Hardware-in-the-Loop Test Systems for Electric Motors in Advanced Powertrain Applications

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ABSTRACT

Electric drives are growing in importance in automotive applications, especially in hybrid electric vehicles (HEV) and in the vehicle dynamics area (steering systems, etc.). The challenges of real-time hardware-in-the-loop (HIL) simulation and testing of electric drives are addressed in this paper. In general, three different interface levels between the electric drive and the hardware-in-the-loop system can be distinguished: the signal level (1), the electrical level (2) and the mechanical level (3). These interface levels, as well as modeling and I/O-related aspects of electric drives and power electronics devices, are discussed in detail in the paper. Finally, different solutions based on dSPACE simulator technology are presented, for both hybrid vehicle and steering applications.

INTRODUCTION

Hybrid drivetrains combine well-known state-of-the-art powertrain technology with powerful electric motors and storage devices in various configurations. Applied and operated properly, they can provide fuel savings of about 20%, compared to a conventionally operated car, under real driving conditions. Other advantages are the remarkably low emissions, which make hybrid vehicles an attractive solution for highly polluted urban centers [1]-[5]. These advantages are achieved without reducing the total torque, as the hybrid powertrains usually benefit from the additional torque of the electric motors, which is available from standstill.

But not only in hybrid configurations there is increasing use of electric motors. Any auxiliary drive that needs to be decoupled from engine speed requires electric motors to allow operation if the engine is switched off. The auxiliary drive may be the alternator, pump, or HVAC compressor. Most of these motors are AC-controlled and connected by DC buses.

Compared to traditional powertrains, electric traction drives and electric auxiliaries add additional degrees of freedom to the system with regard to functionality and packaging, which leads to a more complex and distributed control system (hardware and software) [6]-[8].

Despite the increased complexity, the development and testing time cannot be increased accordingly, if time-to-market, cost and quality goals must be met. Moreover, testing the new components in an older powertrain is often no option, because these developments result in completely new systems which cannot be constituted by predecessors.

Hardware-in-the-loop (HIL) simulation is therefore a very promising technology for early testing of single components and of the distributed control system, or interaction between the control units.

HIL TESTING FOR ELECTRIC DRIVE APPLICATIONS

Electric drive controllers have different requirements regarding the HIL simulator than an ECU for a combustion engine or a vehicle dynamics controller [9], [10]. As in the case of a simulator for a combustion engine, the HIL simulator for an electric drive computes the resulting torque from a measured excitation, and this computed torque has to be incorporated in a vehicle dynamics or a powertrain model to close the loop.

**Fig. 1:** Typical current and voltage ranges of different in-vehicle electric drive applications
However, there are two major differences. First of all, the control loop of the electric drive is not only closed by an engine speed loop but also by a current loop. Compared to a combustion engine HIL simulator, where only low-power actuators are controlled electrically, in electric drive applications the entire controlled power is electrical. So if there is a demand for real or simulated loads to close the current control loop, this results in setups with an installed power of several tens of kW to up to hundreds of kW (Fig. 1). This could mean that a complete motor test bench has to be integrated in order to test under real power conditions.

Fortunately, most of the software tests can be performed without operating the power electronics, by means of simulating the electric motor on a signal level. Different topologies of test systems, from a desktop signal-level tester to complete mechanical test benches, are discussed in the following sections.

REAL-TIME MODEL AND I/O FOR ELECTRIC DRIVE HIL SYSTEMS

An important issue for electric drive HIL applications is that the control loops require significantly higher real-time model dynamics, as they are computed in the 5-20 kHz range. Without special attention to this point, the motor model might even become unstable [11]-[13].

An optimized I/O interface tailored to the specific signals of electric motor applications is crucial to the real-time simulation of electric drives. First of all, an accurate measurement of the typical three-phase center pulse PWM control signals is necessary. The required time resolution is considerably smaller than 1 µs, so this has to be done in hardware. These measurements have to fit a model of the power electronics where effects such as switching delays or dead times are handled.

The current and position sensor simulation may be done by standard I/O channels, but hardware support might be necessary for higher frequency signals of digital encoders or resolvers. Moreover, particular attention has to be paid to model discretization at higher speeds (refer to the section REAL-TIME MODEL APPROACHES).

TEST REQUIREMENTS

The test system has to support different tests depending on the level of system integration focused on.

Open-Loop / Closed-Loop Component Test

a) The basic test focus might be simple open-loop evaluation of the gate driver signals or the current measurements. The signals to observe could be the PWM period and the dead time between the gate signals within each inverter leg. These tests could be carried out manually with an HIL test system, but are normally run automatically as a basic test procedure of every test suite.

b) On the next test level, the control loops will be closed. The test focus in an electric drive test system is on the current control loops. While the robustness even of a fixed-point implementation of a control approach can be tested in an offline simulation, the timing and the cooperation of software and configurable hardware – for example, a pulse pattern generation by FPGA hardware - can only be tested using the real controller board.

System Level (Powertrain) Test

Unlike tests on a single component ECU, tests on an overall powertrain control system have to take into account the various connections between the devices under test (combustion engine, transmission, electric motors, battery management, etc.). These may be coupled by controller networks (CAN, LIN or FlexRay bus) or by electrical and mechanical systems which have to be covered by the system model.

