

Teaching Power Electronics in the 21st Century

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Abstract

Advances in power electronics and changing demands do make necessary changes in education of power electronics. This concerns the theoretical (lectures) as well as the practical part of the education. The use of the new media (interactive e-learning), problem-based and project-organized learning are possible ways to improve the quality of the education. In this paper a web-based learning tool for Power Electronics and two project-oriented practical for power electronics education are introduced: problem-based learning in the first year of study (theme project) and the design-oriented practical for the fourth year of study as a supplement to lectures on power electronics.

Introduction

Engineers, after having obtained their degrees, were supposed to have sufficient academic qualification to start a life long career. The rapid changes in society have also generated a demand for more flexible engineers having many more qualifications than just a high level of technical or scientific specialisation. Nowadays universities tend to think in terms of much broader skills, one of the main ones being the ability to learn, not only during the time in college but also in the professional life. New forms are introduced, such as teamwork, problem-based and project-organised learning, and design education [1, 2, 3]. These new educational forms are finding their way into power electronics education too [9-12].

The drawback of a purely theoretical approach is that in the undergraduate electrical engineering curriculum less attention is paid to the phenomena that loom up by laboratory experiments and to the exploration of system components. The result of this, in combination with the rapid development of computer applications, is that hands-on and laboratory experience vanishes and computer simulations are paid more and more attention [4].

Traditional education is based on lectures and related practical. There is a variety of excellent text books oriented to teach the basic concepts [5] and a lot of attention is also paid to the practical [10, 12, 14, 15]. The changing world and fast advance in power electronics requires changes of the power electronics education. This is also proven by the increasing number of contributions at power electronics conferences like given in the references.

The web-based learning tool is introduced at the ETH Zurich and project-oriented education at the Delft University of Technology in order to support or partially replace the traditional lectures. The web-based learning tool and two of such projects for two different groups of students are introduced in this paper. Each of them has its own philosophy and goal as explained in the following. The paper is divided into three parts each addressing a separate educational tool and aspect. These are: Web-Based E-Learning Tool for Power Electronics (iPES), Theme project and Power Electronics Practical. The educational tools concerning power electronics are introduced in the order how the students obtain them in their curricula.

Theme project (first year of study)

Traditionally, the first year curricula in engineering consist of numerous and often mutually isolated courses. Students appear to

have great difficulty in understanding the relation of the course contents and the field they have chosen when they started. This often leads to a lack of motivation. Furthermore, in the first year engineering students often are more trained in analysis rather than synthesis. Finally, typical engineering skills such as creativity, communication, teamwork etc. appear to be less emphasised as the 'hard issues' such as mathematics and physics.

The other importance of the project is that fresh students get involved in power electronics – something they do not have any practical experience in contrary to computer technique, telecom or information technology. This way we hope to make energy technology and particularly power electronics attractive to the next generation of the students. The motivation of the students is challenged by others as well [11, 13, 17].

We have tried to solve the mentioned problem by introducing a "course" in the format of small working groups, which run throughout the first year. The groups carry out small projects and a tutor with an advisory role supervises them. One of the themes of the project is "Electrical Energy". It is compulsory for all first year students. The structure will be discussed in more detail later. The pedagogic philosophy can be best described as 'teach me how to do it myself'. Project-oriented education related to power electronics is finding its way also elsewhere with different levels of complexity [11-14].

Specific objectives for the "Electrical Energy" project

The image of power engineering is often that of a traditional, not developing and old-fashioned field. Power electronics in particular is not known at all. Many students can not even give any answer to the question what power electronics is and what it studies.

The selection for a direction of the study is however made after the second year. The tendency today is that students select subjects they are familiar with such as computer technique, telecommunication and information technology. This choice has little to do with the actual market situation and the needs of the society. The project can positively contribute to that selection in benefit of power electronics. The first specific objective is to propagate energy technique and specifically power electronics and to positively influence the direction and choice of the study for this subject.

Renewable energy and wind and solar energy attracted considerable attention over the last years. The relation and link to power electronics is often missing by the students. The second objective

is thus to propagate the renewable energy sources and to place them in context with power electronics. Another issue to be addressed briefly is to avoid environmental pollution making power electronics more attractive [16].

The young generation can nowadays think in terms of bits and bytes but not in the terms of energy and most important in terms of amount of energy. The physical understanding of the amount of energy needed for a simple task such as the one described next in the project is beyond the expertise of most of the students. The third objective is to learn to think in terms of energy and also to efficiently deal with the energy.

General, educational objectives and framework of the “Electrical Energy” project

The key issues of the educational objectives of this module are:

- learning to think in alternatives;
- learning that in real life there are always more solutions to a problem than just one;
- learning to evaluate alternative solutions by first formulating criteria;
- learning to think in terms of functions, rather than implementations;
- learning to use knowledge and skills as a means rather than a goal;
- learning to perceive technology in a context.

