An Integrated Virtual Learning System for the Development of Motor Drive Systems

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***Abstract*—This paper describes the basic concept of an integrated virtual learning system as an instructional tool for the development of digital signal processor (DSP)-based control schemes for motor drive applications. The system is comprised of a graphical user interface (GUI) front-end and a hardware-in-the-loop custom DSP for rapid prototyping and efficient testing of digital control algorithms. The circuit design and control algorithm development of a pulse width modulation (PWM) voltage source inverter (VSI) for 3-phase brushless DC (BLDC) motor control applications is used to describe the functions of the system. It is shown that the virtual learning system provides a cost-effective learning tool for students or engineers in training and can serve as a supplement to a conventional laboratory based system.**

***Index Terms*—Digital signal processing, motor drive system, object-oriented approach (OOA), simulation, virtual learning systems.**

I. Introduction

DEVELOPMENT of a motor drive system involves various aspects of electrical engineering, including circuit theory, digital circuits, control theory, and motor drive systems technology and requires broader knowledge than in the past. Digital control schemes of motor drive systems are replacing traditional functions used to implement discrete analog and digital circuitry. A trained motor drive systems developer must be able to combine signal processing and computer software technology with hands-on experience on the actual system implementation.

The conventional way of providing practical experience to electrical engineering students is through the use of extensive laboratory-based systems. Such systems require an actual hardware setup and a set of laboratory measurement systems that sometimes are costly to build and difficult to maintain. For safety and security reasons, access to the laboratory-based system is usually limited to a certain time and can only be given in the presence of a local facilitator.

This paper seeks to present the basic concept of a virtual instruction environment and to give a detailed description of a virtual test bed for the development of a PWM voltage source inverter for control of brushless DC (BLDC) Motor drives. Related works have been reported in [1]–[8]. In this research, a virtual instruction system attempts to create a realistic environment that facilitates learning by letting students participate in the process. The advantage of virtual instruction lies in the possibility of communicating information through high-speed communication systems, when needed, with a local facilitator to supervise the learning process at a local site. The local facilitator is a professor at a local university that will use the developed virtual system for instruction.

The present teaching approach uses simulations (including animation and other graphics, where appropriate) to assist the student in "visualizing" the concepts and to provide the student immediate graphical feedback during the learning process. The virtual learning system is developed based on modular instructional technology curricula. The learning tool is composed of successive modules, each introducing new topics or concepts to the student. The knowledge content of each module has to be balanced for the optimal transfer of information, preventing the risk of overloading the student. All modules have a similar structure, consisting of the following.

1) An explanation layer, where the student is familiarized with the information related to the basic fundamental notions. This layer resembles an in-class lecture presentation.
2) An exploration layer, which can be compared to the example problem presented in a class. In this layer the student has to apply the knowledge acquired to a practical example.
3) An (instructional) diagnostic layer. This layer has two objectives. The first is to provide an interactive learning sub-module with a hierarchical structure. At each level, a question is asked and multiple answers are given. The student will select one answer and the interactive learning sub-module will indicate whether the correct answer was chosen. The process continues until all topics in the module are covered. Some topics will be addressed in the form of a problem rather than in the multiple-choice fashion. The second objective is to time-test the student and to establish whether the student should be allowed to go to the next (deeper) level. This approach corresponds with the exam portion of a classical teaching approach.

In this paper, the design and development of a virtual learning system for a VSI motor drive system is discussed. The developed virtual system includes a software environment with simulation packages plus a true DSP board inserted in the host PC. The software simulation packages, which take the place of the true hardware devices in the conventional test bed, such as a true power converter and a true motor, are what the concept

Manuscript received December 9, 1999; revised August 28, 2001. This work was supported in part by Delphi Automotive System, TRW, and the Ford Motor Company Research Lab.

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Publisher Item Identifier S 0885-8950(02)00721-6.

"virtual" means here. The system is configured to closely resemble the hardware in order to be used as a "virtual test bed" for actual hardware development. To achieve this objective, DSP controller hardware has been included in the virtual test bed for direct implementation of control algorithms for the chosen controller architecture.

