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Electric Vehicle Drive Trains: From the Specification Sheet to the Drive-Train Concept

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Abstract— **Within the last years, the research for electric vehicles has significantly increased. Thereby the development of the drive train can be considered as a main challenge. The developers have to face the difficulty of identifying suitable drive trains out of many variants. This paper will show up a procedure to identify and evaluate appropriate drive train configurations for an underlying drive train concept. As the electric motor is one of the main components, with high influence on the overall efficiency, particular attention will be paid to it.**

Keywords—**electric vehicle, electric drive train, specification sheet, electric traction machine, concept study, efficiency, machine comparison**

I. INTRODUCTION

Transportation and mobility have become important topics in our general life today, where mobility also is a symbol for quality of life. Simultaneously the negative aspects of mobility have to be regarded – namely exhaust emissions – what leads to a trade-off. For a few years, international conventions like the Kyoto protocol and the voluntary self monitoring of the ACEA (European Automobile Manufacturers Association) for CO_2-emissions of passenger cars exist. Additionally the rise of fuel costs, based on the limited availability of fossil fuel is another matter of fact, leading to the ambition of reducing fuel consumption with involving emission reduction. Electrical vehicles (EV) are promising concepts to fulfill these aims. Today’s forecast scenario estimations assume that hybrid vehicles (HEV) as well as battery electric vehicles (BEV) won’t only serve a niche market in the future [1], [2].

The development of future vehicle concepts deals with the challenge to identify optimized drive trains for each underlying vehicle concept. HEVs supply many approaches for drive train concepts influenced by the application of both mechanical and electrical drive train components. Thus the complexity of concept choice for HEV drive trains is more difficult than for BEV drive trains. A purpose design approach offers a multitude of possible drive trains, which can also offer vehicle dynamic functions, in addition to their main longitudinal dynamic functions [3], when using more than one energy converter. As a result of this, today implemented BEV drive trains differ in both number and package of the electric machines.

On account of this, vehicle developers are faced with the recurring difficulty of identifying appropriate drive train concepts with the basis of an underlying vehicle concept and specification sheet. A method for solving this basic problem is described within this paper. This is clarified by an additional example of a BEV for urban use.

II. CONCEPTION PROCESS

Based on the start up from “a white piece of paper” the shown up method allows the identification and relative evaluation of possible drive train concepts fitting the underlying target vehicle concept (e.g. urban, transport, sport).

The general procedure can be segmented into these basic steps:

- Systematic synthesis of the solution space
- Qualitative evaluation
    - Selection of possible successful solutions
- Quantitative evaluation
    - Definition of evaluation criteria
    - Definition of evaluation functions
    - Definition of evaluation scenarios
    - Definition of weighting factors
- Preconditions procurement for quantification process
- Execution of the conception and evaluation process

Initial point for the whole driveline definition and choice process is the characterization of the target vehicle, which can be described by outline and performance measures. The data of the example vehicle, which will be used further on are summarized in Table 1.

The starting point for the drive train concept phase is represented by the definition of a vehicle basic concept with an underlying specification sheet containing global vehicle parameters and requirements. Regarding the drive train dimensioning, the main characteristics, supported by the specification sheet, are driving performance properties, such as maximum velocity and acceleration on the one hand and weight, dimensions, friction coefficients of the vehicle on the other hand.

Putting this together, the calculation of driving resistances with respect to different points of operation is possible. Furthermore the electric range of the vehicle for a predefined scenario is heavily influenced by the overall efficiency as well as the – not regarded – energy storage system.

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Table 1: Specification sheet for city car concept.

city car concept	
vehicle segment	Small urban passenger vehicle
passenger seats	4
wheel base	2520 mm
length	4100 mm
vehicle weight	1100 kg
cross section area A	2.0 m^2
c_w-value	0.29
rolling resistance coef. f_r	0.01
dyn. wheel diameter r_{dyn}	0.30 m
acceleration 0-60 km/h	6 sec.
acceleration 0-100 km/h	16 sec.
driveaway cap. at gradient	52 %
special operating point	30 km/h @ 12 %
maximum velocity	140 km/h
total range [NEDC]	200 km

All results showing up in this paper are based on the parameter and requirement inputs from the given specification sheet.