The course has the format of small working groups of ten students, which run throughout the first year. The study load of the course is equivalent to 11 ECTS credit points. The groups carry out small projects and a tutor (a member of the academic staff) with an advisory role supervises them. The pedagogic philosophy can be best described by the traditional Montessori-approach (though not explicitly applied): ‘teach me how to do it myself’ [2, 3]. It was decided, that, within the framework of this course a project has to be incorporated, that, apart from the general problems mentioned above, might help to solve the problem as discussed in the introduction, viz. the ignorance of the field of electrical energy [4]. This paper encounters the project aimed to propagate power electronics and electrical drives study specialization.

The “Electrical Energy” project

In order to meet the general and specific objectives of the project the assignment was defined. The project assignment is in a first place very simple: there is a need to get water from the drain, which is 1 meter deep. The drain is located in a remote place, in an area where no source of electricity is available. As a tool there is a crane with a basket or a water pump available. Available sources of energy are sun or wind energy which are both available for a limited time interval. The designed system could use any of the two available energy sources with any of the two loads, viz. the crane and the pump (Fig. 1). There are thus basically four different combinations. Taking into consideration the rest of the building blocks the number of possible combinations of connections of components (building blocks) is even larger.

Selection of the building blocks

The available basic building blocks (Fig. 2) are:

- Solar cells;
- Windmill;
- Up/down chopper;
- Super caps energy storage;
- Pump;
- Crane.

