HARDWARE IN THE LOOP SIMULATION OF ENERGY SYSTEMS IN THE VTB ENVIRONMENT

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Abstract — this paper describes new results related to hardware in the loop (HIL) computer simulations within the Virtual Test Bed (VTB) simulation environment. Implementation of HIL simulations expands the possible applications of time domain simulators and provides hardware-specific results which are not easily obtained by other techniques. Hardware in loop increases the validity and accuracy of the system simulation and relieves one of identifying all of the parameters of at least one of the system models. The modified coupling scheme that improves the stability of HIL simulations is described, implemented and tested on a practical electromechanical system.

Keywords — real time, hardware in the loop, simulation, system, stability, coupling scheme.

I. INTRODUCTION

Improvements in performance of modern power and energy systems rely heavily on computer simulations. Accuracy and consistency of the simulations depend on the chosen numerical techniques and on the adequacy of the models used in the simulations. Mathematical models are key components of every computer simulation. Employing mathematical models in computer simulations is a very convenient, relatively low cost, and efficient approach to the studying system dynamics. However, mathematical models have inherent disadvantages. Models are never the same as actual physical devices. Typically, models are valid only over specified ranges of operating conditions, and their application is limited by the approximations inevitably followed during development of the model. For example, models for a DC motor typically do not consider the effect of electrical sparking during rotor winding commutations even though such effects are well-known in real devices. Such effects are not generally present in models because it is very difficult to model the process and because the characteristics are strongly dependent on the physical conditions of the brushes and collector.

An alternative approach is to employ a real physical device instead of its mathematical model during system simulation. This provides a way to validate a model that may have been used in preliminary studies, and it provides a route to incremental prototyping of the system — moving from an entirely software-based representation of the system to a full hardware-based representation of the system. In this case, part of system is represented by mathematical models, and another part is represented by the actual physical device. This approach is known as hardware in the loop (HIL), and it was first formulated in the 1960s in microelectronics. Prototyping using HIL provides benefits beyond those just described. For example, it can be used during design of a system that will be operated under severe environmental conditions. Suppose that an electronic power converter module will be operated in open space under conditions of cryogenic temperatures and high radiation. A mathematical model of the specific power transistor may not exist, and may be extremely difficult to create. But one can create an artificial environment around the transistor in the lab and then use HIL to carry out simulations of the system performance, or to make comprehensive identification of its mathematical model for future use. There are other numerous instances, when HIL is valuable [1], [2].

In this paper, we describe a new HIL application within the VTB environment for virtual prototyping. The advantages of employing VTB for hardware in the loop simulations are as follows. First, the environment is open, i.e. it accepts computational objects that satisfy certain standards. This important feature allows easy introduction into the VTB of the interface between hardware and software. Second, the VTB is specifically designed to support power and energy systems studies. It employs an efficient computational engine that is well suited for simulations of large scale, nonlinear and stiff systems. Finally, the VTB provides access to a reasonably large set of the mathematical models developed over the years. This set constantly widens and has emphasis in the areas of power and energy systems, electro-mechanics, and power electronics.

II. THE VTB SIMULATION ENVIRONMENT

The goals and architecture of the Virtual Test Bed (VTB) are described in some detail in reference [3]. The Virtual Test Bed (VTB) employs the time domain simulator for virtual prototyping of power and energy systems. One of the unique capabilities of the VTB is highly interactive user involvement with the simulation. This capability allows a user to change the system configuration, the values of components or control algorithms during a simulation and to immediately see the results of those changes as reflected in a waveform display that is much like that of a traditional laboratory oscilloscope. The combination of these two features allows one to rapidly explore the detailed waveform behavior of a power electronic system.

One challenge in implementing such an interactive user environment is to achieve high computational efficiency so that the user is unhindered by the response of the computing system. Such performance is achieved in the VTB by a variety of techniques, including distribution of the computing load to multiple computers, employment of the HIL and the design of an efficient computing engine. The basic network solver of the VTB is based on the algebraic companion approach [4], [5] which is itself an extension of the resistive companion approach [4]. The algebraic companion method is based on incorporating the descriptions of all parts into one comprehensive numerical model and subsequent simultaneous solution of the system of equations by direct procedures in a single simulation process.

