

Electric Drive Transient Behavior Modeling: Comparison of Steady State Map Based Offline Simulation and Hardware-in-the-Loop Testing

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ABSTRACT

Electric drives, whether in battery electric vehicles (BEVs) or various other applications, are an important part of modern transportation. Traditionally, physics-based models based on steady-state mapping of electric drives have been used to evaluate their behavior under transient conditions. Hardware-in-the-Loop (HIL) testing seeks to provide a more accurate representation of a component's behavior under transient load conditions that are more representative of real world conditions it will operate under, without requiring a full vehicle installation. Oak Ridge National Laboratory (ORNL) developed such a HIL test platform capable of subjecting electric drives to both conventional steady-state test procedures as well as transient experiments such as vehicle drive cycles. This facility was used to compare the behavior of an electric drive installed in a BEV with the two methods: offline simulation built from the experimental steady state efficiency map, and HIL experimentation of the same electric drive simulating the same BEV. The aim of this study is to evaluate the accuracy of steady state map based simulation against experimental HIL results in the case of an electric drive. This paper first outlines HIL test procedures as well as the key aspects of utilizing steady-state maps to develop a model of the drive. Then both quantitative and qualitative differences in the experimental results obtained from the two processes are presented. Differences in specific transient behaviors between the two methods are discussed. Although both methods agree well in most transient situations, direct comparison of the offline simulation against the HIL results demonstrates that transient behaviors are not captured entirely by simulation alone.

CITATION: Chambon, P., Deter, D., Smith, D., and Bauman, G., "Electric Drive Transient Behavior Modeling: Comparison of Steady State Map Based Offline Simulation and Hardware-in-the-Loop Testing," *SAE Int. J. Passeng. Cars – Electron. Electr. Syst.* 10(1):2017, doi:10.4271/2017-01-1605.

INTRODUCTION

In a world of increasing environmental concerns and tightening government regulations on vehicle efficiency, battery electric vehicles, as well as hybrid vehicles, provide an attractive alternative to standard internal combustion engine powered vehicles. Since BEVs naturally exist in a highly dynamic operating environment, it is crucial for manufacturers to possess a method to characterize the dynamic behavior of the electric drive they are installing in their vehicles. For the purpose of this paper, an electric drive consists of an electric machine, its inverter and associated control algorithms. This process of testing an electric drive for its transient behaviors can be performed using a number of different methods.

The conventional way to characterize an electric drive is to undergo testing coupled to a dynamometer. Electric drives can be tested through several steady-state conditions in order to generate data for various operating conditions. This allows for torque curves and efficiency maps to be generated. One alternative to time-consuming dynamometer testing of an electric drive is developing an offline physics-based model to represent the electric drive inside of a BEV

[1]. By simulating both the electric drive and the rest of the vehicle, rapid tests can be performed to assess its performance in a large variety of situations and applications. To capture the behavior of the real electric drive in the simulation, characteristics calculated from limited dynamometer testing such as steady-state testing can be built into the simulation.

HIL testing provides a combination of simulation and physical testing, a physical electric drive communicates with a simulated vehicle environment that allows the electric drive to be tested with the flexibility of an offline simulation. One benefit to this arrangement is that no part of the electric drive is simulated, therefore all of its inherent characteristics and behaviors are captured by HIL testing, which eliminates any errors that may be made by a purely offline simulation due to incomplete representation of the electric drive physics or controls. This paper will describe the procedure used to test both methods, list the alterations made to optimize the simulation, and compare the results of an offline simulation with HIL testing.

ORNL VEHICLE SYSTEMS INTEGRATION LABORATORY

The facility used to conduct this study is the Vehicle Systems Integration (VSI) laboratory located at the National Transportation Research Center (NTRC), a part of Oak Ridge National Laboratory (ORNL). This laboratory consists of two test cells equipped with dynamometers, a dedicated battery emulator, dSPACE real-time HIL platforms, and associated instrumentation. The first test cell can handle up to a class 8 truck powertrains, whereas the second cell is designed for smaller powertrain components. The latter was used for this paper due to its focus on component-level testing. A 250 kW low-inertia AVL dynamometer is able to absorb and push torque from the unit under test while controlling its speed and measuring the associated torque. The dSPACE HIL platform handles the real time modelling of virtual components as well as the interface with the components physically present in the cell. This interface is capable of recreating and transmitting every signal that a component or system is expecting in a vehicle such as sensors, actuators and communication networks, allowing it to behave exactly how it would in a real application. The battery emulator allows the HIL environment to accurately recreate almost any battery or energy source behavior while requiring none of the extensive charging times. Temperature control of the test cell is also available in order to provide a consistent testing environment. Figure 1 provides a view of the VSI lab test cells.