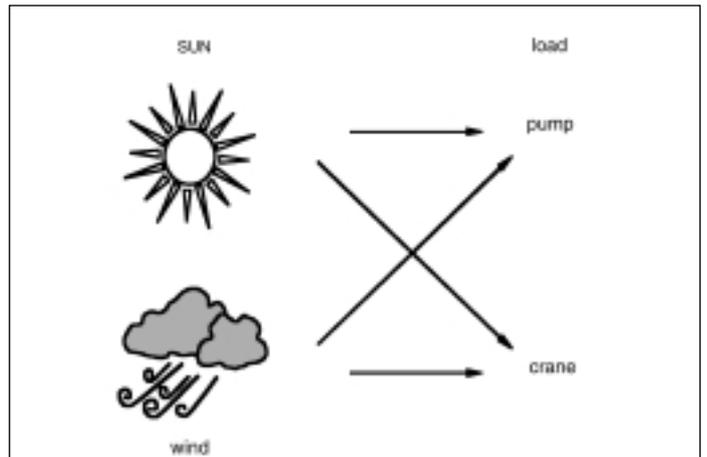


Fig. 1: Available sources and load

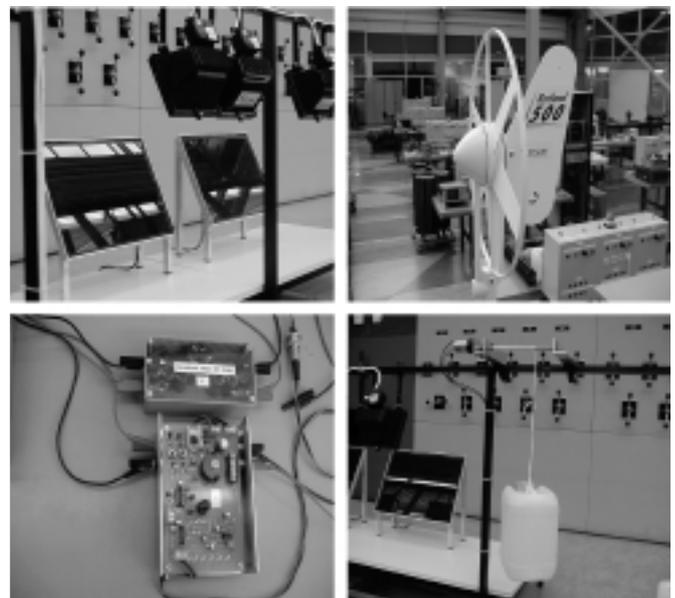


Fig. 2: Solar cells, windmill, dc-dc converter, super caps, crane

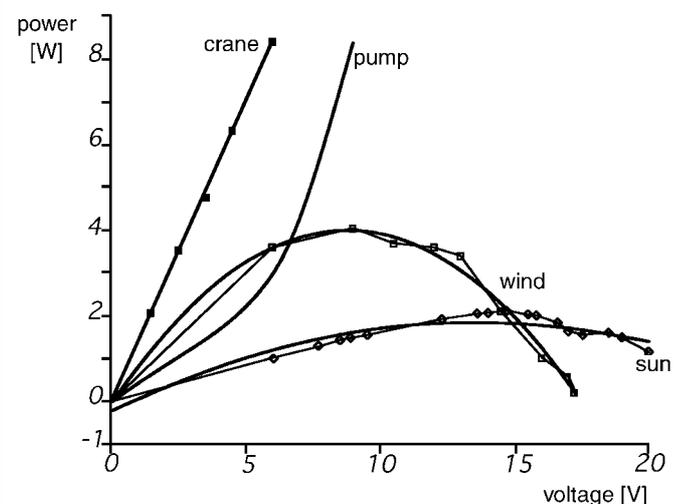


Fig. 3: Electrical characteristics (power) of the available components

The building blocks are selected with respect to the specific objectives. As renewable energy sources a wind energy generator and solar cells are selected with the aim to propagate the renewable energy sources and also to think in terms of energy. A fan drives the windmill which delivers a peak power of 4.1 W. The wind is available for four minutes. Similarly the two solar cells deliver a power of 2.1 W for a time interval of six minutes. Solar cells are illuminated with a set of lamps. Purely taking in consideration these facts the amount of energy per available source can be calculated. The result is 984 Joules which can be obtained from the windmill generator compared to 756 Joules from the solar cells. Another effect taken into consideration is that the solar cells deliver the energy immediately after the lamps are switched on while the windmill has a starting up effect and it takes some time to obtain the maximum power. The start up takes also longer if the windmill is loaded.

The crane and the pump are selected to show the importance of high efficiency of the components of an electric drive. Good understanding of the component but also creativity in selecting the optimal working point in the complex system are here the key points. As can be seen from Fig. 3 the voltage of the crane is limited to 6 V (parameter of the used machine) which must not be exceeded. To connect the crane to a windmill the power converter has to set up the working point.

The power converters (up/down chopper or d.c.-d.c. converter) do place power electronics in the context of a larger energy system. Straightforward linking of any of the two energy sources to the loads does not lead to satisfactory results because of the mismatch between these sources and the loads. This latter fact is essential. Therefore, the need of energy conversion becomes apparent. The application of power electronics conversion is consequently introduced in a natural way. The up/down chopper can change voltage from 3-25 V to a voltage of 3-50 V. The detailed understanding of the power converter operation is beyond the expertise and expectation of this project and its function is explained by a simple imagination of a 'd.c.-d.c. transformer' able to change voltage and current.

Organisation of the project

The project is simultaneously and independently performed by several groups of students. Each group is formed by 10 students. The time available for this project is limited to a four half days. The amount of work and limited time forces the group to divide into subgroups with different tasks. Usually it is a subgroup of two students per available component. By the design the result of each subgroup is of the same importance. This means that students have to accept results not only of several subgroups but also have to critically evaluate work of their colleagues. Working in teams and training communication skills by the interaction between the subgroups are the important and necessary abilities. By this they also learn to perceive technology in context as one of the educational objectives.

Evaluation of the educational objectives

Let us evaluate the other educational objectives. The students learn to think in alternatives and learn that in real life there are always more solutions to a problem than just one. Every group obtains a different solution with a different result. This results in a different amount of water obtained from the drain. The students learn to evaluate alternative solutions by first formulating criteria such as power, energy, time, voltage, and current. Without this many measurements prove to be at the end unusable for the ultimate system design. The students learn to use knowledge and skills as a means rather than as a goal. The goal is to get water from the drain the knowledge about the components is only a means of obtaining it. Specific knowledge about power and energy

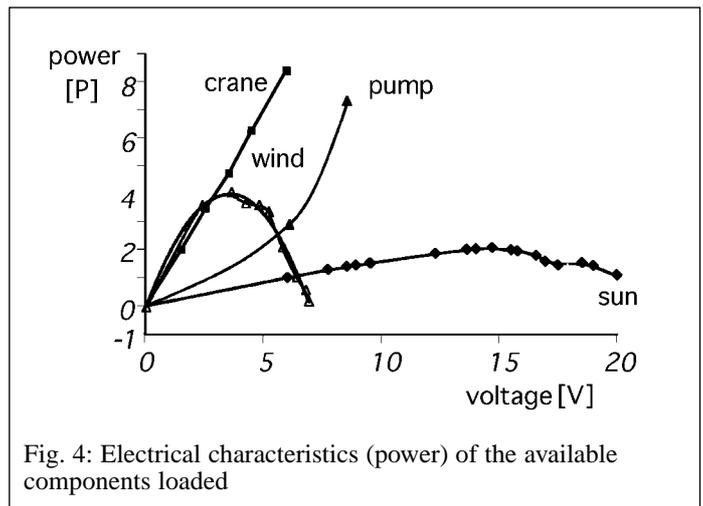


Fig. 4: Electrical characteristics (power) of the available components loaded

as well as knowledge about the components e.g. the converter is required. To obtain this knowledge certain skills such as experience with measurements and measurement techniques are necessary. Evaluation of alternative solutions based on formulated criteria is the essential part of the process. As already mentioned the students learn to perceive technology in a context of a larger project.

Project implementation

The essence of the project and final objectives comprise:

- finding the optimal working point of each element (source, load) with the use of a power electronics converter and learn to manipulate energy in an efficient way;
- the proper use of energy storage elements (super caps);
- matching voltages and currents and maximal allowable parameters of the components;
- implementation of a complete system.