Maximum desired vehicle velocity is 140 km/h. Acceleration characteristics are defined from 0-60 km/h and 0-100 km/h as well. It is necessary to ensure that these values are determined as locked. However changes made later can result in a recommencement of the whole concept procedure.

As a precondition there are no further restrictions concerning the drive train concept for the described vehicle concept. This leads to a wide field of possible drive train configurations. Dealing with this difficulty, the following description of the concept phase is showing up a methodical, structural procedure to handle this problem.

A. *Systematic synthesis of solution space*

To define applicable drive train configurations for the underlying vehicle concept, the determination of a possible solution space is necessary as a first step. This solution space includes the collectivity of all suitable drive train concepts. For this setup of the later called topology matrix, the degrees of freedom have to be defined first. These degrees of freedom are characteristics, describing the components concerning location, quantity, type etc. The solution space here includes variants for two-wheel drives as well as 4-wheel drives.

The following characteristics were defined as degrees of freedom:

- Number of installed electric machines (limited to four)
- Type of machine (central motor (a), wheel-near motor (b) and wheel hub motor (c))
- Alignment of the machine (longitudinal or lateral)
- Location of the machine (axle-near, vehicle centered, axle-distant)
- Type of transmission (N/A, stepped transmission, shiftable transmission)

At this point it is easily noticeable that some combinations depend on each other, so that some options can be defined as equivalent (e.g. wheel near motors require always two machines per axle). These specifics have to be regarded when preparing the topology matrix. The identification of similarities and the selection of successful solutions is described in the following.

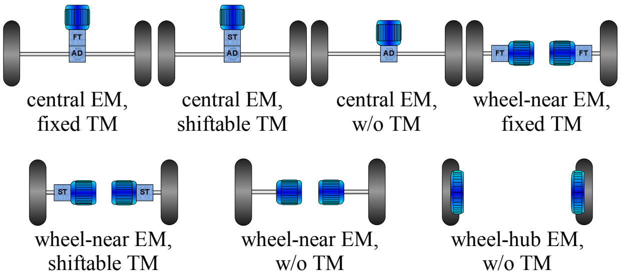
B. *Qualitative evaluation*

As a result of the collection of all possible combinations with filtered dependencies the spanned solution space soon gets huge and unmanageable (some hundred combinations). A reduction of solutions now manifests as an indispensable next step. To reach this reduction without confining the innovation grade of the drive train concept – which means to avoid loss of solutions – another approach will be followed from here.

By the limitation onto one axle the solution space can be dramatically decreased. Anyway, no solutions are lost because of the possibility to combine the solution space for one axle with the same one for the second axle when regarding a four-wheel drive.

The second restriction is the exclusion of cardan shaft drive trains. This advisement is the conclusion of the idea of the electric drive train in general. Using the flexibility of the arrangement possibilities of electric motors in comparison to ICEs, it is possible to install the motor(s) near by the wheel and therewith optimizing efficiency and package of the drive train. Additionally the won space in the drive shaft hump can be used for the battery system for example.

Table 2: Drive train configurations (with reduced solution space).



central EM, fixed TM
central EM, shiftable TM
central EM, w/o TM
wheel-near EM, fixed TM
wheel-near EM, shiftable TM
wheel-near EM, w/o TM
wheel-hub EM, w/o TM

All these measures lead to a significantly reduced solution space as shown in Table 2. This solution space, however, does not provide any information about the capability of usage of the drive train concepts for the investigated vehicle concept.

C. *Quantitative evaluation*

The identification of convenient drive train concepts for an underlying vehicle concept needs to define process tools for evaluation. With the help of evaluation criteria the drive train concepts will become concrete. The criteria are individual and have to be worked out for the special underlying application. To gain quantitative information of the criteria, it is necessary to find underlying evaluation functions. As the results can differ in importance for the underlying vehicle concept, they have to be weighted differently on the basis of suitable scenarios for the vehicle concept.

