Design of Electric Motors for Hybrid- and Electric-Vehicle Applications

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***Abstract*—An increasing ecological awareness and the shortage of fossil-fuel resources are strong incentives to develop more efficient vehicles, with lower fuel consumption but without reducing driving comfort. The hybrid electric vehicle, combining the drive power of an internal combustion engine and of one or several electrical machines, is a promising concept. In addition, the development of powerful batteries with large capacities enables the electric vehicle to be an alternative as well. Since these machines are not operated at single operation points, they must be designed depending on later application, i.e. depending on frequency distributions of the operation points resulting from vehicle simulations and defined driving cycles. Furthermore, the installation space available for the electrical machine is very limited, especially in the case of hybrid electric vehicles. In this paper the selection process of the electrical machine type and a possible design approach in the case of a limited installation space is described.**

I. Introduction

An increasing awareness on ecological issues and the fossil-fuel shortage are strong incentives to develop more efficient vehicles, with lower fuel consumption but without reducing driving comfort. The hybrid electric vehicle, which combines the drive power of an internal combustion engine and that of one or several electrical machines, is a promising concept in this regard. In addition, the development of powerful batteries with large capacities enables the electric vehicle to be an alternative as well.

According to the pursued concept, the applied electrical machine has to be optimized for a range of operating points. In the case of a parallel hybrid electric vehicle for example, it must offer a fast start/stop function, it must also operate as a generator, as support traction in the so called boost operation, as a drive during electrical traction, as well as an electrodynamic brake for recuperation. In addition to the specifications on torque and speed resulting from named functionality, the main demands are: a high overall efficiency within a large range of the torque-speed characteristic, a high overload capacity, small installation space and weight, and a high reliability at low cost. With such requirements in power, efficiency, installation space and weight, the design of the machines is particularly challenging.

Since these machines are not operated at single operation points, they must be designed depending on the intended application. Thus, in a first step the operating range of these machines must be estimated depending on that future application, this means the frequency distributions of the operation points resulting from vehicle simulations and defined driving cycles. In a next step, the electrical machine must be designed in such a way, that the range of best efficiency meets the range of most frequent operation points, i.e. the average overall efficiency must be maximized in order to improve the energy balance and reduce the vehicle's fuel consumption, if a HEV is considered.

Furthermore, the installation space that is available for the electrical machine is often very limited, especially in the case of parallel hybrid electric vehicles in which the electrical machine is integrated into the drivetrain, often between combustion engine and transmission. Due to this integration, the issue of the machine design is rather the question "How much power can be integrated into that space?" than "How can we get that specific power into the available space?".

Due to named issues, this paper discusses the choice of machine type and a possible design approach under the constraint that the outer dimensions of the machine are fixed. Both, the choice and the dimension, are presented with regard to intended vehicle application and the machine requirements resulting from this.

II. Vehicle simulation

The main requirements for electrical machines applied in (hybrid) electric vehicles are the general requirements which are: a high overall efficiency within a large range of the torque-speed characteristic, a high overload capacity, small installation space and weight and a high reliability at low cost.

But to improve the energy balance and to reduce the vehicle's fuel consumption, the electrical machine must be designed individually according to a specific vehicle and its intended purpose, i.e. the overall efficiency must be optimized in the range of used operation points. This leads to the question, what are the expected operation points?

To determine the expected operation points, vehicle-simulation models (see Fig. 1) are used, which contain among others driving cycles, the vehicle data, the transmission, the battery, the battery controller and the main vehicle control unit. A driving cycle is a series of data points representing the speed of a vehicle versus time. For machine design purposes, an average driving cycle should be generated, which includes

