AC 2011-305: TEACHING POWER ELECTRONICS CONVERTER EXPERIMENTS THAT INTEGRATES FUZZY LOGIC APPROACH

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Teaching Power Electronics Converter Experiments That Integrates Fuzzy Logic Control

Abstract—This paper presents a practical approach to teaching power electronics converter experiment that integrates fuzzy logic control. The approach is based on a model-free software-hardware platform for use in converter experiments in a basic power electronics course. This course is an elective topic, and, therefore, the experiments need to motivate the students. The platform is controlled by fuzzy logic-based software (made in MATLAB and LABVIEW environment) and run on a personal computer (PC). The fuzzy logic control incorporates attractive features such as simplicity, good performance, and automation, while using a low-cost hardware and software implementation. The student can manage the fundamental parameters of the converter topology using the software environment**.** The software is designed to provide simple interaction between the student and hardware. The laboratory experiment is performed using a low cost micro-controller PIC16F877 in order to verify the design performance over a wide range of operating conditions. After the basic experiment is explained, students have reinforced their theoretical knowledge of power converters with fuzzy logic. All students have reacted positively to the experiments and overall interest has definitely been increased.

Introduction

Power electronics courses at Howard University have not changed in several decades and are facing particularly strong pressure for change. Students and faculty members considered the courses old-fashioned and outdated, and this lack of interest, in turn, critically limited their ability to understand and appreciate the wide-ranging applications of power electronics. Although students expressed interest in power electronics integrated with digital controls and DSP, the conventional teaching arrangement did not give them needed background and knowledge. As a result, the quality of undergraduate education in the field was diluted. One opportunity arising from the past experience is that we are free to start from scratch with the redesign, and when choosing the dynamic systems that would be the primary focus of the laboratory experiments. We also felt that it would be of greater benefit to the students if we require digital controls to be integrated into power electronics, thus, teaching students what they need to learn.

At Howard University, reforming of power electronics and electric drives courses began in 2004 through Moog funding and has been successfully in nearly doubling student enrollments in these courses[1]. More importantly, power electronics courses today have become widely integrated with digital signal processing (DSP) and digital control technology[2]. There are well-established laboratories which individually provide for the study of power electronics and electric drives[3, 4]. Another article[5] introduces unified machines and drives laboratory capable of various experiments for power electronics, and digital controls. It presents a flexible hardware setup, data acquisition, DSP, and virtual instrumentation. Reference[6] does describe a laboratory environment in detail and suggest a complete formal design procedure that allows code generation and simulation of the equipment together with the control hardware/software. References [7, 8] are related to methodology for laboratory experiments in power electronics. They include instructional software for controlling power electronics converters and simulating some circuits, such as MATLAB or LABVIEW, which are widely used in universities worldwide.

This paper presents an integrative approach to teaching power electronics converter experiments that integrate digital control. The approach uses a collection of tools that include both software (MATLAB and LABVIEW) and low cost hardware (micro-controller PIC16F877). Using human linguistic terms and common sense, a closed-loop control system incorporating fuzzy logic with a small rule base has been developed and implemented for a special class of hard-switching dc-dc converters.

Educational Objectives

The fundamental educational objectives are:

1) to provide hands-on experience in practical power electronics applications;
2) to reinforce and support lecture-based courses in power electronics;
3) to train a new cadre of graduates who value experimentation as an essential and natural part of solving engineering problems;
4) to prepare students for industry as well as advanced courses and research and development oriented careers;

Hardware Description

The students are given a tutorial that leads them through the experiments, describing the hardware apparatus and the actions to be performed in each step. The hardware apparatus used in this experiment, shown in Figure 1, consist of: 1) a DC-DC switch-mode power stage converter[9], 2) a 14-bit PCI Data Acquisition Processor (DAP 840/103)[10], 3) a termination board (MSTB 010-06-C1Z) [15], 4) a Pentium III 550-MHz personal computer (PC) with Windows NT 4.0, and 5) a micro-controller (PIC16F877)[11]. The power stage concept is based on that of a “dual-output forward” configuration operating in a continuous mode of energy storage[9]. The dc-dc converter is equipped with a feedback network that provides as error value to the fuzzy control code running on the PC to generate a control signal, which is the duty cycle. A snapshot of the laboratory setup is shown in Figure 2. Since some components of the system are already available to students, the design steps involving specifications can be performed quickly.