II. Description of the Virtual Learning System

A block diagram showing the structure of the virtual learning system is shown in Fig. 1. The heart of the virtual learning system is an integrated C++ based GUI application compatible with Windows 95/NT. The application integrates electronic versions of the instructional and learning modules with the virtual test bed environment consisting of power converter circuit simulations and a hardware-in-the-loop DSP controller board. The instructional and learning modules are stored in the HyperText Markup Language (HTML) standard allowing them to be accessed from the Internet/Web based client software if the need arises. The virtual environment also provides various GUIs to support the learning, including an HTML browser (Fig. 6) and various virtual instruments, such as virtual scopes, virtual meters, virtual spectrum analyzer (Fig. 7) commonly found in a laboratory hardware test bed.

The circuit simulations run on the PC environment and communicate with a Texas Instruments TMS320C240 Evaluation Module that executes the digital control code for the motor drive system. The circuit simulation engine is structured in such a way so that the simulation can also be run on an external Matlab/Simulink process. This structure provides greater flexibility and allows the use of various Matlab and Simulink functions in the virtual learning system.

A. Integrated C++ Application Environment

The virtual system application environment is designed using the object oriented approach (OOA) and implemented in C++. OOA allows for better system partitioning and visualization in designing complex systems. Moreover, C++ code is relatively easy to maintain, reuse, and modify and allows for groups of programmers to work on separate parts of the code. Programs written in C++ can be maintained and updated more easily and addition of functionality to the code is relatively straightforward with fewer risks of introducing errors. By using object-oriented language features, codes comparable in efficiency to languages such as Fortran can be written in C++, while saving valuable implementation time due to the ease of code reuse and maintenance [9].

Using the OOA, the system is first decomposed into objects that represent the actual hardware implementation. These objects are then further decomposed into individual component building blocks and implemented as classes in C++. The controller object consists of the DSP controller object and the PWM timer object. The user interface objects consist of a collection of objects such as scopes, waveform analyzer, and other graphical user interface objects. The circuit object implements the motor drive circuit simulation. The motor object implements the 3-phase brushless dc motor. A global timer object is created to control the simulation timing of the virtual system.

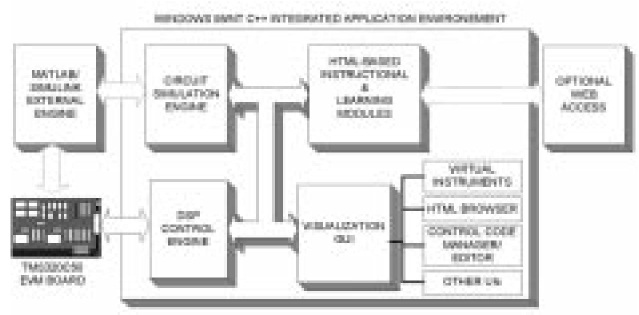

Fig. 1. Virtual learning system for power converter design and control.

Nowadays, visual programming packages for C++ are widely available that can save considerable time in designing and implementing the GUI for a virtual system. The software has been designed to use the multiple document interface (MDI) application design. MDI applications spawn child windows that reside within the client window, reducing the amount of memory required at load time. The system has been developed using Borland Builder, which is an object-oriented visual programming tool for rapid application development that allows producing 32-bit Windows 95/98/NT executable files [10], [11]. With this development approach, the learning system can easily be made suitable for an asynchronous learning environment where users work on their home computers at their own pace.

B. Circuit Simulation Engine

The virtual learning system described in this paper is intended for the design and control of a VSI motor drive for 3-phase BLDC motor control applications. The circuit diagram for the VSI motor drive employed for this purpose is shown in Fig. 2. The circuit simulator provides the computational engine for the circuit responses using the state space based approach with ideal power switch models. The ideal power switch models are preferred here since they allow the students to build up an understanding of different circuit operational modes and allow for the development of state space equations for control purposes. The simulation engine is specifically tailored for and controlled by the instructional/learning module. The instructional/learning module, for example, can ask the simulation engine to simulate an individual stage of the power converter independently.

