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Model-Based Design and Testing for Electric Vehicle Driveability Analysis

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***Abstract*—In this paper a model-based design and testing method focusing on the electric vehicle driveability aspect is proposed. The design approach is divided into two steps. The first step is the Model-in-the-Loop co-simulation coupling a vector-controlled electric drive modelled in MATLAB/Simulink to a planar forward-facing electric vehicle LMS Imagine.Lab Amesim model. The second step represents a mechanical-level Hardware-in-the-Loop test for a physical electric drive that integrates the electric vehicle model in the real-time testing case. Two different sampling times of the vehicle control unit are considered and their influence on the vehicle responsiveness and on the longitudinal jerk acting on the driver is analysed through both offline simulation and real-time testing.**

Keywords—Model-Based Design; Electric Vehicle; Driveability; Hardware-in-the-loop; Model-in-the-loop

I. INTRODUCTION

The growth of the hybrid and electric vehicle (EV) market due to environmental concerns generates a need for rapid development of ad hoc electromechanical components. To achieve this objective, physics-based system engineering can be merged with control engineering from a very early design stage by means of virtual prototyping and testing [1,2].

Design techniques proposed in the literature combine signal flow modelling for control design (signal simulation) with physical modelling in various domains (e.g. the interaction between electro-mechanical components) for system design [3,4]. Tests can be conducted at signal, power and mechanical levels in order to evaluate the controller, the combination of controller and power electronics and the whole electrical drive respectively [3,5].

The electromechanical system development and the control system development adopt the ”V” approach that resumes to propagate the system level requirements to component design and validate the system performance at increasing interrogation levels [1].

Because driveability is a subjective standard depending on human-vehicle interaction, and therefore usually needing a real person for evaluation, incorporating it in the design process represents a cost-saving benefit by decreasing the time to market of the designed product [6].

This research aims at acquiring a deeper insight in such EV modelling and testing procedures by introducing the interaction between the physical e-drive with the vehicle model during its design process. The focus is on testing the effects of the Vehicle Control Unit (VCU) control strategy on the driver’s comfort.

II. METHODOLOGY

The proposed approach enhances the closely related, concurrently submitted work [7], where a Model-Based Design (MBD) approach is adopted for testing the battery energy consumption under different reference driving cycles on a forward-facing EV model. A driver model taking the role of a PI controller assesses the vehicle speed and gives acceleration and braking commands to the VCU, consequently translating these signals into electric motor torque commands and mechanical braking.

Because the EV model has a gearbox with a fixed gear ratio resulting in no gear shifting effect, the main component that has an influence on the vehicle driveability is the VCU with its control strategy.

By adding additional vehicle dynamics to the model (i.e. longitudinal wheel slip, longitudinal stiffness and damping on the suspensions) we can monitor and adjust the torque response imposed by the VCU in order to keep the longitudinal jerk acting on the driver within acceptable comfort limits.

The approach is divided in a MBD phase and a testing phase of an EV system characterized by Model-in-the-Loop (MiL) and by Hardware-in-the-Loop (HiL) implementation, respectively (Fig. 1).

As noted in [1] MiL consists of combining multi-physics simulation software with control software in an offline environment, whereas in HiL hardware components are tested while their environment is emulated in real-time on an embedded platform. The MiL process starts prior to HiL testing and can be used in a later development stage to further fine-tune the HiL testing in a safe and rapid fashion.