The PCI Data Acquisition Processor occupies one expansion slot in the PC and has onboard processor, (TI486SXLC2-50 CPU), 14-bit A/D converter, 50ns TIME resolution, 800K samples per second, memory, and a dedicated multitasking real-time operating system. The MSTB (010-06-C1Z) termination board allows secure connection of discrete wires to the DAP 840/103 and it combines analog and digital termination on the same board. The feedback network is built around an opto-coupler that provides ground isolation between the input and the output with a potentiometer for the adjustment of the two output voltages to desired levels. The termination board, DAP 840/103, reads the error value from the feedback network using an input channel pipe to the PC in binary format. The source program (written in MATLAB and LAPVIEW language) running on the PC is configured to read the data and correctly processed.

Using a microcontroller the duty cycle is generated by a peripheral Interface Controller (PIC16F877), which uses the Harvard Architecture and mostly used in RISC (Reduced Instruction Set Computer) Computers. It has a separate program bus and data bus, which can be of different widths. A single instruction cycle time of the PIC 16F877 is 0.2 µs. A code was written using MATLAB and loaded into the PIC16F877 to generate pulses at 100 kHz with variable duty cycle depending on the input data received through pin 3 of the RS232 sent by the fuzzy logic control algorithm running on the PC.

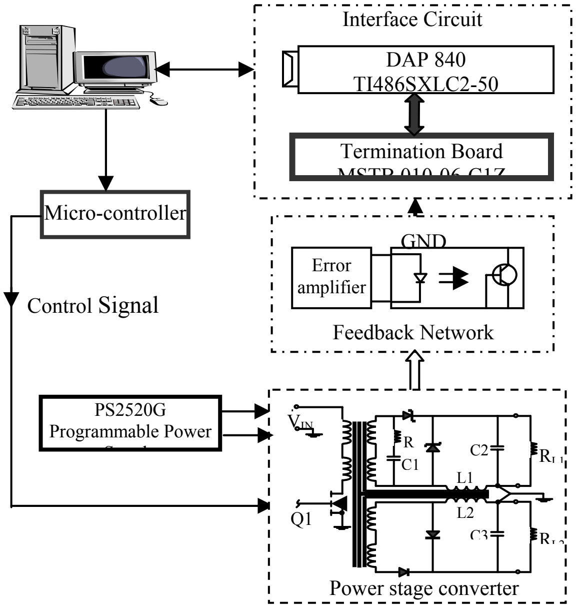


Fig.1 Experimental setup

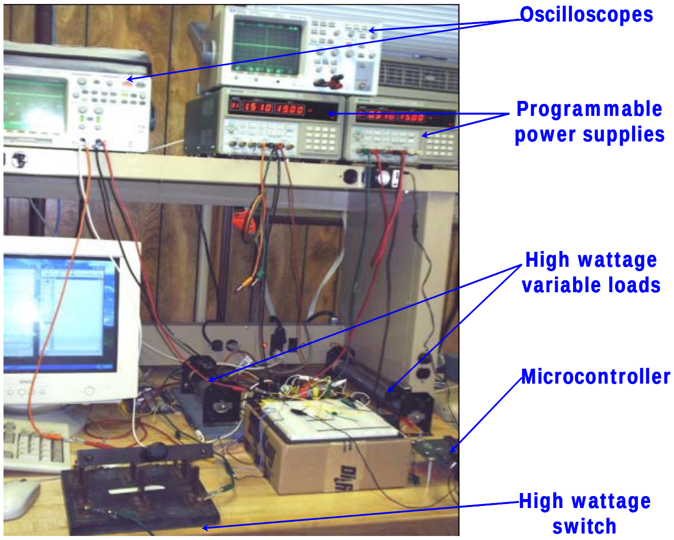


Fig. 2 Snapshot of the laboratory setup

Fuzzy Control Design

The students are asked to develop a two-input single-output fuzzy control algorithm. In this experiment, the students first obtained the inputs variables which are chosen as the voltage error, e(k) and the change in voltage error, Δe(k). The students immediately recognized that the input to the dc-dc converter would be the duty cycle that is actually the output of the fuzzy control algorithm. The students are then asked to put together a fuzzy control structure for their design. The students quickly discovered that a fuzzy control structure would consist of three building blocks:

1) fuzzification block that expresses quantitative action to qualitative action;
2) fuzzy inference engine that generates fuzzy rules;
3) defuzzification block that articulates qualitative action to quantitative action.