The structure of the circuit simulation engine is shown in Fig. 3. The state space equation generator automatically computes equations corresponding to each circuit mode of the power converter based on a network list file similar to SPICE. A switching sequence algorithm is then used to select the current state space equation. This equation is based on the currents and voltages across the switches, which in turn are calculated by the solver using the control signals from the control engine. The state space equations generated by the simulation engine can be optionally transferred to an external Matlab/Simulink process, which can then be used to simulate the motor drive circuit.

C. DSP Control Engine

The DSP Control engine provides the interface for the circuit simulation and the DSP control board. The DSP control engine performs and controls the following tasks.

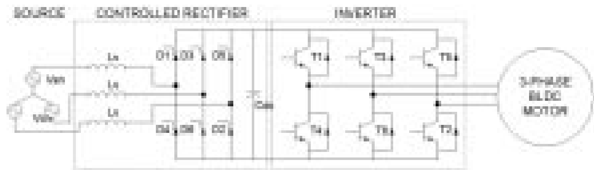

Fig. 2. VSI motor drive for brushless DC (BLDC) motor control.

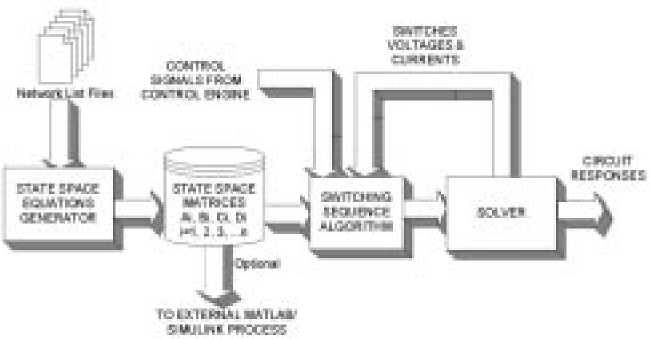

Fig. 3. Circuit simulation engine structure.

1) Compiling and downloading of the user control codes to the evaluation module (EVM) board.
2) Controlling execution of the control code on the DSP.
3) Retrieving A/D signals from the circuit simulation engine and passing them to the DSP.
4) Passing control signal information calculated by the DSP back to the circuit simulation engine.
5) Retrieving control code variables on the DSP for display.

Fig. 4 shows the DSP hardware in the loop structure in relation to the overall system structure [12].

D. Instructional and Learning Modules

The instructional and learning modules are designed based on the virtual learning system described earlier. All modules have a similar structure, consisting of an explanation layer, an exploration layer, and an (instructional) diagnostic layer. An example will best illustrate these concepts. The example is based on the "VSI Motor Drive" subsystem. The basic operation of the inverter does not permit switches on the same leg to be closed at the same time. Furthermore, because of the finite turn-on time and turn-off time of the power switching devices, the designer must provide a delay such that both power switches in one leg of a converter are never closed at the same time. To accomplish this goal, a deadband is introduced in the PWM signals. The following example submodule is intended to assure that a student has mastered the principles involved in the need for the PWM signals deadband. The example submodule includes the following.

Explanation Layer: Basic concept of power devices turn-on and turn-off time, operation of an inverter, different PWM strategies such as sine-triangle and harmonic elimination.

Exploration Layer: Experiment with an inverter operation and observe its behavior through simulation and graphics. Fig. 6 shows parts of the explanation and exploration layers as displayed in the application browser. Different example programs

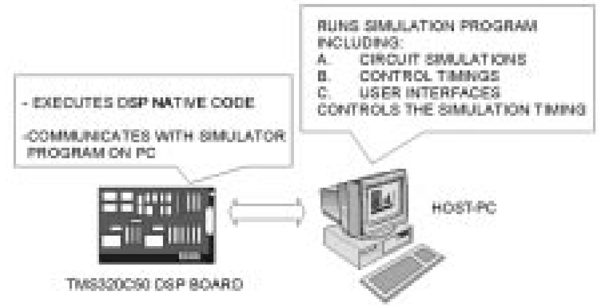

Fig. 4. DSP hardware in-the loop system.

for the DSP are employed to illustrate the effects of various PWM strategies. The outputs of the motor drive are observed on the virtual instruments in the system. Students can observe that the "harmonic elimination technique" does yield fewer harmonics in the output when compared with the other scheme.