III. CONCURRENT SIMULATION WITH HIL IN THE VTB

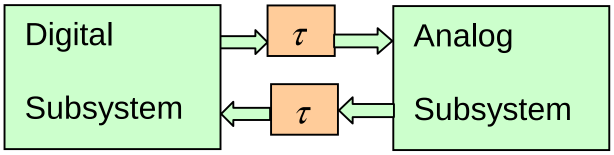

Figure 1. Structure of system with HIL.

Simulation of systems with hardware in the loop is usually accomplished by organizing two or more processes operating concurrently in a common time frame (see fig. 1). In this case, each process computes the performance of its own part of the system and communicates its results to the other processes via a common simulation backplane. For analysis of dynamic systems, all the simulators should be controlled by a common clock mechanism. However, the simulation process in every processor is more or less independent and may be executed with its own parameters or continuously in time for the case of a hardware model. The dynamics of the virtual subsystem (fig.1) are described by equations in the following general form:

$$\begin{bmatrix}\mathbf{i}\\ \mathbf{0}\end{bmatrix}=\begin{bmatrix}\mathbf{f}_1(\dot{\mathbf{v}},\dot{\mathbf{y}},\ldots,\int\mathbf{v},\int\mathbf{y},\ldots,\mathbf{v},\mathbf{y},\mathbf{u},t)\\ \mathbf{f}_2(\dot{\mathbf{v}},\dot{\mathbf{y}},\ldots,\int\mathbf{v},\int\mathbf{y},\ldots,\mathbf{v},\mathbf{y},\mathbf{u},t)\end{bmatrix}, \tag{1}$$

where $\mathbf{f}_1,\mathbf{f}_2$ are arbitrary vector functions, $\mathbf{i}$ is a vector of terminal through variables (terminal currents), $\mathbf{v}$ is vector of terminal across variables (terminal voltages), $\mathbf{y}$ is a vector of device internal state variables, $\mathbf{u}$ is a vector of independent controls.

The analog subsystem consists of one or more hardware devices. Finally, blocks τ in fig. 1 represent an interaction delays between the two subsystems. These delays are inherent in any HIL concurrent simulation and are the primary cause of instability [6].

IV. STABILITY AND MODIFIED COUPLING

Time discretization and application of a suitable integration technique to the equations (1) result in the algebraic companion form (ACF). ACF is employed in VTB as a standard description for mathematical models. By applying energy conservation laws at each node of the system and accounting for the connectivity constraints, the VTB network solver uses the ACF description of each system component to build the comprehensive system of algebraic equations that describe the system. These equations have the following general form:

$$A(\mathbf{x}(t),\mathbf{x}(t-h))\mathbf{x}(t)-B(t-h)=0\,, \tag{2}$$

where $\mathbf{x}=\left[\mathbf{v}^{T}\,\vdots\,\mathbf{y}^{T}\right]^{T}\in R^{n}$, $A\in R^{n\times n}$, $B\in R^{n}$, h denotes integration time step and t is the time. The solution of the system $\mathbf{x}(t)$ is reached by solving equations (2). If virtual subsystem contains nonlinear devices, the algebraic system (2) is nonlinear. In this case, matrix A depends also on the state of the system at time instance t. Therefore, the solution $\mathbf{x}(t)$ is obtained via Newton's iterations.

Employment of HIL is equivalent to partitioning of the system in two or more parts, depending on the number of hardware devices used (see fig.1). Such a partitioning of the original comprehensive model (2) to its decomposed form (fig. 1) can be expressed as follows:

$$Q(\mathbf{x}(t),\mathbf{x}(t-h),\mathbf{x}(t-\tau))\mathbf{x}(t)+S(\mathbf{x}(t),\mathbf{x}(t-h),\mathbf{x}(t-\tau))\mathbf{x}(t-\tau)-B(t-h)=0\,, \tag{3}$$

where Q is a nonsingular matrix for $\forall\mathbf{x}\in R^{n}$. Furthermore, expression (3) is consistent only if $Q+S=A$. The convergence of the system (3) is characterized by the iteration matrix

$$W(\mathbf{x}(t),\mathbf{x}(t-h),\mathbf{x}(t-\tau))=-Q^{-1}(\mathbf{x}(t),\mathbf{x}(t-h),\mathbf{x}(t-\tau))S(\mathbf{x}(t),\mathbf{x}(t-h),\mathbf{x}(t-\tau))\,, \tag{4}$$

i.e. if the eigenvalues $\lambda_i(\mathbf{x}(t),\mathbf{x}(t-h),\mathbf{x}(t-\tau))$ of the iteration matrix (4) are within the unit circle for $\forall\mathbf{x}\in R^{n}$, than system (3) is stable.

