HIL Simulation of Power Electronics and Electric Drives for Automotive Applications

Thomas Schulte, Axel Kiffe, and Frank Puschmann

Abstract—**Hardware-in-the-loop simulation is today a standard method for testing electronic equipment in the automotive industry. Since electric drives and power electronic devices are more and more important in automotive applications, these kinds of systems have to be integrated into the hardware-in-the-loop simulation. Power converters and electric drives are used in many different applications in vehicles today (hybrid electric or electric powertrain, electric steering systems, DC-DC converters, etc.). The wide range of applications, topologies, and power levels results in various different approaches and solutions for hardware-in-the-loop testing. This paper gives an overview of hardware-in-the-loop simulation of power electronics and electric drives in the automotive industry. The currently available technologies are described and future challenges are outlined.**

Index Terms—**Automotive Applications, HIL Simulation, Real-time Simulation.**

I. Introduction

POWER electronic devices are becoming increasingly important in automotive applications, due to electric vehicles (EVs) and hybrid electric vehicles (HEVs), but also due to the increasing number of power electronics in conventional cars. The electronic control units (ECUs) in cars are typically tested by means of hardware-in-the-loop simulation (HIL). HIL benches ([1]) emulate an ECU's real environment by simulating the plant in real time and providing an interface for connecting the actuator and sensor lines, Fig. 1. This lowers costs and improves test efficiency by enabling automated testing in a laboratory under repeatable conditions.

When the development of automotive electronics began, standard or self-made equipment was used to test ECUs by simply stimulating the input channels and measuring the behavior of the outputs. HIL simulation had to be introduced when the ECU's internal functions, including diagnostic and plausibility checks, became too complex to be tested by pure input/output stimulation. Afterwards HIL simulators became larger and more powerful, and simulation models as well as test automation software became more comprehensive [2].

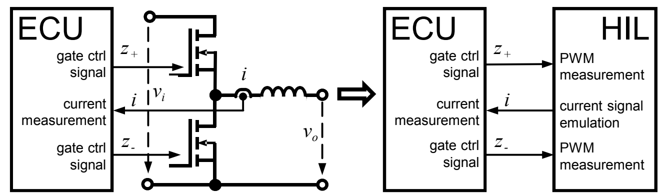

Fig. 1. Real system (left) and HIL simulation (right).

Today only minor parts of the ECU's software relate to the feedback controller. The major parts relate to diagnostics, failure reactions, plausibility checks, limp-home functions, communication, bus management, etc. Testing by HIL is more applicable to these functions since the accuracy of the HIL simulation is usually too poor to test and optimize controllers, e.g., for vehicle dynamics or powertrain control. Nevertheless, it is necessary to close the control loop by HIL simulation for testing the general functions and reactions of diagnostic and plausibility checks. To test communication, diagnostic functions or failure reactions, the ECU needs to be in its normal operation mode. Without closed control loops, the diagnostic functions and plausibility checks would cause failure reactions and the ECU's behavior might differ significantly from its normal operation. This in turn might activate a limp-home mode in which special, different control laws are applied and diagnostic trouble codes are stored, which would prevent systematic testing of the diagnostic functions themselves.

Considering the above testing aspects and the costs of HIL simulation with respect to model development and maintenance, it is reasonable that HIL simulation today is usually just accurate enough to avoid failure reactions in the ECUs, but not accurate enough to test and optimize the structures and parameters of the closed–loop controllers. Therefore, simple behavior models are often used in HIL projects in practice, to save time and money, but nevertheless well-proven physical models are always preferred, since they are more reliable and more stable when the ECU's functions are changed and expanded.

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II. HIL SIMULATION FOR POWER ELECTRONICS AND ELECTRIC DRIVES

HIL simulation for electric drives has been done for many years now, e.g. [3]. In automotive HIL simulation, it became more and more important from about 2004 onwards, due to the increasing development efforts for hybrid-electric vehicles. Today, controlled electric drives are used for a large variety of different important and safety-critical systems in modern vehicles. They can be found in hybrid-electric or electric powertrains as well as in electric steering systems or gear box actuation. Most of these applications have in common that they incorporate a complex distributed control system (hardware and software) comprising several ECUs and having significant requirements with respect to reliability and safety. HIL testing is therefore an obvious choice, and many different solutions have been presented, [4].