1) *Description of the process tools*

The identification of evaluation criteria with their underlying evaluation functions allows the solutions to be compared. Combined with the scenario-based weighting, this leads to the possibility, to rate the solutions and to identify the best fitting drive train concept(s).

The identified criteria for the evaluation process are the following:

- costs
- installation space requirements
- modularity & scalability
- weight
- driving dynamic performance
- safety
- efficiency

Determination of costs is a difficult point. At least there are only a few BEVs on the market and only a few studies on components available. Due to the lack of information of costs for some of the components, a relative comparison of costs on the base of identified studies is made. This was leading to a simple linear function for the costs. The same procedure has been chosen as well for transmission and drive shaft components.

The installation space requirement of each drive train concept has to be specified with the help of estimations through empirical values and literature. The procedure of the evaluation here is comparable to the procedure of identifying the costs, thus, it is a relative comparison.

Identification of modularity and scalability comes in place when regarding 4-wheel drives and the option of application in other vehicle concepts as well. The meaning of modularity, in general, describes the possibility of exchanging different components for the same application. An example situation would be the case, when the electric motor of a drive train is changed without the need of adapting the other components. Changing the axle from front to rear could be also an approach for modularity as an example. Anyway, this criterion also includes a conclusion concerning the scalability in power for a drive train concept by the allowance of exchange of the components (e.g. variation of motor diameter for higher torque).

The weight criterion evaluates the overall weight of the specific drive train concept including the weight of all involved components. In a GETRAG report, functions for weight, dependent on power for electrical machines and transmissions, have been released [4]. In the case study, the weight estimations have been made by using these empirical values as well as values from design tools for electric machines and drive shafts. To be comparable, the solution values have been considered relatively.

Driving dynamic performance describes the capability of the specific drive train to integrate functions like torque vectoring, for example. In this case the application of two electric machines (one per wheel) is obligatory. In addition to that, the machines have to fulfill specific dynamic performance requirements as well.

The safety aspect is one of the most important criteria and should be analyzed right in the beginning. The consideration of safety aspects by regarding a drive train configuration laid the focus on the electrical components, to name the electric motor and converter. These components have to be assessed concerning functional failure. This could be, for example, an electrical short circuit inside the components. Safety aspects concerning the electric motor will be described later on in the electric machine chapter.

Efficiency is a criterion of overriding importance as well. It is an expression for a lot of subareas and stands for the overall quality of the drive train. All components within the drive train can be characterized by their individual efficiency. The component with most influence on efficiency is the electric machine. Therefore, this component will be described in more detail in the following.

After description and quantization of the evaluation criteria it is necessary, to scale them to get a homogenous point allocation.

The scaling of evaluation criteria then gives the possibility to go over to the last step: the weighting of evaluation criteria with respect to well predefined scenarios. The weighting of criteria can be performed by different methods. One of them is the confrontation within the triangular matrix. The matrix includes the criteria on the title row and title column. Now the criteria can easily be compared to each other giving them graded numbers (e.g. -1,0,1 or -2,-1,0,1,2; depending on the resolution demands). By scaling the sum points of each criterion, a weighting factor can be determined.

The second method is the so called AHP (Analytic hierarchic process), which basically is an enhanced form of the confrontation matrix procedure but using a full matrix with all entries. The criteria are rated from 1/9 up to 9, where the opposite relationship of the criteria then is assessed by the reciprocal value. The weighting factor then is determined by modal analysis in combination of scaling [25].

D. *Preconditions*

In order to enable the quantification process, a sufficient database must be available for the solution of the calculation and simulation approaches. This is why the type and extent of required data is depending on the evaluation criteria, which have been chosen for the whole process.

The quantification of each evaluation criterion can be made in high detail and depth. As the focus of this paper lies on the electric machine, the evaluation of the different electric machine types, considering the defined evaluation criteria, will be analyzed in detail in the following.

