Hardware-in-the-Loop Testing of Hybrid Vehicle Motor Drives at Ford Motor Company

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Abstract-This paper describes the usage of Hardware-In-the-Loop technologies at Ford Motor Company for the development of hybrid vehicle cars. At the heart of these HIL tests are models of electric motor drives. Several challenges exist in executing these models in real-time, especially in faulty or uncontrolled modes. This paper describes the key features of these drive models, as well as examples of HIL tests conducted with these models by Ford Motor Company.

I. INTRODUCTION

In recent years, steady increases in the cost of gasoline, coupled with the consumer's embrace of low-emission, environmentally-friendly technologies and more stringent government-mandated fuel economy standards has forced automotive designers to change the way they design current and future vehicles. This has lead to increased development of fuel-efficient electric and hybrid-electric vehicles that are not only more efficient than traditional combustion engine vehicles, but also offer the performance that consumers have become accustomed to. However, such development leaves automotive engineers facing significant design and engineering challenges.

To meet these challenges, automakers are developing a variety of electric and hybrid electric architectures that range from all-electric vehicles, to hybrids that incorporate technologies like fuel cells, to Plug-in Hybrid Electric Vehicles (PHEV). Such automotive design architectures rely heavily on new, complex power electronic, electrical and mechanical systems, which often must be designed, tested and integrated concurrently. Although these new technologies represent the future of the auto industry, they must also be engineered within ever-shrinking development times, within budget and with a high degree of quality and reliability. Indeed, this transformation of the automotive industry may represent one of the greatest engineering challenges of the 21st century.

HEVs may integrate a variety of propulsion sources, including gasoline/diesel, fuel cells, electric batteries and other alternative fuels. The management of multiple propulsion sources adds to a vehicle's design complexity and relies on Electronic Control Units (ECU), which play the key role in controlling powertrain functions. However, ECUs must undergo rigorous testing prior to on-road testing of prototype vehicles.

The validation and verification of ECUs for automotive powertrain applications is now typically conducted using Hardware-in-the-Loop simulation (HIL) [1][2][3][4][5]. By using HIL throughout the design process, beginning at the earliest stages possible, multiple systems that must be designed in parallel can also be tested, validated and verified in parallel. The result is a complete virtual vehicle simulation that enables full control strategy analysis prior to the development of costly prototypes.

The use of HIL simulation to simulate test conditions and vehicle behavior has resulted in reduced development times and costs, and higher quality HEV products. HIL simulation is used extensively at Ford Motor Company with these objectives. This paper will outline these testing efforts from Ford Motor Company along with the underlying model challenges related to HIL-simulation of electric drives.

II. HIL TESTING OF HYBRID VEHICLE MOTOR DRIVES AT FORD MOTOR COMPANY

Ford Motor Company dedicates considerable effort to improving the design of their automotive products using HIL testing technologies. These tests include all aspects of vehicle design including: engine control development, transmission control, body electronics, chassis control systems, traffic control & active safety systems and communication issues. Hybrid driveline design and control is one key aspect of the new generation of hybrid vehicle.

At the heart of the hybrid driveline is the electric motor drive. Although electric motor drive technology is very mature, its use in the automotive industry is new and extreme caution must be taken to ensure the safety and reliability of hybrid driveline designs meets the very high quality expectation of consumers. The HIL simulation of electric motor drives also comes with numerous challenges. Some of these challenges, along with corresponding solutions, are explained in the next section.

III. Real-Time Models and Challenges

In most hybrid vehicle designs, the permanent magnet synchronous motor (PMSM) is preferred because of high efficiency and high power density. Fig. 1 shows a typical PMSM drive: it is composed of a PMSM and a 3-phase IGBT inverter. In hybrid car applications, the inverter is typically driven by an HIL-connected controller with PWM frequencies in the 2-20 kHz range, and dead-time in the range of 2-20µs.
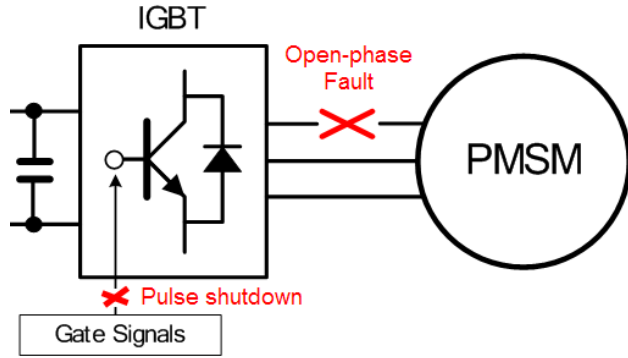

