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# Application of an e-machine emulator for power converter tests in the development of electric drives

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#### Abstract

In the development and validation of electric drives developers are facing great challenges. The existing facilities for testing power electronics do not always fit the desired requirements. In this paper a test bench including an *electric machine emulator* will be presented, which physically reproduce the power flow of a permanent magnet synchronous motor. The core of the e-machine emulator is a real-time flux based e-machine model that contains the characteristics of the desired machine. Furthermore, the performance of an e-machine emulator in comparison to a dyno test bench and the benefits for the development of alternative propulsion has been investigated. In the investigation could be shown, that the flux deviations at stationary workpoints are under 1% in the area of constant torque.

Keywords: hardware-in-the-loop (HIL), simulation, permanent magnet motor, electric drive, AC motor

## **1** Introduction

In the development of hybrid and electric vehicles the permanent magnet synchronous motor (PMSM) is preferred by many automobile manufactures due to its high efficiency and power density. Voltage-source inverters with field-oriented control are generally used to control these machines. There are two classic test bench configurations for the application and validation of the inverter hard- and software:

- Hardware-In-the-Loop (HIL) systems with e-machine simulation on signal level
- Dyno test benches with target machine and load machine

In HIL systems the gate signals to the power switches are connected to a PWM-acquisition and a real-time e-machine model, which calculates the proper phase currents. The current sensor signals of the power inverter are stimulated artificially through a d/a converter. A classic HIL system is only valid within its system limitation. Physical effects on the IGBTs, current sensors and on the power parts are only reproduced by simulation. Dyno test benches are

closer to the target system, because the entire drive including power electronics and target emachine is present. The mechanical load is gen-erated by a load machine. This configuration is very close to reality; however it is very expensive, maintenance-intensive and has only limited speed dynamics because of the high inertia of the load machine. Furthermore, a cost intensive target machine especially designed for integrated transmission is necessary. An e-machine emulator is an alternative test concept which emulates the power flow of the real e-machine, but completely without rotating mechanical parts. In addition, it is possible to simulate many different e-machines with little effort through variation of the model parameters. Compared to the HIL system the e-machine emulator has the additional benefit, that the power stage of the inverter can be operated without hardware changes. The interfaces between emulator and inverter are in contrast to HIL not signal lines, but phase lines with real power flow. Four possible test configurations for inverter test are shown in fig. 1. First approaches and prototypical implementations of e-machine emulators were published in the end of the 1990s [1][2][3]. The described implemen-tations (here: Virtual Machine) used simple industrial B6-Inverters as actuators to control the



Figure 1: Test configurations for inverter tests

target phase currents. However, it turned out that the e-machine emulator requires much higher dynamics and lower current ripples as the Device Under Test (DUT). In publications [4] and [6] approaches were presented that reaches higher switching frequencies, lower current ripples and an improvement of current dynamics by using a multi-level inverter. For some years commercial vendors distribute such systems, which make it interesting for the automotive industry. In this paper, such an e-machine emulators test bench is presented. It focuses on the accuracy improvement through the application of a flux based emachine model. Finally, the static and dynamic emulation performance of the e-machine emulator in comparison to a dyno test bench will be investigated.

#### 2 System Description

The inverter test bench shown in fig. 2 was build up together with a commercial vendor for e-machine emulators (S.E.T. GmbH, *Wangen im Allgäu*). Two power supplies are required to supply the DUT and the e-machine emulator with DC voltage. The three phase wires of the DUT



Figure 2: Overview of the inverter test bench

are connected to the e-machine emulator via coupling inductance. Fig. 3 illustrates the structure of the hardware setup. The phase currents and voltages are measured in parallel through the e-machine emulator. The measured phase voltages are input variables for a real time e-machine model. Inside the model the target phase currents will be calculated by the numerical solution of a differential equation. The target and the actual phase currents are used as input variable to the current controller, which controls a high dynamic multi-level inverter. The ripple current of



Figure 3: Em-emulator hardware setup

the multi-level inverter is much smaller in comparison to a two-level-inverter due to the higher sum clock rate of the PWM. Studies on this topic and control procedures were presented in [4] and [7]. The multi-level inverter consists of parallel inverters (B6 bridges) with phase-shifted control of the gate signals and coupling inductance between each of the inverter legs. The structure of the the multi-level inverter is shown in fig. 4. The appropriate phase currents, which flow in



Figure 4: Structure of the multi-level inverter with four inverter legs per phase [7]

the real e-machine, are continuously adjusted by combining e-machine model, current controller and multi-level inverter. The position of the emachine is necessary for the field oriented control, which is measured by a resolver, an encoder or Hall sensors. This signal is simulated electrically by the e-machine emulator. The voltage detection, model calculation, current regulation and PWM generation takes place in a FPGA. The emulation accuracy depends mainly of the performance of the e-machine model. This will be considered in the next section.