The students soon realized that "fuzzification" translates a numeric value for the error e(k) or change in error Δe (k) into a linguistic value such as big or small with a membership grade. The students also documented that "defuzzification" takes the fuzzy output of the rules and generates a "crisp" numeric value that used as the control input to the dc-dc converter. Additionally, the students learned that the controller qualitatively captures the dynamics of the dc-dc converter and executes this qualitative idea in a real-time situation. In this way, the students obtain a physical sense of fuzzy control concept. Ultimately, the students are being able to create prototype scheme of the converter topology (Figure 3). In building their prototype, the students successfully defined the function of the feedback network as a *precision voltage reference* with a nominal voltage of 2.5 V. Then, the students combined the 5V and 15V outputs potentials in a resistive-sampling network in such a way that, the output voltage of the network is 2.5V when the potentials are closed to their nominal magnitudes. After that, the students internally compared this output voltage to the reference of the *precision voltage reference* and any error difference detected is amplified and fed back.

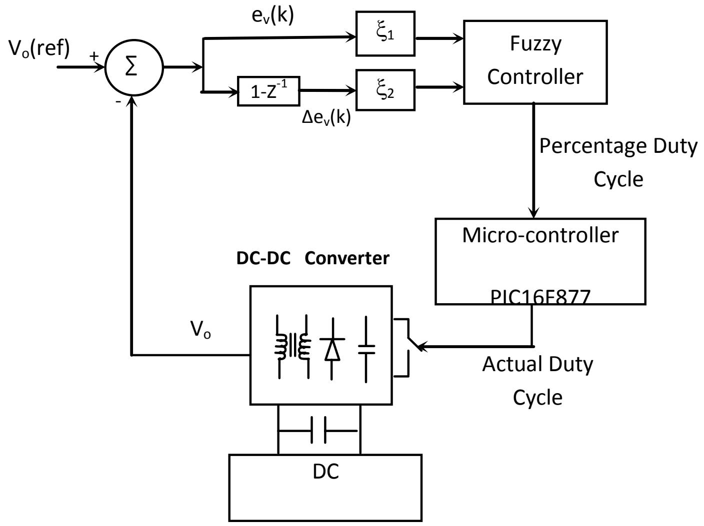


Fig. 3 Converter topology integrates fuzzy control

Lastly, the students represented the converter topology by a "black box" from which we only extract the terminals corresponding to input voltage (V_i), output voltage (V_o), and controlled switch (S). From these measurements, the controller provides a percentage duty cycle signal for a peripheral interface microcontroller PIC16F877 which generates the converter actual duty cycle.

Membership Functions and Rules Generation

In order to determine the ranges of membership functions, the students are asked to perform various experimental test cases on the converter topology. This will help the students in the design of their linguistic control rules of the fuzzy logic controller. The students are instructed to focus on the responses of the dc-dc converter with and without the action of the controller. That is, they are asked to observe how the changes of the control signal and the variations of the error signal with respect to the variations of the input voltage. Observing the various voltage ranges in the test cases is anticipated to assist the students in choosing the ranges for the input and output memberships set. A summary of the experimental test cases performed by the students is depicted in Figs. 4a through 4c. Fig. 4a shows the trajectories of the duty cycle, the output voltage, and the input current with variations in the input voltage. From Fig. 4a, the students observed that when the input voltage increases, the control signal pulses get reduced to maintain the output voltages at their required level. The other information gives the range of the control signal (i.e. 16% - 50%) required for the working range of the dc-dc converter.

The students conducted a similar test case while the error of the system was been observed. Fig. 4b shows four different test cases of variations of the error voltage and duty cycle with increase in the input voltage plotted together. The figure shows four variations of the error voltage with the control signal at 16%, 24% 32% and 40% duty cycle. For the 40% duty cycle test case, the feedback network becomes active at an input voltage of 18V. When the duty cycle was reduced to 32%, the feedback network becomes active at around 21V of the input voltage. At 16% duty cycle, it was realized that the feedback network was not yet active at 36V of the input voltage.