There are numerous possible solutions and it is not the objective of this paper to describe the best solution since such a solution would be based on dynamical models and deep analysis of the components and the use of a control theory. Surely there is a scientific solution to the project assignment, but it is impossible to expect it from the first year students. Still it is interesting to follow how some students intuitively approach the so called scientific solution. Each element has an optimal working point. For example, the used solar cell output power is optimal at a certain value of the load as can be seen in Fig. 3. Similarly, there are optimal working points for other components (Fig 3). The 'optimal' point requires to define a criteria before searching. With the help of the dc-dc converter the source characteristics can be made different to suit the load better. In Fig. 4 the characteristics of the windmill is 'shifted' by the use of a d.c.-d.c. converter in order to match the characteristics of the crane. In the real system this is changing dynamically by loading the windmill generator. The winner group discovered this fact and changed the duty ratio of the converter during the operation achieving a simple regulation effect. By creating a simple hand controlled power point tracker the better use of energy is achieved. Since the energy sources are available only for a limited time, the students learn to think in terms of available amount of energy and efficient energy conversion respectively energy storage. The use of the energy storage allows using the crane or the pump for a longer time than the availability of sources. At the same time use of energy storage allows the utilization of energy by start up or shut down of the source. The used components have their electrical parameters defined. Even if it would be advantageous these parameters cannot be exceeded. As it appears during the evaluation this is not

always clear to the students. Although every team obtains the same tools and means the results prove to be quite different. The group that learns to manipulate the energy in the most efficient way achieves the best result. The students obtain experience with the power electronic component (d.c.-d.c. converter) and they learn that the use of energy conversion leads to more efficient energy transfer. At the same time they learn to develop alternative solutions and select an optimal solution given a particular criterion.

Assessment

The key issue of the final assessment is a real working system. Furthermore, we introduced a competitive element. After completion of the project by all teams, the teams come together in a final session where all teams have to show their results in a short presentation. A panel of three assessors assesses each group. The assessment of the teams concentrates not only on the transported amount of water but also on the quality of the presentation. Although it is not realistic to expect a scientific result from the first year students, the criteria such as good study and understanding of components, and creativity are assessed too. Creative solutions are especially rewarded. From the electrical point of view it is very important that students take also electrical parameters into consideration. These are e.g. the maximal allowed voltage of the super caps, of the crane etc. Exceeding these parameters for a short time does not have to lead to a disastrous effect on a short term but affects the system on the long term concerning reliability and lifetime. Therefore, exceeding some of these parameters lowers the assessment results. The team that obtained the best result gets a small prize.

Web-based e-learning tool for power electronics (fourth year of study)

Numerous papers were published on distance-learning via the internet, where typically multi-media rich web pages are offered to a student taking lessons on a certain subject, while keeping contact to other students and the teacher via, e.g., e-mail, chat-rooms, or on-line tests. This approach gives the advantage of full working place-independence for the student. If there are not pressing deadlines for homework and tests, there is also the advantage of a certain amount of working time-independence. Today, there are different web-based platforms available which offer tools like chat-rooms, presentations, web-page generation etc. in one package. The user (the professor) doesn't have to write code (like Java, HTML or XML) but has to only configure the platform according to his certain subject and has to insert teaching material. Other papers are focusing on the style of teaching under the impression of extensive usage of multi-media like video clips, audio or slide shows in the lecture room or via the internet, where especially the efficiency of these new methods in teaching is discussed. As a platform for delivering a large amount of multi-media based material often the internet is proposed, although the often limited bandwidth seems to be problematic. In this approach the contents of the lesson is extended by visual and audio-format material.

There are only few papers dealing with the combination of text explaining the theory with interactive programs which allow the student to perform experiments via a simulator or to solve engineering problems. A main problem with this approach is the seamless integration of text and interactive programs which is necessary to give the student a tool which allows to start studying immediately without wasting time on the installation of a large number of plug-ins, or of a few complex executable programs which might be unstable on some computer systems. The technology of such a successful integration is realized with the new e-learning tool iPES discussed in the following.

Simulation and interactive animation

When studying a certain power electronic circuit, the explanation to the student is based on the different current paths in dependency of the switching states and certain impressed currents and voltages. With traditional teaching the current paths are drawn into the power circuit diagram using different colours, or presented by slide-shows in the lecture room. Using the new e-learning tool iPES (www.ipes.ethz.ch) interactive animation programs give the student the opportunity to influence parameters like transistor switching states and to watch the resulting change of the current paths which is visualized by coloured dots moving according to the direction of the current flow [8].

General aspects of interactive learning

The learning or teaching of a technical subject is often challenging as there is a large number of possible reactions of a system to parameter changes. Also, there is frequently a sequence of states occurring in steady state. The conventional presentation of such contents is to provide a sequence of figures showing time- and/or parameter-dependent snapshots of the system behaviour in case of a parameter change. The pictures are presented on paper (in textbooks) or by using a beamer (in the lecture room). If the same contents is presented in the form of a short movie, the dynamic system behaviour is immediately obvious. Techniques like slow-motion and repeating sequences, or highlighting important areas of the system can be used to focus the attention of the student on the important issues. One problem with this approach is the subjectively different time students need to develop an understanding of a technical problem. In the lecture room students are limited in influencing the speed of the animation. Another negative effect is that students understand what they see but are not able to remember and apply that knowledge afterwards.