Depending on the test purpose, the HIL benches could be large, incorporating several real-time processors (multi-processor system) if all ECUs need to be connected. Nevertheless, HIL simulation for an electric drive or power electronics is usually the most ambitious task within the overall setup, since there are two major differences compared to other systems which are typically incorporated in HIL simulations. First, the dynamics of the electric domain are much higher, which results in special requirements on the real-time system and the model. Second, the controlled electric power is much higher (up to hundreds of kW), which influences the interface between the ECU and HIL simulator.

An ECU which controls power electronics or electric drives, e.g., in hybrid vehicles, electrical vehicles, etc., can be integrated into a HIL simulation by using various interfaces between the ECU and the HIL simulator [5]. So-called signal-level simulation means that the power stage is replaced and the gate control lines and measurement lines are connected to the HIL bench, Fig. 2. The gate control signals for the semiconductor switches are captured by appropriate equipment, while the measurement signals for voltages and currents are generated by the bench. This signal-based simulation is very flexible and does not require heavy equipment, due to the absence of the high power components.

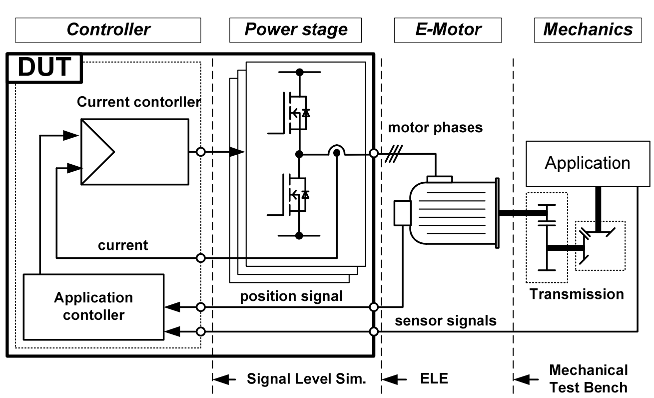

Fig. 2. Interfaces for the HIL testing of electric drives.

If this manipulation has to be avoided, for example, because the internal circuit is too closely integrated or an ECU from the field has to be tested, the only option is to perform simulation at the so-called power-level. Power-level simulation typically involves a mechanical test bench where load torque is applied to the real electric motor by means of a brake or an electric load motor, Fig. 3. This can also include large parts of the mechanical system, like the gearbox.

As a flexible alternative to using a mechanical test bench, the electric motor can be simulated by electronic load emulation (ELE), where the real currents and voltages at the ECU's motor connectors are simulated without having the real electric motor or any mechanical system connected, e.g. [6]. To test electrical drive systems in the low-power segment (< 2 kW), like electric steering systems (e.g., electric power steering, EPS) or actuators for gear boxes (e.g., automated manual transmission, AMT), mechanical benches or electric-power-level simulation by electronic load emulators are usual, because these relatively small control units cannot be split up to separate the signal processing part from the power stage. In the higher power segment, e.g., in hybrid electric or electric drivetrains, signal-level simulation is the most common method of HIL software testing, since it is economical because the real power is not used. For more comprehensive testing of the power stage and the overall drive system, mechanical benches are used.

While low voltage/low-power electronic load emulation ([7]) is a certain standard today, electric power level simulation for high power and higher voltages is still an ambitious task [8], since the required electronic loads are large and expensive.