Both the test coverage and speed of a system-level test might be increased if an HIL system for electric motor components can be easily combined with existing test systems for engine or transmission controllers to build a hybrid powertrain HIL simulator.

Diagnostic Tests

Finally, there might be test issues related to the diagnostics software parts, which are becoming more important. Diagnostic software is tested using some kind of electrical failure insertion unit connected to the ECU outputs or in between the simulated sensors and the ECU. In safety-critical areas particular, for example, electric power steering, this is mandatory and feasible for electric drive ECUs, too.

However, for hybrid traction drives with output voltages of several 100 V, electrical failure simulation is difficult, and requires large setups and a lot of protection and safety measures.

INTERFACE LEVELS FOR ELECTRIC DRIVE TEST SYSTEMS

As mentioned in the last section, different interface levels between the ECU and the HIL system can be established for electric drive test systems. These are introduced in the following three subsections and in detail in the section I/O Concepts and Integration.

1) SIGNAL INTERFACE LEVEL

On the signal interface level, the input signals of the HIL simulation are usually the gate driver control signals, and the outputs are the winding currents. Any power electronic devices are removed from the device under test.
The test system is connected to internal interfaces of the electric drive: to the input signals of the gate drivers and to the output signals of the current transducers. These internal connections have to be made available, either by designing accordingly (design-for-test) or by modifying (“cracking”) the ECU to access the internal signals. Additionally, the test system is connected to the standard I/Os of the controller, such as interfaces to a motor position sensor or the communication interfaces (CAN, FlexRay, etc.).

The signal test level approach can be applied to all the electric drive applications mentioned above, there are no power or safety restrictions.

2) ELECTRICAL INTERFACE LEVEL

In this approach, the real power stages are included in the test and only the motor is simulated by an electronic load. With this interface level, there is no need to remove any parts from the device under test, and there are only minor safety restrictions especially compared to a mechanical test bench (refer to next section). Using an electronic load for simulating the electric motor without manipulating the ECU therefore probably provides the broadest test scenario.

With respect to the electric level and software functionality including closed-loop operation, tests like parameter deviation or any kind of electrical fault can be simulated. As with simulation on signal level, no mechanical bench is needed and the system is quite flexible. However, it requires high-performance electronic loads which can sink all the power coming from the ECU. For simulating
the electrical characteristic, a good bandwidth is essential as well.

As with the signal test level, there is full access to the motor model. Motor parameters can easily be modified.

MECHANICAL INTERFACE LEVEL (3)

This test level requires a mechanical test bench which is capable of applying mechanical load torques or forces to those parts of the real system which are physically incorporated into the HIL environment. If this is just the real electric motor, a simple rotational load is sufficient. Incorporating parts of the mechanics like gearbox, rack-and-pinion system, etc., leads to much more complicated configurations, partly requiring more than one load drive or linear drives. Besides solutions incorporating hydraulic actuators, electrical drives are commonly used to form a test axle together with the electric motor of the vehicle system.

For low-power systems, such as electric steering systems, the max. torque is up to 30 Nm and the speed is up to 6000 rpm. This can be obtained by standard industrial electrical drives in combination with simple mechanical test benches. Hybrid vehicle applications require much higher torque and power and need large-scale electric drives and mechanical test benches requiring among other things plenty of space, special safety measures, and an infrastructure that is similar to engine test benches (cooling, etc.).

The setpoint values for the load motors can be static, but in an HIL environment these values are typically calculated in a vehicle dynamics model (e.g. [14]). The interface signals to the test bench can be discrete analog and digital signals, though protocol-based interfaces are preferred. For precise measurements of (angular) position, speed or torque, additional sensors and transducers might have to be added.

Using a mechanical test bench can be considered state-of-the-art testing of electric drives in many cases. The main advantage of this approach is that only limited knowledge about motor or controller is required, catalogue values are usually sufficient. The main disadvantage is the lack of flexibility, e.g., to change any mechanical or motor parameters.

Table 1 compares test system features and properties on the different interface levels.

<table>
<thead>
<tr>
<th>Properties</th>
<th>1) Signal level</th>
<th>2) Electrical level</th>
<th>3) Mechanical level</th>
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<tr>
<td>Safety requirements</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
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<td>Computational power</td>
<td>High</td>
<td>Medium to high</td>
<td>Medium</td>
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<td>Test system pricing</td>
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<td>Testing production SW/HW</td>
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<td>SW + HW</td>
<td>SW + HW</td>
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<td>Typical applicable power range</td>
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<td>approx. 200A / 30V</td>
<td>No restriction</td>
</tr>
<tr>
<td>Testing with varying plant</td>
<td>No restriction</td>
<td>No restriction</td>
<td>Difficult</td>
</tr>
<tr>
<td>parameters</td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>Limited</td>
</tr>
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<td>electronics model</td>
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Table 1: Comparison of test system features on the three interface levels

REAL-TIME MODEL APPROACHES

The selection of appropriate I/O is an important task for the design of an HIL test system. It is even more important, however, to select an adequate model that will capture all major effects and cover the given real-time requirements deterministically.