#### **3** E-Machine Model

Many publications [4][5] dealing with e-machine emulation uses a linear PMSM-model with con-

stant inductances shown in the eq. 1.

$$u_d = R_s i_d + L_d \frac{d}{dt} i_d - \omega L_q i_q$$
$$u_q = R_s i_q + L_q \frac{d}{dt} i_q + \omega L_d i_d + \omega \psi_p \qquad (1)$$

The disadvantage of the model is that the saturation of the electric motor ferrite core and the space harmonics in the air-gaps are neglected. In this paper an alternative e-machine model will be presented that overcome these restrictions. The model equations are described in a rotor fixed dq-coordinate system. In this case, the first step is to transform the input phase voltages into the dq-system by the Clarke and Park transformation. The equation below describes the flux based model.

$$u_d = R_s i_d + \frac{d\psi_d}{dt} - \omega \psi_q$$
$$u_q = R_s i_q + \frac{d\psi_q}{dt} + \omega \psi_d$$
(2)

The eq. 3 calculates the air gap torque.

$$T_e = \frac{3}{2}p\left(\psi_d i_q - \psi_q i_d\right) \tag{3}$$

In fig. 5 the implementation of the flux based PMSM model is shown. The  $\psi_{dq}2i_{dq}$ -Block con-



Figure 5: Implementation for the flux based PMSM model

tains the conversion of the flux linkages  $\psi_d$  and  $\psi_q$  to the stator currents  $i_d$  and  $i_q$ . Flux harmonics can optionally be added to the flux linkages  $\psi_d$  and  $\psi_q$  as function of the electrical machine angle  $\varphi_{el}$ .

$$\hat{\psi}_{d} = \psi_{d} + \psi_{d,harm} = \psi_{d} + f_{hd} \left(\varphi_{el}\right)$$
$$\hat{\psi}_{q} = \psi_{q} + \psi_{q,harm} = \psi_{q} + f_{hq} \left(\varphi_{el}\right) \qquad (4)$$

An approach to calculate the harmonic functions  $f_{hdq}(\varphi_{el})$  was already presented in [8]. The eq. 5 shows how the look-up tables for the harmonics

can be calculated, where  $\psi_{h,n}$  are the flux amplitudes of the *n*th harmonic of the back emf.

$$f_{hd}(\varphi_{el}) = \sum_{k=1}^{\infty} (\psi_{h,6k-1} + \psi_{h,6k+1}) \cdot \cos(6\varphi_{el})$$
$$f_{hq}(\varphi_{el}) = \sum_{k=1}^{\infty} (-\psi_{h,6k-1} + \psi_{h,6k+1}) \cdot \sin(6\varphi_{el})$$
(5)

For considering the saturation effects, the flux linkages  $\hat{\psi}_d$  and  $\hat{\psi}_q$  has to convert to stator currents. The  $i_d$  and  $i_q$  currents components are stored in two 2D-lookup tables, where  $\hat{\psi}_d$  and  $\hat{\psi}_q$  are the input values. The data acquisition of the flux tables is discussed in the next section.

$$i_d = f_1^{-1} \left( \hat{\psi}_d, \hat{\psi}_q \right)$$
$$i_q = f_2^{-1} \left( \hat{\psi}_d, \hat{\psi}_q \right)$$
(6)

Alternatively, the d-and q-currents can be calculated by constant inductances, which corresponds to the equation 1 (linear PMSM model without saturation).

$$i_{d} = \frac{\hat{\psi}_{d} - \psi_{p}}{L_{d}}$$

$$i_{q} = \frac{\hat{\psi}_{q}}{L_{q}}$$
(7)

The preferred model can be chosen through a switch. The fig. 6 shows the implementation of the  $\Psi_{dq}2i_{dq}$  Block, that contains the flux and harmonics tables of the PMSM-model. The advan-



Figure 6: Implementation of the Flux-to-Current-Block  $(\psi_{dq}2i_{dq})$ 

tage of the flux based model in comparison to the linear model is the high accuracy in the simulation of saturation and harmonic effects.

