State of the Art of Real-Time Hardware-in-the-Loop Simulation Technology for Rail Vehicles

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Abstract

Due to the increased complexity of the control system in modern locomotives real-time hardware-in-the-loop simulation is of considerable importance for controller design and integration test of the complete control system. In this contribution the general structure of the electrical traction drive systems of locomotives and the principal requirements for simulation of such systems in real-time mode are introduced first, and then the state of the art of simulator hardware, modeling technique and numerical computation are reviewed, and third of all technical trends are pointed out.

1. Introduction

Nowadays modern electrical locomotives are powered by converter-fed AC motors and controlled by digital controllers. Since dynamics of such traction drive systems are determined not only by power components, but also by distributed computing, inter-controllers communication and real-time capability of control software, a simulative investigation and an integration test of such systems are order of magnitude more complex than those in previous generations. Based on conventional simulation platforms on non-real-time mode the real-time effects of the control system and the effects of controller hardware cannot be studied. In order to achieve a maximum test depth at a minimized risk and cost, a real-time hardware-in-the-loop (HIL) simulation system is of considerable importance. Using it, closed-loop behaviors of the traction drive system can be simulated utilizing the original traction control unit [1– 4].

In this contribution the general structure of the traction drive systems in modern electrical locomotives and the principal requirements for simulating such systems in real-time mode are introduced in Section 2. The historical and recent developments of hardware technologies in real-time HIL simulation are reviewed in Section 3. Techniques in modeling and numerical computation of electrical traction drive systems are discussed in Section 4. In Section 5 conclusion and technical trends are summarized.

2. Overview of Traction Drive Systems and General Requirements for Simulation

The traction drive system for one bogie of a typical freight locomotive is shown in Fig.1, which is split by a DC link circuit into two parts: the line-side part and the motor-side part. The line-side part consists of a traction transformer, three parallel-connected line converters (four-quadrant converters, 4QC), which has the task of converting a 50 Hz / 25 kV single-phase AC voltage into

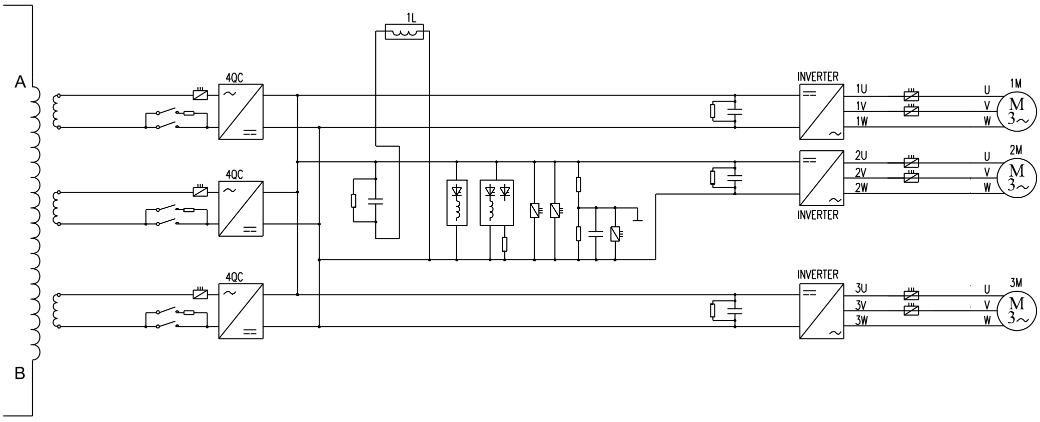


Fig. 1. Main circuit of the electrical traction drives system for one bogie.

a quasi constant DC voltage. The motor-side part consists of three traction motors powered by traction inverters, which convert the DC voltage into three-phase AC voltage with variable voltage magnitude and variable frequency (VVVF), which is suitable for supplying the induction motor drives. The energy flow conducted by the 4QC is not exactly balanced at any time instant. The difference is either stored or supplied by the DC link circuit.

In order to support the controller design and integration test controllers in HIL mode, the following principal requirements in simulation system are indispensable:

- **Real-time computation with fixed simulation step-size:** Since the real traction control unit (TCU) of locomotives has a control cycle time of about 40 to 60 µs, a very small fixed simulation step size less than 40 µs is required. Within this time frame, the I/O operation of the simulator should be fulfilled and the entire simulation model of the traction drive system shall be computed to the next simulation step. Hence, high-speed processors and high-speed I/O hardware, incl. digital analog converter (DAC), I/O board for capturing of PWM signal and for simulation of position sensors, are required.
- **Parallel computation:** Due to the large scale and higher bandwidth (in comparison with mechanical systems) of electrical traction drive systems utilization of multiprocessor technique and ultra high-speed inter-processors communication technique are indispensable.
- **Modular and extensible structure:** A modular and extensible structure in hardware as well as in software is usually required so that the simulation system can be easily rebuilt for other rail vehicle applications.
- **User-friendly programming interface:** Because the end users of the simulator are typically railway vehicle experts, who are not experts at real-time simulation technique, user-friendly graphical and block-oriented interface for system modeling is usually required.

