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DEVELOPMENT TRENDS IN THE ELECTRIC MOBILITY

Abstract: The goal of the German Government is to bring one million electrical vehicles on German streets until 2020. For this reason in Dortmund the center of excellence TIE-IN (Technology platform for interoperable electro mobility, Infrastructure and Grids) is founded. In this paper concepts for the development of electrical drive chains are described. One research approach for testing electrical vehicles is the use of a special power absorption roller, which is able to emulate up and downhill drives for testing the vehicle dynamics and the recuperation ability. Another concept for testing electrical drives is the use of a test station for the automotive drive chain. With this test bench the behavior of single components like the electrical machine or power electronics and their coaction are analyzed. Simultaneously a simulation library for electrical vehicles is developed. With this library it is possible to simulate single components, the electrical drive chain or the whole electric car in advance. The comparison with the test station allows defining higher grades of simulation models.

Keywords: *electric vehicle/car, electrical machines, electrical drive chains, modeling, simulation*

1. Introduction

As in current studies described [1] the market penetration of electrical vehicles is highly depending on customer acceptance influenced by battery cost and range. Therefore, researchers at TU Dortmund are developing further strategies to increase the efficiency over a wide operating area of drive chain. In this context our research group at the Institute of Electrical Drives and Mechatronics aims to optimize interaction between motor, power electronics and batteries to increase holistic machine efficiency. The next step is to reduce power requirement of electric vehicles by using the maximum recuperation potential, supported by kinetic energy, to increase operating range of battery cars. To investigate these goals, in the framework Project TIE-IN, a special concept of power absorption roller for electrical driven motorcars is used. The differences between the requirements of conventional motor power testing stations and power absorption rollers are the result of motor characteristics. Compared to combustion engines, electrical drive systems are able to provide a high torque at low speed. Concurrently they have got lower moments of inertia at the drive shaft than combustion engines.

In the drive chain of the vehicle, reliable cooling not only has to be ensured during emulation of long uphill drives. By constructing cooling systems for electrical drive chains in automotive there has to be considered, that a quantity of heat is converted by recuperating process on downhill drives. When the temperature in traction motor rises above a critical limit, e.g. permanent magnets of synchronous machine will be destroyed irretrievable.

An advantage of power absorption rollers is, to emulate interaction between components of electrical drive chains under consistent laboratory conditions. This approach provides an objective benchmarking of different cooling strategies. In [2] the possibility of a consistent evaluation environment is described, to use it in every step of development. To design components cost and time-effective the approach of *frontloading* is pursued. Necessary changes can be detected at an early instant of time. This approach provides manageability of development costs and number of prototypes. To permute *frontloading*, a 100 % correlation between dynamometer results and complete chain of development is necessary.

For this reason the gained results do not only have to be reproducible, but only close to reality driving resistances are emulated by a polynomial approximation by power absorption roller. Driving resistances of vehicles are calculated by concentrated loads. These are: resistance of rolling F_{roll}, air resistance F_{air}, acceleration resistance F_{acc} and the resistance of slope F_{sl} (Fig. 1).

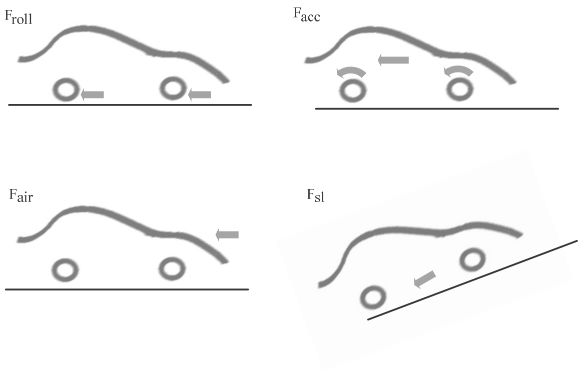

Fig. 1. Driving resistances at simulation of realistic ambient conditions

The resistance of rolling

$$F_{\mathrm{roll}} = mgc_1 \cos\alpha \tag{1}$$

depends on the vehicle-mass m, the resistance coefficient c_1 and the angle of elevation α. A first approximation for air resistance is:

$$F_{\mathrm{air}} = \frac{1}{2} c_{\mathrm{w}} \rho A_{\mathrm{F}} \left(v + v_{\mathrm{a}}\right)^2 \tag{2}$$

where c_{w} means air coefficient, ρ air density, A_{F} effective face of vehicle, v velocity of vehicle and air velocity v_{a}. The engine also has to get overcome the resistance by accelerating the car

$$F_{\mathrm{acc}} = \left(m + \sum_{i=1}^{n} \frac{J_{\mathrm{i}}}{r_{\mathrm{w}}^2} N \right) \frac{dv}{dt}, \tag{3}$$

with mass moment of Inertia J_{i} of rotating vehicle components, wheel radius r_{w} and gear transmission ratio N.