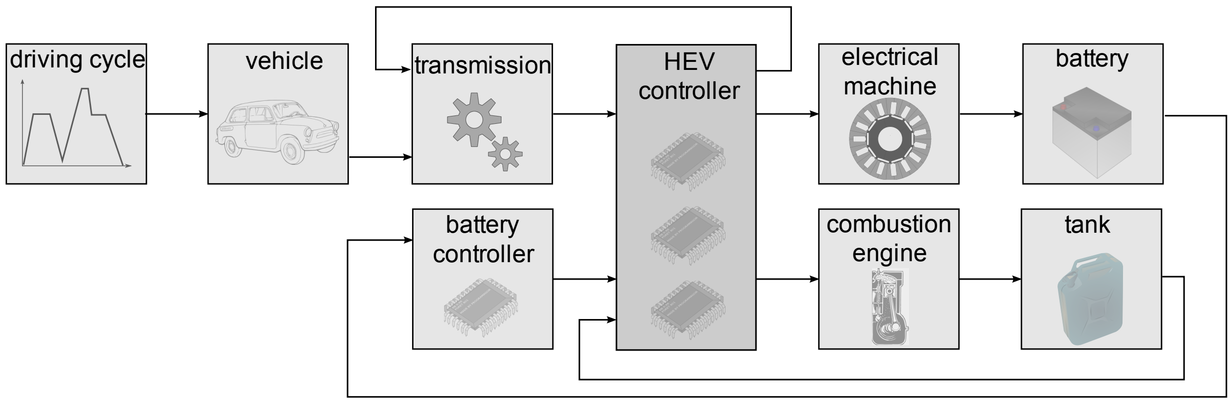


Fig. 1. The vehicle simulation model for parallel HEV.

weighted parts of urban, extra urban and highway driving cycles according to the vehicle's intended purpose. The vehicle model itself should contain its mass, drag coefficient and friction losses. Transmission ratios and their efficiencies are described by the transmission submodel. The hybrid electric vehicle controller, monitoring all conditions, controls all components regarding the vehicle's driving and control strategies.

The results from these vehicle simulations can be among others the fuel consumption, the energy balance, the battery's state of charge and the frequency distribution of the electrical machine's operation points (see Fig. 2). It is to be considered: the detailed the vehicle model, the better the prediction of expected operation points, which are required for the choice of machine type and the machine design.

III. The Choice of Electrical Machine Type

Considering the development and the prototype presentations of electrical and hybrid electrical vehicles over the last decade, one can see that several machine types (see Fig. 3) were applied: the induction machine (IM), the permanent magnet excited synchronous machine (PMSM) and the switched reluctance machine (SRM). The application of all these machines suggests that they have advantages and disadvantages of their own which render them interesting in different hybrid vehicle concepts.

Hence these machine types are compared in the following of this section. To compare the power density, an analytical pre-design was performed for a nominal power of 30 kW, a nominal speed of 3000 min^{-1} as well as a nominal line voltage of 400 V. These values are based on an average of commonly applied machines in HEVs. To assure a maximum utilization and a sufficient comparability, a quadratic design was used for each machine.

A. *Induction machine*

Induction machines with squirrel-cage rotor belong, as well as the DC machine, to the most technically mature machines, but they offer a higher power density and a better efficiency when compared to the DC machine. The dominant losses in IM machines are the ohmic losses. Due to the lower magnetization current in the field-weakening range, the ohmic losses are reduced and accordingly the IM provides a wide speed range in combination with a comparatively good efficiency at high speeds. The required magnetization current and the ohmic losses in the rotor decrease the efficiency in the range of nominal speed, when compared to PMSMs. A disadvantage is the heat in the rotor as a result of the losses, which requires cooling and restricts overload capacity. Furthermore, an air gap as small as possible is necessary to decrease the magnetization current, but this requires tighten tolerances during fabrication and thus increases production costs.

Here, the pre-designed IM (according to [1] and [2]) has a volume of 12.1 dm^3 and a power density of 2.5 kW/dm^3. The pole pair number is $p = 2$, since this gives the best nominal-to maximum-speed ratio and the best performance. Due to its advantages, the IM is the most commonly used machine in electrical vehicles.

