Faster Inverter Software Validation in a Full Vehicle Model

A novel simulation approach enables realistic validation of electric drive systems on standard hardware as well as fast, continuous testing of inverter software suitable for daily use for the first time. IPG Automotive and Persystems present how detailed power electronics can be simulated efficiently and integrated seamlessly into virtual vehicle environments.

Software has a major impact on performance characteristics of electric drives. Control algorithms for power, torque and rotational speed as well as strategies for energy recovery, thermal management and protective functions affect efficiency, drivability and reliability. A key component of the electric powertrain is the traction inverter, transforming High-Voltage (HV) Direct Current (DC) from the battery into three-stage Alternating Current (AC) and actuating the traction motor electrically, **FIGURE 1**. Increasing electrification results in the growing significance of inverter software as a differentiating factor for overall powertrain performance.

INVERTER SOFTWARE

The software manages highly dynamic power and torque controls, modulation strategies and protective functions, and coordination with superordinate vehicle systems. Modern control strategies enable fast adaptation in the milliseconds or microseconds range and have a direct influence on driving experience, torque dynamics and traction. In the field of energy recovery, precise software control provides high regenerative power close to the physical limits, without compromising stability or safety. At the same time, it affects the load on power semiconductors and

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the machine and thus the durability of the drive system.

The performance results from the interplay between power electronics, the electric machine and the attuned control algorithms, **FIGURE 2**. Semiconductor technologies such as Silicon Carbide (SiC) Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) enable higher switching frequencies and efficiency levels, but they require more sophisticated control, protective mechanisms and system integration. Leveraging these potentials largely depends on the quality of the control software.

This results in the core challenge of validating inverter software under varying dynamic operating conditions as well as on system level. For this purpose, high-precision models of the regulation circuit (plant models) are required which realistically model the switching-based behavior of the power electronics and the electromagnetic properties of the machine.

SOFTWARE VALIDATION

In practice, inverter software is often validated via hardware-in-the-loop systems. These systems offer a high model fidelity, but they are hardware intensive and offer limited scalability. At the same time, detailed electrical simulations on standard computers are oftentimes too slow, with the result that even short driving scenarios require multiple hours of computing time. The proposed simulation approach based on Structure-Preserving Algorithms (SPAs) addresses this bottleneck. Highly detailed plant models can be computed with significantly reduced computing time while simultaneously preserving the structural properties of the physical system. This enables a robust and efficient simulation of switching power electronics on standard computer hardware. Extensive validation loops with physically realistic models can hence be performed early in the development process. In addition, the integration into virtual vehicle platforms supports a system-wide evaluation of complex drive architectures and promotes the closer connection of software development, hardware design and system integration.

ELECTRICAL SIMULATION

Research environments apply SPAs to reliably map high-dimensional dynamic systems with complex energy flows in the long term. Transferring these concepts to scientific engineering applications places high demands on efficiency, scalability and industrial integration. With OverDrive, Persystems provides an electric plant model based on Functional Mock-Up Unit (FMU) that enables the use of structure-preserving numerical methods for the simulation of electric drive systems. OverDrive describes electrical networks in a way that the energetic structure and consistency of power flows at the discrete numerical level is preserved. This allows for reliable and efficient simulation of systems with switching power electronics, non-linear machine models and highly dynamic control loops, opening new possibilities for scalable validation of traction inverter software.

A core aspect of this approach is the ability to model electric drive systems with a level of detail known from specialized power electronics development tools. The SPA-based solver supports modeling that compares to established environments such as Matlab/Simulink in terms of functionality. Switching semiconductor components can be represented explicitly including all switching states, losses and parasite effects. High-resolution machine models from electromagnetic simulations can be integrated directly and enable modeling of non-linear effects such as magnetic saturation, angle-dependent inductances or harmonic distortions. Additional layers of the electrical sys-