Figure 1. Rendering of the ORNL VSI laboratory test cells. The test cell used in this paper sits in the foreground but both cells share the battery emulator (blue cabinet) on the mezzanine

OFFLINE SIMULATION ENVIRONMENT

The offline simulation environment used for this study is Mathworks Simulink but the vehicle architecture and its parameterization was generated with Autonomie, a vehicle modeling program developed by Argonne National Laboratory. For this project, it provides a physics-based model for a two-wheel-drive BEV as seen in Figure 2. Individual vehicle systems such as the electric drive, energy storage system (ESS), and supervisory controls are modeled in separate “blocks” and their interactions can be readily analyzed or altered. A driver block inside the model follows a pre-determined vehicle speed trace provided by the test cycle that the simulation is running. Vehicle parameters such as final drive ratio, rolling resistance, mass, and drag are integrated into relevant blocks in the model to accurately

represent the target vehicle. By changing the test cycle, the simulated vehicle can be tested under a large variety of different conditions that include both transient and steady-state operations. This ability to rapidly test any engine, powertrain, or vehicle in numerous different situations is one of the most important benefits of simulation in comparison to real world testing.

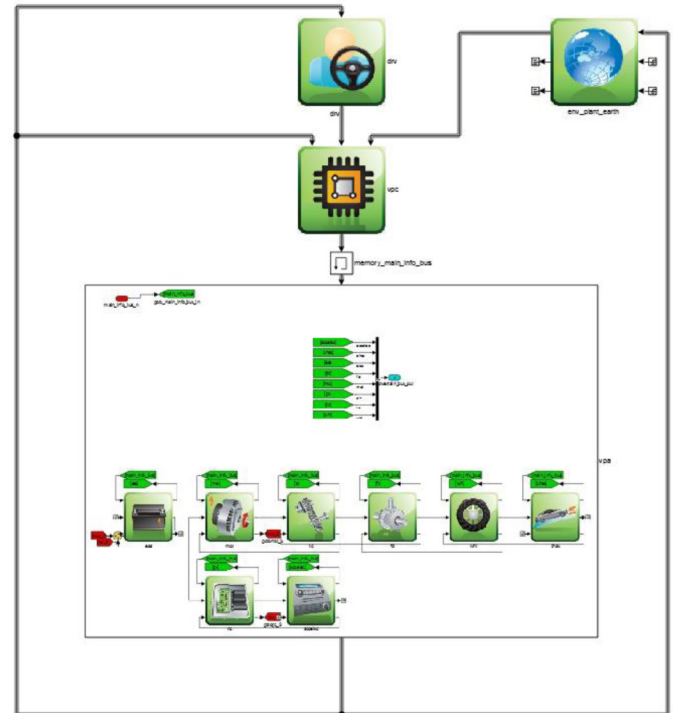


Figure 2. Simulink model of BEV

Electric Drive Steady State Mapping

Essential to obtaining accurate simulation results is representing the electric drive effectively in the simulation. The conventional method of achieving this is to obtain efficiency maps of the electric drive through steady-state testing of the physical components [2, 3].

The TM4 HSM 120 motor and CO150 Motor Control Unit (MCU) were selected as the electric drive for this study. The MCU combines the inverter and the controller into one unit. They were commissioned in the VSI lab component test cell as shown in Figure 3.

Starting from the manufacturer’s specifications a test plan was defined. It consisted of generating motoring and regenerative torque curves as well as steady state mapping spanning the practical operating speeds of the motor up to 10,000 rpm. Using the dynamometer to hold the motor at the desired speed and commanding a specific amount of torque from the MCU through the inverter CAN interface. Torque outputs ranging from -180 Nm to $+180$ Nm in 10 Nm increments were tested. Motor speed increments were 500 rpm. For all mapping tests, voltage was held constant at 350V by the battery emulator. Speed measurements came from the dynamometer speed encoder. Torque was measured with an HBM T40B torque flange and MCU current and voltage inputs were instrumented with a Hioki 3390 power analyzer.