Fig. 1   A PMSM drive with possible fault points

The design of versatile real-time motor drive models that supports these specifications presents important challenges, some of which are explained next.

A. TSAM: Time-Step Averaging simulation method.

Simulation of this kind of drive is problematic for several reasons. Most notable of these is that the PWM signal driving it typically has a very high frequency. Also, some events, like dead-time, are shorter in duration than the achievable time-step of the simulator. More generally, electric motor drives have bandwidth that is sometimes several orders of magnitude higher than their ICE counterparts and therefore require much smaller simulation resolution (i.e., time steps).

The textbook approach to simulating a drive with events in the µs range would be to use a very small sample time (sub-µs range), but this is not realistic in a CPU-based approach. There are ways to get around this problem. One is to synchronize the simulation on the PWM period of the drive, read the PWM signal duty-cycle, and to use an average-model of the PMSM drive. This approach neglects the carrier component of the simulation and imposes some restrictions on the system to be simulated. So, how does one conduct an HIL test of a driveline with two PMSM drives for example, when the simulator can only synchronize with one?

A preferred approach is to use the 'Time-Step Averaging Method' (TSAM)[1][6][7]. In TSAM, the inverter conduction time is computed directly from high-definition sampling of the gate signals at the I/Os (Called Time-Stamped Digital Input). An interpolation method is used to ensure the inverter applies the correct voltage-time product at the PMSM (whose equations integrate this voltage into flux) and accurate results are obtained, even with dead-time of a shorter duration than the simulator sampling time. As a result, the carrier component is included in the simulation results.

Note also that the TSAM approach is required because of the limitation of achievable sample time with CPU-based computational engines. If the simulation of the drive is made on an FPGA, TSAM or synchronization techniques are not required because of the very low sample-time achievable on an FPGA, typically between 250 nanoseconds and 1µs [8].

B. Simulation with faults and uncontrolled modes

Another important aspect of HIL simulation is to test the behavior of the system in abnormal scenarios or control modes. Such scenarios are numerous, but the most common ones are:

➢   short-circuit or open-phase faults,

➢   controller emergency IGBT pulse shutdown,

➢   natural rectification by the diodes of the inverter.

In some of these cases, the HIL simulation approach is a particularly interesting and valuable alternative to testing with physical prototypes, since testing with physical prototypes at an early stage could result in costly damage to real devices.

The RTeDRIVE inverter model developed by Opal-RT for Ford Motor Company supports these working modes, which is not the case for standard average models. The RTeDRIVE inverter model supports 'high-impedance' mode in which the inverter output current can be forced to zero. This has important implications in faulty or rectifying modes.
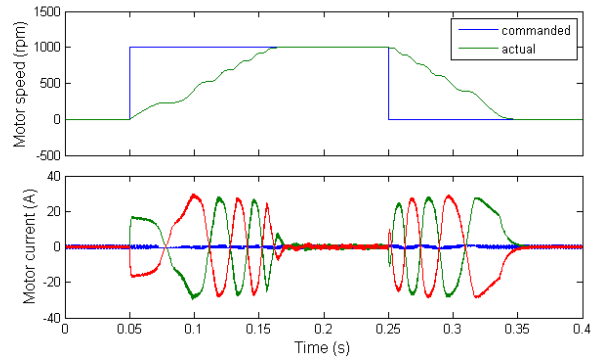

Fig. 2   Motor start-up with an open-phase condition.