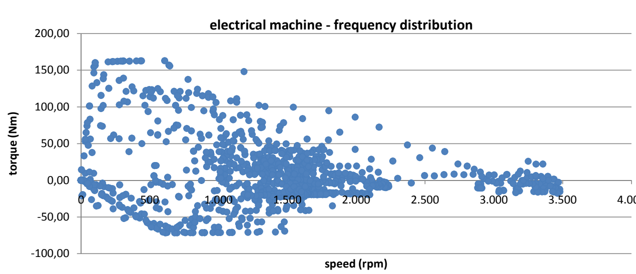
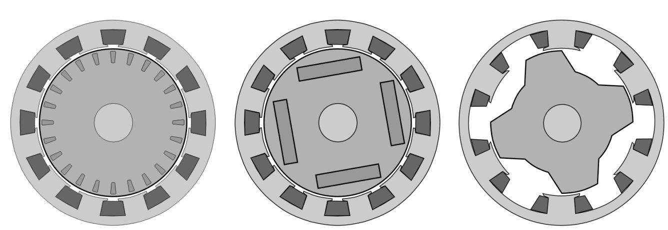


Fig. 2. Exemplary frequency distribution for the parallel HEV.



(a) IM (b) PMSM (c) SRM

Fig. 3. Schematics of electrical machines.

B. PMSM

The magnetic excitation of the PMSM is provided by permanent magnets in the rotor. This machine benefits from the high energy density of the magnets, because the permanent magnet excitation requires little space. Since no excitation current is required, the PMSM provides a high overall efficiency in the range of nominal speed. The dominant losses of the PMSM are the iron losses, which mostly occur in the stator, so they can be easily dissipated by a case cooling system. Hence, the PMSM exceeds the IM in power density and efficiency. Its major disadvantage is the relative high cost of rare-earth magnets, such as NdFeB. Another disadvantage is the additional current component required for field weakening, whereby higher stator losses occur and the efficiency decreases at high speeds. Furthermore the overload capacity is restricted by the magnet characteristics. Due to their electrical conductivity, eddy-current losses appear, which heat up the magnets and must be considered especially at high speeds and high load currents. To prevent the magnets from irreversible demagnetization, high magnet temperatures in combination with high stator currents must be avoided - a reliable temperature detection is essential.

The analytically pre-designed PMSM has a volume of 4.9 dm^3 and a power density of 6.1 kW/dm^3 - the design was performed by the in-house software *ProMotor* [3] following the design rules in [4]. As a result of their advantages the PMSM belongs to the most suitable machines for HEVs. Moreover, decreasing magnet cost are making PMSMs more appealing nowadays.

C. Switched reluctance machine

The principle of the SRM has been well known for a long time, but it was not applicable until the progress of power electronics. The SRM provides a power density and efficiency comparable to the IM. However, it has a simple construction without rotor winding and with concentrated stator windings, and therefore a better thermal characteristic. In addition, it is cost-effective in production and low-maintenance. To reach a high power density, a high magnetic air-gap induction is recommended - this however increases acoustic noise radiation. Measures for noise reduction decrease the power density and diminish the appeal of the SRM compared to the IM. Another disadvantage is the high torque ripple at low speeds. In addition the control of the SRM is more complicated than that of a three-phase drive, due to the high non-linearity of the determination of the current-switching angle. Therefore, the SRM was used in only a few prototypes of HEVs, until now.

TABLE I
RESULT OF ANALYTICAL ROUGH DESIGN.

	IM	PMSM	SRM
number of pole pairs p	2	6	12/8
maximum efficiency η	89%	97%	88%
rotor diameter D_r (mm)	162	136.8	159
active length l_i (mm)	127	140.8	159
outer diameter D_a (mm)	258	196.3	269
length with end windings l_a (mm)	232	161.5	207
volume V_a (dm^3)	12.1	4.9	11.8
power density (kW/dm^3)	2.5	6.1	2.6

TABLE II
EVALUATION OF THE ELECTRICAL MACHINES.