Starting up with the quantification process, the required torque and power will be determined at the wheel to fulfill static and dynamic vehicle driving demands, as described in the specification sheet. Afterwards, the dimensioning of the required components for the drive train can be performed and their characteristics can be quantified by the defined criteria.

These calculations are executed by use of a longitudinal-dynamics tool based on Matlab/Simulink.

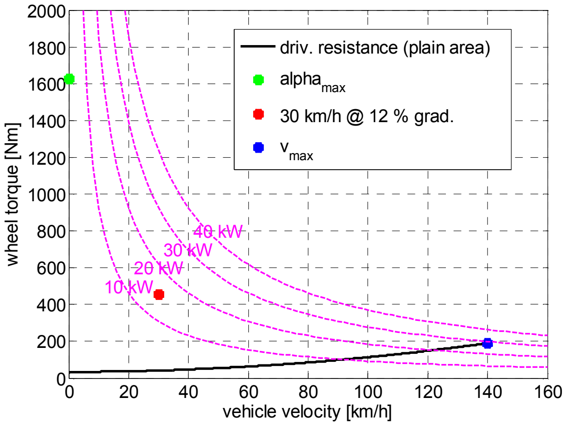


Figure 1: Wheel torque characteristic for city concept vehicle.

Input parameters have to be supplied from the specification sheet. The output is the required driving power at the wheel [5]. A graphical plot of the results for static vehicle driving demands of the city car concept is given in Figure 1.

The figure shows operating points like driving resistance in the plain area, maximal driveaway torque at 52 % gradient ($\text{alpha}_{\text{max}}$), 30 km/h at 12 % gradient and the maximum velocity.

The calculated driving power requirements resp. torque-speed characteristics curve at the wheels are independent from the drive train concept at first instance. However location of the propelled axis has to be regarded (front-driven, rear-driven or four-wheel driven) because of available traction forces between wheel and street surface. The rotatory mass inertia is estimated by empirical values at this point.

The calculations for the case study led to a continuous necessary power of almost 30 kW at the wheels to fulfill the driving demands given in the specification sheet.

E. *Execution of process*

After the calculations the results can now be used to quantify all power-based evaluation criteria equations. As an example for the evaluation of each criterion and component the electric motor, mainly influencing the overall efficiency, will be analyzed in detail in the following.

Nevertheless detailed description of evaluation functions of all components could be given as well, but, due to the complexity they won't be amplified at this point. The calculations of costs and mainly volume and package aspects led to the solution that a rear driven drive train concept will meet the requirements best for this case study (small urban passenger vehicle).

As the basic drive train consists of the electric machine(s), transmission(s) and side shafts, attention to these components has to be paid when regarding evaluation criteria. In this case, the evaluation equations, especially costs, weights and efficiency have been kept simple by the assessment of empirical values, based on calculated power demands.

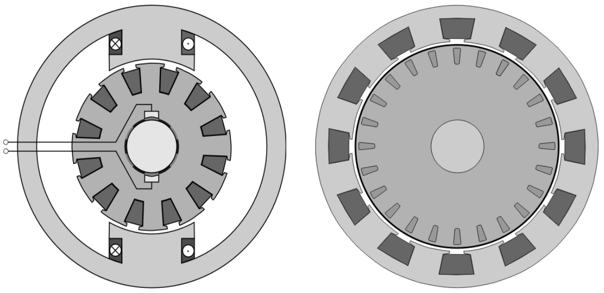
The efficiency of the side shafts (if applied) was estimated with 99%, where the efficiency of fixed stepped transmissions was estimated with 98.5% and 97.5% for shiftable transmissions. Shiftable transmissions, however, have been assumed with a fixed shifting point to reach favorable operating points (PMSM to reach smaller speeds at higher torque; ASM to reach higher speeds with lower torque, cf. chapter of electrical machines). As a matter of course, the detailed design of transmissions (ratio(s), shifting point) has to be made as a concomitant process of the machine design.

The following chapter reveals detailed information of the electric machine to point out the differences of several machine types, regarding their main characteristics, always regarding the defined evaluation criteria.

