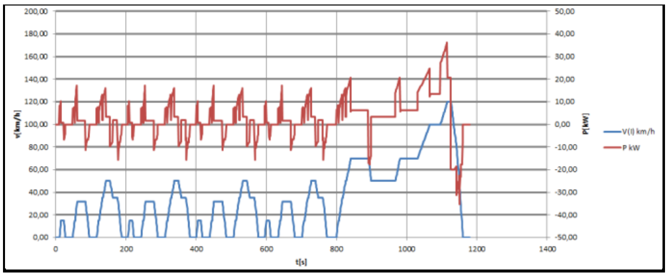

Fig. 11. NEFZ-cycle passenger car 1.500 t, power E-machine

The described machine reaches in this operation cycle at low power and low velocity an averaged efficiency of

$$eta\_NEFZ = 95{,}5\%.$$

The real cycle above (Fig. 3 and 4), which was the base for the powertrain layout with maximum speed of 185km/h and 120kW rated power gives an averaged efficiency of

eta_Realzyklus = 95,4%.

An efficiency of more than 90% is demanded from the car development for permanent excited synchronous machines.

B. *Dinemsions, Weight*

- Stator: iron, windings+interconnection 5.0 kg
- Rotor incl. magnets 4.9 kg
  - Magnets 1.29 kg
- Active mass total **9.9 kg**
- Housing, shaft, bearing, cooling 5.5 kg
- Mass total **15.5 kg**

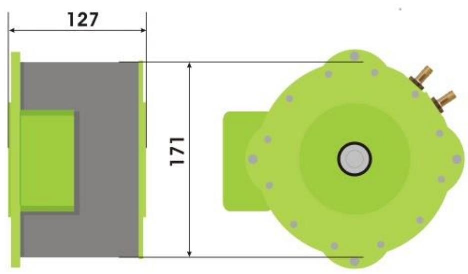

Fig. 12. dimensions

- Stack length 94 mm
- Outer diameter stator 160 mm

Power and torque data

- M_max 240 Nm maximum torque
- M_dauer 140 Nm continuous torque
- n_max 13000 rpm maximum speed according to 185 km/h
- n_eck 4700 rpm characteristic speed with M = M_max
- P_max 120 kW rated power
- P_dauer 70 kW continuous power

Overall parameters for the given layout:

- Specific magnetic force on the air gap (cont.) 6.0 N/cm²
- Specific magnetic force on the air gap (max.) 10.2 N/cm²
- overload capability: 1.7
- Mass specific torque 15.4 Nm/kg
- Mass specific power 7.8 kW/kg

V. Conclusion

The described electric machine characterized by

- permanent magnet rotor with buried magnets
- magnetic flux concentrating layout
- no magnetic bypasses
- prefabricated coils

enables very high power and torque densities. Frame size and weight are below the values reached by layouts with open flat magnets and transversal flux machines (TABLE I).

The apparent power is minimized to typical 150% of the mechanical power by the advantageous application of the control regime with active field weakening above nominal speed.

An excellent machine efficiency of 95% is reached in power train applications for electric drives in combination with clearly reduced material, weight and volume.

[1] Neudorfer H., *Vergleich unterschiedlicher Antriebsmaschinen im Traktionsbereich*, Inst. für elektrische Energiewandlung, TU Darmstadt, Vortrag 11.04 2008

[2] Wiedemann G. E., *Ableitung von Elektrofahrzeugkonzepten aus Eigenschaftszielen*, Fakultät für Maschinenwesen, Dissertation 2013