An interesting faulty mode is when one phase of the PMSM is opened. In this degraded case, the drive can still produce accelerating torque. Fig. 2 shows a test in which the motor speed is increased to 1000 RPM and then decreased back to zero with an open stator phase. The simulation is made in real-time at 10µs time step and is in agreement with reference simulations made using SimPowerSystems models, See [6] for a complete description.

Natural rectification occurs when all IGBTs are turned off and the PMSM back-EMF is rectified by the anti-parallel diodes of the inverter. This back-EMF amplitude is proportional to speed and machine flux. When rectification occurs, the DC-link charges up and the motor produces a braking torque. For a DC-link voltage of 283V and a motor magnet flux of 0.2423 Wb, this rectification starts just above 2100 RPM for this motor with 3 pairs of poles. See [6] again, for a complete description of motor parameters used in this test.
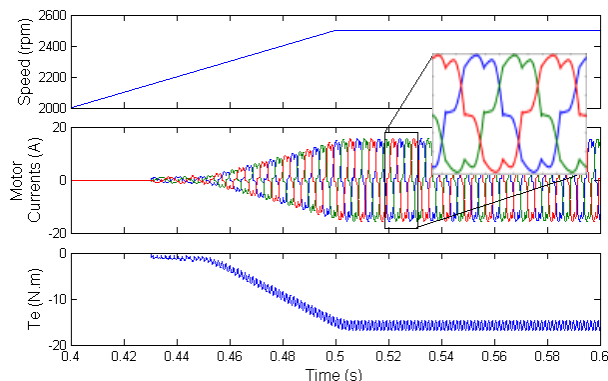

Fig. 3   Natural rectification mode with all IGBT gates OFF.

It is worth mentioning that native SimPowerSystems models could not be used here to achieve real-time simulation speed. This is especially critical with the inverter model of SimPowerSystems, which is too slow for real-time simulation.

C.   Simulation start-up issues

Another challenge that may seem deceptively simple is the simulation start-up. At start-up, the controller checks a wide variety of conditions to make sure it is properly connected. One of these tests consists of verifying that current sensor readings are near zero when the controller is not sending gate pulses to IGBTs. If the inverter model does not support high-impedance mode, the controller protection will engage at start-up.

Another interesting situation related to HIL simulation start-up is that the controller may put the IGBT gate output in hi-Z mode during initialization. In a real drive system, this places the inverter in an inactive high impedance mode. The situation can be different when the controller is interfaced with a real-time simulator.

Indeed, the signal conditioning stage of the Time-Stamped Digital Inputs of the real-time simulator is constructed using opto-isolators, as described in Fig. 4. The interface is used to obtain a galvanic isolation between the controller and the simulator. Care must be taken with this isolating stage. If the controller IGBT gate signals at 'Controller Digital Output' are zero, the 'internal digital input' (in the simulator) will also

be zero, as expected. But if the controller sets its output in hi-Z mode, the simulator will read a digital input of 1, because of the pull-up resistors. This condition must be detected correctly to ensure that the inverter is turned OFF during controller initialization.
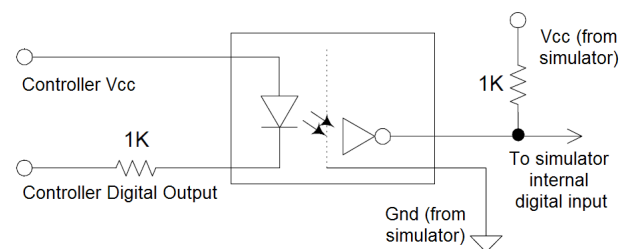

Fig. 4   Opto-isolation circuit of the real-time simulator

IV. EXPERIMENTAL TESTS CONDUCTED AT FORD

The RT-LAB HIL simulator has been used at Ford to test the next generation Fusion Hybrid vehicles, as well as other types of hybrid vehicles. These tests are described next.

A.   Electric drive configuration of Ford Fusion Hybrid

The Fusion Hybrid combines an internal combustion engine with an electric motor to produce traction. A 2.5 liter Atkinson cycle engine is the Fusion Hybrid's prime mover. It generates 156 horsepower and is coupled to a continuously variable automatic transmission. Electric power comes from a 106 horsepower AC motor, for a combined maximum output of 191 HP, all driven through the front tires.