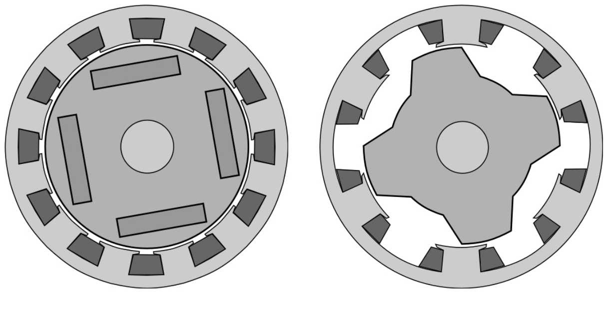
F. *Machines for electric vehicle drive trains*

Considering the development and the prototype presentations of electrical and hybrid electrical vehicles over the last decade, approaches with several machine types can be found (Figure 2), namely the direct current machine (DC), 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 electric and hybrid vehicle concepts.

To get a closer view, these machine types are compared in the following. 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. To assure a maximum utilization and a sufficient comparability, a quadratic design was used for each machine. The analytical pre-designs were validated by finite element computations (FE). Parameterized geometrical models were used to generate the FE-models, based on the geometry determined by the analytical design. By this means, the analytically calculated values of the induced voltage, the torque, the power and the expected air-gap



(a) DC (b) IM



(c) PMSM (d) SRM

Figure 2: Schematics of electrical machines for EVs.

induction were verified. An average deviation from the numerical simulation of about 2-3% has been found, thus the analytical design is deemed accurate enough. Furthermore, iron losses were calculated to determine the overall efficiency in combination with copper losses and approximate mechanical losses.

1) *DC-Machine*

The DC machine allows the most simple regulation and, due to the possibility to connect this machine directly to the vehicle‘s battery, no complex power electronic is required. However, for powers higher than 20 kW, DC machines require commutating poles and compensation windings, so they are larger and more expensive. Due to the missing possibility of field weakening, the permanent magnet excitation, which would increase the machine‘s power density, is not feasible. Another disadvantage is the commutator and its brushes, which decreases the reliability and increases the maintenance costs. Most losses of the DC machine occur in the rotor, which makes it necessary to add a complex cooling system at high power and restricts the overload capacity.

The analytical pre-design of the DC machine, performed according to [6], gives a volume of 19.2 dm^3 and a power density of 1.6 kW/dm^3 (Table 3). These values result from a volume determination depending on the pole pair number p. The volume decreases significantly by increasing p in the range of small pole numbers, increasing the pole pair number beyond $p = 6$ gives only small improvements. However, increasing the pole number also increases the iron losses inside the rotor and thus decreases the overall efficiency. A pole pair number of $p = 5$ was chosen as a compromise solution.

In summary, the DC machine has moderate power density, low efficiency and reliability but has the advantage of low costs and simple controllability, especially for small rated power.

2) *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 compared to the DC machine. The dominant losses in IM machines are the copper losses. Due to the lower magnetization current in the range of field weakening, the copper 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 copper losses in the rotor decrease the efficiency in the range of nominal speed compared to PMSMs. A disadvantage is the heating 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 [6] and [7]) 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.

Table 3: Results of the rough design.

	DC	*IM*	*PMSM*	*SRM*
number of pole pairs	5	2	4	12/8
rated efficiency	84%	88%	92%	88%
rotor diameter (mm)	239.5	162	150	159
active length (mm)	70	127	170	159
outer diameter (mm)	430	258	210	269
length end windings (mm)	62	105	35	207
volume (dm^3)	19.2	12.1	7.1	11.8
power density (kW/dm^3)	1.6	2.5	4.2	2.6

3) *Permanent Magnet Synchronous Machine*

The 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 high costs 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. To prevent them 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 7.1 dm^3 and a power density of 4.2 kW/dm^3 - the design was performed by the in-house software ProMOTOR ([8], [9]) following the design rules in [10] and [11]. As a result of their advantages the PMSM belongs to the most suitable machines for electric traction drives. Moreover, decreasing magnet costs are making PMSMs more appealing nowadays.

