Teaching digital control of switch mode power supplies

ABSTRACT

This paper explains the methodology followed to teach the subject *'Digital control of power converters'*. The subject is focused on several theoretical lessons plus the development of an actual digital control. For that purpose an *ad hoc* dc-dc converter has been designed and built. The use of this board together with some software tools seems a very powerful way to help to the students to learn the concepts from the design to the real world.

INTRODUCTION

Digital control is not new in power electronics. It is possible to find some developments using a microprocessor for motor control three and four decades ago. In most of the cases the control implements complex algorithms and the high cost of the controller is only justified in high power applications such as motion control and three-phase systems. The arrival of digital control to switch mode power supply (SMPS) was much later. One of the reasons is that SMPS used to switch with high or very high frequency requiring very fast processors [1]; the other is the cost. Thus, the first references appear in the late 90s. In the last 10 years, is easy to find papers and sessions in IEEE APEC and PESC conferences dedicated to digital control.

Now the possibilities of using digital control in SMPS are wide: DPS, microcontrollers, FPGAs and specific commercial ICs. The competitive cost of many of these devices together with the advantages of digital control (flexibility, reprogrammability, monitoring, advanced functions such as auto-tunning, efficiency optimization, adaptive control ...) make this topic very interesting for the industry. However, it is not easy to find engineers with very good skills in this topic mainly because a good knowledge is required in two subjects: power electronics and digital electronics. Therefore, this topic has been included in many academic programs to cover these needs.

The purpose of this paper is to explain the methodology and the experience of teaching the subject "Digital control of power converters" of the Master of Industrial Electronics of the Universidad Politécnica de Madrid.

TEACHING METHOD

The course is composed of two parts: theoretical classes and an assignment. Needless to say that in the theoretical lessons the basics concepts are explained. Those lectures are illustrated with many examples obtained in the state of the art of digital control applied to SMPS of the last years (some of them are in the references). The main objective is to stimulate the students to think new ideas.

However, the main part of the subject is the assignment. The students should control a real dc-dc converter from a digital device. We develop a specific board for this purpose (see next section). The mandatory task is to close the loop of the converter using a DSP or any other platform. A second optional task can be chosen from a list filled with ideas taken from the state of the art (see again next section). Simulation is the first step but to pass the subject, it is necessary to operate the converter with real power.

The purposes of this assignment are twofold: to force the students to understand the basic theoretical concepts and to face the real problems that may appear in a prototype.

DESCRIPTION OF THE ASSIGNMENT AND AVAILABLE TOOLS

This subject is given in the last semester of a research Master Degree so, despite a wide theoretical content is covered, an important part of this course relies on the practical implementation of the theoretical concepts of the lessons. Due to the several tasks of the assignment, students have been organized in groups of two to avoid exceeding the amount of hours programmed for the subject.

The practical assignment of the course consists of the design and implementation of the digital control of a SMPS. The specifications and the board soldered and tested are given to the students. Main tasks to be accomplished are:

- Design of the inductors: The specifications for the design and the software (PExprt) are given and the knowledge for this task is acquired in the previous semester. Main motivation of including this small task is that each group has different inductors so the control optimization parameters are not the same for all of them.
- Modeling of the power stage of the SMPS: The SMPS is a two-phase synchronous buck converter, described later in this section, and the software tool is Matlab-Simulink. The averaged model is implemented and simulated to validate the design. SIMPLIS tool is also available.
- Calculation of the discrete domain regulators: Output voltage and inductors currents loops have to be calculated and simulated, using Matlab-Simulink tool.
- Design and implementation of the digital control strategy: there are several mandatory basic functionalities and a special control strategy, more complex, to be selected from a list or proposed by the students.
- Test and optimization of the SMPS testbench.

The selected test bench for the digital control implementation is a two-phase synchronous buck converter, which has been designed, soldered and tested before providing it to the students. The photograph of the prototype can be seen in Figure 1 and main characteristics are:

- Input voltage of 12V (auxiliary supply voltage of 5V for the control stage)
- Nominal output voltage of 3.3V (able to operate up to 5V)
- Switching frequency of 100kHz
- Nominal output power of 12.4W
- Three different loads (1.5Ω, 2.7Ω and 10Ω) are included in the board, each one connected in series to a switch to control the load and to allow the introduction of load steps as a function of the generated control signals.