The modified coupling scheme used in VTB for HIL simulations greatly improves the stability of the numerical process. Modified coupling is based on the concept of incorporating an approximate simplified model of one subsystem into the model of the adjacent subsystem, and subtracting the delayed reaction of the incorporated model from its current reaction. Thus, employment of the modified coupling scheme results in the following changes in equation (3):

$$\begin{aligned}&Q(\mathbf{x}(t),\mathbf{x}(t-h),\mathbf{x}(t-\tau))\mathbf{x}(t)+S(\mathbf{x}(t),\mathbf{x}(t-h),\mathbf{x}(t-\tau))\mathbf{x}(t-\tau)+\\&S^*(\mathbf{x}(t),\mathbf{x}(t-h),\mathbf{x}(t-\tau))\mathbf{x}(t)-S^*(\mathbf{x}(t),\mathbf{x}(t-h),\mathbf{x}(t-\tau))\mathbf{x}(t-\tau)-B(t-h)=0\end{aligned}\,. \tag{5}$$

If the approximate model is somewhat close to the original, then the difference $S-S^*$ is small. Since the iteration matrix is expressed as $W=-(Q+S^*)^{-1}(S-S^*)$, the stability of the system (5) is greatly improved compared to system (3).

From a circuit point of view, the modified coupling scheme can be represented by the circuit diagram shown in fig. 2.

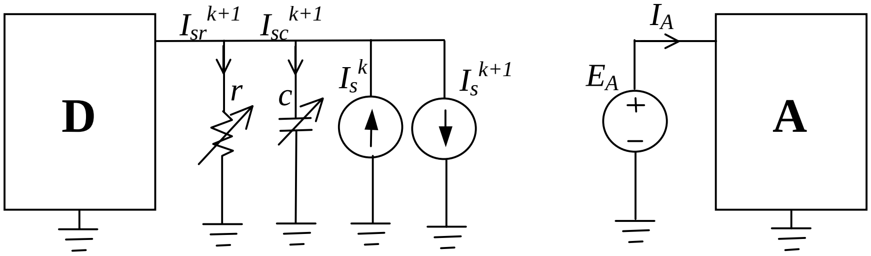

Figure 2. Modified Coupling Scheme

In figure 2, character D represents the virtual part of the system; symbol A denotes an analog or hardware part. It is proposed to introduce the stabilizing elements r and c to improve the convergence of the HIL system. The stabilizing elements are variable and their values are adjusted automatically during the simulation run-time. After several integration steps, the values of the stabilizing elements become somewhat close to the input impedance of the analog part A, which according to the equation (5) improves the stability of the HIL system. In order to compensate influence of the stabilizing elements on the solution of the system, the current source I_s^k is used. The compensation is realized by subtraction of the currents I_{sr}^k, I_{sc}^k through elements r and c at iteration k from the total current at iteration $k+1$.

V. EXAMPLE: HIL SIMULATION OF THE ELECTROMECHANICAL SYSTEM

To illustrate the proposed approach to the hardware in the loop simulations within the VTB environment, the electromechanical system presented in fig. 3 was considered.

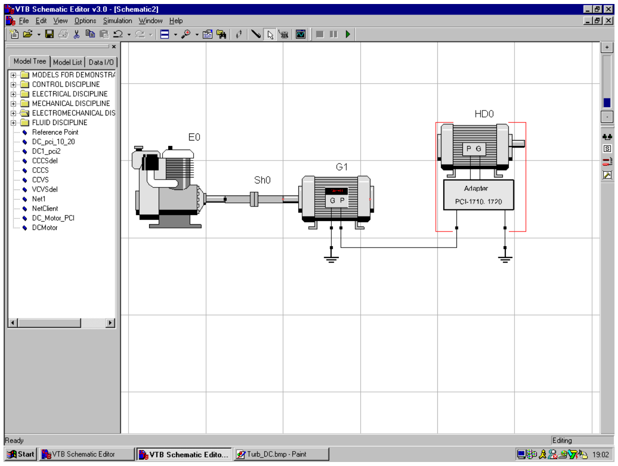

Figure 3. Simulation of the electromechanical system with HIL.