The basic model part, which is necessary for interface level (1) and for level (2), is a real-time model of the currents and the torque. Depending on the rest of the model environment, a dedicated dynamic model of the rotating motor might also be necessary, if this is not already covered by a vehicle dynamics model.

For solutions based on the measurement of the gate driver signals (signal interface level), a model of the main effects of the power electronic circuits might be necessary, too. This part of the real-time model has to be adapted to the I/O used for measurement of the gate signals.

The next subsections describe in detail the electric drive and power electronics model requirements and their solutions.
ELECTRIC DRIVE MODEL

Continuous-Time Model

The stator of an AC electric drive with sinusoidal flux and current distribution can be represented by the stator voltage equation (1). For IM both the rotor voltage equation (2) and the equations for the flux linkage (3), (4) are necessary too¹ ([15], [16], Fig. 6).

\[
\mathbf{u}_s = \mathbf{R}_s \mathbf{i}_s + \frac{d\mathbf{\Psi}_s}{dt} + j\omega_s \mathbf{\Psi}_s
\]  

(1)

\[
0 = \mathbf{R}_r \mathbf{i}_r + \frac{d\mathbf{\Psi}_r}{dt} + j\omega_r \mathbf{\Psi}_r
\]  

(2)

\[
\mathbf{\Psi}_s = \mathbf{L}_s \mathbf{i}_s + \mathbf{L}_m \mathbf{i}_r
\]  

(3)

\[
\mathbf{\Psi}_r = \mathbf{L}_m \mathbf{i}_s + \mathbf{L}_r \mathbf{i}_r
\]  

(4)

For PSM the stator flux is given by:

\[
\mathbf{\Psi}_s = \mathbf{L}_s \mathbf{i}_s + \mathbf{\Psi}_p
\]  

(5)

In both cases the stator equation can be expressed using only currents and voltages as:

\[
\mathbf{u}_s = \mathbf{R}_s \mathbf{i}_s + \frac{d\mathbf{\Psi}_s}{dt} + \mathbf{u}_s
\]  

(6)

Lumped motor parameters are assumed. \( \mathbf{u}_s \) in (6) is the EMF.

The torque of the motor, as the interesting signal from the application point of view, is then proportional to the cross product of the field and the current vector.

\[
\tau_m \sim \mathbf{\Psi}_s \times \mathbf{i}_s
\]  

(7)

A more general representation of the stator dynamics is given by a state-space representation of the motor (Fig. 8):

\[
\frac{d\mathbf{i}_s}{dt} = \mathbf{A} \mathbf{i}_s + \mathbf{B} \mathbf{u}_s + \mathbf{S} \mathbf{\Psi}_r \omega_s
\]  

(8)

where:

\[
\mathbf{A} = \begin{bmatrix} -1/T_s & \omega_s \\ -\omega_s & -1/T_s \end{bmatrix} \quad \mathbf{B} = \begin{bmatrix} 1/L_s & 0 \\ 0 & \frac{1}{L_r} \end{bmatrix} \quad \mathbf{S} = \begin{bmatrix} 0 \\ -1/L_s \end{bmatrix}
\]

Fig. 8: State-space representation of the motor stator

The bilinear system matrix \( \mathbf{A} \), where the feedback terms are not constants but depend on the rotor speed, is typical of AC electric drives. The eigenvalues of this scalar system are \( \hat{\lambda}_{1,2} = \pm \frac{1}{T_s} \cdot \omega_s \).

The rotor voltage equation of the IM will not be analyzed any further in this paper, but could be described in the same way. With the focus on the dynamic of the stator current \( \mathbf{i}_s \), the EMF \( \mathbf{u}_s \) in (6), induced by the rotor current, will be considered as partially constant.

The motor model given in (8) can be implemented using the three scalar winding currents \( i_s, i_b, i_c \) as state variables. This would lead to three parallel models of the three motor windings (Fig. 14). The models are coupled by the star point voltage. The main advantage of this approach is to support nonsinusoidal flux distributions around the rotor angle. This is a realistic approach, especially for PSM drives.

¹ All variables are complex space vectors. \( \omega_s \) represents the electrical angular speed of the rotating reference system.
Alternatively, the motor model can be computed in a rotated dq reference frame. This allows a rotor flux model related to the direct current (ψr, ~ Ψr) component and a direct test feedback of the direct and quadratic current components (dI, qI) used to control the torque and the flux [17], especially for simulating a vector-controlled IM drive.

Discrete-Time Model

The continuous-time state-space representation of the stator can be transformed into a discrete time representation by expansion of the system matrix A into a series:

\[ \Phi(k) = e^{A(kT)}T \]

If this expansion is truncated after the linear term, this is the Euler solution, where:

\[ \Phi_{IM} = \begin{bmatrix} 1 - \frac{T}{T_s} & \omega_s T \\ \omega_s T & 1 - \frac{T}{T_s} \end{bmatrix} \]  

Fig. 9: Stability area of the Euler discretization

However, the system response of the continuous and the discrete-time system can only be guaranteed to be identical for a given stimulus, resulting in a wide variety of approaches to discretizing a given system.