III. REAL-TIME CAPABLE MODELS

A basic part of any HIL simulation system is a real-time-capable model. Regardless of the chosen interface concept, the model of an electric drive or power electronics calculates

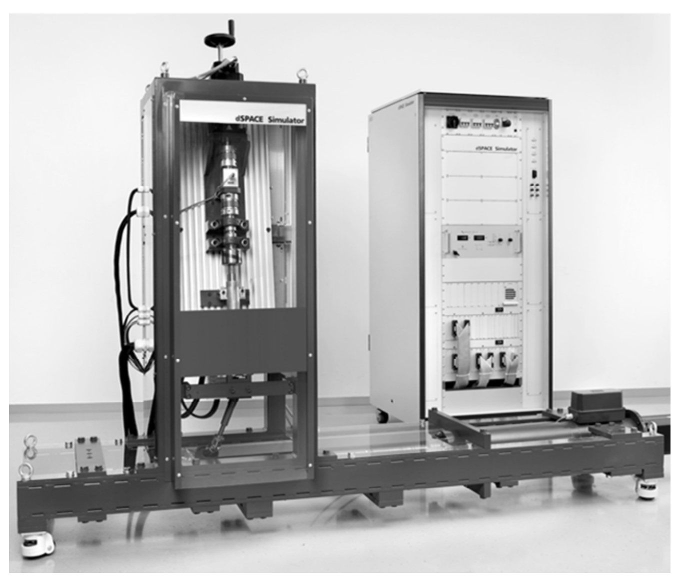

Fig. 3. Mechanical test bench for an EPS including a linear actuator for the steering rod force.

voltages, currents and torque from the control signals (gate driver signals). The development of real-time-capable models of power electronic circuits or electric drives is still an ambitious task. The approaches can be classified by different aspects, but the sampling strategy and the handling of discontinuities are significant criteria anyway.

IV. Sampling Strategies

Digital controllers for electric motors measure currents and voltages and calculate the control algorithms one or two times a switching period by utilizing a pulse-synchronous measurement. Therefore in a HIL simulation it is generally sufficient to update the output signals to the controller by using the same rate as the control algorithm itself [5]. Two different sampling strategies are presented below.

A. Low-Rate Synchronous Sampling

When the electric circuit or drive model runs at the same sampling frequency as the controller, it needs to be executed synchronously to the control algorithms or PWM period T_S to avoid subharmonic beats, see Fig. 4a. This requires a synchronization mechanism for the HIL simulation, e.g., based on a phase-locked loop [5]. The simulation accuracy and stability can be critical in some cases, due to a delay of at least one sample step in providing the output values. The synchronization itself could be instable if the switching frequency is varied. Anyway, the low-rate synchronous sampling strategy fails in some cases, e.g., in current mode control.

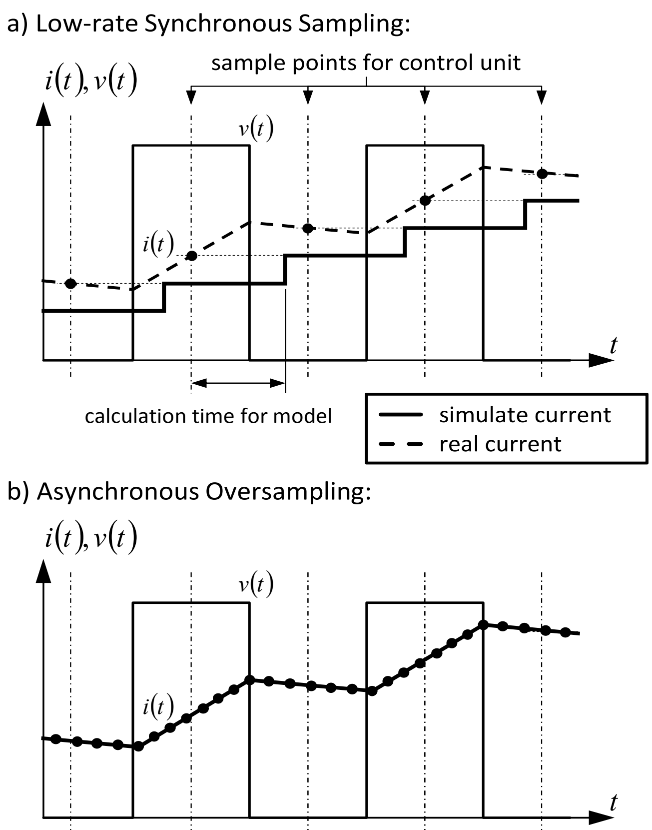

Fig. 4. Different sampling strategies: The figure shows the principle voltage and current waveforms (simulated and real) obtained by the two sampling strategies for an inductive load driven by a pulse-wise voltage.