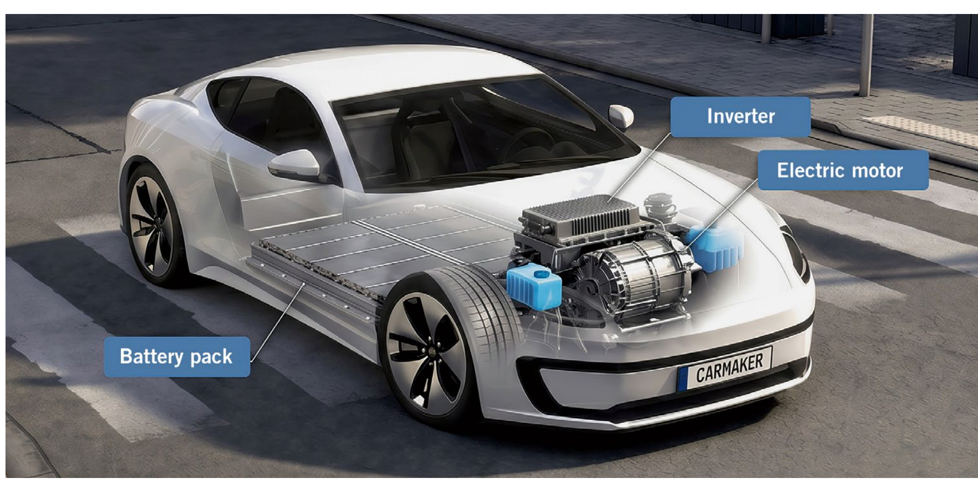

FIGURE 1 Schematic diagram of a battery-electric vehicle showing the traction inverter, electric motor and high-voltage battery as the central components of the electric powertrain (© [M] IPG Automotive | Persystems)

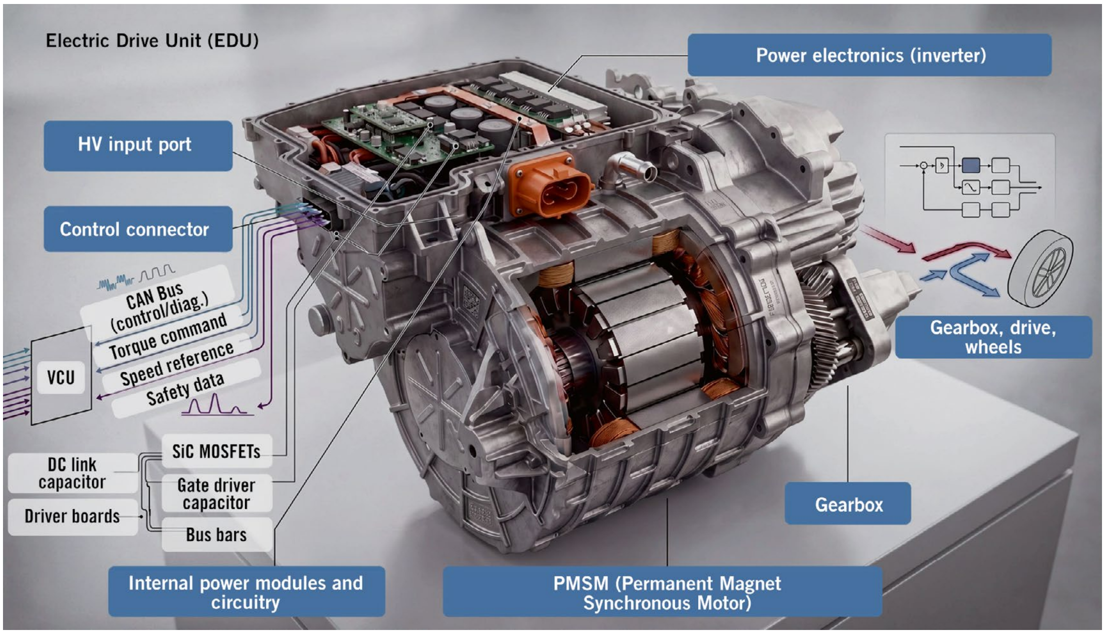

FIGURE 2 Integrated electric drive unit with power electronics, traction inverter, permanent magnet synchronous motor and transmission (© IPG Automotive I Persystems)

tem, such as battery models or line impedances, can be considered, creating a consistent map of the energy system. Control structures such as torque controls can be linked directly to the plant models. The structure-consistent, numerical formulation ensures efficient calculation, even for detailed models, without losing physical consistency. Existing legacy models can be adopted to a great extent.

SYSTEM INTEGRATION OF THE TRACTION INVERTER

A significant part of the innovation potential manifests on system integration level – the inverter control interacts with vehicle dynamics controls, brake systems, energy management strategies and superordinate vehicle controls. These functions directly access the torque provided by the inverter, so that the inverter becomes an active actuator in the vehicle dynamics control architecture. One relevant example is the coordination of electrical energy recovery and mechanical brake on the software side. Both systems must be closely coordinated to ensure reliable vehicle deceleration and maximum energy recovery. This task is managed entirely by the control software and requires fast and robust communication.

With the proliferation of multi-motor architectures, the importance of software-based integration continues to grow. Several electric drives require a coordinated control of multiple inverters for optimal torque distribution. For individual wheel drives, inverter control can directly contribute to the implementation of torque vectoring.

A crucial benefit of electric drives lies in their highly dynamic control systems. Power and torque controllers work within the milliseconds range and can react immediately to road conditions when coupled with vehicle dynamics sensor signals. The inverter software thus becomes a key element of modern traction and stability controls. In addition, suitable software control can increase the durability of drive systems by limiting power peaks, thermal loads and mechanical load changes.

