Conceptual Design of a Pure Electric Vehicle

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***Abstract* – As part of this paper, a concept for a purely electric vehicle was developed. The idea is to develop the vehicle from scratch and to optimize the drive train using a structured approach. Therefore it is necessary to come undone from properties of conventional vehicles and design a new concept independently. So the aim of that is to develop an energetically efficient design of the vehicle. The main focus lies on the drive train and its respective components.**

I. Introduction

Energy is one of the leading topics of the 21st century. Both the well-known finite nature of fossil fuel supply as well as the with energy recovery accompanied climate change arrogate an always updated cogitation about alternative possibilities of raw material substitution. This contains especially the topic mobility.

An important part of mobility fulfills passenger cars that have been propelled almost exclusively by an internal combustion engine so far. The electric machine forms an alternative with its valuable characteristics for mobile applications, e.g. different machine types, high efficiency and silent operation.

These findings led to the electrification of vehicles in the last years. Thereby, automakers basically tried to integrate electric drives into existing cars what seems to be comprehensible considering costs and risk aspects for vehicle development. Beyond that, the vehicular electric drive was not able to establish so far since the electric energy storage with its current characteristics stands for concept's essential weakness facilitating solely a small range. The development of a pure electric vehicle requires a disentanglement of the familiar conventional vehicle characteristics. Thus, the goal is to develop a vehicle concept whose drive train offers a high efficiency with minimum energy consumption on the one hand and is well-configured regarding demand on the other hand.

A precondition of a novel electric vehicle concept development is to analyze which technologies already exist or are applied respectively. Current redevelopments and their influence on other deployable technologies have to be considered as well.

Table I shows the inquest results of electric vehicles. In the several listed categories interesting trends can be identified that could also be confirmed by statistical investigations undertaken in the context of this paper (see III).

TABLE I
VEHICLE CONCEPTS – DEC. 2008

Vehicle	Machine / Position	Max. speed	Weight	Storage	Range	Seats
Lightning GT	Wheel hub motors	209 km/h	1400 kg	Li-Ti[1]	400 km	2
Tesla Roadster	Induction machine/ Rear drive	200 km/h	1220 kg	Li-Ion[2]	350 km	2
Loremo	Electrical machine	170 km/h	<600 kg	Li-Ion	150 km	2+2
Mini E	Induction machine/ Front drive	152 km/h	1465 kg	Li-Ion	240 km	2
The Zenn	Rotating field mach.	-	617 kg	Pb[3]	54-90 Km	2
Think Ox	Perm. magn. Synchr. Mach./ Front drive	135 Km/h	1500 kg	Li-Ion	200 km	5

II. Approach

To develop an electric vehicle concept it is initially necessary to define a precise process. The schematic procedure and its single dimensioning steps are shown in Fig. 1.

The process starts with the analysis of statistical results that will directly be included in concept making. These results partly arise from traffic statistics investigations and build requirements and basic conditions for drive train design. The definition of the other vehicle-specific values that are necessary for the requirement estimations of the electrical machine is done with the concept making.

In the next step the several derived drive train configuration will be calculated. With the results the electrical machine and power electronics requirements can be found. Finally, on the basis of the New European Driving Cycle (NEDC) the requirements of the energy storage will be estimated. With the aid of these values a simulation will be generated that replicates the characteristics of the concept car. Consecutively, the concept evaluation takes part using defined criteria. The evaluation enables a new consideration of the utilized basic conditions of concept making.

[1] Lithium-titanate-accumulator
[2] Lithium-ion-accumulator
[3] Lead acid-accumulator

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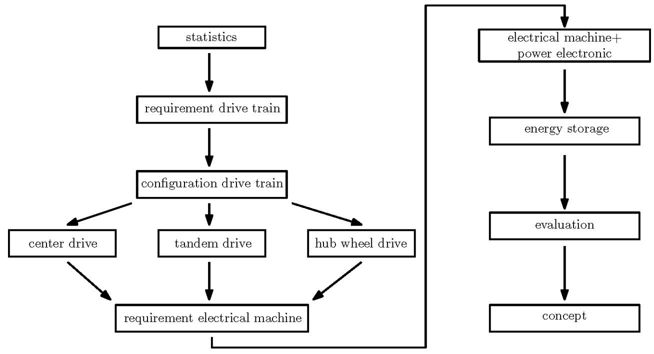

Figure 1: Concept making procedure.