	IM	PMSM	SRM		
power density	⊙	⊕⊕	⊙	⊕⊕	very good
efficiency	⊕	⊕⊕	⊕	⊕	good
costs	⊕⊕	⊖	⊕	⊙	neutral
reliability	⊕⊕	⊙	⊕	⊖	bad
technical maturity	⊕	⊙	⊙	⊖⊖	very bad
controlability, costs	⊙	⊕	⊖		

The pre-designed SRM (referring to [5]) has a volume of 11.8 dm^3 and a power density of 2.6 kW/dm^3. The design of the SRM is a 12/8 machine, that means it has 12 stator slots and 8 rotor slots.

D. Comparison and applicability in EVs or HEVs

As a result of the previous discussion, the machine characteristics and their advantages and disadvantages are summarized in Table II.

The induction machine features the best reliability at low production cost, but a complicated and expensive field oriented control is required to reach high powers and dynamics. It has the best average overall efficiency over the whole speed range, but its maximum efficiency does not reach the values of a PMSM. So the IM is advantageous if a good efficiency over a wide speed range is required and if the installation space is not restricted, because it only allows a moderate power density. That means the IM would be suitable in the case of electric vehicles or series HEVs.

The switched reluctance machine is comparable in power density and efficiency with the IM, but inferior in the remaining points. Its main disadvantages, and exclusion criterion until now, has been the high torque ripple at low speeds and a significant acoustic noise radiation

The permanent magnet synchronous machine offers the best power density; this permits a high power machine with small weight, even in the restricted installation space of a vehicle‘s engine compartment. It offers the best maximum efficiency in a defined speed range. For these reasons the PMSM can be most suitable to achieve a fuel saving hybrid electrical vehicle. However, due to its rare-earth magnets, it is the most expensive machine type as well.

Comparing these results with several other machine comparisons in papers, reports or surveys like [6] - [9] shows distinctive similarities.

The machine choice for (hybrid) electric vehicles depends on the (hybrid) vehicle systems and its demands. In a series hybrid and full electric system, the electrical machine must be designed for the maximum vehicle power and the full speed range. Using an IM would be advantageous in this case, because of its good efficiency over a wide speed range and its low cost. A PMSM designed for the full vehicle power is more expensive, but is preferable if installation space and weight are the deciding factors. In a parallel (and power-split) hybrid

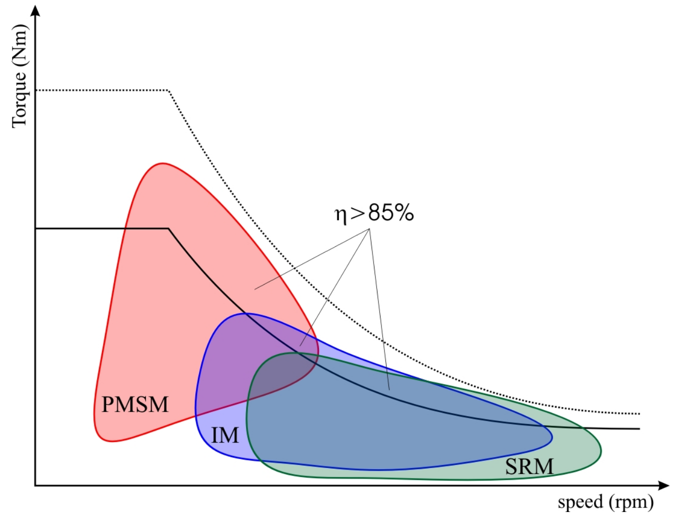


Fig. 4. Exemplary efficiency maps of different machines with constant power.

system, the speed range depends on the connection to the gear box, the gear-selection strategy and the HEV functionality, but typically it is restricted to lower speeds. Here the application of a PMSM is appropriate, due to its high efficiency at low speeds. The high power density reduces the installation space and simplifies the integration into the drivetrain. Due to the comparatively lower machine power, required in the parallel system, the cost are lower for this system.