Figure 3. TM4 HSM 120 motor and CO150 motor control unit installed in ORNL's VSI lab component test cell

Electric Drive Model

The experimental electric drive efficiency map generated by the steady-state testing was post processed before being inputted into the offline simulation. One issue with the experimentally generated data is that the actual torque can be slightly different than the commanded torque. For example, instead of generating exactly 10 Nm of torque, the electric drive might have experimentally generated 10.56 Nm. In order to obtain efficiency data points at precisely 10 Nm increments, a linear interpolation of the experimental data is performed. This resulting efficiency map captures positive motor speed efficiencies for propulsive and regenerative torques and has breakpoints that are exactly 500 rpm and 10 Nm apart. The efficiency map is mirrored symmetrically to represent efficiencies for negative motor speeds. Although negative motor speeds will not occur in the test cycles used for this study, the Simulink model requires efficiency maps in this four quadrant format. Figure 4 shows the resulting efficiency map after all necessary adjustments have been made. During offline simulation, the model performs another linear interpolation to determine the efficiency of the simulated torque demand and motor speed between breakpoints. The dynamic response of the electric drive is represented by the time constant of a first order filter.

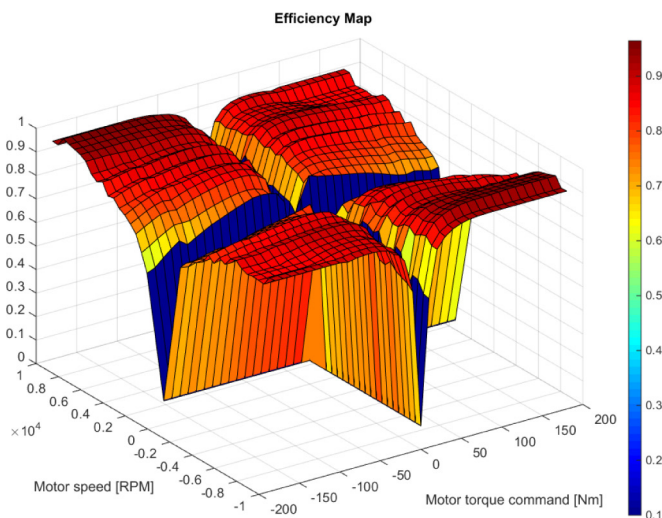


Figure 4. Experimentally generated efficiency map of the electric drive

Vehicle Model

In order to match the electric drive size, the modelled test vehicle for this study is a small sedan vehicle. The model of a Nissan Leaf previously validated with experimental data was used as the starting point and modified to receive the HSM120 electric drive experimental data. Since the purpose of this study was to analyze transient behaviors, the simulation was run on five different test cycles: the EPA Urban Dynamometer Driving Schedule (UDDS) cycle, the Highway Fuel Economy Test (HWFET) cycle, the US06 cycle, the Air Resources Board (ARB) Transient cycle, and the World Harmonized Vehicle Cycle (WHVC). Six types of metrics were extracted for the electric drive on each of these test cycles: total, positive, and negative mechanical energy as well as total, positive, and negative electric energy.

HARDWARE-IN-THE-LOOP TESTING

Principles of HIL

Hardware-in-the-Loop testing has become an integral part of the automotive industry's process for testing and developing components or vehicle systems. The value of HIL testing on components such as electric drives, hybrid controllers and batteries [4, 5, 6], as well as for control algorithms development [7] has been thoroughly demonstrated. Manufacturers and researchers are drawn to the numerous benefits of HIL testing that include rapid performance testing, simpler and safer controls development, convincing repeatability, and powerful flexibility to test a variety of vehicle architectures or test conditions.

A virtual testing environment that interfaces with physical components is what makes HIL such a powerful tool for developing or characterizing vehicular systems. Figure 5 gives a representation of how this virtual environment interfaces with the physical components. Physical components "believe" that they are in a real vehicle and exhibit the same behavior they would under real-world circumstances. Depending on the needs of the specific experiment, the virtual environment can include as much as an entire simulated vehicle or as few as a handful of simulated components.

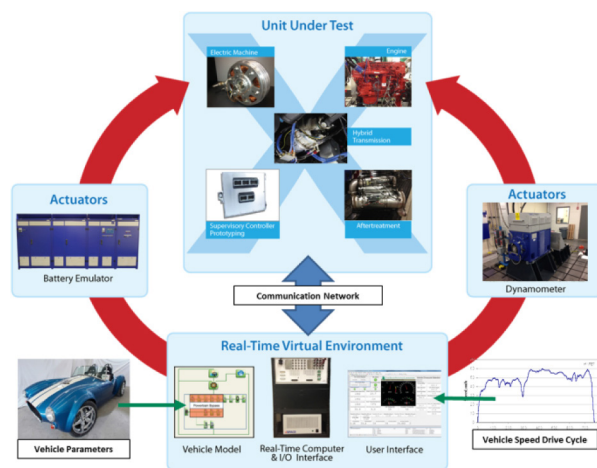


Figure 5. Hardware-in-the-Loop principle.