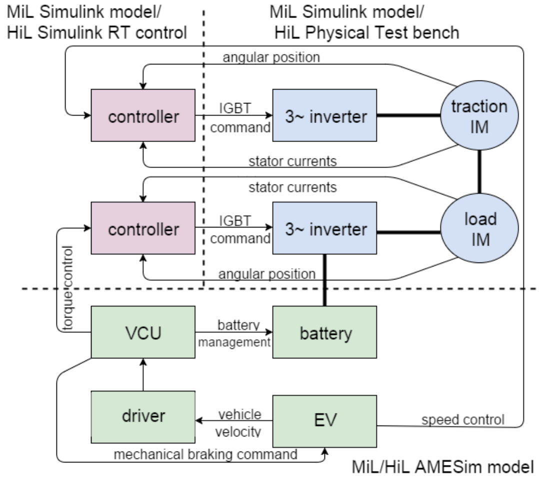

Fig. 1. Diagram of the MiL and HiL co-simulation process

The MiL consists of a co-simulation approach where the LMS Imagine.Lab EV and environment model is imported as an interface block into a MATLAB/Simulink model of two mechanically-coupled, indirect-field-oriented-controlled (IFOC) induction-machine (IM) drives. One machine is torque controlled and represents the EV propulsion system while the other one is speed controlled and represents the EV load (i.e. the speed reference imposed by a roller in a real vehicle test-bench). Simulink's fixed step solver clocked at the simulated IGBT transistors switching frequency of 8 kHz (in order to mimic the conditions of the real-time test-bench) runs the whole co-simulation process.

LMS Imagine.Lab Amesim is an integrated simulation platform for multi-domain mechatronic systems that is strongly connected to the physical understanding of the phenomenon described [8].

For the HiL stage, physical machines and inverters replace their corresponding Simulink models. The test-bench consists of two mechanically-coupled 45 kW, 8-pole IMs (extended parameters are presented in TABLE I.) powered by two modified FPGA-controlled inverters. The electric drive control strategy is the same as in the MiL stage, however its implementation on the test-bench takes into account the real-time requirements of rapid control prototyping. The LMS Imagine.Lab Amesim model is integrated inside the control through a process of real-time file generation for the target PC running Xenomai, a Linux kernel real-time operating system.

TABLE I. INDUCTION MACHINE PARAMETERS

parameter	***value***	***unit***
rated Speed	735	rpm
number of phases	3	-
moment of inertia	2.55997	kg m^2
phase resistance	0.2718	Ω
rotor equivalent resistance	0.02474	Ω
stator leakage inductance	0.001595	H
stator and rotor inductance	0.052872	H
magnetizing inductance	0.051276	H

For driveability concerns we need to model the planar motion of the vehicle (a model that has 3 degrees of freedom: pitch rotation, longitudinal translation and vertical translations) together with the suspension dynamics. The following modelling assumptions are taken in consideration: the engine block and longitudinal suspensions are considered blocked.

Because the parts through which the reaction force generated by the force applied on the road through the tyre is propagated have an influence on the vehicle's dynamic behaviour [9], they have to be modelled as well (Fig. 2):

- Flat road model - with the value of the adherence equal to 1;
- Wheels and tyres model - the simplified Pacejka model with a dynamic method of longitudinal slip calculation;
- Planar vehicle suspension - having stiffness, damping and unsprung mass as parameters;
- Differential - ideal model, with no inertia or friction.

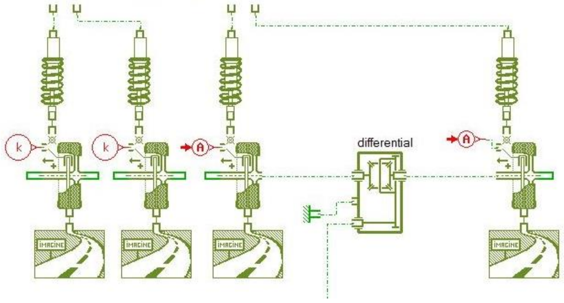

Fig. 2. Vehicle suspensions, tyres and differential submodel in LMS Imagine.Lab Amesim

III. SIMULATION AND EXPERIMENTAL RESULTS

As mentioned in [10], in order to achieve real-time capabilities the offline model has to be reduced to the point where the results converge to those of the real-time testing scenario. This can be obtained with ease, in the MiL stage, by using the Performance Analyzer tool inside LMS Imagine.Lab Amesim. Its aim is to gather information about the model in order to assess and improve the performance of the solving process (e.g. the frequency at which the damping of the planar vehicle suspension is varying inside the model can be correlated to the integration step size in order to obtain accurate real-time results).

Using two different values for the VCU control (see Fig. 3.) sampling period, serving as the filtering time constant for the torque command (0.1 and 0.2 s), the reaction of the VCU to the acceleration command imposed by the driver in order to produce the desired mechanical characteristics is investigated.

The sampling period can be characterized as the latency to which the driver reacts to the test stimulus (i.e. the reference speed profile).