Moreover, the choice of the machine type depends on the control strategy of the hybrid electrical vehicle. It is to be determined in which operation points the electrical machine will be used. That means, the frequency distribution of the operation points during a driving cycle must be considered. In Fig. 2 a typical frequency distribution for a parallel hybrid vehicle is depicted. Most operation points are in the range of low speeds up to 2000 $\min^{-1}$, the maximum speed does not exceed 3500 $\min^{-1}$ - so the operation points are distributed over a limited speed range. According to this, we have to choose an electrical machine which has its best efficiency at lower speeds. In Fig. 4 the exemplary efficiency map of different machine types is depicted. The lines are equipotential lines, that surround the range of an efficiency $\eta > 85\%$. The PMSM has its best efficiency at low speed whereas the induction machine and the SRM have their best efficiency at higher speeds and over a wider speed range. In this case the PMSM would be the best choice. But if most of the operation points are at higher speeds or over a wide speed range, the IM should be preferred.

IV. Initial Design Approach for Fixed Dimensions

In the following section a design approach is exemplarily described by means of a permanent magnet synchronous machine, since this machine type is the mostly used machine type of today's HEVs.

Electrical machines are usually dimensioned by means of analytical formulas. In particular, the stator diameter is directly derived from the value of the nominal power [11], [12].

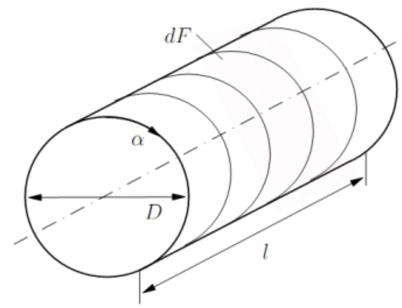


Fig. 5. Geometrical parameters of the stator bore.

But if the available installation space is limited and the outer dimensions are fixed, the approach must be different. In this case the rotor diameter D is a degree of freedom and the stator diameter D_S constant. A given force produces a torque that is proportional to the radius, i.e. the torque is at least linearly proportional to the diameter. Moreover, if the diameter increases, there is more room for magnets around the rotor which increases the specific magnetic loading. Therefore, torque and thus power increase with the diameter. But increasing the rotor diameter lowers the area of the stator. The area available for current injection decreases then, and if a constant current density is assumed, the specific electric loading A decreases as well. As a result, a maximum of the torque can be expected for an intermediate value of the rotor diameter D.

From analytical considerations (see Fig. 5), the tangential force F_α can be calculated from the air-gap field by the means of Maxwell Stress Tensor:

$$F_\alpha = \oint_F B_n H_t dF = \frac{lD}{2} \oint_0^{2\pi} B_n H_t d\alpha. \qquad (1)$$

With the simplification $B_n = B(\alpha)$ and $H_t = \frac{I}{l} = A(\alpha)$, the torque T is given by:

$$T = \frac{D}{2} F_\alpha = \frac{lD^2}{4} \oint_0^{2\pi} B(\alpha) A(\alpha) d\alpha. \qquad (2)$$

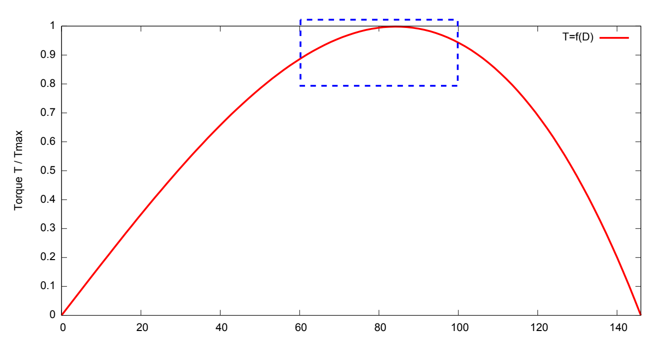


Fig. 6. The normalized torque depending on the rotor diameter.

The specific electric loading A is proportional to the stator area available for current injection and to the current density J:

$$A \sim \frac{I_{tot}}{\pi D} \sim \frac{J}{\pi D}\left[\pi\left(\frac{D_S}{2}\right)^2 - \pi\left(\frac{D}{2}\right)^2\right]. \tag{3}$$

Therefore, the torque is proportional to:

$$T \sim D^3\left(\frac{D_S^2}{D^2} - 1\right) = D \cdot D_S^2 - D^3. \tag{4}$$

If the fixed outer diameter is $D_S = 146$mm, the normalized torque reaches its maximum at about $D = 84$mm, as depicted in Fig. 6.