Stability of the discrete-time model

The results of the Euler solution are stable only if the eigenvalues of the continuous time system are located within a 1/T circle around the value -1/T on the real axis of the complex plane (Fig. 9).

At higher stator frequencies ωs, especially, this may lead to instable transformation, even with sampling times equaling the PWM period such as 50 µs ...100 µs.

To ensure that the system behavior of the computed model is close to the behavior of the real system, additional parts (later truncation of the series of (9)) have to be included in the expansion of Φ. Alternatively, higher-order integration methods or different methods of discretization could be employed.

Unfortunately, all these approaches use higher-order terms of ωs and T. Because of the bilinear characteristics of the system matrix, it has to be recalculated for each sample step, causing additional computational load due to the higher-order terms. Additionally, this bilinear characteristics leaves no option for discretizing the system numerically, for example by the control system toolbox of MATLAB® by The MathWorks. However, the control system toolbox can be used to evaluate the quality of different approaches for given parameters.

A relatively close match between the behavior of the continuous-time and the discrete-time system even at higher stator frequency is achieved by the Tustin approach [18]. An additional advantage of this approach is that it transforms any stable eigenvalue of the continuous system into a stable eigenvalue of the z plane.

In consequence, depending on the model parameters and the required frequency/speed range, a suitable integration method has to be selected, since Euler might fail.

Control loop issues

An additional important restriction on the sampling time to be selected is the performance of the control loop closed by the real-time model. Modern electric drives use current control loops computed every PWM period, which are typically in a range of 5 kHz to 20 kHz. Sampling of the currents is done in the center of the PWM period – center pulse PWM assumed – to eliminate most of the harmonics caused by the PWM and capture the mean value of the current during the sample time. Thus, the sample time has to be chosen adequately.

1. Mean-value simulation: The first option for any motor simulation is to compute a mean-value model. To do so, the mean values of the PWM signal are sampled once per PWM period (typically in the center). These mean values equal the originally desired mean value of the voltage as computed by the current controller. These voltages are fed to the model resulting in a mean-value of the current, ready at the output well before the next center pulse (see Fig. 10).

2. Oversampling simulation: The second option is to evaluate the I/O (gate times) and the motor model considerably faster than once per PWM period. This then leads to a quasi-continuous simulation of the plant. Harmonics are included in the simulation, and of course in the computed current signals. However, to avoid artifacts due to harmonics in the wrong place, oversampling by at least 8 to 10 is required (see Fig. 11).
Both approaches, the mean-value approach and an oversampled, quasi-continuous model, can be used for interface levels (1) and (2). In general, using higher sampling rates is advisable to avoid stability problems in the discretized model.

As can be seen from Fig. 10 compared to Fig. 11, while the instantaneous input voltages are quite different for the two approaches, the mean values of the computed currents are identical for an identical operating point.

The main advantage of the mean-value approach compared to the quasi-continuous approach is the reduced computational load. On the other hand, the calculated current signals are usually delayed by 1.5 – 2 sample steps compared to a continuous system, depending on the integration algorithm. This is visible in Fig. 12. In a real system the effects of a pulse pattern, activated at trigger point 1 would be visible in the currents sampled starting with trigger point 2. In a discrete time mean-value simulation however trigger point 2 is the one where the new pulse pattern is measured and available as an input to the model, resulting in corresponding currents starting with trigger point 3. For dynamic current control loops, for example, in combination with dead beat algorithms, stability could be affected. The quasi-continuous approach should be used in these cases.

For the HIL simulation of the plant interfacing at the gate driver signals (signal interface level), the basic behavior of the power electronic devices and circuitry has to be emulated. The main influence on the effective voltage at the inverter output during regular operation is determined by the dead time between two corresponding gate signals. An additional effect is caused by the saturation voltages of the non-ideal switches. Additionally, the behavior of the circuit after events such as the breakdown of one of the inverter legs should be covered.

From the pulse pattern generation point of view, the dead time restricts the practical voltage vectors to inner areas of the 6 sectors of the voltage plane. The voltage is therefore discontinuous at the borders of these sectors.

However, even if this is taken into account by the pulse pattern generation, the effective voltage at the inverter output still differs from the value computed from the DC link voltage and the gate turn-on time.

The reasons are:

1. The gate times of the two devices in an inverter leg are separated by a dead time. To prevent short circuits, the first switch is turned off before the second is enabled. The current, however, is continuous. A positive current could be carried into the motor by the HSD of an inverter leg or, if the HSD is switched off, by the freewheeling diode in parallel to the LSD. The resulting voltage at the inverter leg is therefore
high only during the gate high time of the HSD and the turn-off delay time. The average voltage $U_v$ is therefore:

$$I_v > 0: \quad U_v = \frac{t_{\text{on,HSD}}}{t_{\text{PWM}}} U_d$$

$$I_v < 0: \quad U_v = \frac{(t_{\text{on,HSD}} + t_D)}{t_{\text{PWM}}} U_d = (1 - \frac{t_{\text{on,LSD}}}{t_{\text{PWM}}}) U_d$$

For a PWM period $t_{\text{PWM}} = 100 \mu s$ and a dead time of $t_D = 2 \times 4 \mu s$ this error is about 8%.