When driving up or downhill the slope resistance also has to be taken into account

$$F_{\mathrm{sl}} = mg \sin\alpha, \tag{4}$$

In addition of concentrated load resulted load is:

$$F_{\mathrm{res}} = F_{\mathrm{roll}} + F_{\mathrm{air}} + F_{\mathrm{acc}} + F_{\mathrm{sl}} \tag{5}$$

2. Test station concept for components

The test station is built as a modular concept for analyzing electrical and electromechanical vehicle components. It is possible to analyze single components e.g. the power electronics or electrical machines just like the whole electrical drive chain at any operation point. The structure of an electrical vehicle drive chain, as seen in Fig. 2, consists of a battery pack, DC/DC- and DC/AC-Converters and at least one electrical machine. The mechanical parts are particularly gearboxes, differentials and wheels. For the test station the battery pack and the DC/DC-Converter are both replaced by one High Voltage DC-Source.

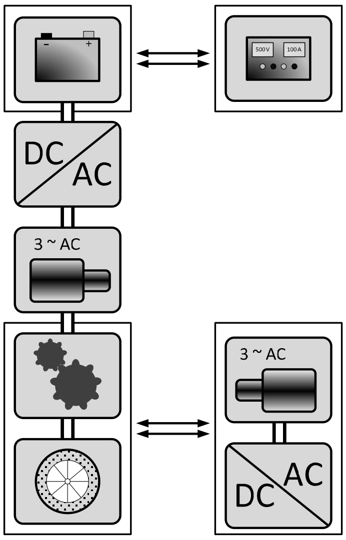

Fig. 1. Drive chain vs. test station

Because the research focus lies on the electrical and electromechanical components all mechanical parts are emulated by a load machine. The amount of torque, prepared by the electrical machine, depends on the driving resistance at the local operation point.

2.1 Load machine

The load machine has to comply with the high requirements of the testing environment. These are e.g. constant torque about a large area of speed and a small moment of inertia to gain fast dynamics. To fulfill all of these needs the test station is equipped with an interior permanent magnet synchronous machine (IPMSM), by a rated power of 94 kW. The load machine is able to provide a constant torque of 200 Nm from zero to the rated speed of 4500 rpm. At higher speed the machine reaches the field weakening area and can be accelerated to a maximum of 10.000 rpm.

2.2. Controlling the test station

The test station is operated by a control- and observing unit. This processor is handling and saving the different types of measured signals, like currents, temperature, motor torque or rotation speed and is simultaneously detecting critical operation points. The necessary software is developed in *Matlab* and will be continuously enlarged for different types of testing scenarios. The setup for the testing process, like control parameters or development of user-defined driving cycles is also managed by the test station-Software. The test station for components of electrical vehicles is also a platform for comparing simulation models.

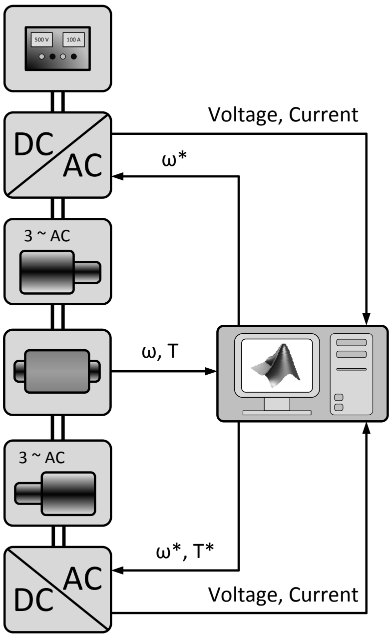

Fig. 3: Structure of the control system

At the Institute of Electrical Drives and Mechatronics a simulation library for models of the electric drive chain is built. These simulation models are developed in the simulation environment *Matlab/Simulink*. With this library it is possible to simulate single components, the electrical drive chain or the whole electric car in advance. The comparison with the test station allows defining higher grades of simulation models, for example parasitic effects within electrical machines. This synergistic effect of the test station and the simulation library provides a good concept for a development platform.

3. Simulation of drive chains

The simulation library is developed within the context of the project TIE-IN, with the cooperation of different institutes of the faculty of Electrical Engineering and Information Technology. The Institute of Electrical Drives and Mechatronics is focused on the electrical machine. Today the majority of E-Mobiles are equipped with a permanent magnetic synchronous machine, with rare earth magnet material. The advantage of these machines is a high power density, which is perfect for the use in automobiles. Induction machines are also used in the electrical automotive engineering, e.g. the *Tesla Roadster* with an engine output of 225 kW. These types of machine are robust and much cheaper than permanent magnetic synchronous machines with their expansive magnets. Both types of machines are included inside the simulation library for different levels of detail.