Another degree of freedom is the pole pair number p, which influences the rotor size and thus the volume of a machine when using analytical formulas - increasing the poles increases the force generated by the motor. Furthermore, the stator-yoke height and the length of the end winding take up less space with increasing pole pair number (see Fig. 7). With a decreasing volume at constant power or vice versa, the power density increases. However, increasing the number of poles implies decreasing the magnet width and enlarging the relative amount of magnet leakage flux, which in turn reduces the air gap flux density. So the force will not increase indefinitely but will actually decrease with a further increase of the magnet poles. Thus there exist an optimum number of magnet poles.

Moreover, iron losses increase more than proportional with frequency, and the higher the pole pair number the higher the frequency of the stator currents and of the alternating magnetic field. The iron losses are the dominant losses in PMSMs at high rotational speeds. So the total losses increase significantly with increasing pole number at this speed range and thus the overall efficiency decreases.

Since the effect of the pole pair number can not be determined accurately by analytical formulae (due to named effects of flux leakage and iron losses), numerical FE simulations are performed. A matrix of geometry variations (see Fig. 8)

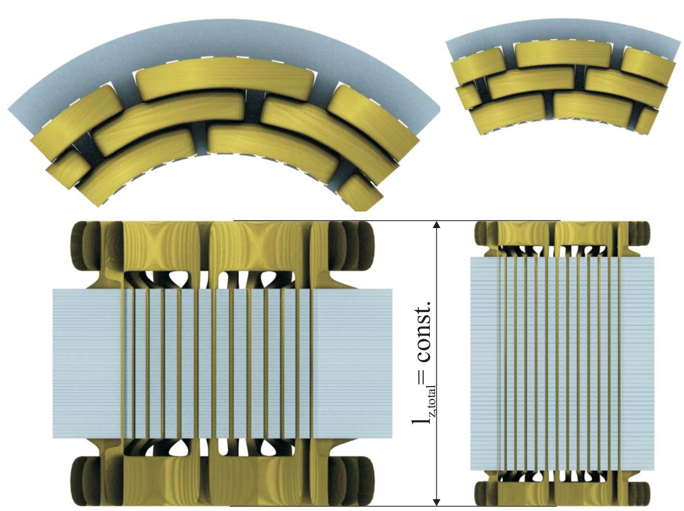


Fig. 7. Active stator lenght depending on $p = 4$ and $p = 8$.

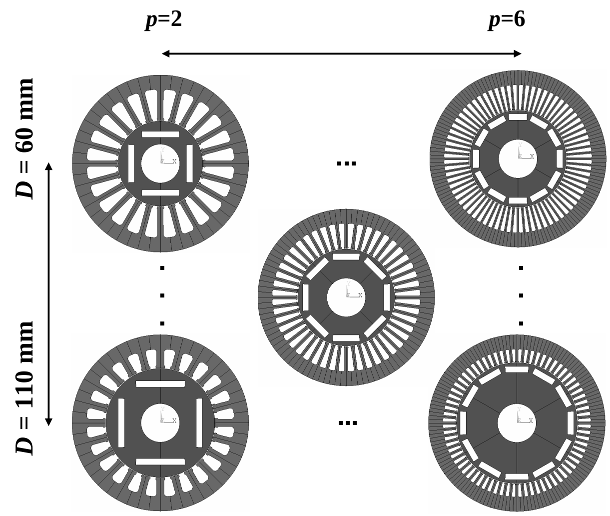


Fig. 8. The matrix of D- and p-variations.

$[p = 2...6, D = 60...110\text{mm}]$ is established in order to study the effect of pole pair variation, as well as to verify the analytical estimation of the optimal rotor diameter.

This analysis is performed on several stator configurations, one with a concentrated winding and two with distributed windings and different slot/pole ratio and short-pitching ($q = 2$ and $q = 1.5$). The following parameters remain constant for all geometries: the axial active length $l = 224$mm, the outer stator diameter $D_S = 146$mm and an air gap of $\delta = 0.7$mm. The nominal current density in the copper was set to the maximum allowed in an air-cooled machine, i.e. $J_n = 6\text{A/mm}^2$, and the copper space factor to $k_{cu} = 0.6$.