Evaluation criteria

The definition of an adequate evaluation concept acts a prominent part within the vehicle concept making. The evaluation criteria that are used in this paper are listed as follows:

- Range and infrastructure
- Energy consumption and efficiency
- Driving comfort and dynamics
- Emissions
- Life cycle
- State-of-the-art of novel technologies

III. TRAFFIC STATISTICS

The approach of the vehicle's new concept making has the goal to integrate mobility and traffic based research results directly into the development process. Therefore, a traffic statistics analysis was made to define constraints for the vehicle that is to develop. The constraints are listed below:

- Number of required passenger seats
- Vehicle's range
- Maximum speed
- Vehicle class

From the investigation follows that 1.46 passengers use one car [2]. Thus, the number of passenger seats is defined by 2.
The identification of the vehicle's minimum range was done by analysis of further traffic based studies. Since these results are characterized by straying effects the maximum stray limit was used as reference value. The vehicle's range was defined to 100 km.
Statistical values about the average speed can also be taken from the mentioned traffic based studies. It follows that the average speed of passenger cars generally lies at 30 km/h [4]. As this includes solely average values it makes no sense to get also the maximum speed value from statistical results. In the real traffic obstacles caused by too slow driving have to be avoided. Therefore, real speed limits are consulted and evaluated. At this point it has to be mentioned that today a limitation of maximum speed exists in most countries. Additionally, due to high traffic density the maximum speed of conventional cars can't be realized. In the context of this paper the vehicle's maximum speed is fixed to 120 km/h [3].
Germany's most utilized vehicle class is the so called compact class. Here, according to the studies the automaker Volkswagen holds the biggest percentage with its model Golf. The evaluation follows that the Golf will be used as a reference vehicle. Its driving dynamics build a constraint for the vehicle design.

IV. DESIGN CONCEPT

This chapter describes the concept design for the relevant aspects. In a first step the defined reference vehicle was investigated. On closer inspection this should serve for basic understanding the driving dynamics of a conventional car, provided with a combustion motor. Interesting in this is which various torque-speed characteristics are given and how they can be modeled by an electrical drive train. The result of these analysis are that converter fed electrical machines are ideally suited for using as power engine. Thus, to adapt in a next step, the characteristic curves to the required boundary conditions.

A. *Requirements to the electrical drive train*

The requirements to the electrical drive train composed of electrical machine and power electronics follows from previous chapter. Within this result it is possible to adapt the drive train accordingly.
The identification of the speed-torque-characteristics were defined, so that this characteristic curves can be adapted to the acceleration time of Golf vehicle for forcing the desired driving dynamics. For further inspection the dynamic behavior of an converter fed electrical machine will be examined considering the overload area. This will be shown by schematic characteristics in fig. 3. The scale of axes is arbitrary. The torque-speed-characteristics were described by two characteristics. The two characteristics envelop the overload area. Generally electrical machines have the property for being overloaded [6]. Considering this property the factor for overload is defined to u and u is being the ratio of maximum torque to nominal torque. As a requirement to the electrical machine it will be defined to u = 1.7.
The maximum time for overloading is set to the desired acceleration time t_{Omax} = 12.9 s and the regeneration time, which is the time between two overload phases, is applied to threefold overload time:

$$t_{reg} = 3 \cdot t_{O\max}$$

Where the electrical machine is yielding constant torque is called constant voltage area and this area is marked with interval (1). Interval (2) provides the field weakening area, where the electrical machine has constant power (see Fig. 2).

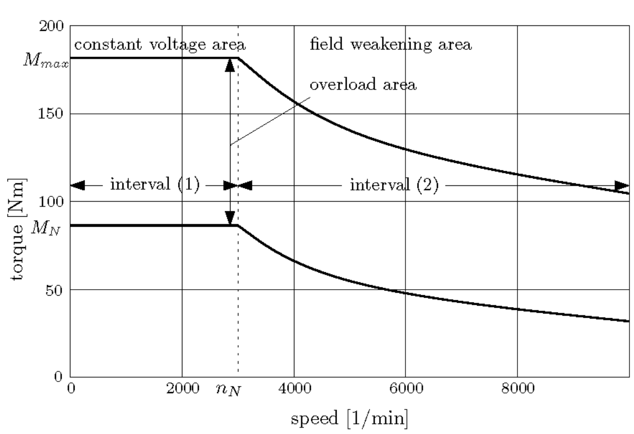

Figure 2: Characteristic curve of a converter fed electrical machine with overload area.

