Session Number

Flexible And Modular DSP Based Real-Time Implementation of Power Electronic Systems

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Abstract

The massive growth of high performance digital signal processors (DSP) in the last two decades has led to a revolution in the wireless communications. Real-time control is being actively pursued in the recent past for applications such as high performance motor drives, VAR and harmonic compensation and energy efficient optimization strategies. Such developments in real-time are seen under topics such as rapid prototyping and hardware-in-the-loop simulation. In this paper, the application of DSP based real-time control technique towards design and development of power electronic equipment is explained through the use of the TI TMS320F240/243 digital signal processor keeping the above ideas in mind. Power electronic building blocks that compose of both hardware and software have been developed and used for rapid prototyping of existing power electronic converters. A modular approach has been followed while building these systems. This modularity has given rise to flexibility in choosing and experimenting with various power electronic systems with the given hardware through a software approach.

I. Introduction

In the last few years, the concept of integrated real-time control has been gaining importance in power electronic applications. This is the reason, why modern power electronic systems employ new techniques such as digital signal processing. Hence a modern power electronics lab should have a powerful thrust towards digital real-time control besides a good exposure to the hardware basics. However most of the literature indicates that the concept of real-time control has been limited to solving specific problems encountered in power electronic systems such as online monitoring of machine parameters for electrical drives, continuous fault diagnostics and real-time control of electrical drives.[1-7] Real-time systems are also being used for harmonic minimization and new filter schemes such as adaptive filtering[8-11]. Applications that are more specific include uninterrupted power supplies (UPS) and extraction of parasitic elements in power semiconductor devices.[12-14] As these applications are specific in nature, they cannot be used to impart any education to a fresh graduate engineer to this approach.

A generic real-time simulation approach using dual DSPs for power electronic systems was attempted a few years ago.[15] However, this approach suffers from the drawback that multiple DSPs were used, thereby increasing the price and complexity of the system. Moreover, this approach was rigid in nature as one could not experiment with a number of power converter topologies in a short span of time. Real-time rapid prototyping tools based on

MATLAB/SIMULINK have also been reported.[16-18] These suffer from the drawback that they deal more with the control aspects than power electronics. Moreover, they lack from being modular in nature and do not give the user an opportunity to quickly experiment with various power converter topologies and do not give much insight into the hardware details. A modular plug and play approach has been reported but this approach suffers from the lack of real-time control and is limited to electrical drive systems.[19]

In all, there is no single approach that can be used for research and education besides giving an equal importance to power electronics and the digital control. In this paper, a software based real-time implementation of power electronic building blocks is proposed. A modular approach to solve a given problem is the heart of this approach. The state-of-the-art digital signal-processing controller TMS320F240 (cost-) optimized for power electronic systems has been used for this work. The system is cost-effective and provides the user a good insight into the power electronics hardware involved. This novel hardware/software co-design approach can not only be used for imparting a modern power electronics education to graduate and undergraduate students but also for research & product development. Real-time control of power electronic systems from a PC- DSP combination is also possible in this approach. The block diagram of such a real-time approach is shown in Fig. 1.[20] It can also be seen that this approach is similar to the Hardware In the Loop(HIL) concept of Fig. 2 and possesses modularity essential for imparting effective education.