The simulation results with the distributed-winding are, as an example, depicted in Fig. 9. The maximum average torque depending on the rotor diameter has, in agreement with the analytical estimation, its maximum at $D = 80$mm. The pole pair numbers $3 \leq p \leq 5$ nearly provide the same torque. However, with increasing p the torque/current ratio is

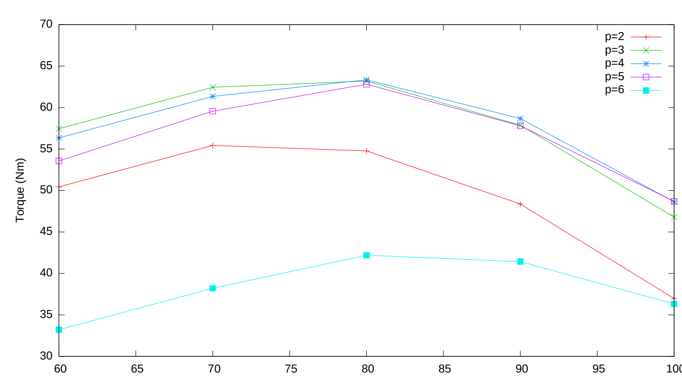
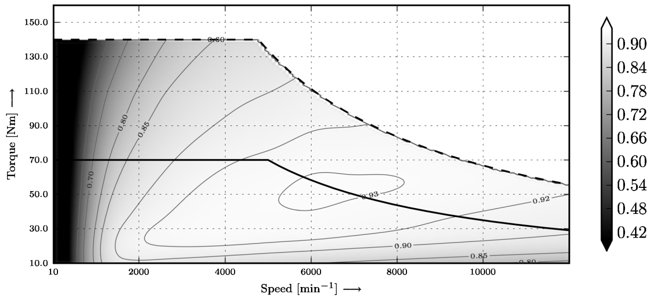
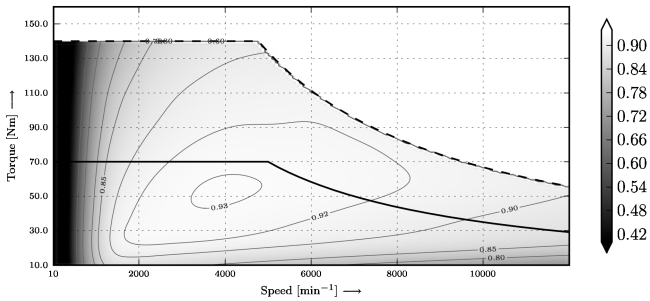


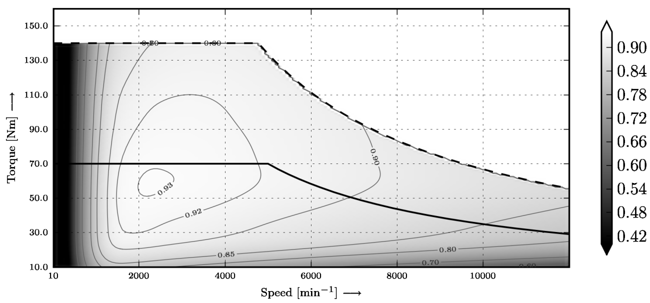
Fig. 9. Numerical calculated torque.



(a) p=3



(b) p=4



(c) p=5

Fig. 10. Efficiency maps depending on the pole-pair number.

improved and thus the ohmic losses of the stator windings are lowered; on the other hand the iron losses increase with the pole pair number. This means, the losses can be moved into the stator by reducing the pole pair number, which make them easier to dissipate. In this case, ohmic losses are increased in the stator and iron losses on the whole, and therefore rotor losses, are reduced. In addition, the range of high efficiency can be moved either to low rotational speeds (high p) or to high speeds (low p). In Fig. 10 the efficiency maps for the pole pair numbers $3 \leq p \leq 5$ are depicted to illustrate the above-mentioned interrelation (the pole-number variation was performed with the final and optimized machine design). The efficiency maps for motor operation are based on the loss calculation including the mechanical losses, copper losses, iron losses and eddy-current losses inside the magnets.