3. Hardware Technologies

A. Analog Processor-Based Simulator

The concept of real-time HIL simulation was first used in rail vehicle industry in the early 1960s. The simulator was based on analog technology. A representative of this generation is AD4-simulator from ABB Transportation Systems [2]. The heart of the simulator consisted of analog integrators (operational amplifier), which had very good frequency response characteristics and were used to fulfill the computational demands. Together with fast electronic switches and control-logic, the steady-state and transient behaviors of the traction drive system of locomotives were well simulated [2].

However, a major disadvantage of the analog processor-based simulators was the poor flexibility, reliability and stability with temperature. “Programming” the simulated system was done through hardwiring on a patch panel [2], which does not meet the requirement of user-friendly programming interface.

In order to overcome this drawback, a hybrid solution including digital and analog processors was developed in the mid-1980s. Thanks to the benefits of digital techniques a relatively comfortable and hardware independent programming environment were implemented. However, due to the computational limitation of digital processors in that time, the integrators, which are the most important computational parts, were implemented by analog technique [2, 3].

B. Digital Processor-Based Simulator

Since the mid-1990s the digital processors provided enough power to simulate rail vehicle traction systems. In comparison with the hybrid solution in 1980s, integrators were implemented full digitally. By utilizing modular hardware structure system flexibility and extensionality were achieved. In combination with advanced software technologies, user-friendly model-based graphical programming environments were implemented. Due to these benefits developing and maintenance costs are distinctly reduced.

One of the popular selected HIL simulators is from the German company dSPACE GmbH. These simulators are based on specially designed dedicated processor boards. Communications between processor boards are implemented by using Gigalink modules. Communication between processor boards and input/output (I/O) boards are implemented by peripheral high speed bus (PHS bus) [5]. Based on this simulator an electrical traction drive system of locomotives was simulated with simulation cycle time of 30 µs in real-time by Adtranz [3].

Another alternative to implement a digital processor-based simulator is using standard personal computers (PC) or PC cluster. In comparison with dedicated real-time simulators, the PC-based solution has great advantage in hardware cost. However, since PC systems are not specially designed for real-time applications, great challenges in I/O accesses, parallel distributed computation and hard real-time computation should be solved. In order to deal with these challenges, the Canadian company OPAL-RT Technologies developed a PC-based HIL simulation solution. Based on this solution, the high-speed inter-processors communication is implemented with shared-memory technique and the low-speed inter-processors communications are implemented with IEEE 1394 (Fire Wire) technique. Field-Programmable Gate Array (FPGA) based coprocessors are utilized to deal with I/O accesses, which enhance the I/O access speed dramatically [6-11]. This simulator was successfully used for simulating diesel-electrical locomotives by General Electric [4]. Based on this solution a very low step-size of 10 µs was achieved by simulating a single PMSM drive system [6].

The main drawback of digital processor-based simulators is the relative long simulation step size from 10 µs to some 10 µs. In simulation of a converter-fed electrical drive system errors will be introduced, if a switching event is located within a simulation step. Actually, because of the fixed step size requirement in real-time simulation, switching events occur almost always within simulation steps. In order to minimize these errors, two approaches are used:

- Utilization of interpolation technique [12]
- Reduction of the simulation step size

The first approach can be implemented on dedicated or PC processor-based simulation systems. However, using this approach the errors can only partly be compensated. In order to achieve more accurate simulation results, the simulation step size should be reduced by using faster computational hardware.

C. FPGA-Based Simulator

Since the introduction of Field-Programmable Gate Array (FPGA) technology in the mid-1980s, its capacity has roughly doubled every year. According to the current state of the art, FPGA devices containing in excess of 700,000 logic cells are available, which enable an implementation of a large control or simulation system on a single FPGA chip.

In the area of power electronics and electrical drives, FPGA technologies have hitherto been used mainly for implementing control algorithms and PWM gating pattern generations, either as stand-alone processors or as companion processors for DSPs [13].