#### 4 Model Data Acquisition

First, its necessary to obtain the e-machine characteristics to fill the 2D lookup tables in eq. 6 with accurate data. One possibility obtaining the flux fields  $\psi_d$  and  $\psi_q$  with respect to  $i_d$  and  $i_q$ is to perform a *Finite Element Method* (FEM) analysis. This solution has the benefit, that the emachine don't have to exist as a physical unit e.g. in early development stages. If a DUT of the target machine is present, an e-machine characterization on a dyno test-bench is a better choice due to the higher accuracy. The structural representation of the used dyno test bench and the measurement setup is shown in fig. 7. The main compo-



Figure 7: Measurement Setup on e-machine test bench

nents of the test-bench setup are the inverter with controller, e-machine and load machine. Two oscilloscopes with together eight channels are uses in the measurement setup. Through the star-point symmetry just two currents  $i_a$ ,  $i_b$  and two voltages  $u_{ab}$ ,  $u_{bc}$  are necessary to determine the system fully. The inverter uses an integrated resolver for the rotor position examination. The electrical angle  $\varphi_{el}$  can be obtained by the measurement and demodulation of the three resolver signals (Sin, Cos, Ext). With the measured phase currents  $\underline{i}_{abc}$ , phase voltages  $\underline{u}_{abc}$  and the calculated electrical angle  $\varphi_{el}$  the stator fixed values are transformed into the rotor fixed coordinate system by the *Clarke* and *Park* transformation. With the transformed  $\underline{i}_{dq}$  and  $\underline{u}_{dq}$  components the stationary magnetic flux  $\psi_d$  and  $\psi_q$  can be obtained with the eq. 8.

$$\psi_d = f_1 = \frac{u_q - R_s i_q}{\omega}$$
  
$$\psi_q = f_2 = \frac{R_s i_d - u_d}{\omega}$$
(8)

For a complete flux field several workpoints with variation of  $i_d$  and  $i_q$  have be recorded. The results for  $\psi_d = f_1(i_d, i_q)$  are shown in fig. 8. The last step is a field inversion of  $\underline{\psi}_{dq}$  w.r.t.  $\underline{i}_{dq}$ .

$$\begin{pmatrix} \psi_d = f_1(i_d, i_q) \\ \psi_q = f_2(i_d, i_q) \end{pmatrix} \xrightarrow{inverse} \begin{pmatrix} i_d = f_1^{-1}(\psi_d, \psi_q) \\ \vdots \\ i_q = f_2^{-1}(\psi_d, \psi_q) \end{pmatrix}$$
(9)

With the inverted flux tables the e-machine model in the previous section (see eq. (6)) can be filled with data of a real e-machine . At last the lookup tables for the flux harmonics  $f_{hd}$  and  $f_{hq}$  can be filled by Fourier analysis of the target machine back emf with eq. (5).



Figure 8: Flux field  $\psi_d$  after e-machine characterization

#### **5** Emulation Results

In this section the results of the emulation accuracy are presented. In the first step the dynamic performance of the em-emulator is investigated through a step response. As an example a torque step of 100 Nm at 400 min<sup>-1</sup> is represented in fig. 9. In the first sub-figure the phase currents with the electrical motor angle are shown. The angle  $\varphi_{el}$  has been calculated through demodulation of the resolver signals. The second sub-figure shows the phase voltages, where the IGBTs begin switching at timepoint 0.035 s. The 3th and 4th sub-figures shows the transformed currents  $\underline{i}_{dq}$  and voltages  $\underline{u}_{dq}$  in dq-coordinate system. The time duration the DUT needs to control the target currents to a stationary endpoint is about 10 ms.

10 the torque step comparation be-In fig. tween e-machine emulator (EME) and real emachine (EM) is shown. The flux harmonics on e-machine emulator were deactivated to neglect the effect of harmonic disturbance on the current controllers. The flux harmonics in the real machine have significant impacts on the current and voltage ripples. The current  $i_q$  reached the stationary endpoint at the EM 3 ms faster as on the EME. On EME the control rise times of both currents  $i_d$  and  $i_q$  are nearly equal whereas the control rise time of the  $i_d$  current on EM is much slower with high oscillations. The stator voltages  $u_d$  and  $u_q$  differs between EM and EME mostly in the dynamic area, when the currents are rising, between 5 and 10 V. Based on the measurements it can be recognized, that the em-emulator is an idealize environment to design current controllers.