3.1. Modeling the IPMSM

The simplest model bases on linear magnetic conditions and a sinusoidal air-gap field. In this case the permanent magnetic synchronous machine can be modeled in the rotor static d/q-coordinates [5].

$$U_{\mathrm{d}} = Ri_{\mathrm{d}} + \frac{d}{dt}L_{\mathrm{d}}i_{\mathrm{d}} - p\omega L_{\mathrm{q}}i_{\mathrm{q}} \tag{6}$$

$$U_{\mathrm{q}} = Ri_{\mathrm{q}} + \frac{d}{dt}L_{\mathrm{q}}i_{\mathrm{q}} + p\omega L_{\mathrm{d}}i_{\mathrm{d}} + p\omega\psi_{\mathrm{p}} \tag{7}$$

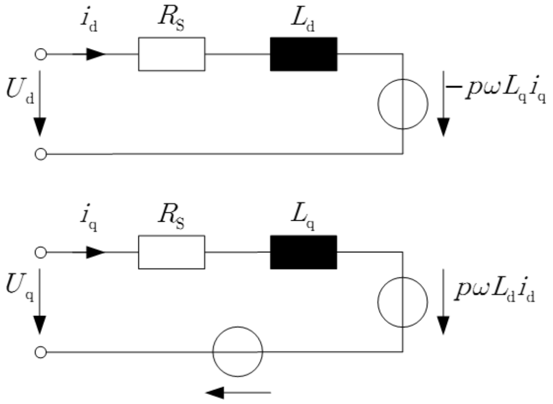

Fig. 4: d/q- system of an IPMSM

U_d and U_q are the transformed voltages and i_d, i_q the transformed currents. The inductance in the direct axe is L_d and in the quadrature axe L_q. The flux linkage of the permanent magnets is described by ψ_p and p is the number of pole pairs. The electromagnetic torque of an IPMSM is given by:

$$T = \frac{3}{2} p \left[\psi_\mathrm{p} i_\mathrm{q} + \left(L_\mathrm{d} - L_\mathrm{q} \right) i_\mathrm{d} i_\mathrm{q} \right] \tag{8}$$

3.2. Modeling the induction machine

The model of the linear magnetic induction machine is based on the space vector modulation. The advantage of this method is the possibility to freely choose the coordinates system.

$$\underline{u}_1^\mathrm{k} = R_1 \underline{i}_1^\mathrm{k} + \frac{d}{dt} \underline{\psi}_1^\mathrm{k} + jp\omega_\mathrm{k} \underline{\psi}_1^\mathrm{k} \tag{9}$$

$$0 = R_2 \underline{i}_2'^\mathrm{k} + \frac{d}{dt} \underline{\psi}_2'^\mathrm{k} + jp\left(\omega_\mathrm{k} - \omega_\mathrm{r} \right) \underline{\psi}_2'^\mathrm{k} \tag{10}$$

$$\underline{\psi}_1^\mathrm{k} = \left(L_{1\sigma} + L_\mathrm{m} \right) \underline{i}_1^\mathrm{k} + L_\mathrm{m} \underline{i}_2'^\mathrm{k} \tag{11}$$

$$\underline{\psi}_2'^\mathrm{k} = \left(L_{2\sigma}' + L_\mathrm{m} \right) \underline{i}_2'^\mathrm{k} + L_\mathrm{m} \underline{i}_1^\mathrm{k} \tag{12}$$

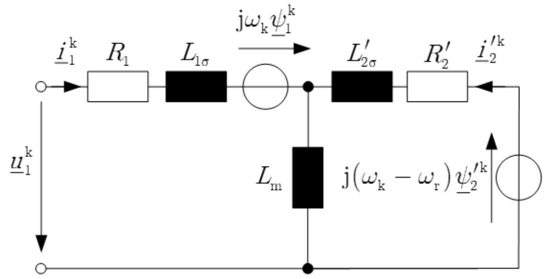

Fig. 5: model of induction machine in k-system

For example modeling the machine in rotorflux oriented coordinates

$$\omega_\mathrm{k} = 2\pi \frac{f_1}{p} \tag{13}$$

creates similar conditions just like permanent magnetic synchronous machine. The stator- and rotor flux linkage are described by $\underline{\psi}_1^\mathrm{k}$ and $\underline{\psi}_2'^\mathrm{k}$, with the main inductance L_m and the mutual inductances $L_{1\sigma}$ and $L_{2\sigma}'$. The angular velocity ω_r represantes the speed of the shaft and ω_k can be chosen freely. It discribes the rotation frequency of the coordinate system. The torque is given by

$$T = -\frac{3}{2} p \, Im\left\{ \underline{\psi}_1^\mathrm{k} \cdot \underline{i}_1^{\mathrm{k}*} \right\} \tag{14}$$

For both types of machines the equation for the rotor dynamics is valid.

$$J \frac{d\omega}{dt} T - T_\mathrm{load} \tag{15}$$

3.3. Simulation structure in *Matlab*

The behavior of the electrical drive chain is affected by all components and many internal and external factors. So there is a need to model other components, like power electronics and controlling structures, as detailed as required. Every component of the same type has got the same interfaces, so there is the possibility to exchange single components, for example synchronous and asynchronous machines.