How far the reduction of p is reasonable depends on the required speed range, according to the frequency distribution of the operating points during a driving cycle. These frequency distributions are required to achieve an optimized machine design, which fulfills the vehicle's demands, and are determined by vehicle simulations as described before - in Fig. 2 an exemplary frequency distribution (motor and generator operation) is depicted for a parallel HEV and an urban driving cycle.

A good compromise in this case is the pole pair number of $p = 4$, examined drive cycles are an intra-urban, an extra-urban, a highway and a start drive cycle. The rotor diameter is chosen to $D = 80$mm. This geometry offered the best match of the range of best efficiency with the range of most frequent operation points - its average efficiency over the driving cycle was 78% (compared to 50% with $p = 3$ and 70% with $p = 5$).

The geometry resulting from this initial design provides a basis for following geometry optimization steps.

V. Conclusion

In this paper an approach for the choice of the electrical machine type and its design is presented. Starting with the vehicle simulation predicting the future operation points of intended vehicle application and purpose. Furthermore, different machine types are presented and compared regarding their applicability. It is shown that the choice of machine type should depend on determined frequency distributions of the operation points and resulting average efficiencies. In addition, the initial design of a permanent magnet excited synchronous motor, under the constraint that the outer dimensions of the machine are fixed, is presented. This initial design is also conducted in consideration of future operation points to improve the energy balance and reduce the vehicle's fuel consumption.

References

[1] G. Müller, K. Vogt, B. Ponick, *Berechnung elektrischer Maschinen,* Wiley-VCH Verlag, 2008.

[2] M. Schmitz, *Fahrzyklusgerechte Auslegung einer Asynchronmaschine fuer Elektrofahrzeuge*, PhD-thesis, Institute of Electrical Machines, RWTH Aachen University, Shaker Verlag, May 1998.

[3] M. Schöning, K. Hameyer, "Virtual Product Development for Electrical Motors", *Proceedings of 6th IEMDC, Antalya, 2007.* Antalya, 2007.

[4] S. Henneberger, *Design and Development of a Permanent Magnet Synchronous Motor for a Hybrid Electric Vehicle Drive*, *PhD-thesis, Katholieke Universiteit Leuven, May 1998.*

[5] S. Risse and G. Henneberger, "Design and Optimization of a Reluctance Motor for Electric Vehicle Propulsion,", *ICEM , Helsinki, August 2000.*

[6] M. Zeraoulia, M.E.H. Benbouzid, D. Diallo, "Electric Motor Drive Selection Issues for HEV Propulsion Systems: A Comparative Study", *IEEE Trans. on Vehicular Technology*, Vol.55, No.6, November 2006.

[7] L. Chang, "Comparison of AC Drives for Electric Vehicles - A Report on Experts' Opinion Survey", *IEEE AES Systems Magazine*, August 1994.

[8] M. Yabumoto, C. Kaido, T. Wakisaka, T. Kubota, N. Suzuki, "Electrical Steel Sheet for Traction Motors of Hybrid/Electrical Vehicles", *Nippon Steel Technical Report*, No.87, July 2003.

[9] J.G.W. West, "Propulsion systems for hybrid electric vehicles", *Electrical Machine Design for Electric and Hybrid-Electric Vehicles, IEE Colloquium on*, pp. 1/1 - 1/9, October 1999.

[10] C.C. Chan, "An overview of electric vehicle technology", *Proceedings of the IEEE*, Volume 81, Issue 9, Page(s):1202 - 1213, September 1993.

[11] J. F. Gieras and M. Wing. *Permanent Magnet Motor Technology.* CRC, 2002.

[12] D. C. Hanselman. *Brushless Permanent Magnet Motor Design.* The Writers' Collective, 2003.