The system consists of the mathematical models of an engine (E0), shaft (SH0), and single-phase AC generator (G1). The hardware model (HD0) provides the modified coupling scheme and data exchange between the virtual subsystem and the hardware. In this example, permanent magnet DC motor is used as the hardware.

The specific details of HIL implementation within the VTB environment are shown in fig. 4.

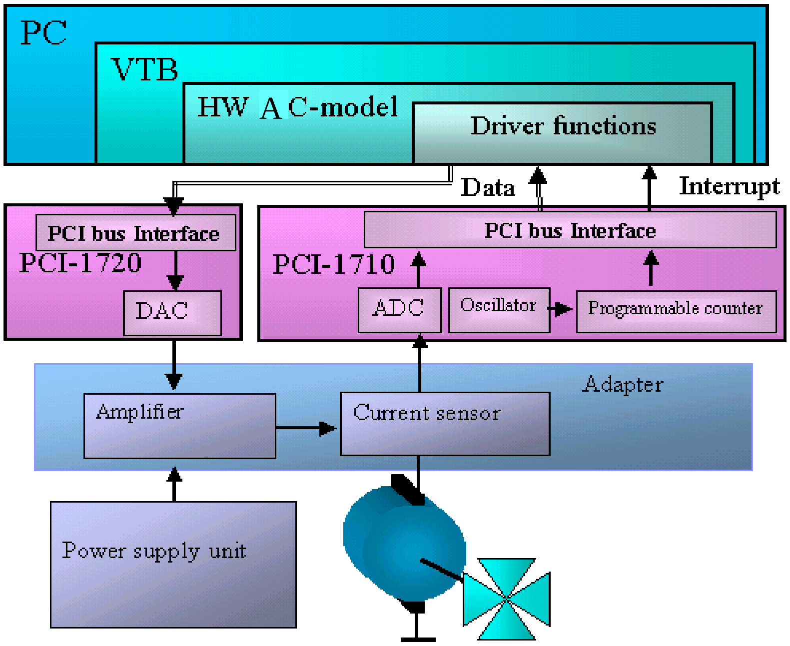

Figure 4. Block-diagram of the HIL implementation within the VTB environment.

As can be seen, the virtual subsystem interacts with hardware, through the DAC-ADC boards, which have to be present in the computer. These boards also provide real time synchronization of the hardware with software simulation running in the computer. The power amplifier and necessary sensors are also needed and are specific to the hardware used in HIL simulations.

It is necessary to point out that the proposed system for HIL simulation has a certain degree of freedom in use of the hardware. Indeed, during HIL simulation, the reaction (e.g. hardware current) of the hardware is measured depending on the specific action (e.g. voltage change) of the software part. Therefore, in this sense, the HIL simulation is invariant to the type of the hardware device used in the system simulation. For example, for the test system shown in fig. 3, the hardware (the permanent magnet DC motor) can be substituted by any other device which has two terminals, provided that the adapter (see fig. 4) is consistent for use with this device. For instance, the permanent magnet DC motor can be safely replaced with a resistor if the power amplifier and current sensor are able to deliver the necessary power to the device.

The results of the HIL simulation of the system presented in fig. 3, are shown in fig. 4 and 5.