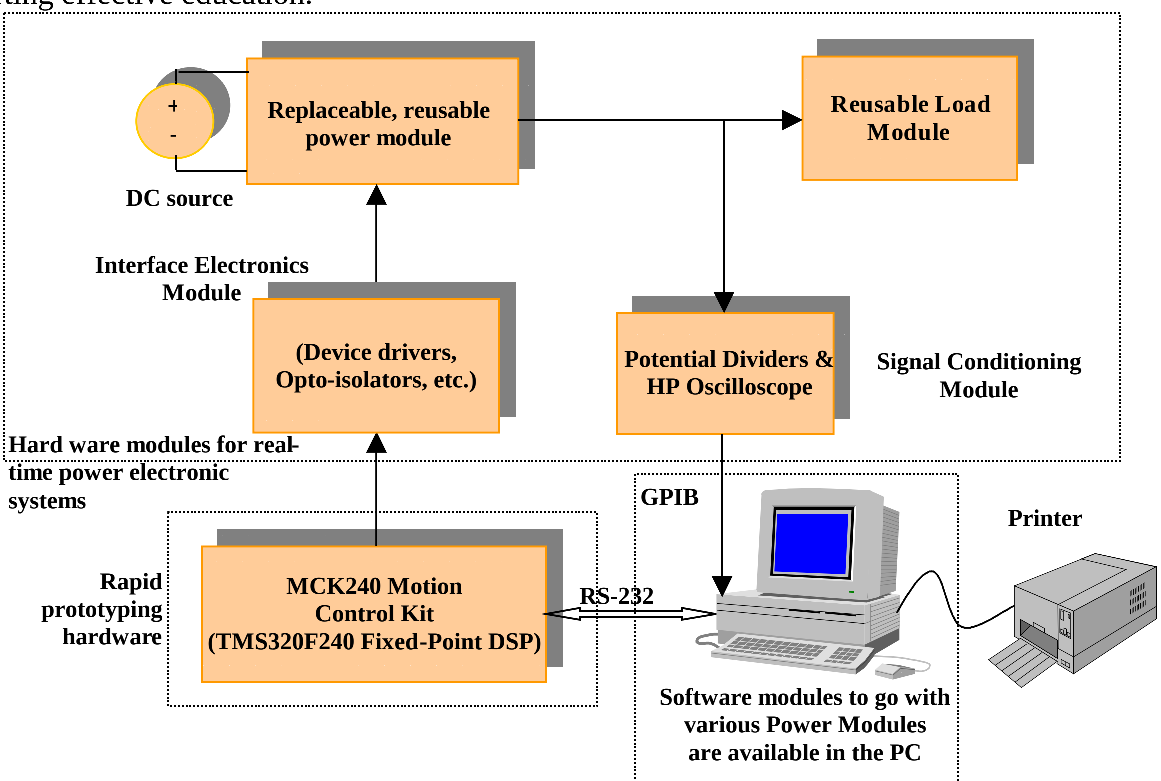

Fig. 1. Modular real-time implementation of power electronic converters

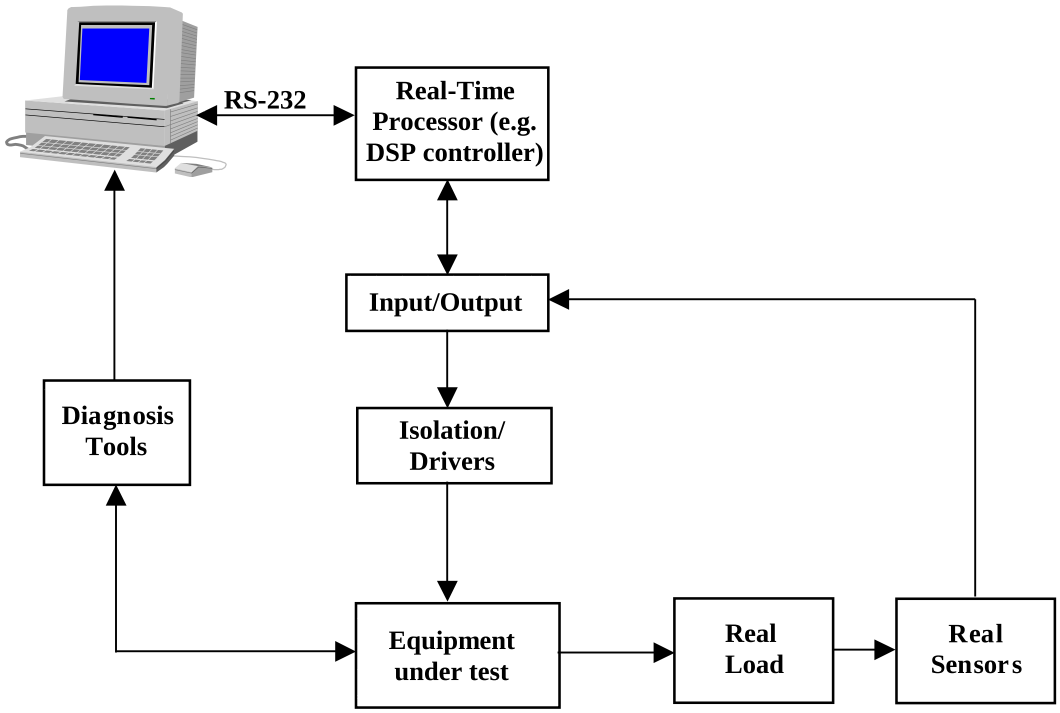

Fig. 2. A typical hardware-in-the-loop simulator

II. Real-time systems, Rapid prototyping and Hardware-in-the-loop simulation

The emergence of powerful and cheap digital signal processors that have combined the peripherals of a microcontroller and the capability of fast complex signal processing has led to a revolution in the field of real-time controllers. Today's digital signal processors (DSP) are capable of speeds in excess of 10 million instructions per second (MIPS). This dramatic improvement in the field of digital electronics together with the introduction of software engineering tools have led to the establishment of real-time technologies (like hardware-in-the-loop simulation and rapid prototyping) as a standard for industrial research and development.[21] A number of powerful computer aided tools are available today that support graphical application programming, real-time operator interaction, data logging, and logged data analysis.[21] Such tools also include efficient hardware platforms for rapid prototyping (based on digital signal processors, RISC processors and even microcontrollers), I/O and communication (e.g., the Local / Controller Area Network) for automation.

Real-time systems are managed by a real-time operating system whose goal is to manage the resources of a system to be within the stipulated real-time constraint parameters.[22] Some such important parameters are interrupt latency, task switching time, task execution time and task turnaround time. The heart of a real-time system is a real-time processor (which can be a digital signal processor, powerPC, RISC processor or even an 8-bit microcontroller). Programs that run on a real-time processor are called real-time tasks. They are triggered by periodic or aperiodic events, which are usually either hardware or software interrupts. Periodic events (such as timer interrupts) occur at a constant rate and at predictable points of time, whereas aperiodic events are generated from peripheral devices at non-predictable points of time. Rapid prototyping and HIL can be considered as emerging real-time technologies.[23] Rapid Prototyping is often considered as a building block for a complete real-time system.

Rapid prototyping (RP) is the process of implementing a design quickly, using dedicated software and hardware tools.[23] The system to be designed is in the form of software written on a dedicated RP software tool. Examples of such software tools include MCWIN from Technosoft Inc. and TDE tools from dSpace GmbH. These tools possess real-time kernels, which can be incorporated into the test code. The software variant of the required control design can then be downloaded into a dedicated RP target hardware, which then serves as a functional prototype for design. The designer can now play with the parameters of the control design in a real-time environment. The design can then be easily optimized and refined to fit a specific application. One of the important advantages of RP is the short turnaround time, which is very important in the industry since iterations and modifications in a design occur frequently.[23] Rapid prototyping is very widely used today in the automotive sector.[24-26] It is also being used at educational levels though mostly in the field of mechanical and metallurgical engineering.[27] The block diagram shown in Fig. 3 represents a typical rapid prototyping scheme using MATLAB/SIMULINK.