The goal is to compare the operating behavior of the simulation models with the test station for electrical drive chains. The easiest way to do this is with a velocity profile. In this case there must be a speed regulation for the electrical machine. One option to do this is the vector control or field oriented control [7].

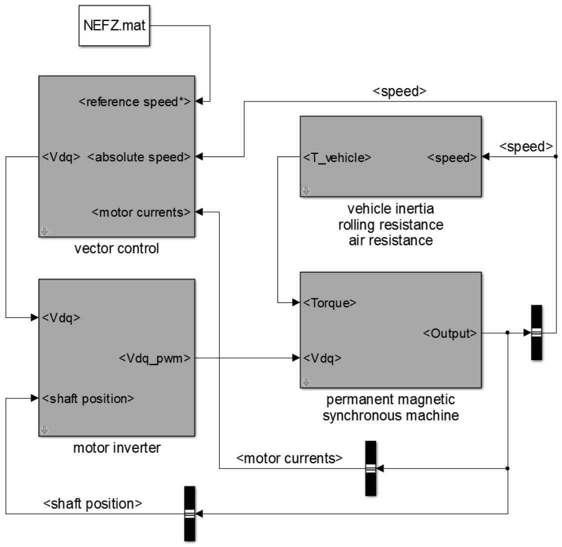

Fig. 6: Example for an IPMSM drive chain

Within this method the differential equations for the electrical drive are modeled in the rotor flux oriented coordinates system. The results of this are identical magnitudes for the transformed voltages and currents, which can be regulated by simple PI controllers. Fig. 6 shows the structure for the simulation of a velocity profile in *Matlab/Simulink.* The electrical machine is supplied by a pulse-controlled inverter, and regulated by a vector control structure. The motor speed is given to a model of driving dynamics, which generates the driving resistances. The driving resistances are converted to an equivalent torque at the shaft of the machine. Fig. 7 and Fig. 8 are showing the results of the simulation.

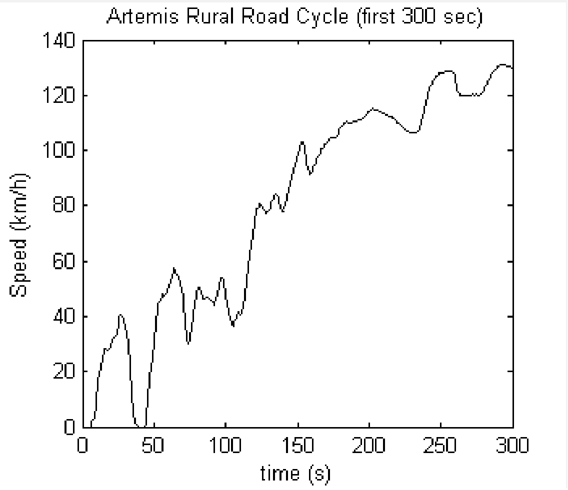

Fig. 7: driving cycle velocity profile

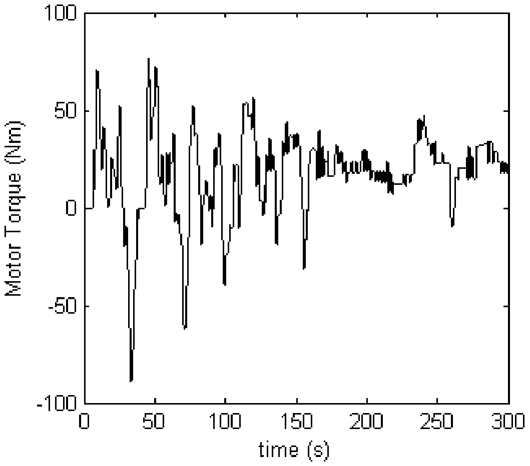

Fig. 8: Motor Torque at the artemis road cycle

4. Conclusion

The paper shows three different techniques for the research and development of the electrical drive chain. With a power-absorption-roller there is the possibility to test the whole electric vehicle under reproducible conditions. The test bench for components allows the testing of new components and their characteristics inside the whole electrical drive chain. Highly detailed simulation models are giving the answer of the behavior of electric cars before constructing them. All three techniques together are representing a very good concept for developing new technologies in the context of electro mobility.

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