4) *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

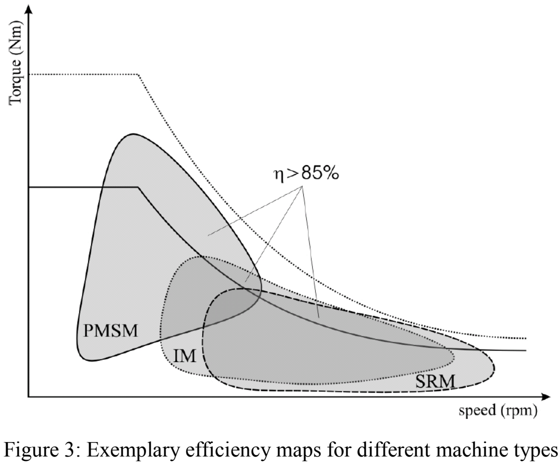
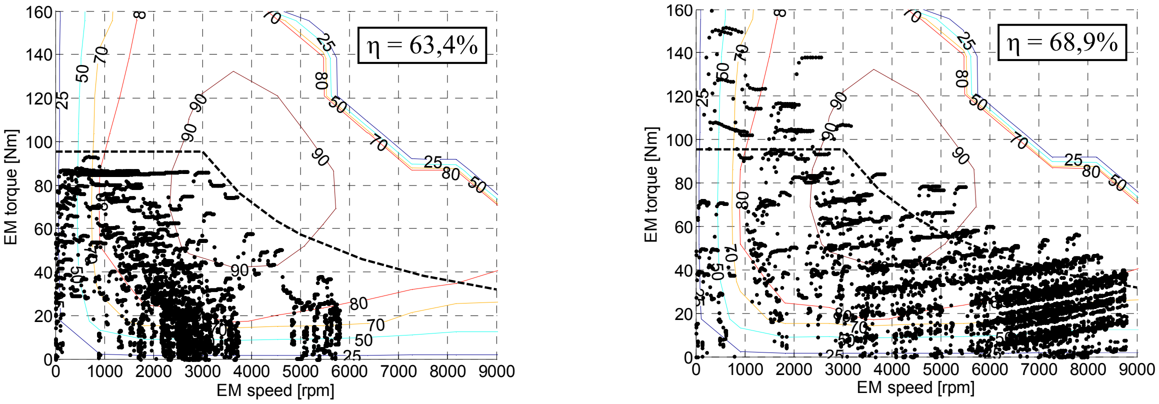
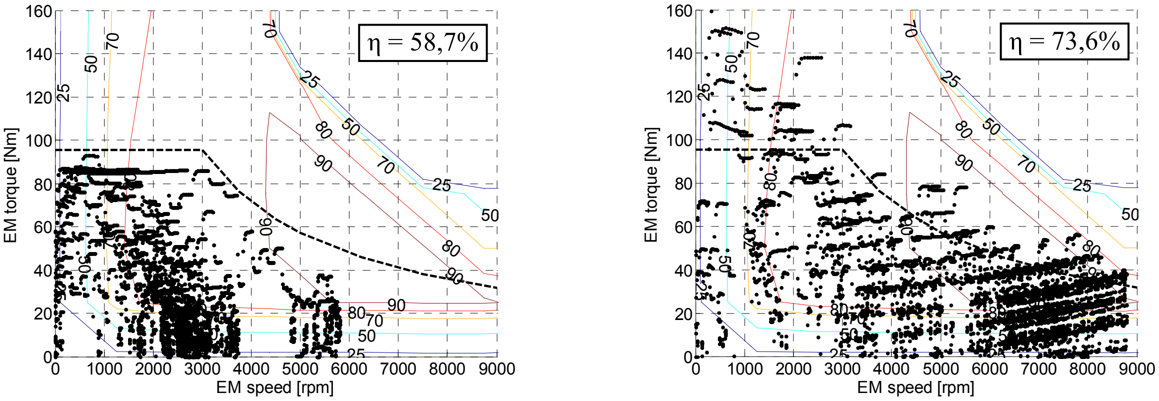


Figure 3: Exemplary efficiency maps for different machine types.