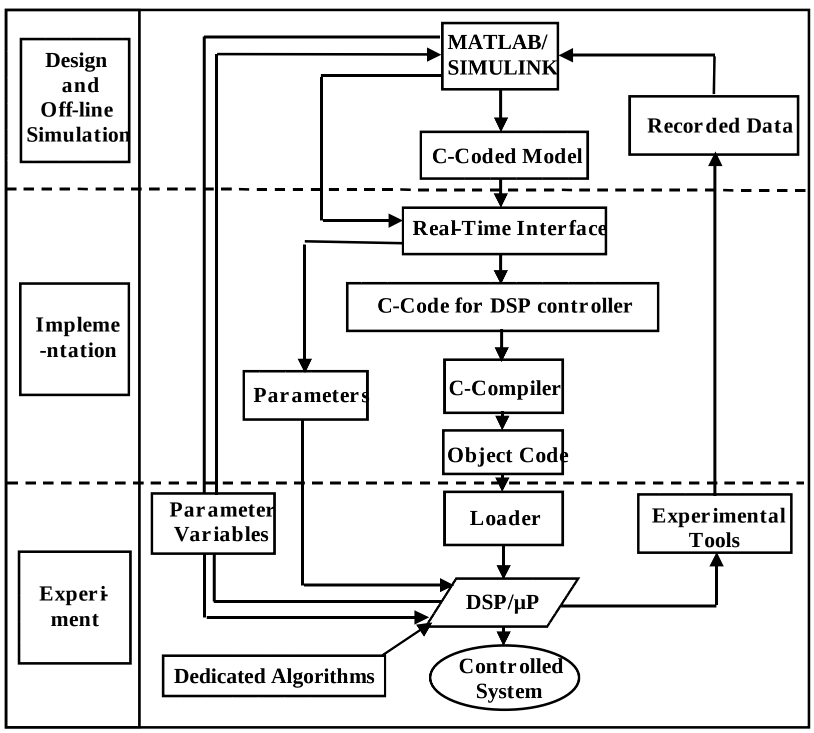

Fig. 3. Rapid prototyping using MATLAB/SIMULINK

HIL simulation as a technology has established itself into several industries particularly in the automotive sector.[24-26] HIL involves the interconnection of at least one physical component to a real-time simulation with the rest of the system being represented through a simulated environment, in a closed loop.[23] Parts of the system that are to be tested with a real system such as a controller can be integrated into the closed loop as real components.[28] This is shown in

Figure 3 where parts of actual hardware are integrated with a real-time processor based software loop. As parts of hardware now come under a software loop, this real-time simulation scheme thus derives its name - hardware-in-the-loop simulation. With this approach, complex interconnected schemes that may have components impossible to mathematically model can be quickly tested and visualized. All conceivable test scenarios for an entire system can be tested and analyzed with this method – from the verification of control algorithms to on-board diagnosis (OBD) tests up to integration tests of networked electronic control units.[24] The saving in cost and time in an industrial process due to the use of this technology are in all, obvious.

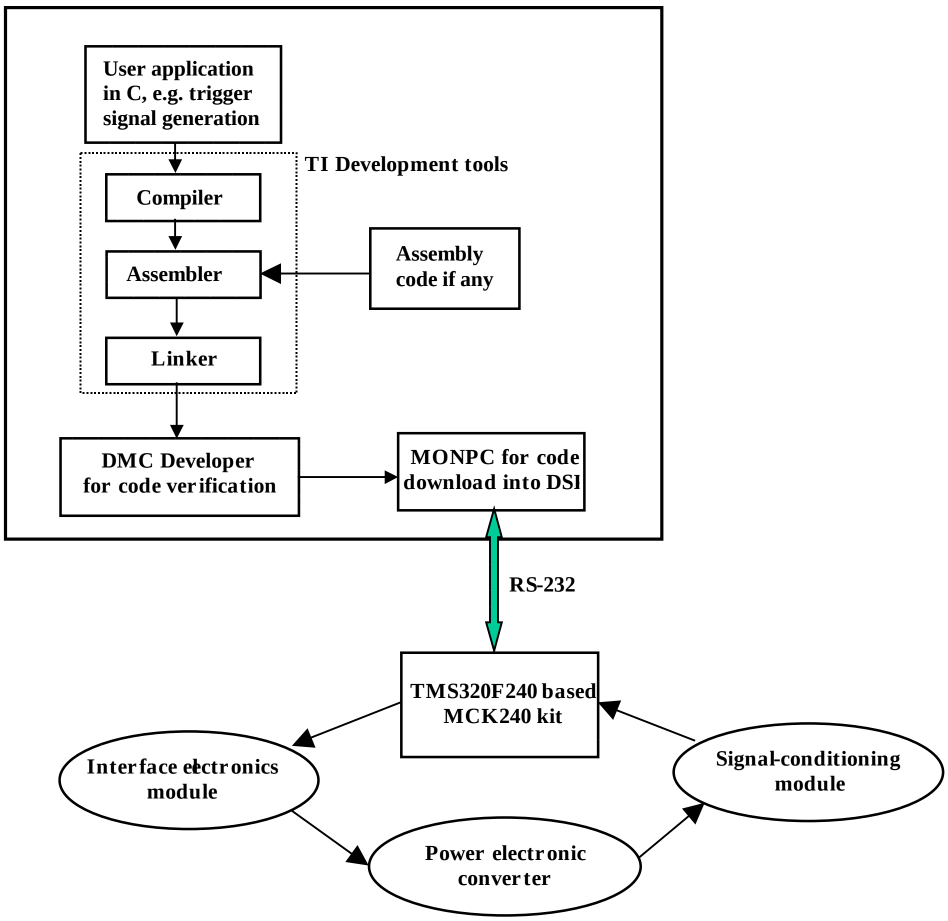

Fig. 4. Rapid prototyping of power electronic systems using the TMS320F240 DSP controller

III. Rapid prototyping using the TMS320F240 DSP controller

A typical rapid prototyping approach for real-time power electronic systems using the TMS320F240 DSP controller based MCK240 motion control kit is shown in Fig. 4. The application program such as a code for trigger signal generation or a control algorithm for a chosen power converter topology is written in ANSI compatible C code. This C code is then compiled, assembled and linked to obtain a DSP executable code. The code is debugged using DMC Developer- the Integrated Debugging Environment (IDE). The machine executable code is downloaded into the DSP using MONPC software. The DSP controller generates the trigger signals or implements the desired control algorithm for controlling the power electronic converter, which happens to be the real-time system here. The signals from the DSP are interfaced to the power converter through an interface electronics module, which provides isolation and signal amplification. Control parameters that are used in feedback such as speed and current can be sensed from the real-time system and fed back into the DSP through a signal-conditioning module that consists of current, voltage and speed sensors. The power converter can also be controlled in real-time from the PC using the command interpreter monitor program. In this way, a rapid prototyping of power electronic systems can be achieved.

IV. Modular DSP based power electronic building blocks for real-time control

In this new approach to modular real-time implementation of hardware/software co-design of power electronic systems, a number of categories of modules have been developed. Software modules have been prepared for generation of firing schemes for various power electronic converters. These modules would be provided in the form of a library. Corresponding hardware modules have also been developed. These software modules can be used for a quick understanding of trigger signal generation schemes for various power converters. The software modules along with the hardware modules can be used for implementing a hardware-in-the-loop simulation for power electronic converter systems as well. The rapid prototyping software chosen here is a Texas Instruments TMS320F240 DSP controller based tool called MCWIN from Technosoft Inc., Switzerland.