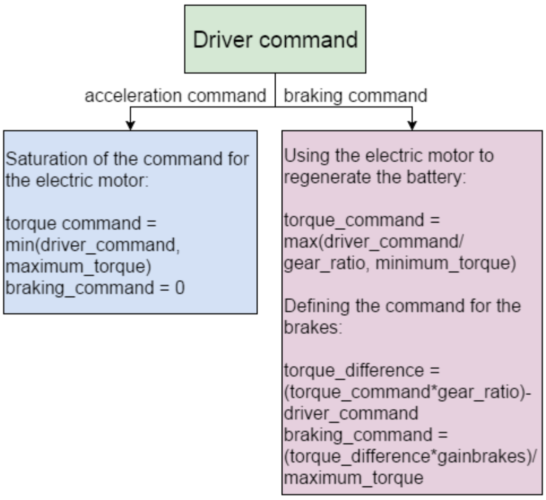

Fig. 3. VCU torque and braking command algorithm in LMS Imagine.Lab Amesim (pseudocode)

It can be noticed in the diagram that a maximum torque control strategy is applied, where the acceleration command of the driver (ranging from 0 to 1) is translated to a torque command, where the pedal signal of 1 sets the electrical machine torque command to the maximum motor torque defined in a data file.

Simulation and experimental tests are conducted to assess driveability and vehicular responsiveness and compare the MiL and HiL results.

Because driveability is determined by the behaviour of the powertrain especially in transient situations [6], the first tip-in stage of the New European Driving Cycle (NEDC) where the vehicle accelerates from 0 to 4.16 m/s in 4 s is taken as test stimulus.

The monitored variables for the MiL and HiL are the IM rotational speed (calculated in the offline model and measured on the test-bench in real-time with an incremental encoder) IM torque (calculated in the offline model and estimated in real-time based on the measured phase currents and shaft angle position) describing the vehicle's responsiveness and smoothness, and the estimated longitudinal jerk on the car body describing the driving comfort.

The first value for the sample time constant taken into consideration is 0.2 s. It can be noticed that, in both the offline and real-time test cases, the driver reaction is too slow for the initial change in the speed reference (the beginning of the tip-in phase) leading to a mechanical torque overshoot in order to compensate for the slow reaction. The obtained mechanical parameters are not in line with the desired smoothness and responsiveness for the electric machine and produce a significant longitudinal jerk on the modelled car body (approximate 12 m/s^3 at the beginning of the tip-in stage and -7 m/s^3 when the acceleration stops in the online test).

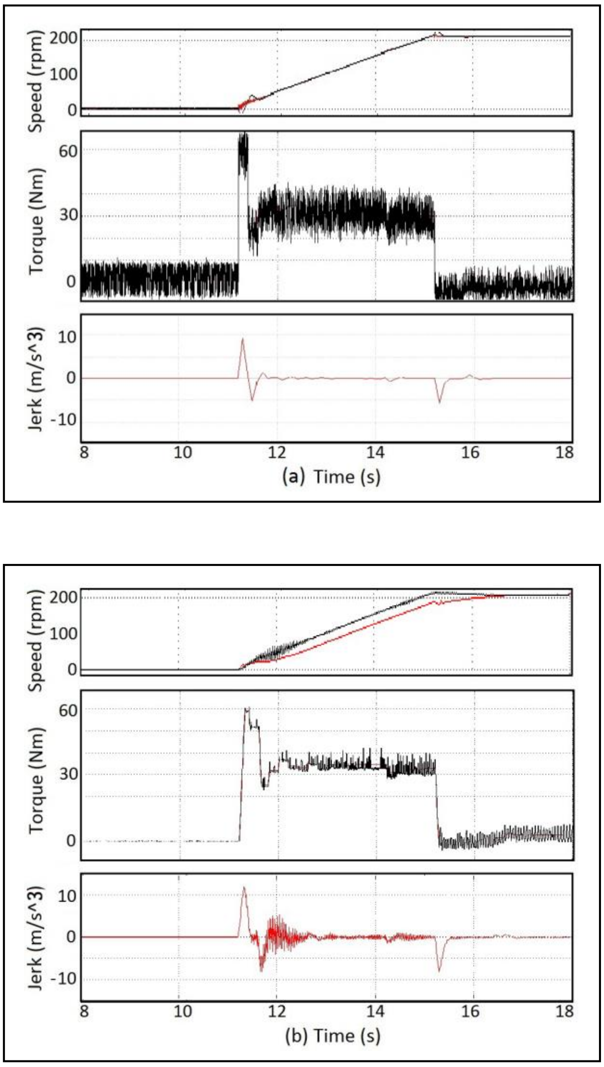

Fig. 4. Mechanical parameters and longitudinal jerk results for 0.2 s VCU sampling time, in the MiL (a) and HiL (b) tip-in stage (first 18 s of the NEDC cycle)