The nominal point stands at the transfer from constant voltage area to field weakening area. This point has to be calculated under the default details. For the calculation of this point the differential equations for both areas (1) and (2) can be formed. They are needed to calculate the definite characteristic. The equations results in:

Interval (1):

$$\dot{v}(t) = \frac{F_{Z,B}}{\lambda \cdot m_F} - \frac{(m_F \cdot g \cdot f_R + \frac{1}{2}\rho_L \cdot c_W \cdot A \cdot v^2)}{\lambda \cdot m_F}$$ [4]

Interval (2):

$$\dot{v}(t) = \frac{P_N}{v(t) \cdot \lambda \cdot m_F} - \frac{(m_F \cdot g \cdot f_R + \frac{1}{2}\rho_L \cdot c_W \cdot A \cdot v^2)}{\lambda \cdot m_F}$$

The unknown values in the differential equations (1) and (2) are the driving power $F_{Z,B}$ on the wheel and the necessary nominal power P_N of the electrical machine. Out of these two equations a linear system of equations with two unknown values can be set up. For calculating the nominal point the linear system of differential equations has to be solved.

To solve the complex linear system of equations a numerical operation is needed [1]. The solution and the resulting characteristic curve of the drive train are graphically shown in Figure 3. Because of the defined overload area the following nominal Data can be deviated. The nominal torque directly at the wheel is M_N=*425.8 Nm* by the nominal speed n_N =*326 1/min*.

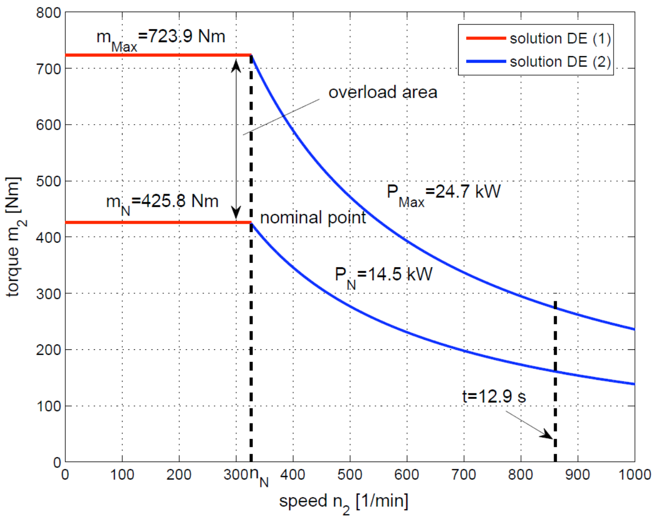

Figure 3: Torque-speed-characteristics of the drive train.

The assumption n_N = *const.* strictly speaking may only be taken for synchronous machines. Approximately it is also true for asynchronous machines, whose characteristic curve is plunge down after the breakdown torque. In this paper for further inspections the nominal point is supposed to be constant.

B. *Requirements for the energy storage*

According to the New European Drive Cycle the requirements to the electrical energy storage can be taken as a basis. During the NEDC a complete range of 11 km is covered. However the results of the statistical analysis demands a range of the conceptual designed electric vehicle of 100 km, so the cycle has to be scaled. It will be characterized in a function of speed in dependence of time. From this course the theoretical value of energy can be determined, which is necessary for passing through the cycle. If the energy of braking phases can be maximally recuperates, there is an energy extrapolated to 100 km range of 3.21 kWh necessary. Without recuperation the energy demand increases to a value of 5.33 kWh. The indicated values represent the energy directly at the wheel. Regarding to the requirements of the energy storage, the efficiency of the drive train has to be involved. This can not be exactly determined because it depends on the individual operating points of different components, such as the electrical machine. However, using the created simulation model of the electric vehicle, the capacity of the energy can be affected.

V. Simulation Results

Using the full vehicle simulations by varying diverse parameters the different driving scenarios can be simulated. After the simulation the results can be analyzed. The simulation model was programmed and built up in Dymola/Modelica.
Figure 4 shows the graphical user interface with the individual components. On this level the user can select different driving scenarios and configure the individual components of the driving train accordingly. The modular structure of the model involves further advantages such as the choice of several electrical machines and varying energy storages.