Diagnostic Layer: This layer is designed to provide a step-by-step understanding of the concept being addressed. A number of questions are asked in order to test the level of understanding of the student. Depending on the performance, the trainee is allowed access to the next (deeper) level. Fig. 5 shows an example of the diagnostic layer designed to address the need for a deadband in the PWM signal generation. Every time a wrong answer is encountered, the corresponding explanation layer section is displayed to make sure that the concept is well understood before the next problem is given.

For the motor drive in Fig. 2, the learning modules cover the materials from the basic circuit operation–including circuit modes and switching principles–to the digital control design. The digital control design includes PWM generation strategies, DQ transformations, and basic control loop concepts. Currently the following main modules are available in the proposed virtual learning system:

- three phase rectifier principles and operations;
- PWM inverter principles and operations;
- brushless DC motor principles and operations;
- basic digital closed-loop BLDC motor control theory;
- PWM generation technique including sine-triangle PWM, hysteresis current control PWM, and space vector PWM.

All the learning modules are in HTML format and can be displayed using the integrated HTML browser provided by the application environment. Optionally, these modules can also be accessed via remote client applications such as Web browsers or other dedicated client programs.

E. Graphical User Interface (GUI)

As explained earlier, the integrated virtual learning system provides a realistic environment for students to experiment with the power converter circuit. For this purpose, the virtual learning system is equipped with different virtual instruments commonly found in a laboratory setup. These include virtual scopes, meters, and spectrum analyzers. In addition to the virtual instruments, the application environment is also capable of displaying the circuit modes of the power converter as shown in Fig. 7 for the rectifier circuit.