After reducing the sampling period to 0.1 s a decrease in the longitudinal jerk to a reasonable value (approximate 7 m/s^3 at the beginning of the tip-in stage and -4 m/s^3 when the acceleration stops in the online test) and the presence of a smoother mechanical parameters response (a less visible torque overshoot), in both MiL and HiL test scenarios can be noticed, as exemplified in Fig. 4.

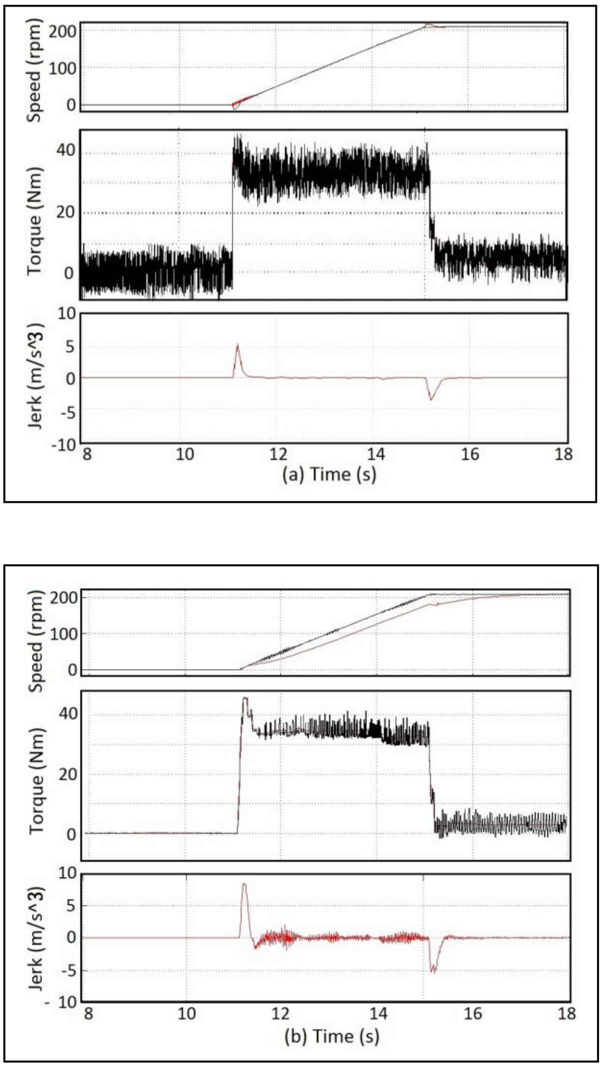

Fig. 5. Mechanical parameters and longitudinal jerk results for 0.1 s VCU sampling time, in the MiL (a) and HiL (b) tip-in stage (first 18 s of the NEDC cycle)

Another important remark is that by cross-checking the results for the two tested VCU sampling times, from the MiL simulation with the ones of the HiL test a good agreement between the different variables can be noticed. This represents a confirmation that electric vehicle comfort model behaves in the same way in offline and real-time cases, thus having real-time capabilities The values of the longitudinal jerk and the mechanical torque are slightly lower in the MiL simulation because of the simplification made to the mechanical parameters (e.g. ideal inertia, viscous forces) and the difference in the complexity of the current PI controllers in the MiL simulation and HiL testing.

IV. CONCLUSION

As a conclusion, a method of estimating the driver comfort and the EV driving response in order to meet comfort demands, using an experimental approach based on calibrating the sampling time of the VCU command algorithm, in MiL and HiL EV design stages is proposed.

The co-simulation approach is preferred due to the advantages of combining control engineering provided by MATLAB/Simulink and system engineering provided by LMS Imagine.Lab Amesim in the simulation stage, and the ease of integrating both the control and system model in the HiL test-bench for validation purpose.

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