This test case shows that when the feedback network is active, the error voltages are all below 2V. The students also noticed that Fig. 4b gives the actual values of the error voltage and the control signals needed at each stage of the input voltage variations. Based on the above observation, the students arrived at a general rule:

IF the error voltage is high (i.e. max 6V) **AND** the change in error is zero (i.e. very small), **THEN** increase the control signal (i.e. duty cycle)

The symbol “IF” of the rules is called the premise, while the symbol “THEN” is the consequence. The “AND” operator is used to link the premises and the “OR” operator to link the rules.

Finally, the students tested a 5V-output voltage level for different constant control signals while increasing the input voltage (Figure 4c). They performed four different test cases for duty cycle values of 16%, 24% 32% and 40%. From Figure 4c, the students noted that the various voltage levels at which the output voltage gets to the 5V mark for the different duty cycles. The students also noted that without any control, the output voltage will continue to increase without any bound.

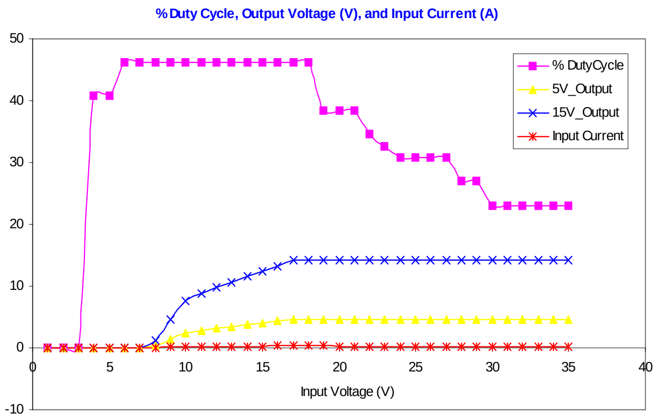


Fig. 4a Trajectories of the % duty cycle, the output voltage, and the input current with variations in the input voltage

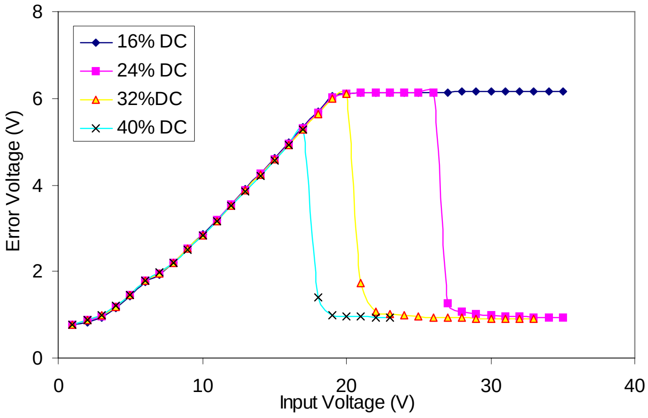


Fig. 4b Variations of the error voltage with the control signal at 16%, 24% 32% and 40% duty cycle.

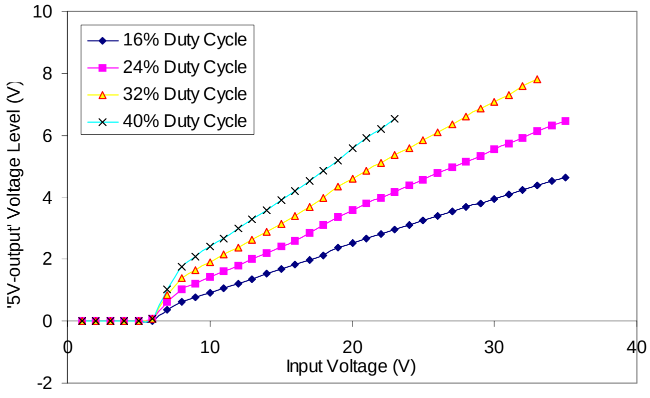


Fig. 4c 5V-output voltage level tested for different constant control signals

The students concluded that these experimental observations were in general very helpful in the design of the fuzzy logic controller.