2. Due to the losses in the power electronic devices, the amplitude of the voltage at the inverter output is less than the DC link voltage. The quantity of this error depends on the switch technology used and the amplitude of the DC link. For a 450 V DC link and a saturation voltage of 2.3 V, the loss would be around 1%.

These effects can easily be covered by a power electronic model, even within a fixed sample step. However, the implementation has to be well adapted to the I/O channel used, because $t_{\text{on,HSD}}$, $t_{\text{on,LSD}}$, $t_D$, and $t_{\text{PWM}}$ need to be measured. Saturation voltages of the devices as well as the turn-on and turn-off delays can be taken from the data sheets.

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![Fig. 13: Basic model of an inverter half](image1)

The basis functionality of such an inverter half bridge block is summarized in (Fig. 13). Depending on the current sign, the effective voltage is calculated from the on-time of the HSD or the LSD. An additional signal $FW?$ denotes whether the current is conducted by the active switch or by its freewheeling diode. It is essential to note that there are no models for discrete power electronics devices used in this block but a simulation of the behavior of the half bridge in total.

It is a little more complex to describe the behavior of the combination of inverter plus motor if, for example, the gate signals of one of the inverter legs stall. In this case the current is commuted to one of the freewheeling diodes and will then decrease to 0. During this freewheeling time the voltage at the inverter output depends on the current sign only. After 0 is reached, all power electronic devices are blocked, and a voltage sensor at this inverter leg would measure the sum of the motor star point voltage and EMF within the motor phase. This can be covered by a power electronic model as well. A voltage selector (Fig. 14) uses the measured gate times and the current signals to decide whether the motor phases are actively controlled, freewheeling, or turned off. However, within a fixed step size architecture the performance, especially of the current cut-off, is related to the step size.

![Fig. 14: Combination of power electronics (PE) model and motor model, here for a three-phase motor model](image2)

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![Fig. 15: Reaction of the model to a loss of gate signals in winding 1](image3)

A sample simulated current for a phase loss situation is shown in Fig. 15. Due to the fixed sample time, there is a small overshoot of the current, but after the change in sign is detected, the current in the affected winding remains zero.

**I/O CONCEPTS AND INTEGRATION**

The following section examines how to integrate the above model approaches into the HIL simulation with respect to the I/O and the overall vehicle model.

1) SIGNAL INTERFACE LEVEL

As mentioned above, the exact timing of the gate driver signals must be provided when electric motor simulation is used on the signal level.
One solution for interfacing with an ECU on the signal level is the DS5202\(^2\) Gate Time Measurement application. It allows all the necessary times \(t_{\text{on,HSD}}, t_{\text{on,LSD}}, t_D, t_{\text{PWM}}\) of a three-phase PWM to be measured for up to four electric motors at a resolution of 25 ns (Fig. 16).

The board can also generate interrupt signals, which are synchronized to the incoming PWM. The interrupt signal is given in the middle of the pulses and can be used to start an interrupt-driven timer task in the real-time system. The board is thus specially designed for simulation on the signal level in conjunction with mean-value models, because it allows the required synchronous operation between model and PWM.

2) ELECTRICAL INTERFACE LEVEL

For interfaces on electrical power level, incorporating the real phase currents \(i_A, i_B, i_C\), a model of the power stage is not necessary, since the simulator captures the phase voltages \(u_A, u_B, u_C\) directly to calculate the phase currents. It should be noted that calculating the active phase voltage by digital signal capturing and assuming a certain DC link voltage \(U_D\) might be too imprecise, because of the influence of the transistors and diodes. The deviation can be up to ±2 V and cannot be neglected in low voltage systems (e.g. \(U_D = 12\) V) such as electric power steering. There are two alternatives to improve the I/O concept.

1. The voltage evaluation can be improved by means of a power electronic model (see above) which calculates the phase voltages \(u_A, u_B, u_C\) more precisely. This workaround breaks the principle of HIL simulation, since it is not based on pure input signals but utilizes a certain knowledge about the systems under test.

Even an assumption about the dead time \(t_D\) is necessary for calculating the voltage deviation during diode conduction, since this cannot be measured. This also means that the system’s behavior might not be represented correctly by the HIL simulation if the ECU malfunctions.

2. The correct voltage-time integral can be directly measured by means of fast analog-to-digital voltage capturing and digital integration as shown in Fig. 17. This principle can be applied to both mean-value models and oversampling models of the electric motor. It avoids any assumptions about the power stages and ECU’s behavior, but requires a special I/O solution.

The DS5202 Electric Motor Simulation application deals with the problem of the oversampling model and comprises a very fast FPGA-based simulation of the stator of an electric motor. The board measures the phase voltages \(u_A, u_B, u_C\) and calculates the stator model at a sampling frequency of 10 MHz. The resulting current values \(i_A, i_B, i_C\) are sent out by analog outputs every 1 µs. The FPGA-based stator model is a 2 degree-of-freedom stator-oriented state-space model of the three phase windings. Parameters of the discrete model and EMF voltage values come from the main processor of the real-time system, where the rest of the motor model is running at a much lower sampling frequency (Fig. 18).