In the new e-learning software tool Java-applets are capable of acting like movies demonstrating complex and/or dynamic system behaviour. Additionally, the applets offer the possibility of an active manipulation of system parameters with the mouse via the graphical user interface and to study the resulting time behaviour and/or frequency behaviour of the system. The associated HTML text gives hints how to operate the system in order to understand why certain system reactions occur. This way of learning is advantageous over the classical approaches described above as the student is actively involved.

Examples

The following examples are part of a full one-semester basic course on power electronics discussing:

- basic topologies of d.c./d.c. converters,
- single-phase PFC rectifiers,
- control theory of PWM rectifiers,
- inverter circuits (H-bridge),
- diode rectifiers (single- and three-phase),
- SCR rectifiers (single- and three-phase),
- d.c.-motor drives,
- theory of phasors and space-vector calculus.

In the following some examples are shown. Since the applets are designed not to be constrained by non-interactive static paper, the following description is naturally limited. However, all examples can be found and tested at www.pes.ee.ethz.ch.

Boost converter

For explaining the operating behaviour of a boost converter it is necessary to show the current path in dependence of the state of the power transistor. In the applet of the power circuit (top-right in

Fig. 5) the actual current path is marked by moving coloured dots and the visual representation of the power switch is different for the on- and the off-state. The second applet (bottom-left in Fig. 5) shows the time-behaviour of currents and voltages over two switching periods just as it could be seen on an oscilloscope in the

laboratory. A main feature here is a vertical line marking the considered point in time which can be dragged by the mouse. This actual time defines the current path animated in the power circuit applet. The third applet (bottom-right) shows the duty cycle required for keeping a desired ratio of input voltage and output voltage in dependency of the (normalized) load. The voltage transfer ratio (the characteristic curve in the diagram) and normalized load (point on the voltage-ratio curve) can be dragged. The operating parameters defined in this way are communicated to the time-behaviour-applet (bottom-left) which is immediately updated. If the current-path state (defined by the vertical time-marker) changes, information is sent to the power-circuit applet.