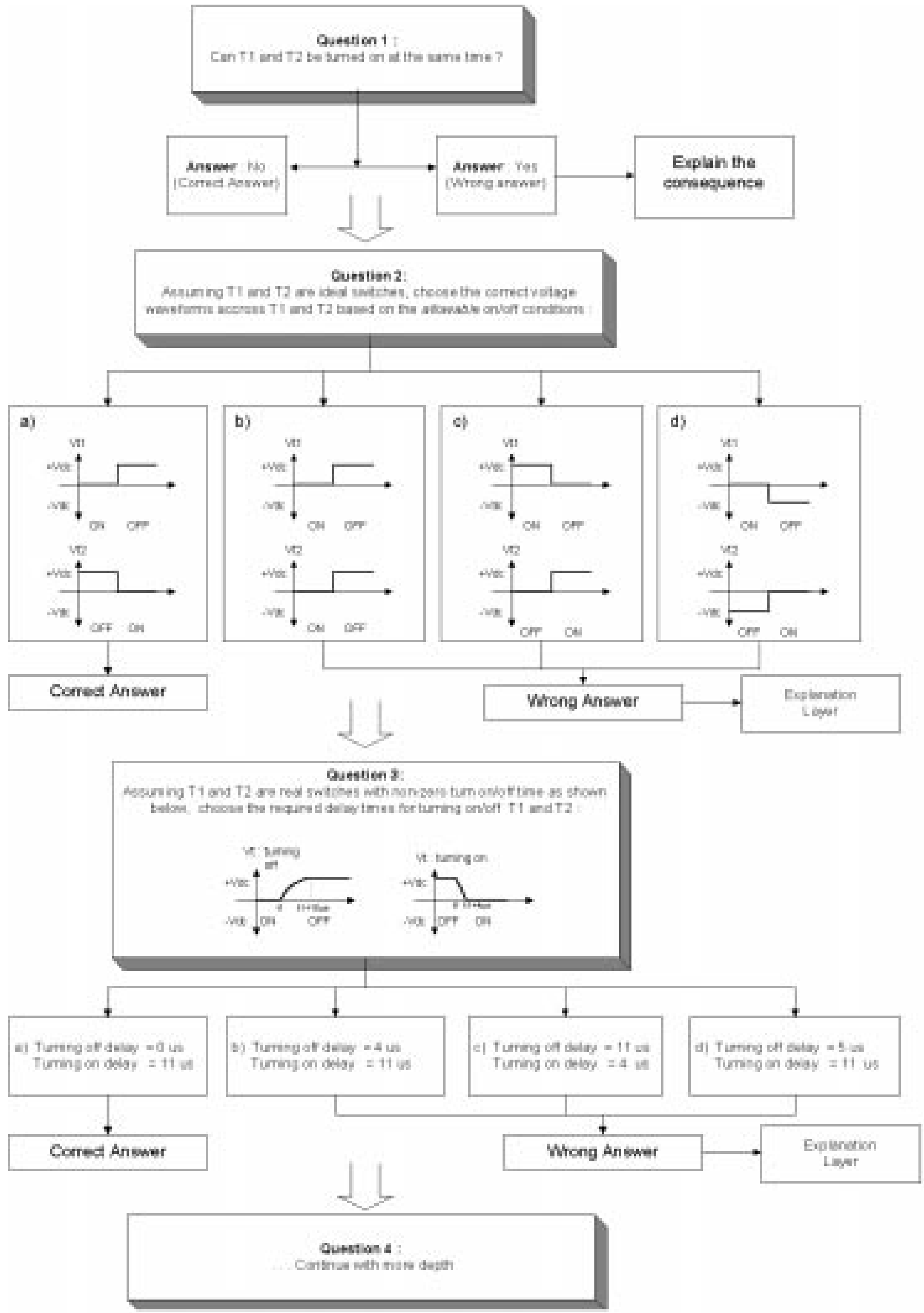

Fig. 5. Example of a diagnostic layer.

Other graphical user interfaces included in the system are the control code text editor, DSP code variable trace, and other customization tools.

III. CONCLUSION

In this paper, we have presented the preliminary concepts for the development of a virtual learning system and the detailed architecture of a virtual test bed for the design and control of a voltage source inverter motor drive for a 3-phase brushless DC motor control application. The explanation layer of the virtual learning system presents the learning material. The exploration layer allows students to perform experiments using the virtual test bed. Finally, the examination layer tests the students' knowledge.

The system can be effectively used as an alternative for a laboratory course for students or a hardware training session for practicing engineers. Through the use of the virtual environment substantial cost savings are achieved, since the need for a laboratory setup with hardware circuits and measurement equipment