To simplify the connection of the board to the control device, the following circuitry has been included:

- Output voltage and the inductor currents are measured. Small instrumentation circuits have been included to obtain signals which are in the measurement range of the ADC (0V-3.3V) for all the operating conditions.
- Drivers for the four switches are included in the PCB.
- Three pins to configure the output load.

The controller device selected for this application is a low-cost DSC (Digital Signal Controller), from TI, TMS320F28027 Piccolo [2] whose evaluation board can be seen in Figure 2. Main characteristics are:

- 32-bit fixed point core.
- Several input 12-bit ADC and a high precision (up to 150ps) dPWM (four modules with 2 channels each).
- The DSC is programmed in C language with the software tool Code Composer Studio. It also includes real-time mode capability, very useful in the debug process.
- A library to optimize the calculation with floating point data has been also used [3].

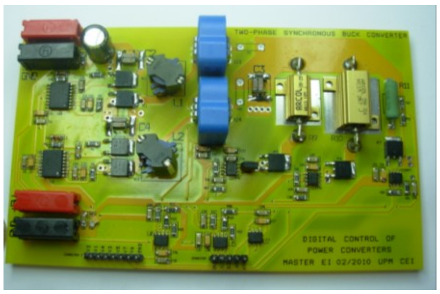

Figure 1: Photograph of the Two-Phase Synchronous Buck SMPS

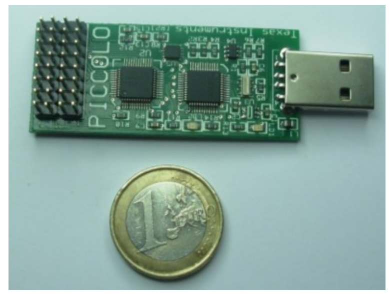

Figure 2: Photograph of the Piccolo DSC Evaluation Board

The evaluation boards, programmed by an USB port, and the low power consumption of the SMPS simplify the set-up for the experimental tests (Figure 3). It consists of the SMPS board, the DSC evaluation board, a low power supply and a computer with CCS installed. It has been given the simplified structure of the program to control the SMPS as the starting point. In practical training lessons, it has been explained its operation and how to complete it to decrease the complexity of learning the operation of the DSC. The task of the students has been to fill the gaps of the code to complete the basic functionality and to program small parts to complete the functionality of the digital controller.

The required basic performance of the digital controller is:

- Implementation of output voltage and inductors currents loops
- Generation of two 100kHz complementary control signals, including the technique of phase-shifting.
- Optimization of the response of the output voltage to a load transient.

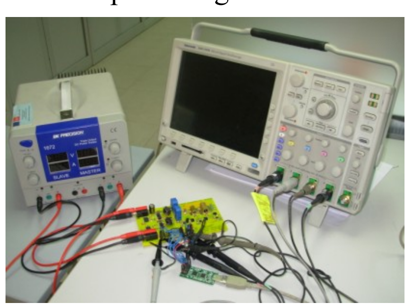

Figure 3: Photograph of the Set-Up for the Experimental Tests

Additionally, different special functionalities have been proposed to the groups in order to implement one of them at their choice: switching between continuous conduction mode CCM and discontinuous conduction mode DCM by turning off the free-wheeling MOSFET as a function of the load to increase the efficiency [4], switching on/off phases as a function of the load [5], DVS (dynamic voltage scaling) [6], minimum time control [7], and dead-time optimization [8]. Two examples of these techniques can be seen in Figure 4 and Figure 5.

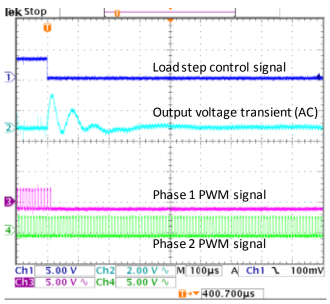

Figure 4: Experimental Waveforms: Commutation of the Phases of the SMPS (100µs/div)

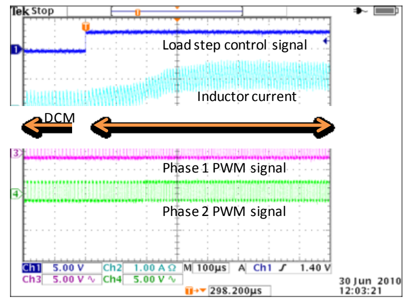

Figure 5: Experimental Waveforms: Switch from DCM to CCM at a Positive Load Step (100µs/div)

EDUCATIONAL EXPERIENCE

Point of view of the students: After the course, a survey was done to get a feedback from the students of the development of the course. This information can be seen in Table I, where are shown the mean values of the answer. As it can be observed, overall results are good and it can be concluded that the students have been satisfied with the experience.