A second starter/generator motor starts the gas engine and provides braking power, which is used to recharge the 275-volt nickel-metal-hydride battery pack. A simplified schematic of this hybrid configuration is depicted in Fig. 5.
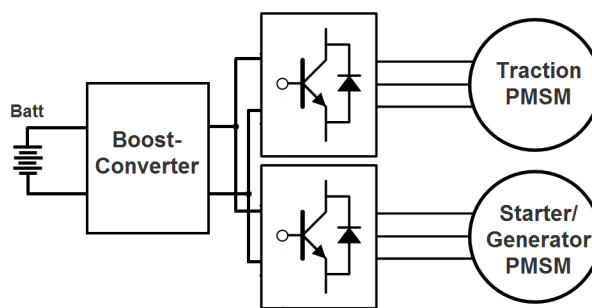

Fig. 5   Dual-PMSM hybrid motor drive configuration

In this topology, the boost-converter is controlled to provide sufficient voltage, in case high power is commanded to the traction motor, and similarly in case there is a need to recuperate energy by the 'Starter/Generator PMSM' (ex: regenerative braking). Consequently, both PMSM motor drives must include the variation of this DC-link voltage into the computation of their modulation index.

B. HIL simulator configuration

Hardware architecture

The real-time power system simulator used is an RT-LAB system from Opal-RT Technologies. RT-LAB is an integrated software and hardware system comprised of multi-core processors (dual quad-core Intel i7 processors) and FPGA-based I/Os.

High-density re-programmable FPGA-based I/Os are used to provide for up to 256 channels of time-stamped digital I/O with a resolution as low as 10 nanoseconds or 128 fast 16-bit analog converters with 1µs conversion times. The FPGA card also allows embedded simulation of PMSM motor drives.

The production controller was attached to the real-time simulator and tested accordingly, as if it were attached to the real driveline.

Software Architecture

The real-time kernel of the RT-LAB simulator used at Ford is QNX. Red Hat Linux is also supported as a real-time OS. These optimized RTOS now enable simulation sample times as low as 7 µs with I/Os.

The simulator comes with the RTeDRIVE Simulink library to provide real-time compatible inverter and PMSM models. Real-Time Workshop is used to generate real-time code to the simulator. Alternatively, Xilinx System Generator can also be used to generate high-level models [8] targeted at the FPGA boards of the Opal-RT simulator (Spartan-3 or Virtex-5).

Model Separation on the Multi-core RT-LAB Target

To obtain the maximum simulation speed, the model is distributed across the 4 cores available on the RT-LAB target, as depicted in Fig. 6.
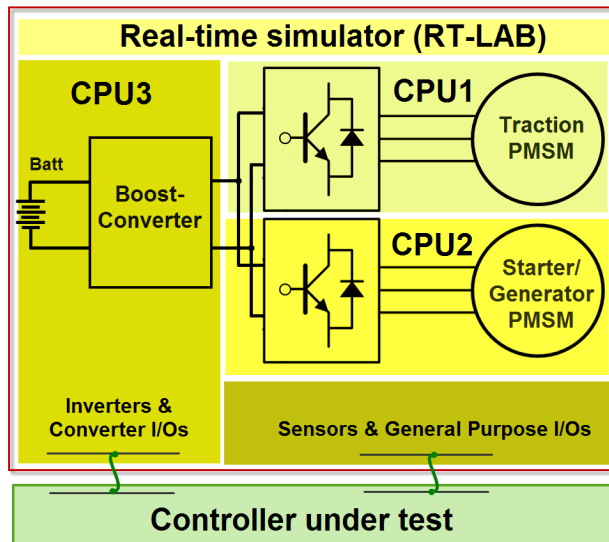

Fig. 6   Task separation of the model

Each motor drive is allocated a core, then the boost converter circuit and all the power electronics I/Os are put in a 3rd core. The 4th core is used for general purpose I/Os and sensor I/Os.

C. Test cases

Several tests were conducted in-situ at Ford Motor Company to verify the effectiveness of the control strategy, as well as some basic protection schemes, such as over-current protection.