The software possesses all the required features necessary for real-time implementation such as data logging, real-time kernel, real time parameter modification and so on. An integrated debugging environment (IDE) named digital motion control (DMC) developer is also provided for debugging and development of the software that is written in ANSI C. The RCP target hardware is the MCK240 V1.0 Tms320F240 DSP Motion Control Kit. The TMS320F240 digital signal processor can operate at 20MIPS. The high-speed central processing unit (CPU) of the processor allows the digital designer to process algorithms in real time rather than approximate results using look up tables. The board is interfaced to a personal computer (PC) using an RS-232 serial communication interface. Graphical visualization software needed for real time applications to display data is also provided using the package HPVEE 5 from Hewlett Packard. The entire setup is split into a number of flexible and inexpensive modules, which can be easily swapped. The real-time application has been presently tested for simple converter topologies. The aim is to present the undergraduate student with the state-of-the-art in power electronics education. The concept can however be expanded to systems that are more complex as well. A brief explanation of the hardware and software modules developed for the lab is presented below. The power electronic building blocks are developed so as to encompass the following typical power electronic applications:

a. AC/DC converter – Single phase and three-phase controlled rectifiers, DC motor drive applications
b. AC/AC voltage controllers
c. DC/DC converters – Buck converter, Boost converter, Buck-boost converter, DC motor drive applications
d. DC/AC inverters – Three phase PWM IGBT inverter, AC drive applications

a.) *Hardware modules*

Power Converter Modules. The base power modules include MOSFET based DC converter, Thyristor based module for line commutated converter and IGBT based inverter module.

Interface Electronics Module. The interface modules provide isolation and gate drive for the power converter base and are available as modules to go with each of the above mentioned power converter modules

DSP Based Control Electronics Module. The DSP based control electronics module is centered on the MCK240 motion control board that was mentioned earlier. The processor used is the TI DSP TMS320F240. The DSP has sixteen ADC channels, nine PWM outputs, three 8-bit digital I/O ports and four capture inputs. The board is used for processing all the control functions and the generation of the firing pulses.

Reusable Load Module. The reusable load module consists of a resistor, a capacitor and an inductor. It can be used as a passive load. An electrodynamometer is used as a mechanical load for loading the electrical motors.

Signal Conditioning Module. The signal-conditioning module consists of voltage and current sensors. The voltages and currents to be measured are sensed and can be seen on an oscilloscope. HP oscilloscopes are used here in almost all the applications mentioned in this paper. The software HP VEE along with a GPIB interface card resident in the PC provides a user-friendly graphical interface between the HP test instrument and the computer. Waveforms can be captured, saved and inserted into document files with ease. In the real-time control of a DC-AC inverter, a hand held Fluke power harmonic analyzer is used to visualize the AC voltages and currents. This instrument is interfaced to the PC using an RS-232 serial communication interface.

Miscellaneous Interface Modules. Other interface modules for implementation of power electronic systems such as line-commutated converters have also been developed. One example of such a module as an input to the DSP controller is the voltage zero crossing detection module used in an AC-DC converter.

b) *Software Modules*

Software modules for the trigger signal generation of various power converter topologies such as DC/DC converters, thyristorized line commutated converters and PWM schemes for IGBT inverter are available in a compiled and executable form. The software module for the PWM inverter is a customized version of an application available from Technosoft Inc. All other modules are written in ANSI compatible C. The C application program is then compiled, assembled and linked using development tools from Texas Instruments. These modules would be provided in a library in the form of executable files that can be readily downloaded from a PC into the DSP and executed for trigger signal generation and control of PE converters..

V. A typical undergraduate experiment

A modern power electronics lab has been established at Iowa State University. An undergraduate power electronics course would include hardware experiments that cover various power converter topologies and systems. More details on the various experiments will be provided at the course website.[29] One such lab experiment involving line-commutated converters is explained here. For such an experiment the following hardware modules are used:

A six SCR power converter module from LabVolts Incorporation.
An opto-coupler based interface electronics module
A voltage zero-crossing detect module
Load comprising of resistors/inductors or a ¼ hp DC motor
A transformer module with five different voltage combinations from Lab Volts
Technosoft MCK240 DSP based motion control kit with TMS320F240
Signal conditioning module with voltage/current sensors, and oscilloscopes with a PC interface.