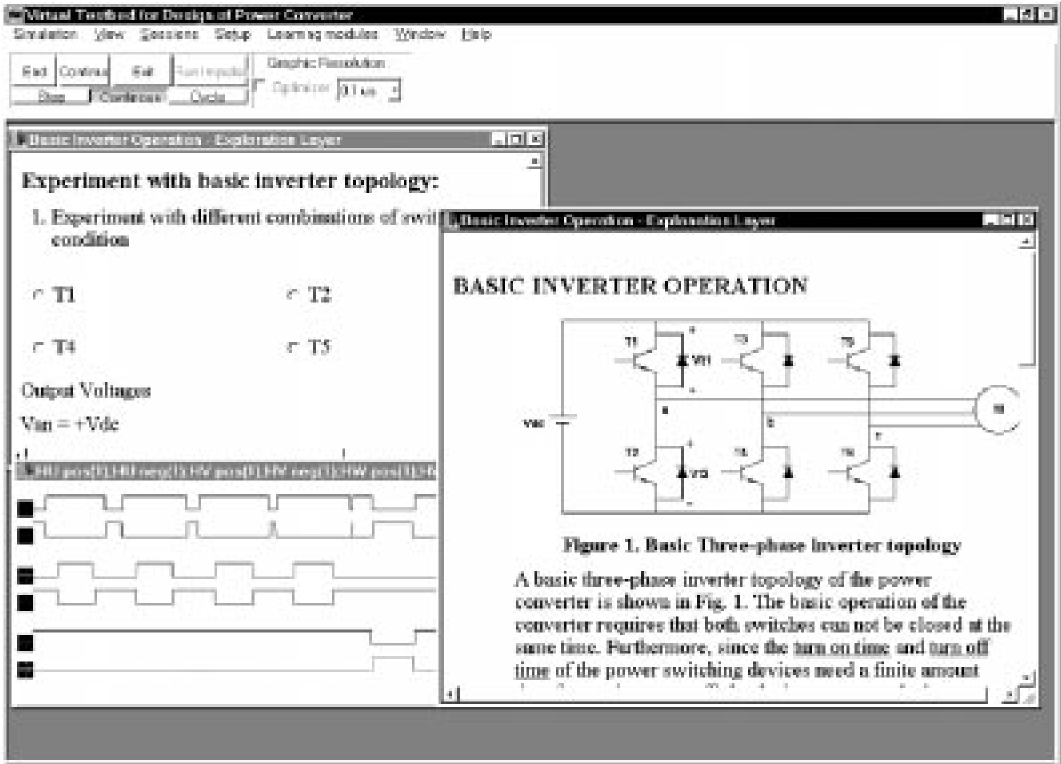

Fig. 6. Learning modules displayed in the application's browser.

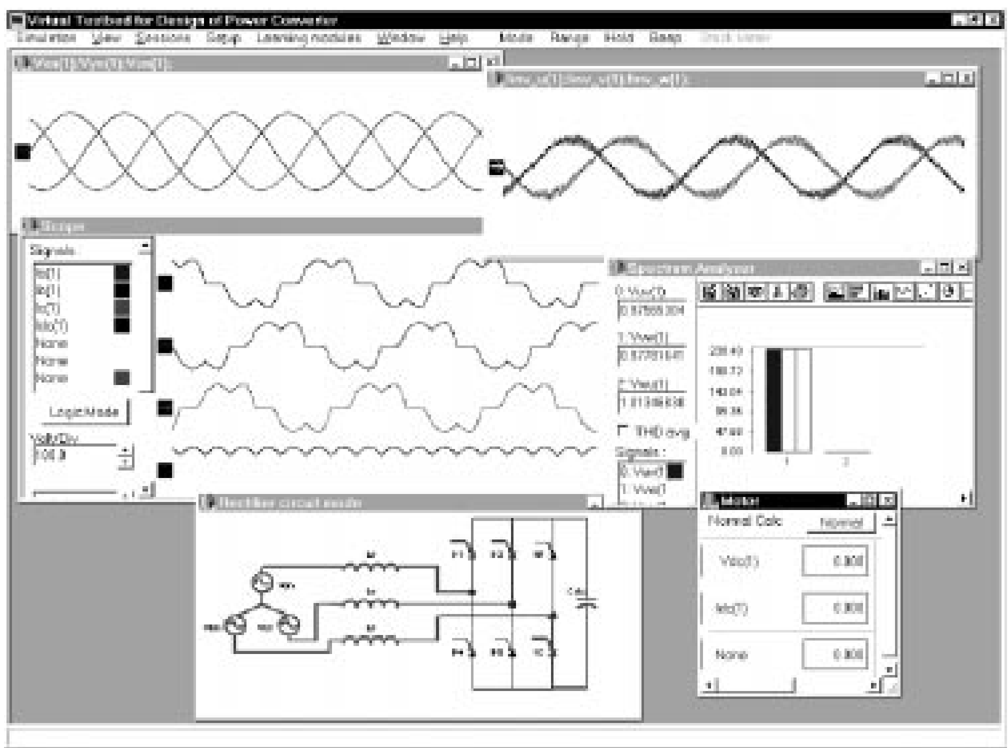

Fig. 7. Virtual instruments and circuit modes.

is drastically reduced. Using appropriate device simulators, this concept can be applied to a variety of learning modules employing a DSP.

We have experimented with this learning module with a small number of students. We are planning to design a general-purpose virtual test bed that will then be used for introductory DSP programming courses as well as for courses on electromechanical systems. Students will develop their control code using the virtual test bed and then test it with actual hardware attached to the DSP.

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