Because the FPGA-based model uses analog voltage measurement and performs fast integration, it is applicable for simulations on electric power level incorporating electronic loads.

\(^2\) The DS5202 FPGA Base Board is part of the dSPACE modular hardware platform and the basis for a variety of different electric motor HIL solutions. It can carry different I/O modules and FPGA codes, allowing flexible use in different applications.
Another big issue is the high-performance electronic loads necessary to reproduce the phase currents of the real system. The electronic loads must combine features like fully active four-quadrant operation, high bandwidth and good steady-state precision. The phase current values calculated by the real-time simulation are used as set values for the electronic loads and transferred by analog or digital signals.

For interfaces on the mechanical level, an appropriate mechanical test bench is the basis for successful HIL simulation. The setup depends on the overall configuration, but the main requirement is to reproduce a load torque $T_L$ or force $F_L$, calculated by the real-time simulation at the mechanical interface plant and to feed back the corresponding actuator positions $\alpha$ and speed $\omega$. In some cases the speed $\alpha$ or position $\omega$ need to be controlled accordingly. Adequate sensors and actuators have to be used for this purpose.

Different kinds of actuators (electrical, hydraulic, pneumatic, etc.) are feasible as load actuators for the mechanical bench but only electric motors combine features like good controllability and availability, low maintenance, low noise and dirt, and finally four-quadrant operation. To avoid backlash, friction, and additional inertia, direct drives without gearbox are usually required. In most cases standard industrial drives are the compromise with respect to cost and performance, although a certain degree of oversizing cannot usually be avoided due to the required torque or force values.

The electrical drive is usually torque-controlled by the HIL simulation. The set value $T_L^*$ is transferred to the drive controller via an analog interface (analog voltage) or via a protocol (e.g. CANopen). Any overlaid closed-loop control for speed or position can be implemented either on the HIL real-time processor or by using the speed or position control features of the drive controller.
The real-time simulation gets the actual speed $\omega$ and position $\alpha$ of the test axle via the test bench’s drive controller or via a separate position sensor. To avoid noise on the speed and position signals, a very high resolution is required, which can only be obtained by high-resolution incremental encoders.

Torque and force sensors are used either just for evaluation purposes or for closed-loop torque or force control, as drive controllers usually support a current control rather than a torque control loop. Additionally, acceleration sensors can be applied, for the compensation of unwanted inertia on the test axle, for stabilization measures, or just for more precise speed evaluation.

Fig. 20 shows an HIL simulator with a mechanical test bench. The system allows combined testing of an active/adaptive front steering (AFS) system (incl. the electric motor) with a vehicle dynamics control (VDC/ESP) system.

**POSITION SENSOR SIMULATION**

An adequate position sensor simulation is often based on a so-called angular processing unit (APU), which comprises a stator speed integration and stator position calculation in hardware. This principle is well known from other automotive HIL applications, such as crankshaft and camshaft simulation of internal combustion engines. and allows very precise position sensor simulation based on wave tables.

Alternatively, the DS5202 Position Sensor Simulation application can be used for precise speed and position sensor simulation. It comprises two independent position accumulators to allow the simulation of two independent mechanical shafts (e.g., two electric motors in a typical HEV application). Different kinds of sensor are possible. The I/O and signal conditioning are prepared for resolver and incremental encoder simulation.

**OVERALL MODEL INTEGRATION**

A common requirement is to integrate the simulation of the electric drive system into a covering mechanical model. Depending on the system under test, this is a drive train model, steering system model, or suspension model, which itself can be part of a more or less overall vehicle simulation model.

The interface plane between the electric motor simulation and the rest of the vehicle simulation is always a load torque $T_\lambda$ (or a force $F_\lambda$) and speed $\omega$ or position $\alpha$. Whether these variables are inputs or outputs of the electric motor simulation depends on the configuration.

1. Usually, the motor inertia $J_M$ is assumed to be handled by the mechanical simulation model and the torque $T$ is the output value of the electric motor simulation while speed $\omega$ is the input value. This configuration avoids additional degrees of freedom.

2. In some cases the integration of the mechanical model (e.g., customer model or third-party model) requires an interface where speed $\omega$ is the output and torque/force is the input of the electric motor model. This configuration requires handling the motor inertia $J_M$ separately and coupled to the rest of the mechanical model by means of a flexible intermediate shaft. Depending on the coupling, this could cause stability problems and might require running parts of the mechanical model at a higher sampling frequency than usual.

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**TEST SYSTEM APPLICATIONS**

The layout of an HIL test system is often customer-specific and application-specific, depending on the necessary test coverage and the technical possibilities (interface levels)

**TRACTION DRIVES**

For traction drives in HEV powertrain applications, the signal interface level is usually the only option if functional tests have to be performed. These test systems focus on the current control loops to be tested under realistic conditions and in real time in combination with simulated or real ECUs, for example, engine or transmission control units (connected via CAN). A typical
approach is to combine an engine HIL system with a second HIL handling the electric motor(s), Fig. 22.