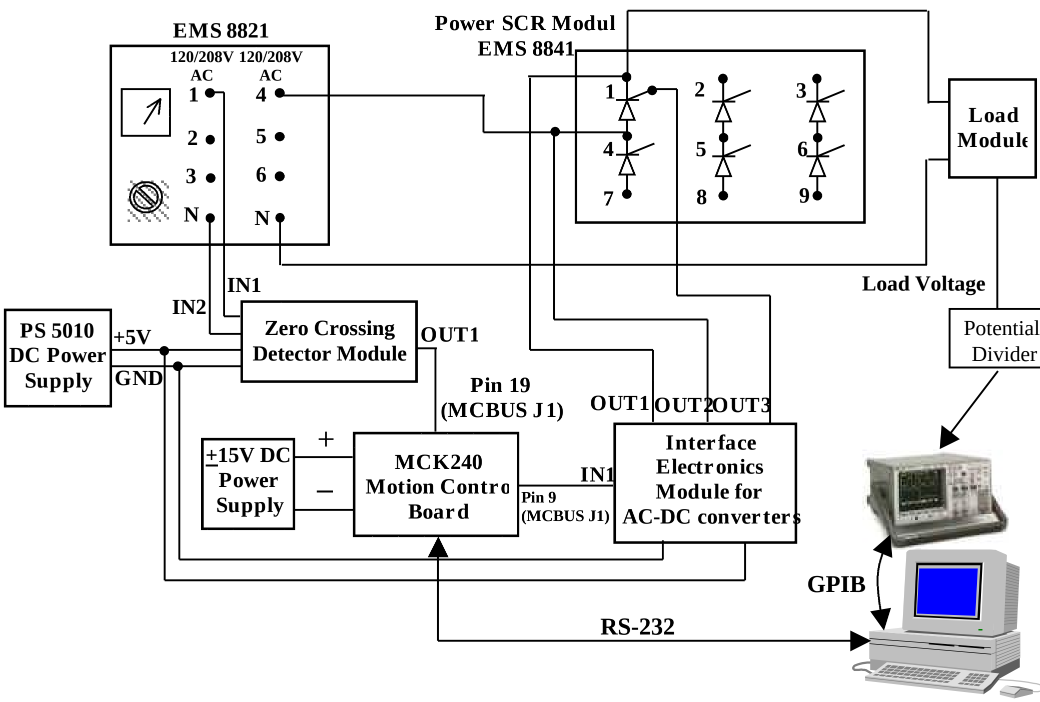

Fig. 5. Physical connection of single thyristor conduction in an ac line

a) *Single- Thyristor Converter*

The hardware modules described here for an ac-dc converter can be easily integrated as in Fig. 5 to obtain a simple single pulse thyristor converter involving one thyristor (Fig. 6). A three-phase power supply module, EMS 8821, from Lab-Volt is used to supply the input power to the ac-dc converter. The trigger signal is generated by the DSP and can be controlled from the PC. The software module available in the PC is downloaded into the DSP platform and run using the development tool MCWIN provided along with the hardware. Fig. 7 shows the trigger signal being generated by the DSP at a delay angle of 45 degrees with respect to the input supply voltage. Fig. 8 shows the output voltage across the load. The load voltage is discontinuous as the single thyristor present in the circuit triggers only during positive half of the input voltage cycle. This experiment also illustrates the principle of triggering of thyristors and the generation of trigger signals for a line commutated converter. The firing angle can be continuously varied from the PC and thus provides real-time control of the converter.

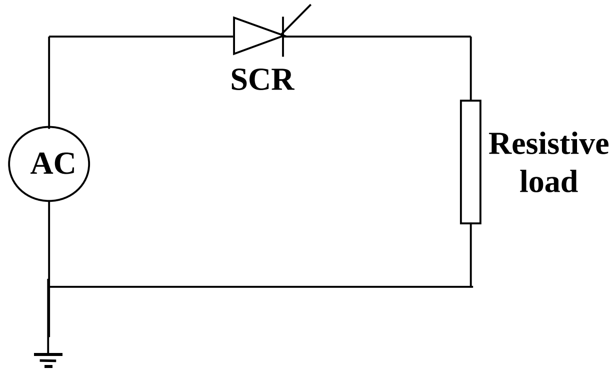

Fig. 6. A single thyristor controlled rectifier

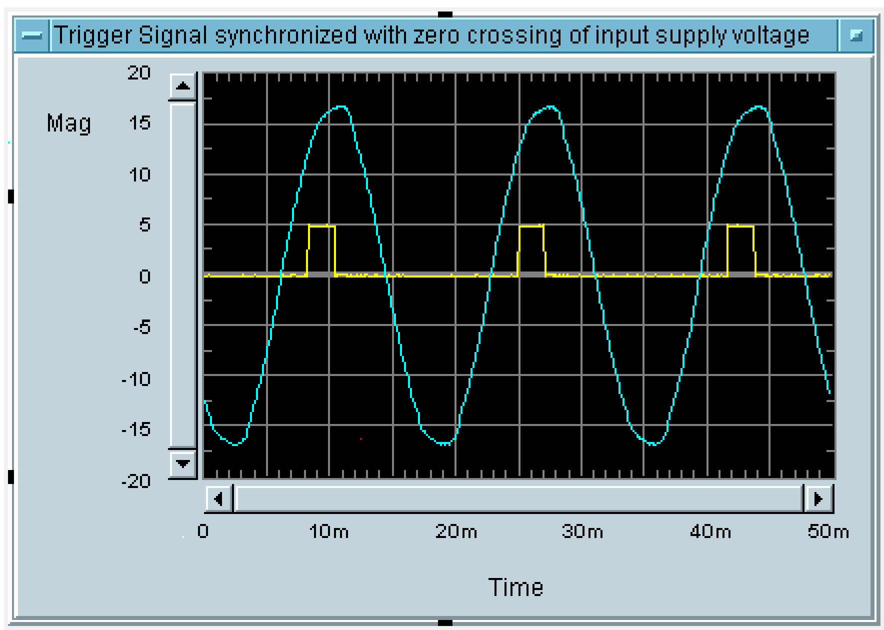

Fig. 7. Trigger signal generation for a single-phase thyristor converter

B. Single-phase midpoint converter

The same setup can be used to obtain a single-phase two-pulse midpoint converter as shown in Fig. 9. Two thyristors are used here along with a midpoint transformer. The software module is the same as used for a single pulse converter. In the single-pulse converter we used only one pulse. However, in this implementation, two pulses are used. All other procedures remain the same as that for a real-time control of a single-pulse converter.