B. Asynchronous Oversampling

If the model is executed considerably faster than the PWM switching and the corresponding control loop (oversampling, Fig. 4b) with an oversampling factor of 10 or higher, the simulation behaves quasi-continuously. Synchronization is not necessary and the delay in providing output values to the controller is considerably smaller. The accuracy and stability of the real-time simulation are significantly increased.

The main advantage of the low-rate synchronous sampling strategy is its lower computation demand. The improvement of accuracy and stability by asynchronous oversampling is dearly bought by a considerably higher computation demand. Assuming a switching frequency of 20 kHz, the sample time of the model should be at least 5 µs or less. Considering the switching frequencies of today's power electronics, a model implementation based on an FPGA (field-programmable gate array) is the only solution.

V. Handling Discontinuities

Discontinuities in electrical systems are caused by any kind of switches, mainly semiconductors like diodes or transistors. In HIL simulation, two different types of switching events can be distinguished. The first type are the model's internal switching events, which depend on the model's internal current or voltage values. An example is a diode which changes the conduction state. The second type are external switching events, which occur when semiconductor devices like transistors are switched by external drive signals (input signal of the HIL simulation).

Real-time simulation usually requires a fixed step size which does not allow classic zero-crossing detection algorithms. However, it is not sufficient to consider the instantaneous states of the switches at the sample points, because with a state-of-the-art real-time processor, the step size T cannot be sufficiently reduced to obtain an appropriate timing resolution for switching events and accurate simulation results. Special measures are required to consider switching events via additional information obtained by signal preprocessing with higher timing resolution than the step size of the simulation algorithm itself. Otherwise the simulation could be inaccurate or even instable.

Well-proven approaches for real-time simulation are known for the continuous conduction mode (CCM) of the power electronics, where standard averaging methods can be used by just capturing external switching events, measured by timing evaluation. The quantities are then averaged, neglecting the behavior of currents and voltages during a sample period T. The equation for averaging periodic quantities $x(t)$ is as follows:

$$\bar{x} = \frac{1}{T} \cdot \int_0^T x(t) dt \qquad (1)$$

where T is the sampling period. This is the standard method for the HIL simulation of electric drives today, and does not adequately take into account the discontinuous conduction mode (DCM), where internal switching events are essential.

Nevertheless, the DCM is a normal operating mode for many power electronic topologies (e.g., forward converter, BLDC motor). Moreover, the DCM occurs in many failure cases in power electronics which are normally operated in CCM (e.g., gate driver failure). Unfortunately, there is still a lack of efficient and reliable approaches for simulating power electronic circuits operated in the DCM in real time. Some candidates will be presented in the following section.

VI. Compensation Methods

An obvious approach to handling discontinuities is to split up a sample step T into a period before and after the switching event. These two subperiods, where different model topologies are valid, can then be simulated separately. External switching events, forced by control signals, can be captured by appropriate I/O timing hardware or calculated from simulated control signals. Switching events that depend on state variables can be calculated, e.g., by interpolation, as shown in Fig. 5. The state variables $\mathbf{x}$ can be recalculated from the determined switching time, using the new model topology. A significant increase in execution time can be avoided by utilizing asynchronous but constant sample steps and simple interpolation and extrapolation mechanisms [9].

Various algorithms are known which differ in the details of their interpolation and extrapolation strategies [10]. However, only one switching event can be considered for each sample step. Otherwise the sample step has to be divided into several subperiods, which usually does not meet the real-time requirement. Moreover, the approach requires a certain oversampling for appropriate simulation results [11], and it can be concluded that compensation methods are only suitable for low switching frequencies.