The next step is to determine the fuzzy sets and the linguistic rules. Consequently, the students selected four linguistic sets for the input variable voltage error, e (k), namely, positive large (PL), positive small (PS), negative large (NL), and negative small (NL). The students also selected three linguistic sets for the change in voltage error, Δe(k), namely, positive medium (PM), zero (ZE), and negative medium (NM). Additionally, five linguistic sets: positive large (PL), positive small (PS), Zero, negative large (NL), and negative small (NL) have been chosen for the output variable of the fuzzy controller. Furthermore, the students utilized triangular membership functions on the controller input. The triangular membership function is chosen owing to its simplicity. For the change in voltage error, Δe(k), The students chose the initial values of the premise parameters (the corner coordinates of the triangle) so that the membership functions are equally spaced along the operating range of each input variable. The scaled input and output membership functions sets are shown in Figs. 5 through 7. The students observed that actual error measured from the feedback network ranges from 0.8V to about 6.0V while the control signal ranges from 16% to 50% duty cycle (Fig. 4b). Hence, the student determined the scaling factors $\xi_1 = 0.167$ and $\xi_2 = 0.01$ in such a way that the normalized inputs e(k) and Δe(k) are well adapted to the universe of discourse [-1, 1] for any operating point.

To obtain control decision, the max-min inference method is used. It is based on the minimum function to describe the "AND" operator present in each control rule and the maximum function to describe the "OR" operator.

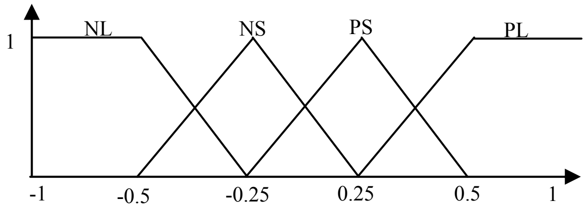


Fig. 5 Membership functions for e (k)

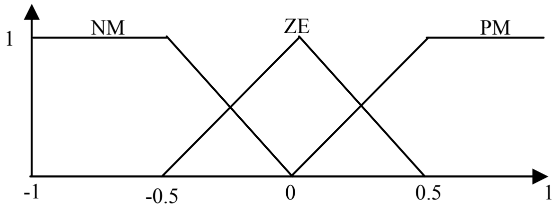


Fig. 6 Membership functions for Δe(k)

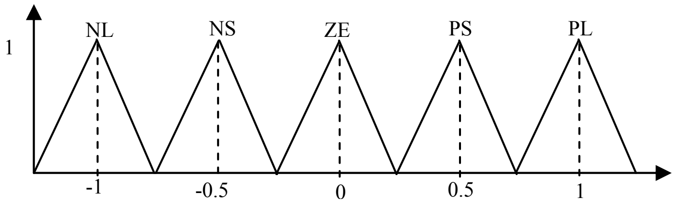


Fig. 7 Membership functions for the control signal

Finally, to express the qualitative action in a quantitative action, the students used the sum-product composition method. It calculates the crisp output as the weighted average of the centroids of all output membership functions. This scaled output corresponds to the control signal (percent duty cycle) that maintains the output voltage at a constant value.

Test Cases

Selected test results performed on the switch mode power stage dc-dc converter are illustrated in Figs. 8-11. In Fig. 8, the students used a step input voltage variations from 21V-to-24V-to-31V and the back to 24V and 21V to complete a cycle. The Students observed that, the fuzzy controller maintains the output voltage at the desired 5V with slight overshoot during each voltage change. The students also investigated the performance of the converter in the absence of the fuzzy controller and the result is shown in Fig. 9. Without the fuzzy control, the students realized that the response of the output voltage follows the step pattern of the input voltage and goes beyond 8V when the input voltage is 31V during its cycle.