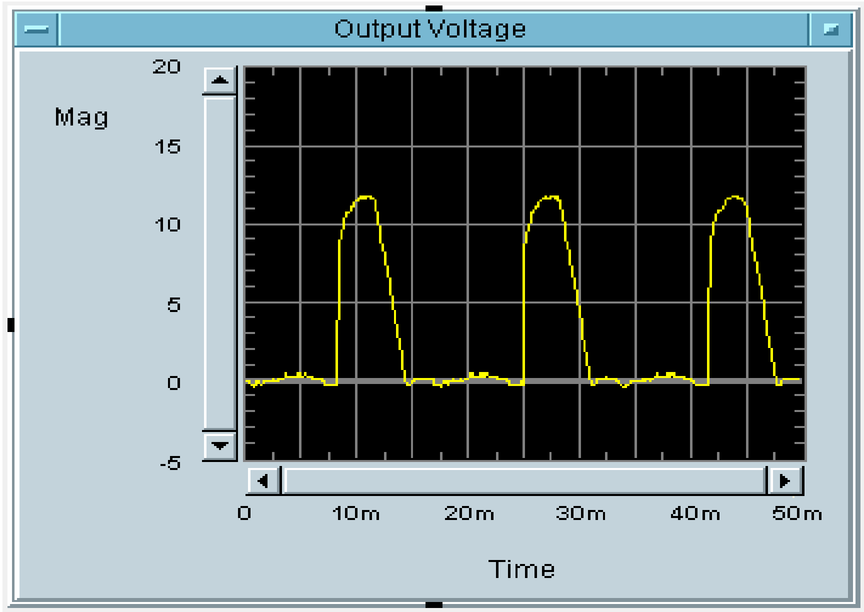

Fig. 8. Output Voltage waveform of a single pulse thyristor converter

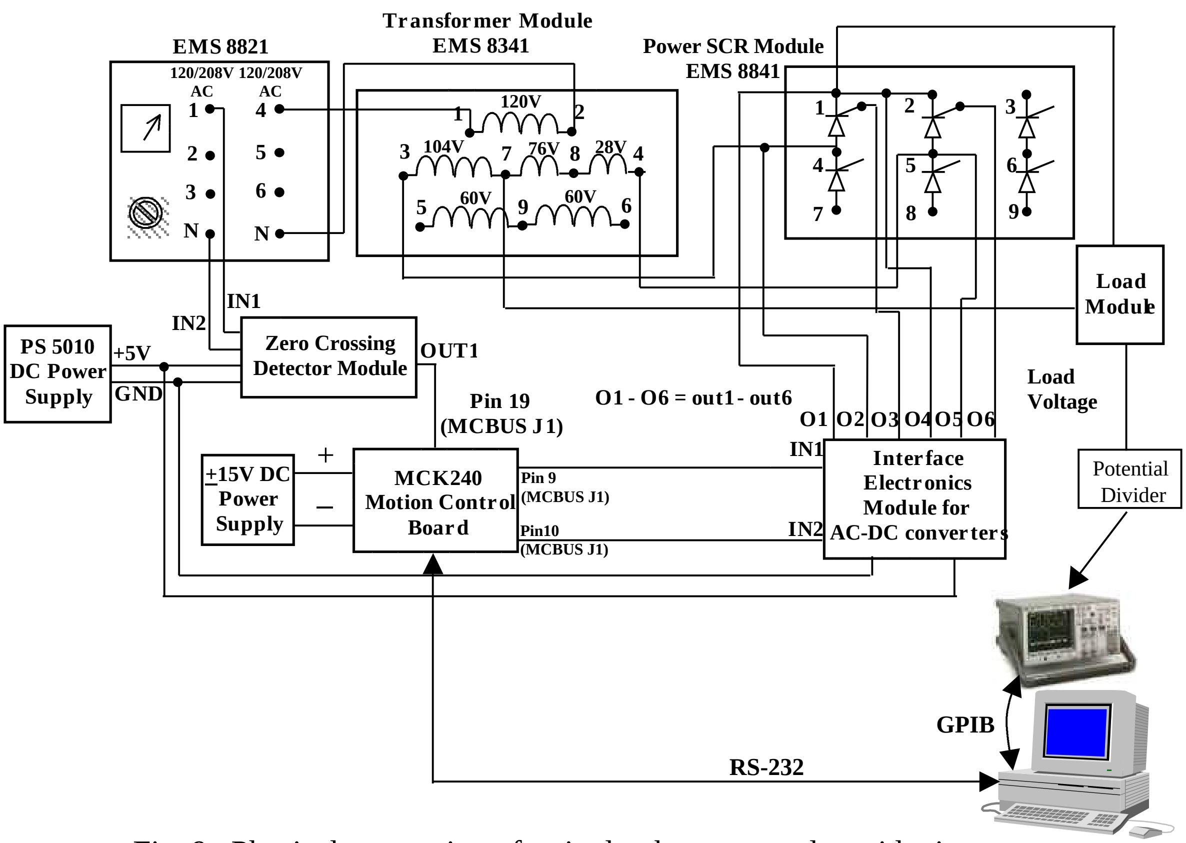

Fig. 9. Physical connection of a single-phase two-pulse midpoint converter

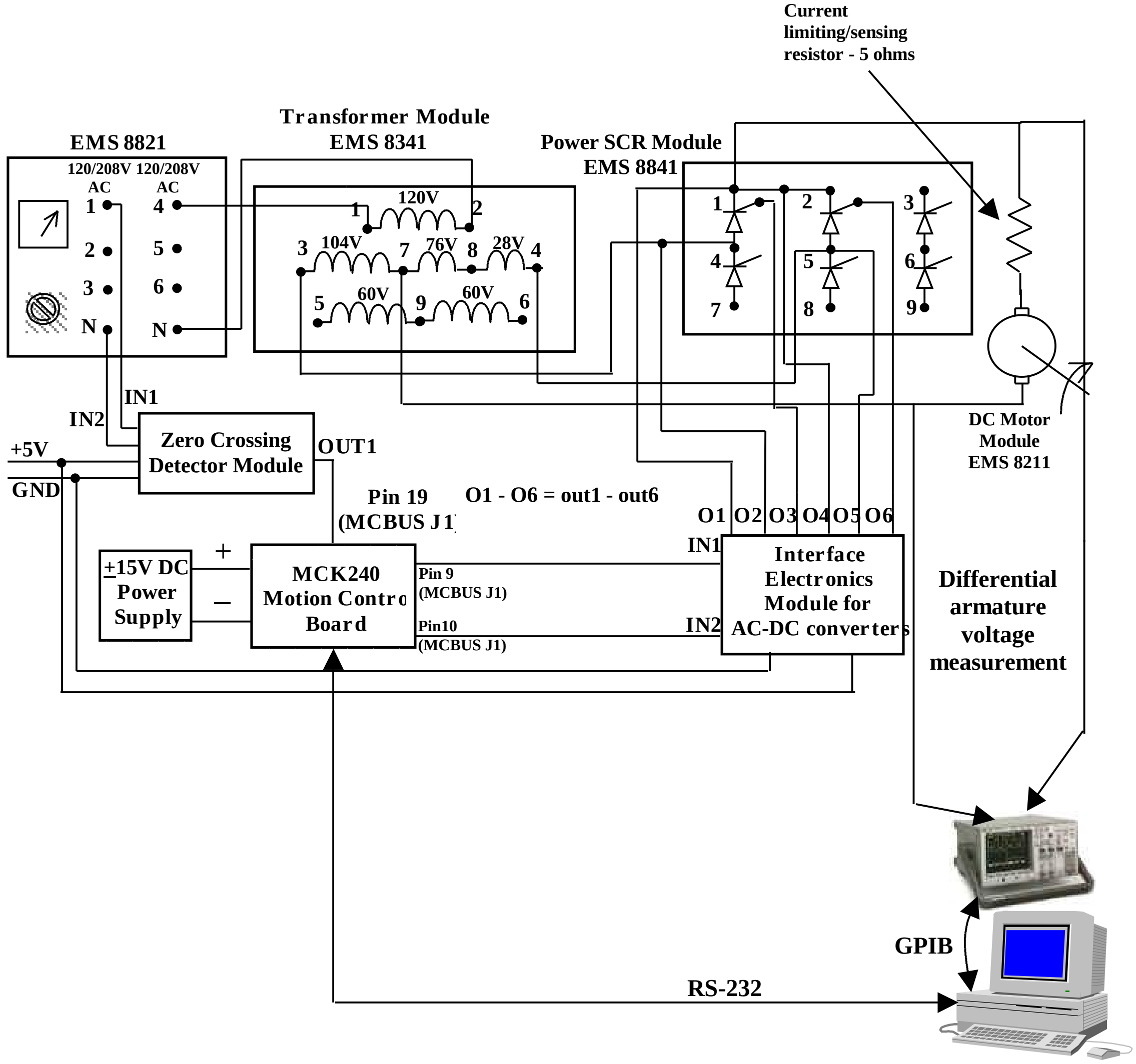

Fig. 10. Physical connection of a single-phase thyristor converter fed dsp based dc motor drive

c). Two-pulse mid-point thyristor converter fed DC motor drive

The real-time concept mentioned above for the control of a two-pulse midpoint converter can be easily extended to the control of DC motors as shown here. The interconnection for the DC motor drive in an open-loop configuration is shown in Fig. 10. All other modules including the software module remain the same. As the delay angle can be varied from the PC, so is the corresponding output voltage of the midpoint converter that feeds the DC motor. The result is a variable speed PC-DSP controlled converter feeding a DC motor drive. The procedure for downloading, running the program and controlling the delay angle from the PC is similar to the ones mentioned in the previous experiments. The same midpoint converter is now used to drive a DC motor. A small resistance is connected in series with the armature. This resistance has a two-fold purpose: (1) It serves to limit the current through the motor when there is a quick fall in the back e. m .f and serves as a protection to the motor and (2) The voltage across this resistor is nothing but a scaled measure of the DC motor armature current. This is shown in Fig. 11. The current can be seen to be discontinuous but it can be smoothened by connecting a DC choke in series with the armature. The armature voltage waveform is shown in Fig. 12. The large ripple in the output voltage is due to the absence of a filter and is typical of a direct midpoint converter fed DC motor drive.