In the next step the static performance of the model shall be considered. The e-machine model, including the e-machine characteristics measured on the dyno test bench, was uploaded on the em-emulator. The e-machine characterization, described in section 4, has been done at the e-machine emulator test bench, where several work-points with  $i_d$ ,  $i_q$  variation were recorded. The results are displayed as an e-motor map in







Figure 10: Torque step comparation between e-machine emulator (EME) and real e-machine (EM) at 1000  $min^{-1}$ 



Figure 11: E-motor map comparation between e-machine emulator (EME) and real e-machine (EM)



Figure 12: Flux linkage field comparation of the e-machine emulator (EME) with real e-machine (EM)



Figure 13: Speed and torque workpoint variation on e-machine emulator



Figure 14: Harmonics comparation of back emf between e-machine emulator (EME) and real e-machine (EM)

fig. 11. To identify the e-machine emulation accuracy, the flux ellipses  $\psi = \sqrt{\psi_d^2 + \psi_q^2}$  and the torque hyperbola  $T_{el}$  (eq. 3) of the real e-machine and of the e-machine emulator measurements are represent in one figure w.r.t.  $i_d$  and  $i_q$ . In the figure it can be seen that the emulation accuracy is very satisfying over a wide range in torque as well as in flux linkage. There are only minor differences of the flux linkage at work-points with high absolute  $i_d$  and low absolute  $i_q$ .

Fig. 12 displays the same results, whereas the flux linkage components  $\psi_d$  and  $\psi_q$  are separated. In the lower-left and lower-right sub-figure the relative variations of the flux linkage components are shown. The *Mean Absolute Error* (MAE) of the  $\psi_d$  component is with 1.1% almost twice as large as the  $\psi_q$  component with 0.59%. In sum, this is a very satisfactory result, because the parameters scattering through the production of electric motors is higher than the error of the emulation.

Up to this point, all the measurements has been done at a fixed rotor speed in the area of constant torque. In the next step the e-machine emulator accuracy has been investigated in the flux weakening area. Therefore, a set of work-points with rotor speed n and torque demand  $T^*$  variation has been recorded at the dyno- and e-machine emulator test-bench. The result are several maps with  $i_d$ ,  $i_q$ ,  $u_d$  and  $u_d$  w.r.t n and  $T^*$ , where  $u_d$  and  $u_q$  are the output voltages of the current controller. The currents  $i_d$  and  $i_q$  are the process variables and controlled by current controllers. Fig. 13 displays the results obtained from the differences of the dyno- and e-machine emulator measurements. It should be noted that the flux weakening area begins at  $1200 \text{ min}^{-1}$ . The d- and q-currents in the area of constant power matches exactly. Inside the flux weakening area there are some differences of  $i_d$  between 4-14%. However  $i_q$  has minor divergences with a MAE of just 0.2%. In the sub-figures bottom left and bottom right the controller output voltages where shown. The MAE of  $u_d$  is just 1.3% and the MAE of  $u_q$  is 2.6%. As can be seen the error in the area of constant torque is less than inside the flux weakening area. One reason for the differences may be the higher line contact resistances at e-machine emulator, which triggers to a volt-age drop on the phase lines. Through the voltage drop the inverter controller increase the negative d-current to reduce the d-flux. So the higher deviations of  $i_d$  in the flux weakening area can be explained. In the next time the test bench phase connections will be optimized to reduce the phase line voltage drop off. Last but not least the capabilities of the em-emulator to replicate flux harmonics has been examined. Therefore, the back emf of the real e-machine has been analyzed with a Fourier analysis. The lookup tables of the harmonics has been calculated with eq. 5 and uploaded to the em-emulator. The back emf comparison between real e-machine and ememulator are illustrated in fig. 14. The back emf has a distinct 5th harmonic, which has been replicated from EM-emulator with good precision.

## **6** Conclusions

It has been shown that an e-machine emulator is an equal and inexpensive alternative to conventional dyno test benches for the test of electric vehicle inverters. The advantages are: no moving parts and no maintenance, flexibility, by changing the model another motor type can be emulated. The challenges are: Data from the real e-machine is needed for the flux look-up tables. These must be acquired from measures of a dyno test bench. Alternatively, data can be acquired from a FEM analysis. Generally the flux linkage deviations are under 1%, which is less than the production tolerances for most electric motors. The largest deviations between model and measurements has been measured in the flux weakening area with 4-14%. Generally the system is performing satisfactory, and will definitely be a part of the future development of electric motor drives and controllers.

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