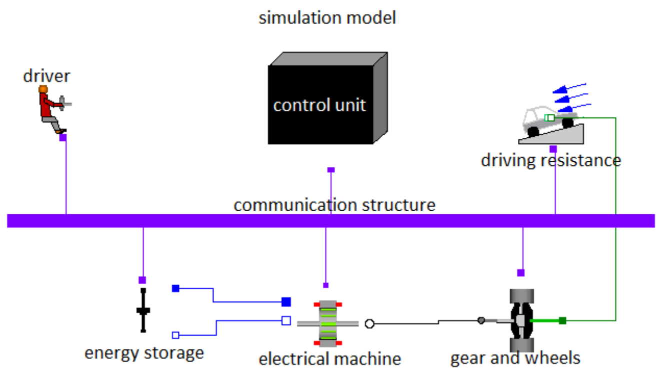

Figure 4: Simulation model of the electrical vehicle.

These components can be selected separately and used for each simulation. Through the central communication structure the physical values can be exchanged. Anytime these values are available in a view and after the simulation progress the results can be evaluated through that.

[4] λ: factor for molding body; m_F: mass of car;
f_R: factor for resistance to rolling; ρ_L: air density;
c_W: factor for drag; A: cross section surface;

A. Results

In this chapter, the results of the accomplished full vehicle simulation were presented. As part of this work the NEDC, FTP-75 cycle and the acceleration trip was simulated and investigated. In the following the results are divided in the simulated scenarios according to the respective operating mode (see Fig. 5).

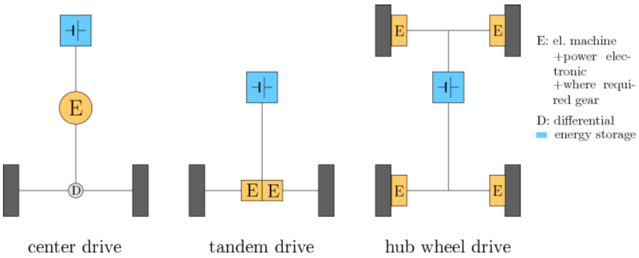

Figure 5: Drive train configurations in electric vehicles [5].

However in this paper only the simulation results of the NEDC were shown.

Center drive

By simulating the NEDC Fig. 6 shows the time varying characteristic of the required energy. The final value of about 0.6 kWh equates to the energy at a range of about 11 kilometers including recuperation. The requirement to the energy storage is to provide energy for 100 km range, though an extrapolation is needed. The simulation shows that the value of needed energy results to 5.45 kWh per 100 km. Considering to the frequently changing loads during a real driving cycle an integral criteria for evaluation has to be taken. By integrating power and losses during the drive cycle different energies can be evaluated. So the load factor represents the required criteria and gives a much better idea about the quality of the drive train as maximum efficiency.

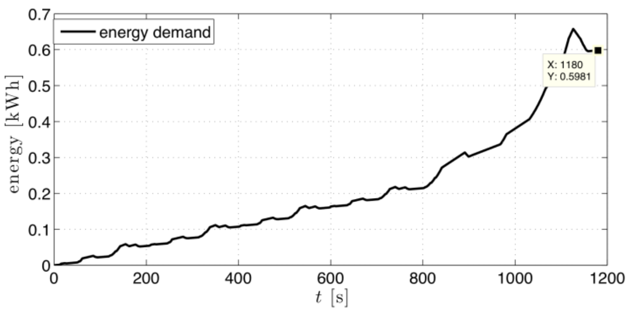

Figure 6: Energy demand during NEDC with center drive.

The load factor doesn´t even change for taking the braking energy into account, although the energy demand and following range varying considerably. Therefore, in this paper the load factor is used for evaluation. To determine the load factor correctly the floating energy of an electric vehicle is presented (see Fig. 7).
The consumer electrical system due to the very low constant power output is neglected. The losses in energy storage are also excluded, because in reality the influence of age and history of the storage is taken affect in its behavior. So only the electrical machine and the gearbox are taken into the balance sheet.

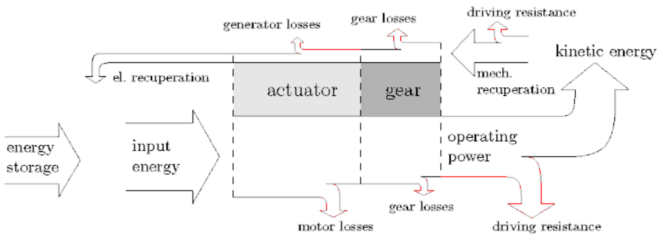

Figure 7: Floating energy in electric vehicles.

In general the load factor results in:

$$\eta_E = \frac{\text{kinetic energy} + \text{el. recuperation}}{\text{input energy} + \text{mech. recuperation}}$$

Although while driving through this profile the electrical machine is working below its actual nominal point, a relatively high value of load factor can be calculated to 86.2 %. This justifies the fact that the electrical machine is operating also under its nominal point with high efficiency. Furthermore the braking phases are not supported by the simulation model based mechanical brake.