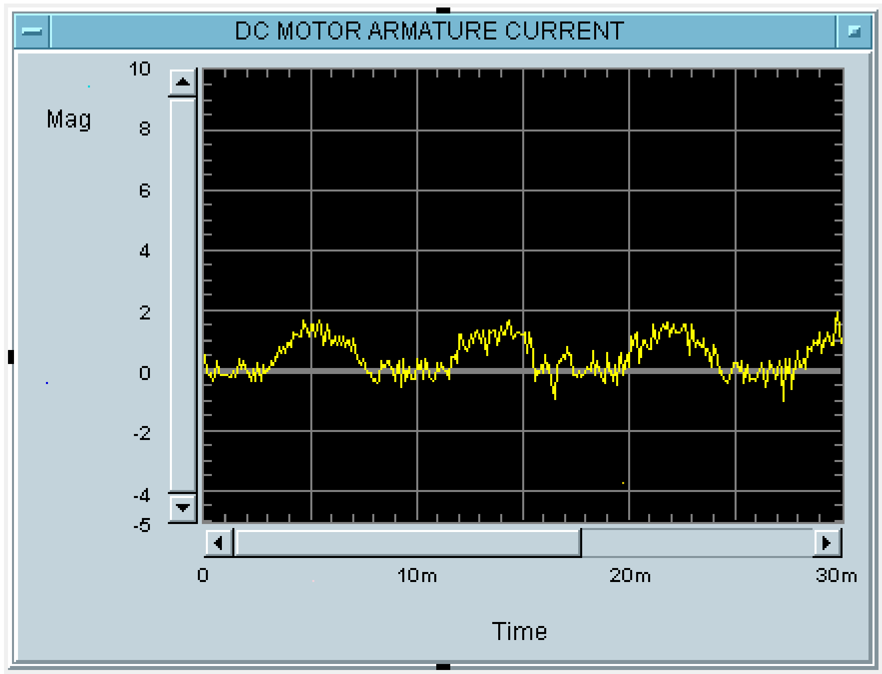

Fig. 11. DC motor armature current

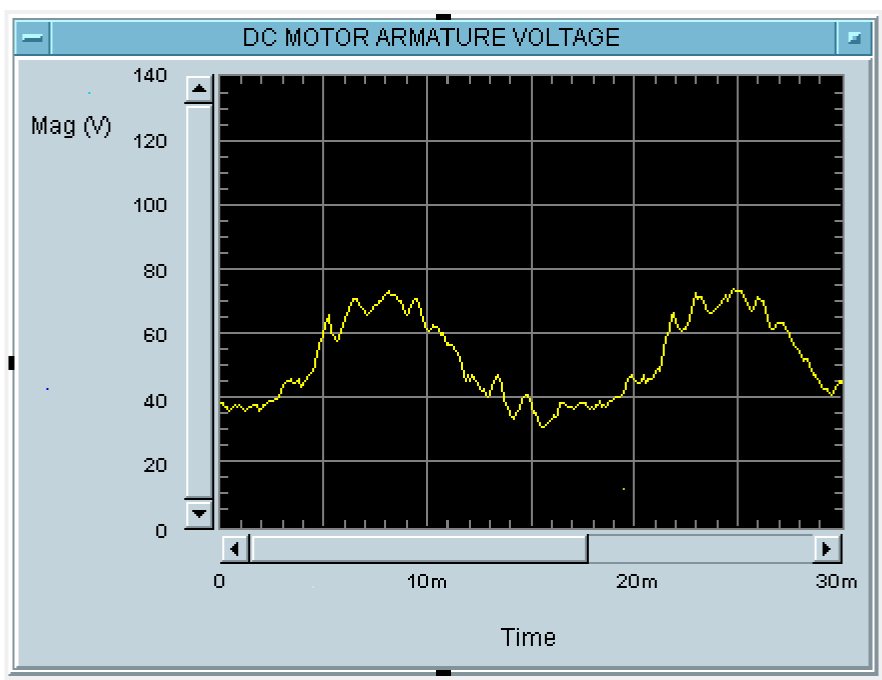

Fig. 12. DC motor armature voltage

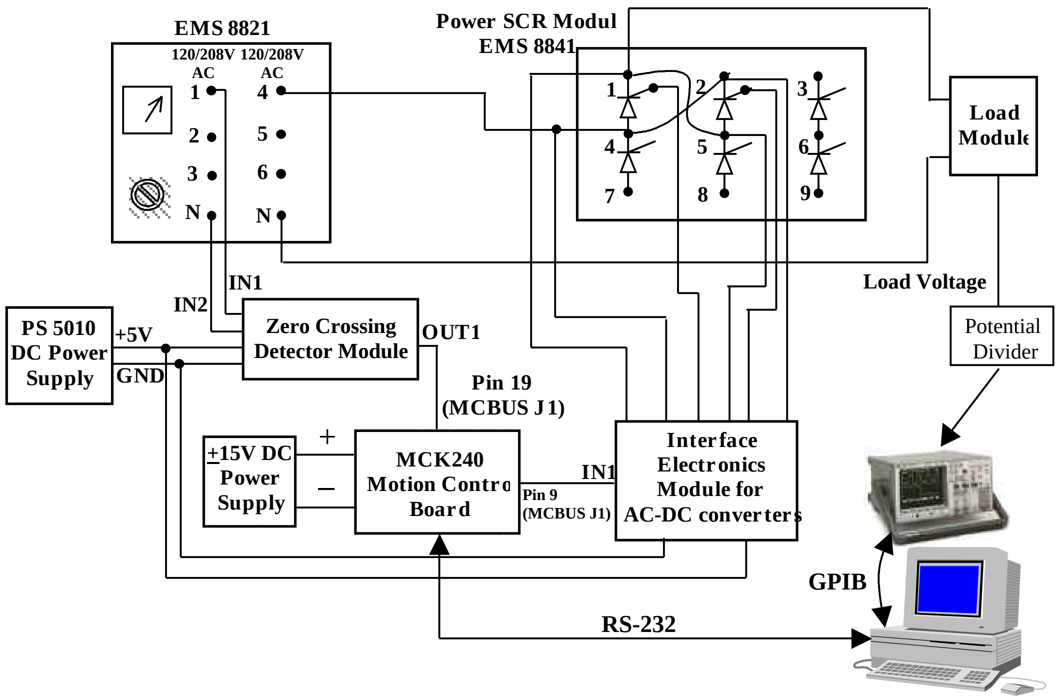

Fig. 13. Physical interconnection of various modules in an ac voltage controller

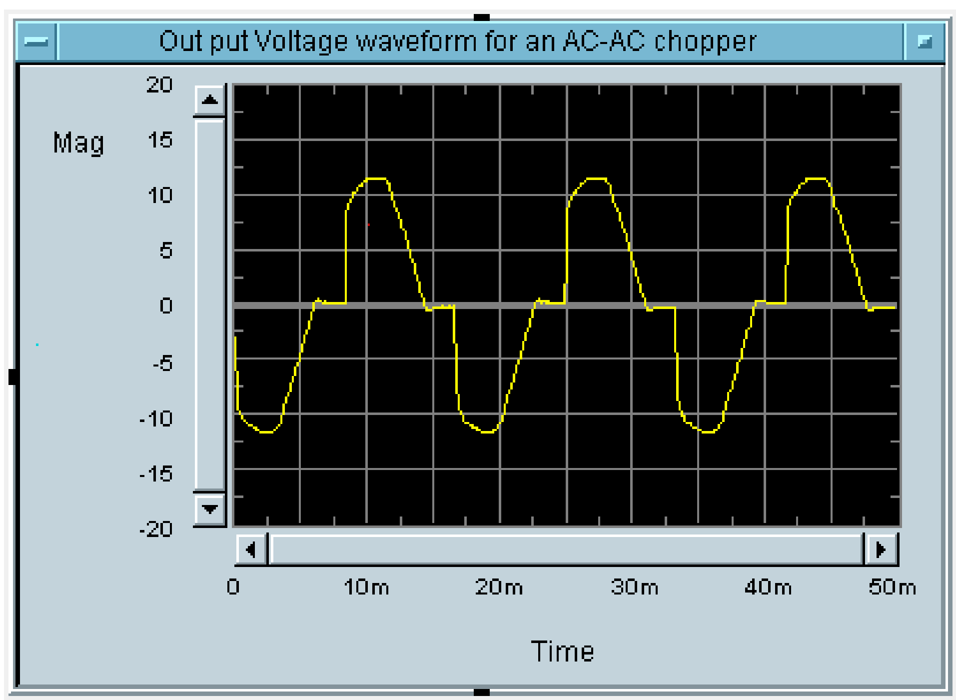

Fig. 14. Output voltage waveform of an ac voltage controller obtained using HPVEE

d). *Single-Phase AC Voltage controller*

The interconnection scheme for a single-phase AC voltage controller is shown in Fig. 13. The trigger generation for this scheme is very similar to the operation of AC-DC converters mentioned in the previous sections. Infact, all the modules including the software module remain the same. In this schematic, two thyristors are connected back to back. Two trigger signals 180^0 out of phase with each other are generated by the DSP for the two thyristors. The procedure for controlling the delay angle from the PC remains the same as that for a single-phase AC-DC converter described in the previous section. The output voltage is shown in Fig. 14. The delay angle and hence the output RMS voltage can be varied in real-time from the PC.

The flexibility in the modular approach is seen here as a number of different topologies that can be quickly experimented. The load voltage waveforms can be seen in the oscilloscope using a 10:1 probe. The results can also be transferred to the PC and stored using the software HP-VEE.

VI. Conclusions

A modern DSP based modular power electronics lab has been implemented at Iowa State University. New concepts such as digital and real-time control along with an emphasis on power electronic converters can be effectively taught using this approach. A modular plug and play concept discussed here offers simplicity and results in considerable reduction in implementation time.

Acknowledgements

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Biography

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