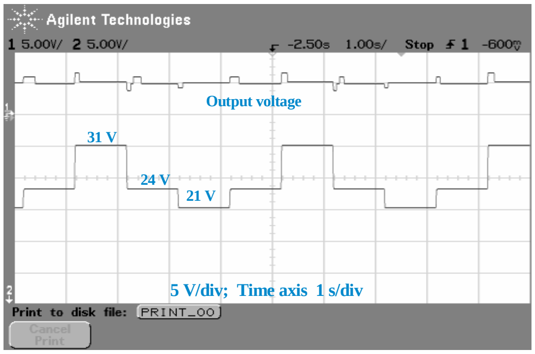


Fig.8 5V-response to step input voltage variations

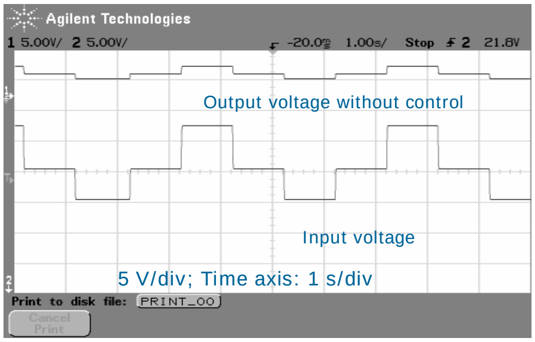
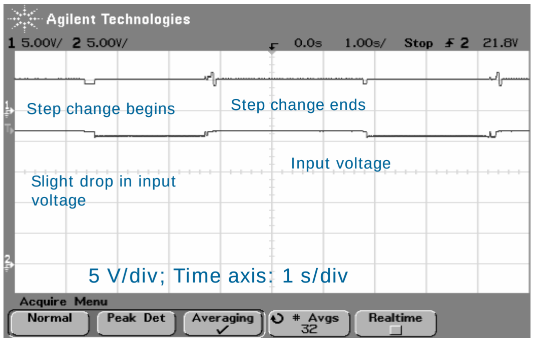


Fig.9 5V response without control to step input voltage variations

Similarly, Figure 10 shows the output voltage response of the dc-dc converter with a step load variations from 10 ohms to 2 ohms, while, Figure 11 shows the response of the dc-dc converter to load transient from 10 ohms to 2 ohms (equivalent output current was about 3A) for about 0.8 of a second. Again, the students observed that the control action of the fuzzy system was able to maintain the output voltage at the desired 5V with slight overshoot in both cases.



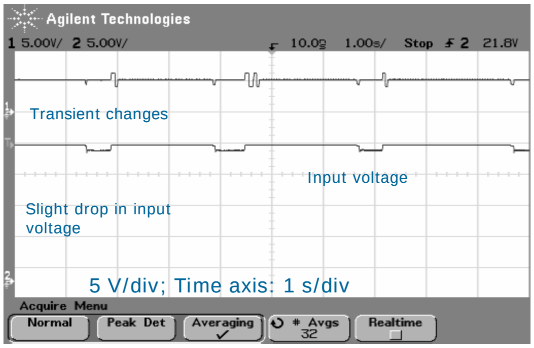


Fig.10   5Vresponse to a load step change

Fig.11   5V response to a load transient

Experience Obtained From the Experiment

Students are satisfied with the use of the platform as presented here, since it is very useful aid in carrying out this experiment and other converter experiments. The degree of satisfaction is supported by the increased number of students registering for the course since the platform was first used in experiments five years ago. The platform combines simulation and control; in addition, it makes the simulation faster and simpler for the student. The authors believe that the simulation is very useful for teaching power converters since it has proven to be a highly effective aid for linking theory and practice.

Initially, the students lack hands-on experience with this kind of equipment, but after getting used to the hardware, they are eager to continue using it. Not only have students developed better experimental skills, they also show an increased awareness of the power of experimentation, and are able to formulate new experiments for the problem at hand. Most of the students are motivated to take related courses in digital controls, microcontrollers, and digital signal processor applications, thus, preparing students to industry as well as advanced courses and research and development oriented careers. We received much anecdotal evidence confirming our belief that hands-on experience and experimentation contribute to developing and eager attitude among the students.

Summary and Conclusions

This article presented a low-cost laboratory setup for integrating diverse concepts including microcontroller, power converter, programming and software development, and electronics. The students carried out all the experiments following a laboratory handout. Experimental result has shown the ease of applying fuzzy control to dc-dc converters, as an interesting alternative to existing conventional industrial controllers. It is expected that the fuzzy logic control considered for the laboratory experiments will likely be used by the students in their subsequent employment after completion of their college education. A course-based laboratory setup allows students to develop fundamental skills in the design and implementation of embedded computer controlled systems. Students are motivated to see that the real-life performance of the apparatus can be controlled and understood.

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