Gearless drive

In the simulation model is only one electrical machine presented, therefore the total torque of the machine is shown.
The conversion to the required torque at two (tandem drive) or four (hub wheel drive) machines occurred linear, because torque act like a floating value. So the division to all axes is the same. The energy-efficient during the total cycle is presented in Figure 8. Compared to the center drive the energy demand of gearless drive is less.

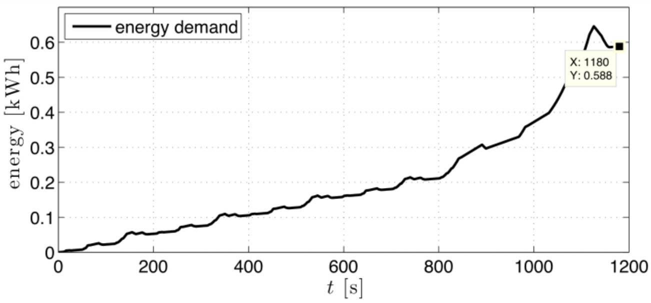

Figure 8: Energy demand during NEDC with gearless drive.

During the whole cycle a value for the demanded energy can be calculated and results to 0.59 kWh. The extrapolation to 100 km shows a value of 5.36 kWh. This means energy savings compared to center drive of about 1.6 %. In addition to that the load factor slightly increases to 87.1 %.

VII. CONCLUSION AND OUTLOOK

During this paper could be shown that electric machines are downright predestinated to be used as actuator for electric vehicles. The torque-speed-characteristic of a reference vehicle of the type Golf can be recreated by a converter fed electrical machine, which emanates from former researches. The explicit calculation of the characteristic curve resulted from solutions of the differential equation of action, what from the torque-speed-characteristics distribution of the electric machine can be diverted from. The actual result of simulation could confirm these calculations.
Concerning the different drives the following conclusion has resulted: Already from the specific research of the several configurations of drive trains arose that the centre drive features shows worse load factor than the gearless drive does, namely because the centre drive has got an additional, lossy gearbox. This emanates from the simulated operational profiles as well. By not using gearbox resulted a saving of energy of 1-2 %. Concerning the direct drives the hub wheel drive is in an inferior position compared to the tandem drive because of the updated unsprunged masses [7]. Furthermore the four required control units and closed-loop controls for the hub wheel drive are more complex regards the system and the costs than the tandem drive. The electric machine has been configured on the basis of the demand for an acceleration time of the vehicle from 0 to 100 km in 12.9 s. The results following from the simulations illustrate that the energy storage for a range of 100 km has to be configured to a capacity of 5.36 kWh, if the New European Driving Cycle serves as a rule and the vehicle is constructed with gearless drive. Concluding the developed vehicle concept is due to a city or commuter vehicle for two persons with a corresponding range and a requested driving dynamics.

Although the presented vehicle concept meets all demands which have been made on the vehicle at the beginning, there is still a demand for optimization in several sectors. For the model of simulation the particular characteristic curves of the electric machines have to be measured and adapted. To achieve a better collection of the arisen losses, you could model the whole machine model not only characteristic curves, but also e.g. with the help of the basis of a signal flow diagram_or an equivalent circuit diagram. From this follows the possibility to scale the losses accordingly when using a machine with a different output. Due to the automatic adaption of the losses to a new machine, the accuracy of all calculations resulted from the calculation of loss can be escalated. In the course of this, converter for the drive control of the machine in the simulation has to be recreated lossy, too. The model energy storage, which currently is modelled in the simulation just as an electric double layer capacitor, has to be adapted over and if necessary it has to be implemented as a dual electrical storage system, extended by an accumulator.

The simulation allows the adjustment of various parameters, which change depending on the design of the vehicle can be varied. For the conceptual design considering the personal demands new requirements can be made, which immediate relates to the use of a vehicle. In addition to that it has to be decided whether the vehicle is used in city area, for commuters or others uses. For example if a midsize car with a lager range is desired, the process of design concept is carried out again. So there are varying Data, which can be entered into the simulation model. Thus, the individual drive train components can be adapted accordingly and a new concept can be formed. Regarding to the concept, it is only the beginning of a process. Out of the simulation results you have the opportunity to make new requirements, e.g. different distance, driving dynamics or Number of seats and think about their consequences. Overall, an optimization process is aimed, that is based on market as well as technological developments.

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