A. Advanced Averaging Methods

Different averaging methods are known for power electronics where the dynamics caused by switching are

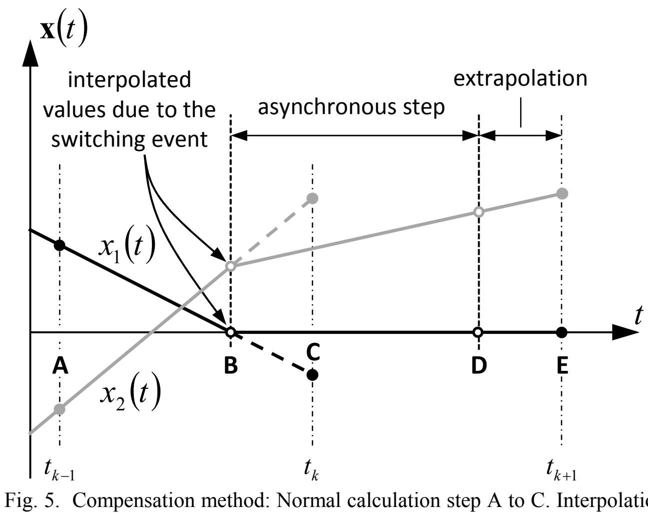

Fig. 5. Compensation method: Normal calculation step A to C. Interpolation of event B. Second asynchronous step B to D and extrapolation to E.

abstracted by averaging all state variables over a switching period T_S. For HIL simulation, the averaging can also be applied over a sampling period T, which might be smaller in the case of oversampling. A well-known approach is the state-space-averaging method (SPAM) [12], in which averaged system matrix are used by applying

$$\frac{d}{dt}\bar{\mathbf{x}} = \left(\mathbf{A}_1 \cdot d_1 + \mathbf{A}_2 \cdot d_2\right)\cdot \bar{\mathbf{x}} + \left(\mathbf{B}_1 \cdot d_1 + \mathbf{B}_2 \cdot d_2\right)\cdot \mathbf{u} \tag{2}$$

where $\mathbf{A}_i$, $\mathbf{B}_i$ are the system matrices for the different segments of the switching period T_S and d_i is their corresponding on-state ratio. SPAM is a promising candidate for use in HIL simulation in general, because unlike other methods, it can easily be applied to different power electronic topologies by generalized algorithms. Nevertheless, the standard SPAM does not consider the DCM, see Fig. 6. A first approach to including the DCM in SPAM was presented in [13], where a correction measure was derived from the physical constraints. In [14] the correction measure was derived more mathematically, yielding correction matrices $\mathbf{W}_i$ by which the DCM can be considered more systematically for different topologies:

$$\begin{aligned}\frac{d}{dt}\bar{\mathbf{x}} = &\left(\mathbf{A}_1\mathbf{W}_1 d_1 + \mathbf{A}_2\mathbf{W}_2 d_2 + \mathbf{A}_3\mathbf{W}_3\left(1-d_1-d_2\right)\right)\cdot \bar{\mathbf{x}} \\ &+ \left(\mathbf{B}_1 d_1 + \mathbf{B}_2 d_2 + \mathbf{B}_3\left(1-d_1-d_2\right)\right)\cdot \mathbf{u}\end{aligned} \tag{3}$$

Although in principle, this modified SPAM allows the DCM to be considered efficiently and with an acceptable computation demand, the segmentation of the interval needs to be known, Fig. 6. While period d_1 (on-state ratio) is determined by capturing the corresponding external control signal, d_2 (diode conduction ratio) need to be calculated. Up to now, no efficient method is known which can be generalized for use with arbitrary topologies. The above disadvantage can be avoided by the discrete state-space-averaging method (dSPAM) first presented in [15] and extended to the DCM in [16]. The dSPAM was applied to