(a) PMSM and city drive cycle.

(b) PMSM and highway drive cycle.



(c) IM and city drive cycle.

(d) IM and highway drive cycle.

Figure 4: Comparison of the IM and PMSM average efficiency for city and highway drive cycles.

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 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.

The pre-designed SRM (referring to [12]) 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.

5) *Further studies of efficiency*

The solutions of the previous calculations concerning efficiency (Table 3) require further investigations, due to the wide spectrum of operating points of the electric machine during a complete drive cycle. This results in scenario and cycle based consideration of operating points, as the definition of efficiency at nominal torque for example, is not sufficient in order to give a statement here.

In Figure 3 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 where the induction machine and the SRM have their best efficiency at higher speeds and over a wider speed range.

In the following this work takes a closer look to the PMSM, representative for machines with an efficiency optimum at lower speeds like PMSM, Brushless DC and Transverse flux machines, and to the IM, representative for machines with an optimum at higher speeds like IM and SRM.

The PMSM offers the best maximum efficiency in a defined speed range. For these reasons the PMSM may be most suitable to achieve a fuel saving hybrid electrical vehicle. The IM has a good average overall efficiency over the whole speed range, but its maximum efficiency does not reach the values of a PMSM. But the IM is advantageous, if a good efficiency over a wide and high speed range is required. This can be related with help of Figure 4, showing ASM and PMSM in urban and extra-urban scenarios. This results in the possibility of the IM to perform equal or even better in efficiency compared to the PMSM for BEV applications with mainly extra-urban application [13].

6) *Impact of fault cases with respect to EVs*

Considering the safety aspect as an evaluation criterion, fault cases of the electric drive have to be regarded in particular. Beside fault cases inside the electric machine,

Table 4: Evaluation of Electrical Machines.

	DC	*IM*	*PMSM*	*SRM*
power density	- -	+	+ +	0
efficiency	- -	+	+ +	0
costs	+	+	0	+
reliability	-	+ +	0	+
technical maturity	+	+	0	0
controllability, costs	+ +	0	+	-
overload capability	-	+	+	+

failures within the converter or its control are also possible, and may cause short circuits, high current or open clamps [14] [15]. Among security exposure, these controller failures can lead to permanent damage of the electric machine, e.g. the demagnetization of the permanent magnets [16] [17]. Independently from the converter, most fault cases inside the electric machine are bearing imperfections (55-75%) and winding short circuits (30-40%) [14] [15].

Beyond that, damage caused by overheat temperatures, such as demagnetization or damage of isolation, lead to highly increased aging of the machine [15].

Relevant to the security of electric vehicles are especially fault cases resulting in torque peaks, such as control breakdown and winding imperfections, as mentioned above.

Parallel and power split hybrids can compensate security-critical electrical fault cases in most cases due to the higher drive power of the ICE in comparison to the electric drive train part. Serial hybrids and BEVs are more critical due to their powerful electric traction drives. The application of mechanical separated twin motor systems or wheel hub motors can provoke the appearance of a yaw moment, which may lead to vehicle instability. This additionally depends on the driven axle, as the rear axle is more critical than the front axle [18].

In the first instance of fault cases, the IM is comparable to the PMSM, resulting in a short circuit torque, because of the magnetization of the machine. But the PMSM fault case causes a permanent short circuit torque, as it is permanently excited by the magnets.

Altogether, this substantiates that fault cases in the electric traction drive have to be investigated in detail during the drive train design, to avoid security endanger driving conditions.

7) *Comparison and applicability*

Comparing the results of the previous discussion with several other machine comparisons in papers, reports or surveys like [19] - [24] shows distinctive similarities. The machine characteristics and their advantages and disadvantages are summarized in Table 4.

The direct current machine has a good technical maturity at low costs for machine and power electronics. But it offers the lowest power density and a bad efficiency. Furthermore it provides an insufficient reliability and requires a high amount of maintenance. The disadvantages exceed the advantages, so that the DC machine does not achieve the high requirements of electric vehicles.