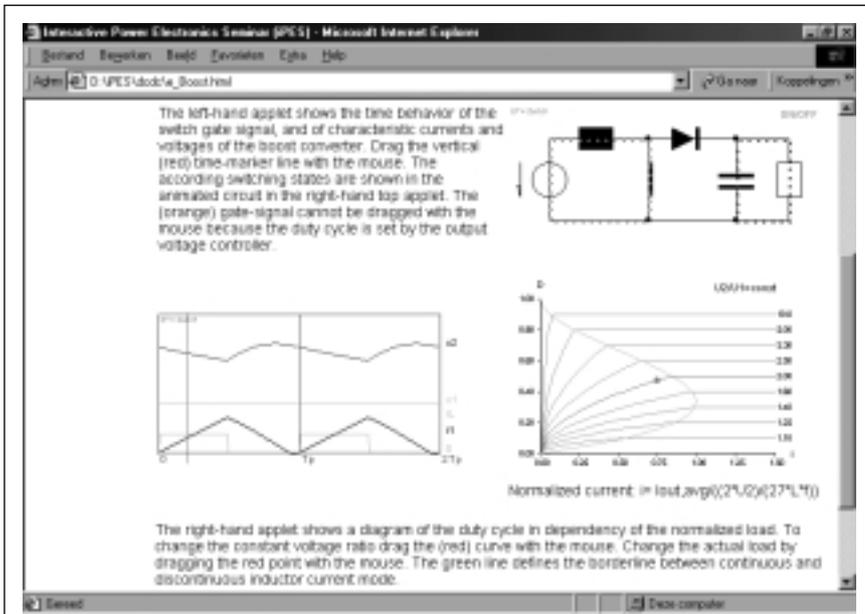


Fig. 5: Interactive learning - Boost converter

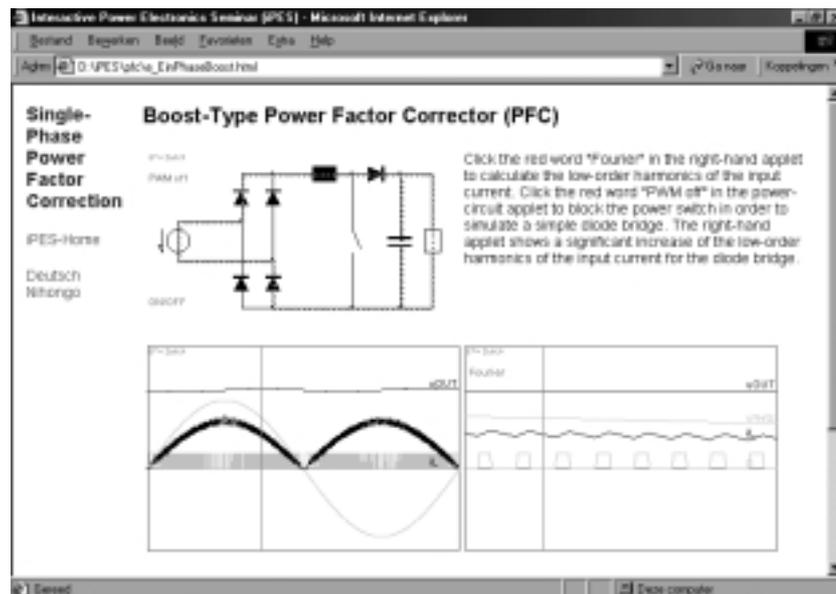


Fig. 6: Interactive learning - PFC circuit

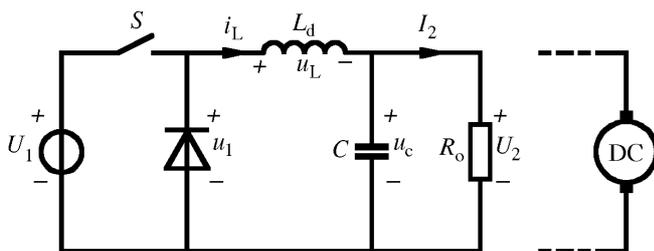


Fig. 7: Buck converter with R load and DC machine

Single-Phase PFC

In the section on the single-phase PFC rectifier (Fig. 6) the mouse-draggable time-marker of the applet showing the time behaviour over a mains period (bottom-left) defines a small time interval shown in a zoom-applet (bottom-right). Here, one can study the details of voltages, currents and switching signals at a certain position within the mains period. The zoom-applet also shows a mouse-draggable time-marker which is coupled with the animated currents of the power circuit applet (top left) as described before. An additional feature of these applets is the possibility to switch for PFC operation into diode bridge operation by a mouse-click. This is easily done by leaving the power switch continuously in the off-state. Another feature is the possibility to switch the zoom-applet into a diagram which shows the harmonics of the input current of the rectifier by a single mouse-click. This feature powerfully demonstrates the advantages of PWM rectification concerning given restrictions for low-frequency current harmonics.

Power electronics practical (fourth year of study)

Innovations of power electronics practical obtained a lot of attention recently. A project- and problem-based practical for electric drives is introduced in [12] with a new laboratory called Flexible Drives System Laboratory (FDSL), including a matrix converter and a total development environment. A drive-oriented practical is addressed in [14] and [15]. In [10] an approach for self-learning in power electronics is introduced. The proposed laboratory setup combines simulation, theory, and measurements on a real prototype without professor's assistance.

The number of the available hours for the practical at the TU Delft is limited. For power electronics it is three half days per four hours in a semester. The selection of the subject is therefore especially important. The selected contents is a design of a buck converter (step-down chopper) with a resistive load later extended to a DC machine (Fig. 7). This converter topology is selected because it forms a basic building block for a voltage source inverter. The practical of a buck converter is therefore in the final part extended to a switching leg of an inverter.