These examples illustrate that the further development of electric drive systems is increasingly taking place at the software level of system networking. The decisive factor in this case is not the individual component, but the interaction of the control functions. Therefore, the ability to test and opti-

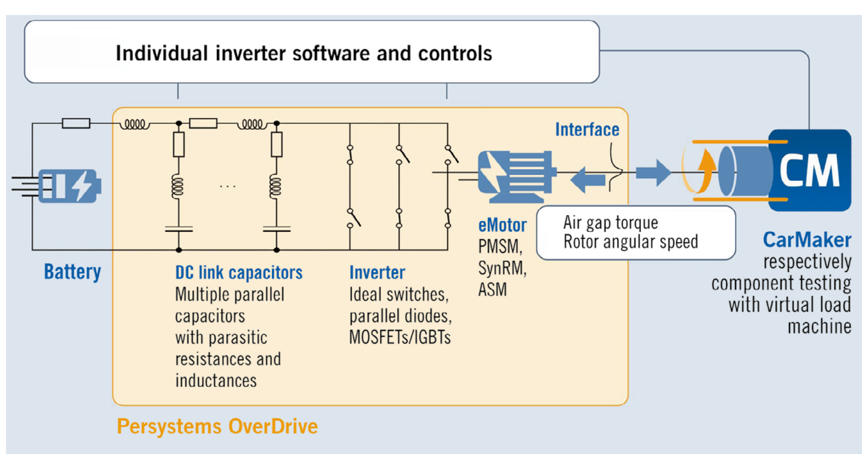

FIGURE 3 System architecture of the inverter software validation using structure-preserving electrical simulation (OverDrive) and integration into CarMaker (© IPG Automotive I Persystems)

mize inverter software quickly and close to reality plays a vital role in the development process of modern electric vehicles.

SOFTWARE ARCHITECTURE OF THE VALIDATION ENVIRONMENT

The requirements for fast and physically consistent simulations of electric drives demand a clear software architecture, **FIGURE 3**. This architecture combines three components: the physical simulation of the electrical system via OverDrive from Persystems, the integration into the full vehicle via CarMaker from IPG Automotive, which models vehicle dynamics, driving maneuvers and interactions with other vehicle systems, as well as the unit under test which primarily encompasses the inverter software with its open- and closed-loop control algorithms. Other control unit functions can be integrated as well.

This architecture enables testing of real control software with physically detailed electrical plant models in a virtual vehicle environment and creates a basis for fast inverter software validation. One advantage that the OverDrive-based electrical network simulation provides is the option to execute full test sequences in a short amount of time. The complete OverDrive-Only test catalog can be run on a standard 64-bit laptop in a few minutes.

In comparison, a hardware-in-the-loop validation with the same test scope takes much more time, while conventional offline simulations with a similar modeling depth require several hours of computing time, **FIGURE 4**.

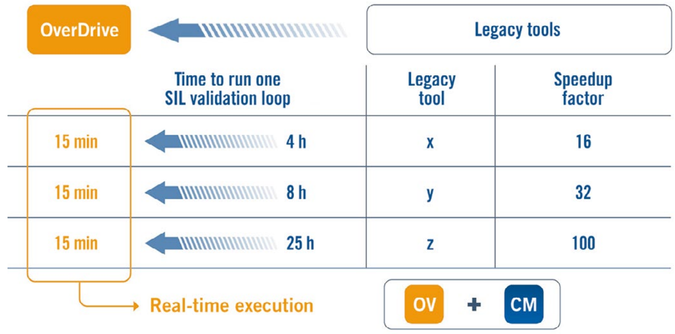

FIGURE 4 Acceleration of the software-in-the-loop validation cycle through structure-preserving electrical simulation on standard hardware (OV: OverDrive, CM: CarMaker; Reference: 12. Gen. Intel Core i7 (Alder Lake)) (© IPG Automotive | Persystems)

The achieved run time is hence a big leap forward in the validation of electric drive systems.

Considering the integration scenarios, the total duration of complete test campaigns is short in run time, so that extensive software validations with component and integration aspects can be carried out efficiently. This method enables complete and reproducible test campaigns and supports automated regression tests as well as iterative development processes with a high test frequency. The test catalogs defined in the study described here are modular and designed for automated processes.

The presented simulation methodology is not limited to traction inverters. Electric machines and power electronics are also used in other vehicle systems, for instance in steer-by-wire systems with safety-critical actuators or in active chassis with electromechanical actuators. As these systems have similar structures concerning power electronics, the structure-consistent simulation methodology can in principle be transferred to such applications and used to develop and validate the associated control software.

SUMMARY

The performance of electric drive systems is essentially characterized by the inverter software and its integration into the full system. SPAs in OverDrive enable physically consistent and efficient simulations of switching power electronics with detailed plant models. The integration into CarMaker enables testing in a virtual vehicle system. The OverDrive-only test catalog runs in around eight minutes on standard 64-bit systems, extensive test campaigns including integration scenarios in around two hours. This facilitates rapid software validation which achieves more frequent software tests, shorter development cycles and the transfer to other actuator systems.