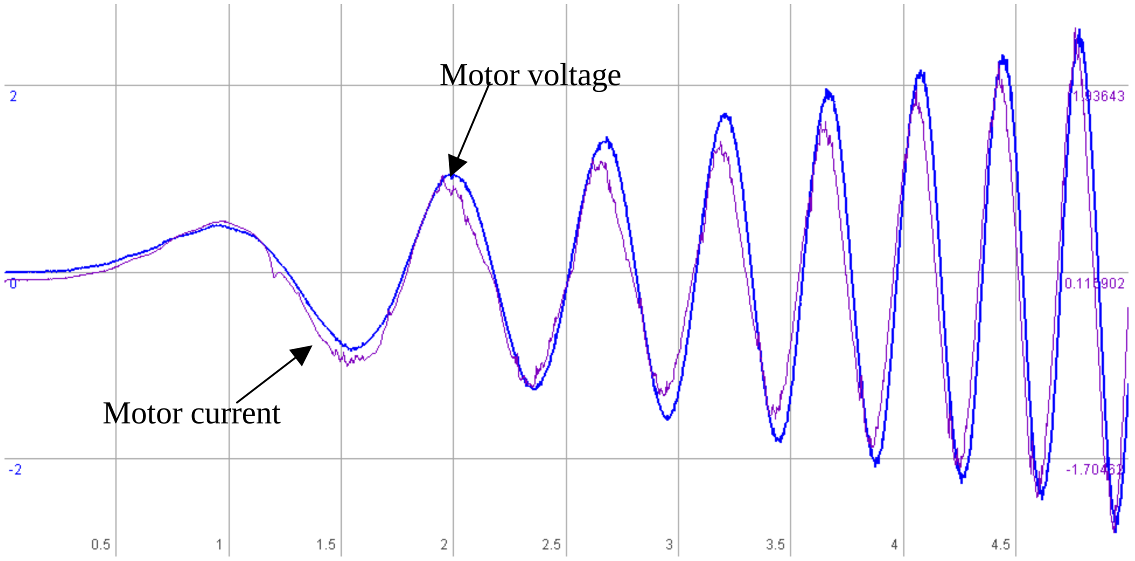

Figure 4. Results of electromechanical system with HIL simulation

The voltage across the DC motor terminals and current through the motor are shown. To illustrate the relative invariance of the proposed approach to the hardware device used in HIL simulations, the same system was used next for HIL simulation except that the DC motor was replaced with a different type of DC motor. The motor voltage and current waveforms for the new system are shown in fig. 5.

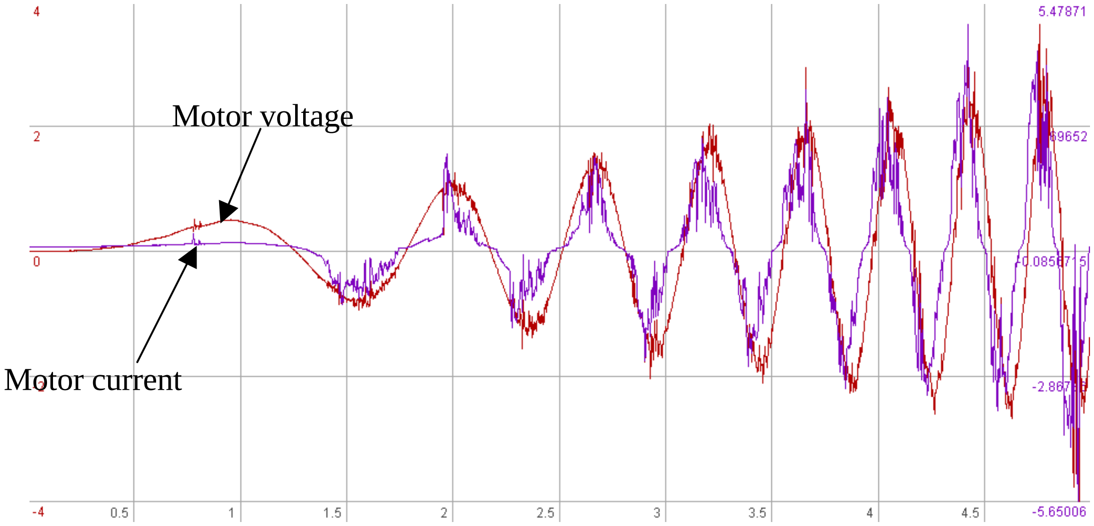

Figure 5. Results of electromechanical system with HIL simulation

As can be seen, the change in the type of motor produced a drastic change in the voltage-current waveforms. These kinds of simulation details are impossible to achieve by applying only mathematical models in simulations. Finally, this shows the robust stability of HIL simulations within the VTB environment when applying the described modified coupling scheme.

VI. CONCLUSION

New results on hardware-in-the-loop simulations within the VTB environment were presented. The hardware in the loop technique was applied in dynamic studies of energy systems. A modified coupling scheme that improves the convergence of the HIL simulations was described and shown to be relatively invariant to the type of hardware inserted into the system.

ACKNOWLEDGEMENT

The work reported in this paper was supported by the ONR Grant No. N00014-96-1-0926. This support is gratefully acknowledged.

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