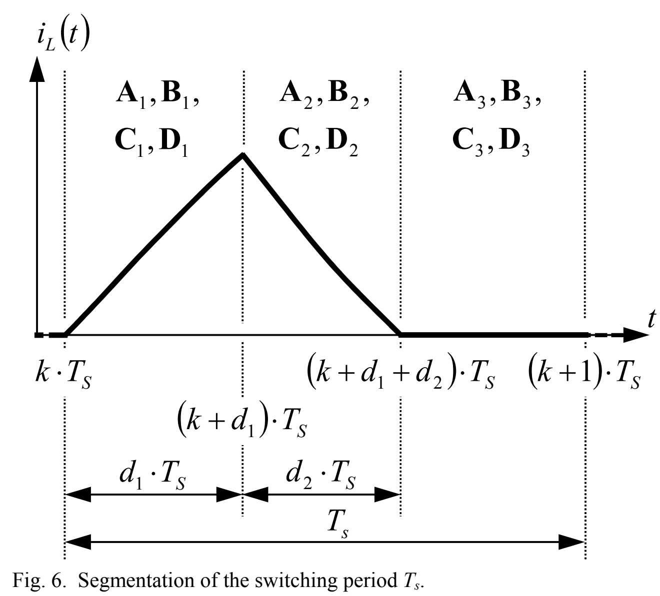

Fig. 6. Segmentation of the switching period T_s.

real-time simulation in [17], also including the DCM. Nevertheless, the computation demand of advanced averaging methods is much higher compared to standard average models used today.

B. High-Rate Oversampling

FPGA-based real-time model implementations enable extraordinarily high sampling frequencies. If a real-time model is implemented on a programmable logic device (e.g., FPGA), the sample time can be close to the absolute timing resolution of the digital electronics (e.g., 100 ns). With this high-rate oversampling, switching events no long require special handling. However, the FPGA-based model implementation is less flexible but more costly compared to processor-based real-time systems, since the tool chain for FPGA programming is currently still less convenient and special tools for model implementation are rare.

Nevertheless some approaches, applications and tools for real-time simulation on an FPGA have already been presented, mainly in the domain of power electronics or electric drive simulation. Besides the general implementation issues of FPGAs, an essential question is how the nonlinear switching behavior can be considered efficiently, which causes an alternating system matrix. Replacing the switches by capacitors (off-state) and inductors (on-state) yields an approach ([18], [19]) which enables a simple implementation, but the choice of parameters is limited. There are also other approaches that use a more direct implementation of the nonlinear feedback path, e.g., in [20] or [21].

High-rate oversampling by FPGA-based models is especially interesting for electric power-level simulation (ref. chapter 2). To connect the real-time model to the power stage, fast analog-to-digital capture of the phase voltages and downstream calculation of the voltage-time integral are necessary. Since the required time resolution is considerably smaller than 1µs, FPGA-based implementation is essential, and it makes sense to combine this measurement method with an FPGA-based oversampling model. A corresponding system is presented in [8], where only the model of the three-phase windings is implemented on the FPGA to preserve a certain flexibility. The remaining part of the electric motor model is simulated on a conventional real-time processor.

VII. FUTURE CHALLENGES AND CONCLUSION

It is impossible to predict how HIL testing in the automotive industry will develop in the future. There is still the idea of testing and optimizing the closed-loop controls and calibrating the ECUs by means of HIL simulation. But in practice, development is more influenced by the test requirements of current trends in automotive electronics and cost efficiency. Over the last couple of years, the focus was on large HIL systems for integration testing of large networks of ECU, HIL testing for driver assistant systems, HIL testing of electric drives, and more flexible HIL systems. The standard real-time models were extended by various modules which correspond to new automotive components like modern exhaust systems (diesel particulate filters or selective catalytic reduction), electric power steering, etc., but only marginally improved regarding their precision. As a careful prediction for the near future, it seems reasonable to assume that more precise simulation of energy consumption might be required.

For the HIL simulation of power electronics and electric drives, currently more powerful but also flexible implementation tools and platforms are desired, which allow modeling based on circuit topology but also take the DCM into account correctly. With respect to performance and generalizability, FPGA-based real-time simulation seems to be more promising than processor-based real-time simulation by advanced implementation methods. Nevertheless, FPGA programming is less flexible and more costly in application and maintenance. Improving the tool chain is the main challenge here. With respect to energy consumption, correct simulation of power-flow and power losses in electronic circuitry might become a requirement. How this can be realized is an open question, since up to now, very simple model approaches for semiconductor switches are used for all real-time models for power electronics.

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