The induction machine features the best reliability at low production costs. It offers a good efficiency, in particular at higher speed. But it only allows a moderate power density and a complicated and expensive field oriented control is required to reach high powers and dynamics.

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 and even in the restricted installation space of a vehicle‘s engine compartment. It offers the best maximum efficiency in a defined speed range. However, due to its rare-earth magnets, it is the most expensive machine type as well.

Because of the advantages in efficiency and power density, leading to a compact machine design, the PMSM has been chosen as the best convenient machine type for the further drive train studies. Seven different machines for each drive train concept have been simulated to quantify the evaluation criteria for the electric machines.

G. *Calculation of weighted drivetrain ratings*

The stepwise procedure of the described method led to the identification of seven drive train concepts in first instance. This was based on the restrictions made in the reduction process of the solution space. For these drive train configurations evaluation criteria were defined, regarding the application purpose of a city vehicle. The quantification of the criteria was made by detailed calculations (for the electric drive), literature studies and on the basis of empirical values (for transmissions and side shafts). The use of a single-axle rear drive concept as drive train configuration showed up to fit best within the city car concept, matching the strict package requirements.

For the weighting of the drive train concept's criteria, it was necessary to quantify all of the remaining concepts. Therefore the design of components, especially the electric machines, has been made to gain numerical information for evaluation.

Using the weighting factors with the evaluation criteria, then finally lead to the identification of suitable drive train concepts for the specific underlying vehicle concept as shown in Table 5. Additionally another city car concept with emphasized demand for driving dynamic performance and less focus on costs and safety was added for a comparison of the weighted influence.

Table 5: Weighting factors for the city car concepts

weight factors	*city car concept*	*performance city car concept*
costs	0.09	0.04
installation space requirements	0.10	0.07
modularity & scalability	0.06	0.02
weight	0.11	0.11
driving dynamic performance	0.02	0.28
safety	0.38	0.28
efficiency	0.24	0.19

Putting all information together, the following results for adequate drive train concept could be highlighted.

Table 6: Overall rating of the city car concepts.

drive train configuration / overall rating	*city car concept*	*performance city car concept*
central PMSM, fixed TM	0.21	0.15
central PMSM, shiftable TM	0.21	0.15
central PMSM, w/o TM	0.16	0.09
wheel-near PMSMs, fixed TM	0.11	0.18
wheel-near PMSMs, shiftable TM	0.12	0.19
wheel-near PMSMs, w/o TM	0.08	0.10
wheel-hub PMSMs, w/o TM	0.11	0.16

Due to the high weight of drive trains without transmissions, they could be discarded as solutions, showing up in the results of evaluation. Because of no demand of driving dynamic functions for the city car concept, the twin-motor concepts make no further sense as they are more cost intensive and need more installation space with additional weight. The performance city car concept on the other hand turns the tide over to the twin concepts, as they are the only solution to fulfill the driving dynamic performance demands (cf. Table 6).

III. CONCLUSION

The identification of appropriate drive train concepts for an underlying specific vehicle concept is not a trivial process. Inquiries in different literature and studies showed up, that there is no standardized process guide for this intention. This was the crucial starting point for the development of the presented method.

The description of the procedure in general reveals that it is possible to work out suitable drive trains, even if there is a huge solution space. It is very important, to go through this process step by step and to ensure, that no solutions have been dropped in the meantime of processing through, although a reduction of solutions can be necessary in a second step. However the availability of a well defined specification sheet is essential for success.

The sharp definition of evaluation criteria is another elementary step, where special attention should be paid to. Anyhow the accuracy of the quantitative definition of each criterion depends a lot on the level of previously knowledge and research depth. But also rough definitions of math functions will lead to a solution as well.

As a final step, the scenario based evaluation and weighting will lead to identify potential drive train concepts for the underlying vehicle concept within the defined application purposes, leveling the way to the next phase: Creating the target specification sheet for dimensioning the components in detail.

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