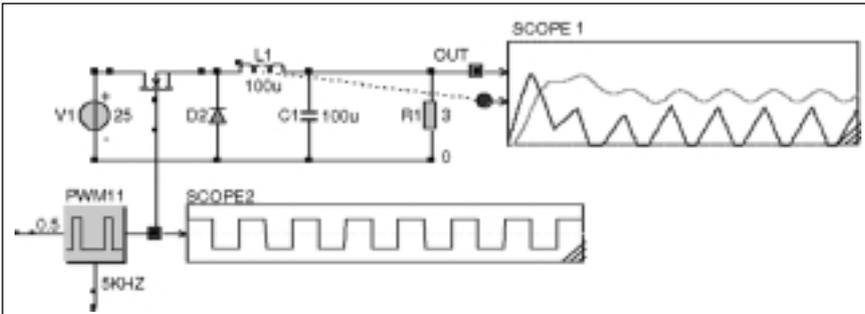


Fig. 8: Caspoc simulation scheme of a buck converter

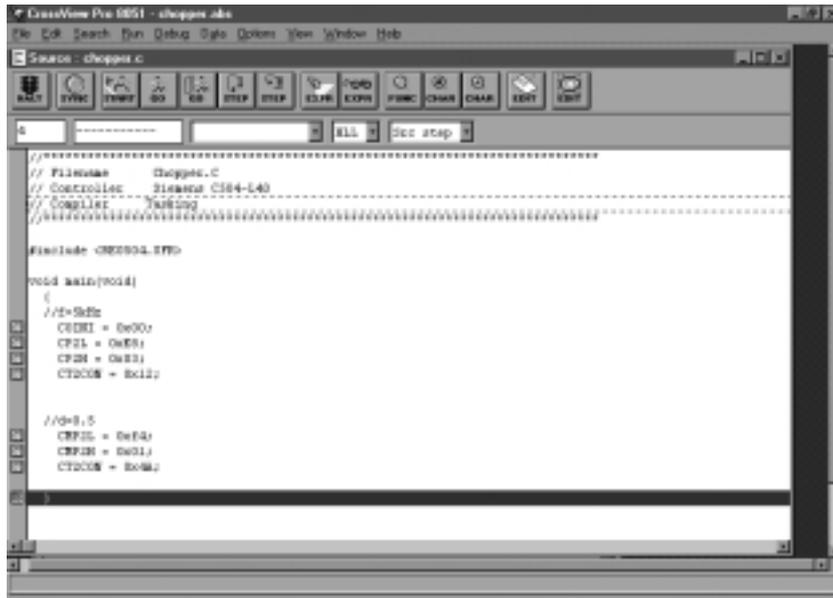


Fig. 9: Programming and debugger tool

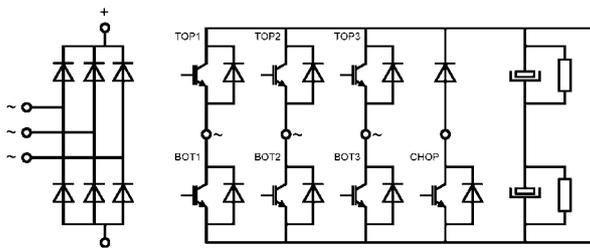


Fig. 10: Available breadboard building blocks

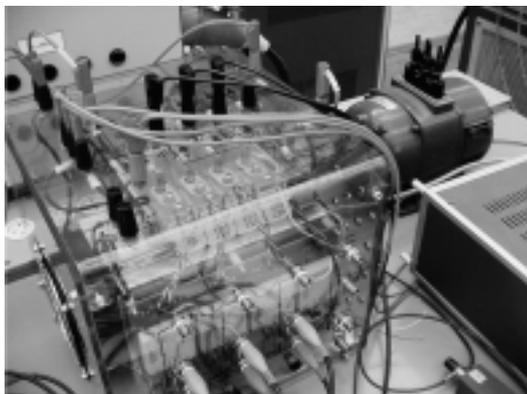


Fig. 11: Power electronics practical

Demonstration of a three-phase inverter with vector modulation concludes the practical.

The objectives of the practical can be summarized by the following points:

- simulate a typical design process of a converter;
- show the physical layout and construction of a modern converter;
- demonstrate the switching effects of power semiconductor switches (e.g. switching on/off and reverse recovery);
- demonstrate the real time effects, delays in the gate drives etc;
- compare the simulated and the measured waveforms, i.e. show the influence of the parasitic elements.

Design process

The main idea of the practical is to simulate a typical design process of a power converter. The design aspect is a very important part, in contrary to a traditional practical with the objective to observe the different phenomena. Here the student has to very actively take part in a design process. The preparation work starts with the homework to collect a simulation program from the internet, to perform the simulation of the system and to collect information about the used microcontroller system.

The design process can be characterized with the following steps:

- simulation of the desired system;
- programming of a microcontroller to generate pulses for the power converter;
- assembling of the breadboard using the available building blocks (Fig. 8);
- measuring the real signals of the system and running the breadboard with the self-built (programmed) modulator;
- comparison of simulated and measured waveforms concerning delays and real time effects etc.

Simulation of the system

The aim of the simulation is to prepare the student for the practical, and to get him acquainted with the basic problems and the operating principle of the converter. The component values for the simulated system are the same as later for the used breadboard. Simulation of the converter system is performed with the simulation program Caspoc [5]. An express version of this power electronics oriented simulator suitable for the simulated example is downloaded by a student from the internet. The user friendly interface allows to simulate simple example as the buck converter. The use of a scope feature is in fact similar to a real scope (Fig. 8). Simulation is an excellent preparation for the measurement. There is a possibility to change the power circuit by dragging and dropping components. One additional feature is animation. Next to the scope waveforms it is possible to see if the switch is on or off and to follow the flow of the current. The change in the control or circuit parameters influences the power flow. This in spite of the fact that the simulated

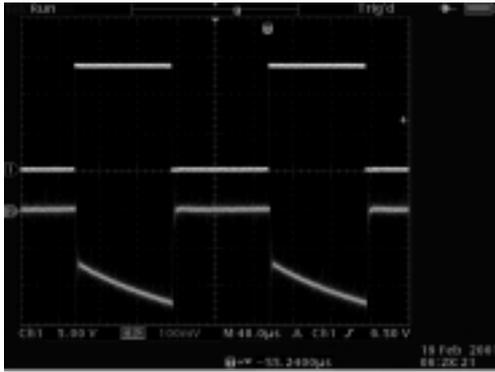


Fig. 12: Measurement of a buck converter; top trace IGBT gate pulse; bottom trace: current of the switch