TABLE I: STUDENTS ASSESSMENT

Score from 1 to 5 (1: poor; 5: excellent)		
1	About the assignment, do you think it is interesting?	4,5
2	Correspondence between the knowledge of the students and the asignment complexity	3,6
3	Available tools for the assignment	4,9
4	Effort cuantification of the assignment (please estimate the number of hours used in the assignment)	27
5	Evaluation Process	4,2
Score from 1 to 5 (1: Highly disagree; 5: Highly agree)		
6	Has this subject increased your interest in digital control?	4,2
7	Do you think it will be useful for your research/professional career?	4,7

It can be seen that the interest of the subject as well as the utility of the knowledge acquired are highly scored. On the other side, students have found the assignment complex compared to their previous knowledge. This can be appreciated also in the commentaries enclosed to the assessment, being the most addressed an increase in the practical training lessons of the DSC to reduce the development time. On the other side, it is also commented the interest in learning the whole process of the digital control of a SMPS, from the averaged model design to the experimental tests.

Several students also propose it the introduction of the FPGA implementation, as an alternative option for the assignment and to do a comparison with the DSC option.

Point of view of the teachers: The experience of the course has been very positive. To be emphasized is the utility of the work done in the preparation of the prototypes, which has allowed to the students to learn the basic concepts of digital control with less effort. The average time for each group has been 27 hours.

This year has been the first of this digital control subject and it may have lacked lectures more focused on the practical issues of the digital controller.

The HW & SW tools of the course have been useful also for the researchers of the laboratory, as it is an additional and fast test bench to validate experimentally theoretical results. As an example, one of the master students continued using the course tools to validate minimum time control strategies for his master final work.

CONCLUSIONS

Digital control is a very interesting topic for research and it can provide some advantages when it is applied to SMPS. Therefore the industry is demanding engineers with this qualification. In addition to some available software tools, to help in the teaching of this advanced subject, a specific board with a dc-dc converter has been developed. This board allows an easy testing of a multiphase converter being possible to close the loops (current and voltage) and to implement functions such a phase shedding, deadtime optimization, dynamic voltage scaling, etc. The students use a digital platform (DSC or equivalent) to control this circuit making it robust to load and line changes. Also, they have to implement one or more the aforementioned advanced functions.

The experience has been very fruitful. The use of this hardware has help a lot to the students to acquire the basic concepts and the face the real problems of this technique. The students have declared that this way of teaching is very useful and it increases its interest in the topic although more practical classes are required.

REFERENCES

[1] D. Maksimovic, R. Zane, R. Erickson, "Impact of digital control in power electronics", Proc. International Symposium on Power Semiconductor Devices and ICs (ISPSD), May 2004, pp. 13-22.

[2] Texas Instruments TMS320F2802xx MCU Datasheet, "http://focus.ti.com/lit/ds/symlink/tms320f28027.pdf"

[3] IQMath library, http://focus.ti.com/docs/toolsw/folders/print/sprc087.html

[4] A. V. Peterchev, S. R. Sanders, "Digital Loss-Minimizing Multi-Mode Synchronous Buck Converter Control", IEEE PESC 2004, Vol. 5, pp. 3694-3699.

[5] L.T. Jakobsen, O. Garcia, J.A. Oliver, P. Alou, J. A. Cobos, M.A.E. Andersen, "Interleaved buck converter with variable number of active phases and a predictive current sharing scheme", IEEE PESC 2008, pp. 3360-3365.

[6] K. Choi, R. Soma, M. Pedram, "Dynamic Voltage and Frequency Scaling based on workload Decomposition" Proceedings of the 2004 International Symposium on Low Power Electronics and Design, ISPLED, 2004

[7] A. Soto, P. Alou, J. A. Cobos, "Non Linear Digital Control Breaks Bandwidth Limitations", IEEE APEC 2006, pp. 724-730.

[8] V. Yousefzadeh, D. Maksimovic, "Sensorless optimization of dead times in DC-DC converters with synchronous rectifiers", IEEE Trans. Power Electron., vol. 21, n. 4, pp. 994-1002, July 2006.