Depending on customer requirements, the parts can be designed to run in stand-alone or combined mode. The connection is normally done by synchronized interprocessor communication links between two (or more) real-time systems, for example, by means of dSPACE’s Gigalink technology (Fig. 22). Up to now most of the HEVs in the market are based on standard components of the OEMs such as standard engines. HEV functionality has more or less only been added to the standard software application.

The same approach can be applied in the test systems, by “simply” adding the electric drive part to the HIL system that is already in use for the conventional drive train.

Reusing a company’s existing HIL infrastructure by adding the HEV-specific functions to an existing system reduces the investment for additional equipment and personnel training, and optimizes HIL usage.

STEERING AND CHASSIS ACTUATORS

Auxiliary electric drives in safety-critical vehicle dynamic applications such as steering or suspension usually have to be tested together with the power stages. For safety reasons a test at the signal interface level is not sufficient, but a test within a lab environment is preferable to a test in a vehicle, especially for tests including electrical faults. These drives can usually be tested at the electrical or at the mechanical level. The real communication can be tested in both test approaches. Both types of test systems can be equipped with an electrical failure insertion unit (FIU). The main advantage of testing at the electrical level using a simulated motor is the additional degree of freedom to simulate varying motor parameters.

On a test bench including the real motor, mechanical parts such as transmissions or parts of a damping system can be included as well. This is useful if a test with only simulated mechanics is not sufficient to validate the control loops. Compared to a test system using an electronic load, this approach lacks flexibility in varying parameters, but ensures the most realistic mechanical behavior of the device under test.

<table>
<thead>
<tr>
<th>1) Signal Interface Level</th>
<th>2) Electrical Interface Level</th>
<th>3) Mechanical Interface Level</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pros</strong></td>
<td><strong>Cons</strong></td>
<td><strong>Typical use cases</strong></td>
</tr>
<tr>
<td>• very flexible (e.g. motor parameters)</td>
<td>• knowledge about ECU internals and motor characteristics required</td>
<td>• power &gt; 2 kW (especially HEV)</td>
</tr>
<tr>
<td>• independent of power level</td>
<td>• ECU must usually be cracked or special design-for-test has to be applied</td>
<td>• tests at automotive suppliers</td>
</tr>
<tr>
<td>• full access to the model</td>
<td>• no tests of power stages possible</td>
<td>• large simulators, were the test focus is not on electric test but mainly on integration testing (e.g. CAN integration) and overall system behavior</td>
</tr>
<tr>
<td>• no real power</td>
<td>• no tests of diagnostics on electric level possible</td>
<td></td>
</tr>
<tr>
<td>• no safety restrictions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• cost-efficient</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pros</strong></td>
<td><strong>Cons</strong></td>
<td><strong>Typical use cases</strong></td>
</tr>
<tr>
<td>• flexible (e.g. motor parameter)</td>
<td>• knowledge about motor characteristics and electric diagnostic functions required</td>
<td>• power &lt; 2 kW</td>
</tr>
<tr>
<td></td>
<td>• full access to the model</td>
<td>• testing at OEMs</td>
</tr>
<tr>
<td></td>
<td>• no knowledge about ECU internals required</td>
<td>• integration testing of dynamic systems e.g. vehicle dynamics incorporation steering system and ESP/VDC</td>
</tr>
<tr>
<td></td>
<td>• production ECU as it is ('black box')</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• no safety restrictions</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pros</strong></td>
<td><strong>Cons</strong></td>
<td><strong>Typical use cases</strong></td>
</tr>
<tr>
<td>• little knowledge about ECU and electric motor required</td>
<td>• inflexible</td>
<td>• testing at the OEM without good knowledge about the electric drive system</td>
</tr>
<tr>
<td></td>
<td>• testing of mechanical parts is possible</td>
<td>• tests with deviation of motor parameters is impossible</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• mechanical test bench required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• safety restrictions (mechanics)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• cost depends mainly on size and power of the test bench</td>
</tr>
<tr>
<td></td>
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</table>

Table 2: Pros, cons, and use cases of the different interface levels
Table 2 compares the advantages and disadvantages of the different interface levels and summarizes some typical use cases. The required investment differs and depends on the power level as well as on the chosen interface level(s). The expenditure for the electrical and mechanical interface levels are almost in the same range. Interfacing on signal level is the most cost-efficient solution.

CONCLUSION

The growing importance of electric drives in automotive applications like powertrain applications (HEV) or vehicle dynamics applications (electric steering systems, etc.) necessitates appropriate hardware-in-the-loop simulation systems for testing the corresponding electronic control units. In this paper the three different fundamental interface levels between the electric drive system and the hardware-in-the-loop system - signal level, electrical level and mechanical level - were discussed with respect to theoretical and practical aspects. Additionally some real HIL test systems that are currently in operation were presented.

One of the main goals was to point out, that the right choice for the interface level strongly depends on the test scenarios and test purposes under consideration of acceptable expenditure.

Notwithstanding the considerable progress in hardware-in-the-loop simulation of electric motors in the recent years, there is still a wide potential for improvements and further developments.