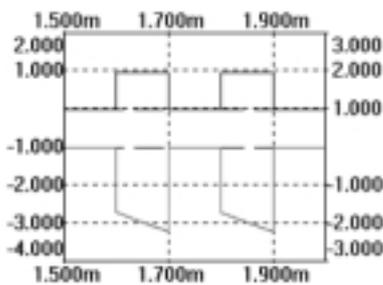


Fig. 13: Simulation of a buck converter; top trace: IGBT gate pulse; bottom trace: current of the switch

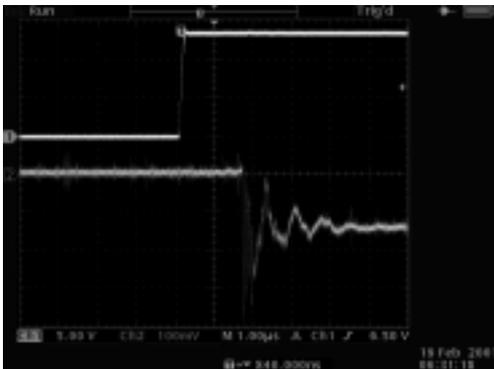


Fig. 14: Measurement of a buck converter; top trace IGBT gate pulse- switching on; bottom trace: IGBT current during switching on

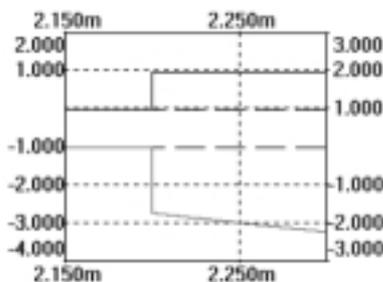


Fig. 15: Simulation of a buck converter; top trace: IGBT gate pulse at turn-on; bottom trace: switch current at turn-on

waveforms are somehow idealized. In fact it is an advantage that the simulated waveforms are measured without parasitics and hindrance of noise influence on the measurement. The comparison with real time effects is made later with the measurement.

Programming the PWM modulation with the micro controller

The selected micro controller is a 8C504 from Infineon [7]. This 8-bit microcontroller features a system on chip that is developed for all kinds of motion control using PWM schemes. The used microcontroller system is a commercially available evaluation kit. The user manual of the controller can be simply downloaded from the internet.

The practical documentation gives the needed addresses and guides through the needed parts of the manual. The programming environment is the Embedded Development Environment from Tasking. The student can download an evaluation copy of the environment so no license is necessary. In this way the student can use the environment in advance for instance at home. The EDE consists of a common user interface with which all of the tools from the tool chain can be reached. The interface can be used for some other controllers (16 bit) as well. The tool chain is formed by an editor, C compiler, assembler, linker, simulator and debugger. The debugger makes it possible to run the program by the microcontroller and stop it via breakpoints. Then it is possible to show the contents of the registers on the PC display (Fig. 9). The PC part of the debugger communicates via a RS232 link with a monitor that is executed by the controller and resides in flash memory. The systems on the controller chip get their functionality via the contents of Special Function Registers. The contents of only a few registers has to be defined by the student. Also the C code is kept as little as possible. But in summary the student is forced to use all the components of the tool chain but with little time and effort needed. This way the student practically designs the microcontroller based PWM modulator

Experimental results and measurements on the system

The breadboard is assembled by the students from the available building blocks (Fig. 10). The building blocks are under the glass for safety reasons (Fig. 11). The layout of a DC bus, snubbers, gate pulse amplifier semiconductor switch modules and the DC bus capacitor are however well visible. In this way the construction of a converter with explanation of aspects such as bus bar, parasitics etc. can be explained. The gate pulse amplifiers are connected with the micro controller which is programmed by the students as explained before. An important aspect is the comparison of the simulation and the real behaviour measured on the system. This is documented on Figs. 12 to 14. The delays in the control electronics, switching operation and other important issues are studied in detail. In the last part the buck converter is loaded with a DC machine and the speed of the machine is controlled in open loop with the calculated duty cycle. In a different practical the buck converter is extended to a switching leg of an inverter and the practical ends with the demonstration of a vector modulated three-phase inverter waveforms observation.

Conclusions

The proposed e-learning tool and animation opens in combination with simulations the way to a better understanding of power electronics. The e-learning software realizes a complete basic course on modern power electronics running over one semester. Due to the underlying technology the tool is very flexible in use. It simplifies teaching when used with a laptop and beamer in the lecture room. Furthermore, it simplifies the studying the basics of power electronics for the student and the engineer who wants to update knowledge at home after work. Interactive animation is very efficient for studying as the student is actively involved.

The theme project is accepted by the students with great enthusiasm too. Besides the mentioned educational objectives it gives the freshmen students the feeling of doing real research. Here, obtaining the working result is an important issue. For most of the students it is the first result of a self-designed system in their life. Power electronic converters are here playing an important role. Different groups with different solutions obtain different results as well. The competition between the groups emphasizes the effort.

The design process together with the power electronics practical gives the students the confidence in their diploma work phase of study. It gives also a manual and imagination of the standard design steps taken in research and development in power electronics.

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