In the area of real-time HIL simulation, FPGAs are mainly used in interface hardware, e.g. PWM measurement and position sensor simulation [1-12], and I/O coprocessor [6-12]. In [13] a real-time simulator based on FPGA in combination with a DSP is presented, in which the DSP facilitates the sequential process, while the FPGA boosts the performance of the simulator. With this approach a simulation step size of 2.5 µs is achieved. In [14] FPGAs were firstly used as stand-alone processors for modeling and real-time simulation of a complete AC drive system including rectifier, DC link, inverter and induction motor (IM). The controller is also implemented on the same FPGA chip. An ultra small simulation step size of 12.5 ns was achieved, which allows a highly detailed and precise simulation of the electrical drive system. However, references of FPGA-based simulator for large scale systems like locomotives are not available, yet.

4. Modeling and Numerical Computation

Since analog processor-based HIL simulators are no longer the state of the art, only digital modeling and computation technique are discussed in this contribution.

Converter-fed electrical drive systems consist of components of continuous nature, e.g. inductors, capacitors, resistors, transformers, motors, etc., and of discontinuous switching components (converters). Hence, the traction drive system of locomotives is a typical hybrid system containing continuous and discontinuous subsystems.

A. Continuous System

The continuous parts are described by using state space model in the first-order ordinary differential equations (ODEs) form

$$\dot{x} = f(x,u), \quad x(0) = x_0 \tag{1}$$

$$y = g(x,u)\,, \tag{2}$$

where $x = [x_1, x_2, \dots, x_n]^{\mathrm{T}}$ represents the system state vector containing elements such as voltage of a capacitor, current through an inductor, speed or position of a motor, etc., u is the external inputs like the line voltage and load torque. Using this form mathematical models for continuous components of electrical drive system of locomotives, e.g. overhead line, traction transformer, DC link circuit [1] and induction motor [14] [15] are built.

The essential task of numerical simulation systems is to calculate the new state vector $x(t_{k+1})$ from the past vectors $x(t_i)$, with $i=k+1, k, \dots, 0$, which is a typical initial value problem [16]. In order to deal with this problem, various numerical integration methods are developed, which are distinguished by explicit and implicit, one-step and multistep methods.

- **Implicit and explicit methods:** Implicit methods use an iterative approach to determine the new state values $x(t_k+1)$. Since the number of required iterations is unknown, this method does not meet the requirement of fixed simulation step size. Explicit methods does not use iteration, but rather approximates the integral by using the past values of x (up to present value $x(t_k)$), so that the algorithm can be written as a system of recursive equations and the required execution time is fixed.
- **One-step and multistep methods:** One-step methods only use one past value $x(t_k)$ for calculating the new value $x(t_k+1)$, whereas multistep methods use more than one past value, e.g. $x(t_k)$, $x(t_{k-1})$, …. Since one-step methods need smaller time step Δt or more evaluations of the models in the interval $[t_k, t_{k+1}]$ to achieve the same accuracy as multistep methods, they are usually computationally more expensive. Hence, multistep methods offer better performance and accuracy than one-step methods. However, because of the discontinuity of converter-fed traction drive systems multistep methods cannot be used after the switching events.

One-step methods, e.g. Euler algorithm [17], trapezoidal approximation [18] [19], are widely applied in real-time simulation of power electronic systems. In order to utilize the advantages of multistep methods mentioned above, a combination of the Adams-Bashforth algorithm (multistep method) and Euler algorithm (one-step method) is investigated, which shows a better compromise in accuracy and computational effort.

However, these conventional integration methods mentioned above cannot accurately deal with discrete events, e.g. switching of power converters, if they occur at the time instance other than multiples of the fixed step size. Hence, there will be errors between the output of the simulated integrator and that of the theoretical integration. One approach to solve this problem is to use variable step size to synchronize simulation steps with switching events, but this solution cannot be used in hard real-time simulation systems. In [12] a novel event-based integration method including a comparator block and compensation algorithms is developed. Using this technique these errors are partly compensated.

B. Discontinuous System (Power Converter)

Out of the view of modeling depth, converter model can be divided into two types [20]:

- **Detailed approach:** Using this approach, the power converters are modeled to resemble the actual circuit as closely as possible. Because of the modeling complexity, such simulations are very time-consuming. Hence, this approach is usually used for offline analysis on device level, particularly to investigate the switching behaviors of devices. Typical required time step size for this approach is in the range of some nanoseconds (e.g. 150 ns for turn-on and 700 ns for turn-off [21]). In a digital computer-based real-time simulator, this approach cannot be implemented, because the step size of this kind of simulator (> 10μs) is much larger than the duration of a switching operation. In a FPGA-based simulator, due to the very small step size (e.g. 12.5 ns [21]) a linearized detailed converter model could also be implemented in a in real-time.
- **Behavior approach:** In comparison with a detailed approach the behavior approach considers only the external behaviors of converters. All detailed device characteristics are ignored. Hence, this approach is more efficient and widely applied in parameter matching, comparison and selection of control strategies, and control design [20].