In order not to show detailed control strategy and calibration, the data presented here only shows the capability of the HIL system rather than exact numbers in physical system. In the boost converter tests for example, as opposed to the real Fusion Hybrid battery (275 V), the battery voltage is set to around 100V and it is boosted in the 200V range.

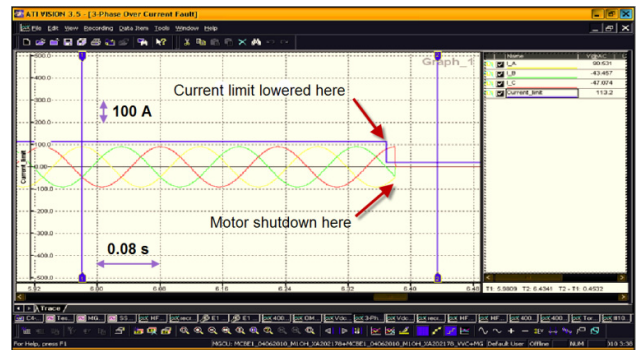Test 1: Phase over-current detection

Fig. 7   Current limit check test

This test aims to verify that the motor will shutdown if a current limit is exceeded. In the test, motor speed is commanded at 100 RPM, and then the current limit is lowered. As shown in Fig. 7, the motor current goes to zero when the current limit is lowered, making the motor current exceed the limit and causing inverter shutdown.

Test 2: Boost converter action caused by speed increase

For this test, the motor initially turns at 1000 RPM with no torque applied. Then the speed is increased to 7000 RPM.
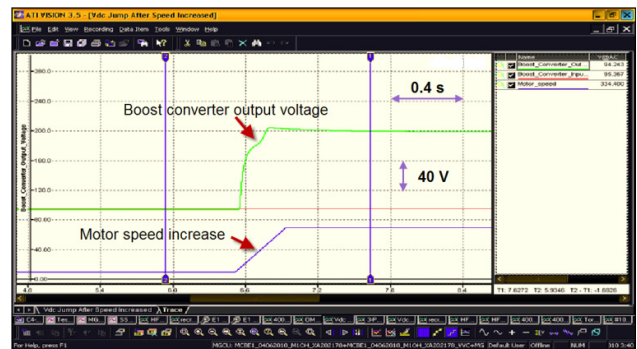

Fig. 8   Change speed causing boost converter start

The boost converter output voltage then goes from 100V to 200V. This is depicted in Fig. 8.

Test 3: VVC boost by changing torque command

In this test, the motor initially runs at 1000 RPM and null torque command. Then, the torque command is modified to 75 N.m. As a consequence, the boost converter output voltage goes from 100V to 165V. This test result is shown in Fig. 9.
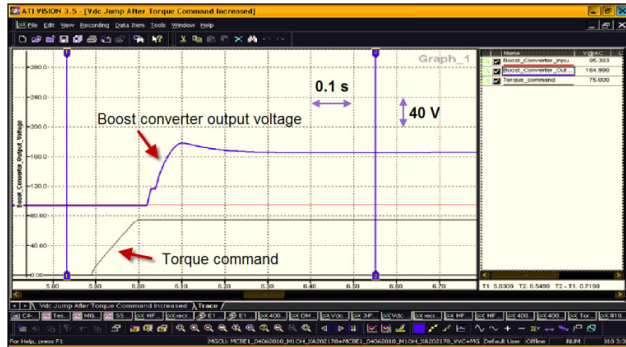

Fig. 9   Change of torque command so boost converter starts

CONCLUSION

Thorough testing of motor drive and driveline is a crucial part of hybrid vehicle design. HIL-based testing using a real-time simulator offers an efficient way to conduct these tests.

Because of the high bandwidth of electric motor drives, it is necessary to simulate them with very small sample times. In addition, special inverter models were designed using the TSAM approach. These models are based on the switching-function approach, but also support non-standard modes like open-phase faults and natural rectification modes.

Used in a high-performance real-time platform, these models enable Ford Motor Company to conduct numerous HIL tests on the Ford Fusion Hybrid motor drive controller.

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