The main issues aspects for the near future will probably be the development of very fast but more flexible electric motor models (e.g. FPGA-based) and more powerful and highly dynamic electronic loads also implying energy recovery.

REFERENCES


### ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Alternating current</td>
</tr>
<tr>
<td>AFS</td>
<td>Active front steering</td>
</tr>
<tr>
<td>APU</td>
<td>Angular processing unit</td>
</tr>
<tr>
<td>ASM</td>
<td>Automotive simulation models</td>
</tr>
<tr>
<td>CAN</td>
<td>Controller area network</td>
</tr>
<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>ECU</td>
<td>Electronic control unit</td>
</tr>
<tr>
<td>EMF</td>
<td>Electromotive force</td>
</tr>
<tr>
<td>EPAS</td>
<td>Electric power-assisted steering</td>
</tr>
<tr>
<td>ESP</td>
<td>Electronic stability program</td>
</tr>
<tr>
<td>FIU</td>
<td>Failure insertion unit</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field-programmable gate array</td>
</tr>
<tr>
<td>HIL</td>
<td>Hardware-in-the-Loop</td>
</tr>
<tr>
<td>HEV</td>
<td>Hybrid electric vehicle</td>
</tr>
<tr>
<td>HSD</td>
<td>High-side driver</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heating, ventilation, and air conditioning</td>
</tr>
<tr>
<td>IM</td>
<td>Induction motor</td>
</tr>
<tr>
<td>LIN</td>
<td>Local interconnect network</td>
</tr>
<tr>
<td>LSD</td>
<td>Low-side driver</td>
</tr>
<tr>
<td>OEM</td>
<td>Original equipment manufacturer</td>
</tr>
<tr>
<td>PE</td>
<td>Power electronics</td>
</tr>
<tr>
<td>PSM</td>
<td>Permanent-magnet synchronous motor</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse width modulation</td>
</tr>
<tr>
<td>VDC</td>
<td>Vehicle dynamics control</td>
</tr>
</tbody>
</table>

### SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathbf{x}$</td>
<td>Complex space vector variable</td>
</tr>
<tr>
<td>$x$</td>
<td>Scalar variable</td>
</tr>
<tr>
<td>$\mathbf{x}'$</td>
<td>Field-oriented space vector value</td>
</tr>
<tr>
<td>$x_s$</td>
<td>Stator signal</td>
</tr>
<tr>
<td>$x_r$</td>
<td>Rotor signal</td>
</tr>
<tr>
<td>$\mathbf{u}_s$</td>
<td>Field-oriented space vector of the stator voltage</td>
</tr>
<tr>
<td>$\mathbf{u}_i$</td>
<td>Stator voltage</td>
</tr>
<tr>
<td>$e_{uv}$</td>
<td>Back EMF voltage</td>
</tr>
<tr>
<td>$U_{v}$</td>
<td>Phase voltage in phase $v$</td>
</tr>
<tr>
<td>$U_{v,FW}$</td>
<td>Phase voltage in phase $v$ while free wheeling</td>
</tr>
<tr>
<td>$U_{v6}$</td>
<td>Inverter output voltage in phase $v$</td>
</tr>
<tr>
<td>$U_d$</td>
<td>DC link voltage</td>
</tr>
<tr>
<td>$\mathbf{i}_s$</td>
<td>Field-oriented space vector of the stator current</td>
</tr>
<tr>
<td>$\mathbf{i}_r$</td>
<td>Field-oriented space vector of the IM rotor current</td>
</tr>
<tr>
<td>$\Psi_f$</td>
<td>Field-oriented space vector of the stator flux</td>
</tr>
<tr>
<td>$\Psi_f'$</td>
<td>Field-oriented space vector of the rotor flux</td>
</tr>
<tr>
<td>$\Psi_p$</td>
<td>Field-oriented space vector of the rotor flux caused by the permanent magnets of the PSM</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Lumped parameter representing the resistive stator losses</td>
</tr>
<tr>
<td>$R_r$</td>
<td>Lumped parameter representing the resistive IM rotor losses</td>
</tr>
<tr>
<td>$i_v$</td>
<td>Scalar winding current</td>
</tr>
<tr>
<td>$\omega_s$</td>
<td>Angular velocity of the stator field</td>
</tr>
<tr>
<td>$\omega_r$</td>
<td>Angular velocity of the rotor field</td>
</tr>
<tr>
<td>$L_s, L_r, L_m$</td>
<td>Lumped parameter representing the stator, rotor or mutual induction</td>
</tr>
<tr>
<td>$\tau_m$</td>
<td>Ideal torque of the electric motor</td>
</tr>
<tr>
<td>$T$</td>
<td>Sample time of the time discrete system</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Stator time constant of the first order model</td>
</tr>
<tr>
<td>$t_{on,HSD}, t_{on,LSD}$</td>
<td>Active gate times measured for the high side driver or the low side driver of a half bridge.</td>
</tr>
<tr>
<td>$t_D$</td>
<td>Dead time with no gate signal active as measured from the gate signals.</td>
</tr>
<tr>
<td>$t_{PWM}$</td>
<td>PWM period time</td>
</tr>
</tbody>
</table>

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