In digital processor-based simulation systems, due to the limitation of the attainable simulation step size, power converters are modeled by using behavior approach, which can be performed at three levels based on the level of abstraction:

- **Ideal switch approach:** In ideal switch approach the switching transients are neglected and the detailed i-v characteristics of an IGBT are replaced by linear behaviors (Fig. 2). Using this approach no extra effort than modeling a conventional continuous circuit is required. As a concession to numerical requirements, the transistor on and off states are represented by “non-ideal” resistances like $R_{On} = 1\ \mathrm{m\Omega}$ and $R_{Off} = 1\ \mathrm{M\Omega}$ [22].

  The main drawback of this approach is that each switch is to be handled individually in the simulation. A system with n switches has 2^n possible switching states. Every transition of the switching states will result in the change of the circuit topology and the resulting system matrix. Though, the system matrix can be reconstructed automatically by the solver, it is a time consuming process [20].

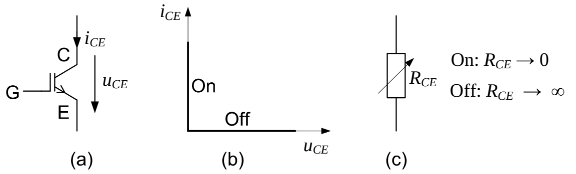
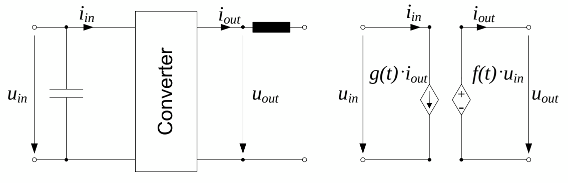


Fig. 2. Ideal switch approach of an IGBT



(a) (b)

Fig. 3. Switching function approach of a voltage source converter

- **Switching function approach:** Using switching function approach the simulation is much faster. In this approach the converter is modeled by controlled voltage and current sources (Fig. 3(b)). The relationship between the input and output quantities can be expressed as [20]:

  $$u_{out}(t) = f(t)\cdot u_{in}(t) \tag{3}$$

  $$i_{in}(t) = g(t)\cdot i_{out}(t)\,. \tag{4}$$

  The switching functions $f(t)$ and $g(t)$ can be realized using several methods. In [20] the principle of this approach is introduced and examples in modeling a one-quadrant converter and a three-phase voltage source inverter are given. However, in this reference the dead time pulses are not included. In [23] a state-machine-based converter model is introduced. In his model, the dead time is involved and the switching-off instant of each individual switch (IGBT or diode) can be detected. As further development of [23] a Petri-net-based converter model using matrix implementation is developed in [16], which shows better computation efficiency. It should be noted that the switching function approach has difficulties to cope with blocked converters, i.e. when the current flow is terminated.
- **Average model approach:** This approach is useful in simulation of power electronic systems with high switching frequency. In this approach, all switching actions are neglected and an average model is achieved using the state-space or generalized averaging technique. Hence, the simulation speed of this approach is extremely fast and this approach is convenient in determining the frequency response of systems. However, as the switching actions are not considered in this approach, it is not possible to monitor each individual switching action and, e.g., to evaluate the switching harmonic effect [20].

Since the switching frequency of rail vehicles is limited to some 100 Hz, switching function approach is proper for this application.

5. Conclusion and Technical Trends

The state of the art and technical trends of HIL simulation technology for rail vehicles are characterized as:

- Digital multiprocessor-based real-time HIL simulation systems utilizing FPGA techniques for I/O processing is the state of the art in rail vehicle application. The continuous subsystem is described by using state space model and the discontinuous subsystem is modeled by using switch function approach. A combination of one-step and multistep method shows a very good compromise in accuracy and computational effort in solving the continuous subsystem. However, due to the limitation of simulation step size of digital processor-based simulation systems, errors introduced by switching events can only partly be compensated by using interpolation algorithms.
- FPGA-based real-time simulator presents an ultra small simulation step-size, which make it possible to implement a linearized detailed converter model in real-time mode. However, no reference shows that it has been utilized for simulating large scale systems like rail vehicles, yet.

In the coming years a hybrid solution including digital and FPGA processors seems to be a good approach for simulating large scale systems. The high dynamic components, e.g. converter-fed IM, are simulated on FPGA processors and the low dynamic components, e.g. railway grid and mechanical parts, are simulated on digital processors.

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