Learning platform for study of power electronic application in power systems

P. BAUER* and O. ROMPELMAN

Delft University of Technology, Mekelweg 4 – 2628 CD Delft – The Netherlands

(Received)

1. Introduction

Present engineering has to deal with increasingly complex systems. In particular, this is the case in electrical engineering. Though this is obvious in microelectronics, also in the field of power systems engineers have to design, operate and maintain highly complex systems such as power grids, energy converters and electrical drives. This is reflected in engineering education, where teachers try to communicate the many aspects of complex systems and where students try to learn and deal with this complexity. The introduction of new technologies (e.g. ICT) in teaching, though very promising at first glance may turn out to be counterproductive when the accent is on teaching, rather than learning. The same technologies may prove to be highly effective, if they are introduced to support the understanding and, consequently, handling and even designing of complex systems.

2. Historical development

Traditionally, in the development of engineering education the key objective was to enable the teacher to convey knowledge and insight to the students. The main element was (and still often is) the lecture where the teacher explains, gives examples, shows calculations, discuss mathematical derivations etc. The accent is on the oral communication, which was supported by on-line hand written messages using the blackboard and chalk. Due to the low speed of hand writing students had some (but often not enough) time to try and understand what was going on.

With increasing complexity of the systems to be discussed (more dimensions, dynamical structures and interactions) teachers began to feel hampered by the speed limitations of...
handwriting on the blackboard. They adopted the use of the overhead projector with great enthusiasm, since this enabled them to do a lot of the writing in the preparatory phase of the lecture. Also students appreciated this, since the, often unclear) handwriting was replaced by well-structured and clearly readable notes. However, what was projected so easily was still hard to understand, in particular since the pace of dealing with subjects was increased. A next problem for teachers was how to convey dynamical structures and interactions. The use of animations (inserted in power point presentations) seemed to be a solution. But again, from the students’ point of view, the improvement was only partial.

In table 1 the positive and negative effects on teaching and learning of the different support system are summarised. It is shown that what is considered as an advantage for the teacher often turns out to be a disadvantage for student learning.

The conclusion is, that in the design of the education the accent was on the teaching (particularly the preparation), which leads to beautiful lectures with a disappointing learning yield. What may be even more serious is, that students got demotivated, since they felt themselves to be unsuited for subject, they experienced to be too difficult for them. The advance in the teaching method does not automatically yield better understanding. New advances in the teaching method allow that more material in the same time is presented. The lectures often happen in the fast tempo with less time to comprehend (figure 1).

Obviously, the problems mentioned above have been identified. While maintaining lectures as the primary educational activity, laboratory exercises have been introduced. The introduction of electronic appliances (e.g. computers, networks with connected student laptops etc.) has facilitated the introduction of interactive teaching and learning environments. Computer animations were developed so that students can more or less repeat the demonstrations as given during lectures or even during the lectures.

In this paper, a program of computer animations is discussed, that was originally and primarily designed for teachers and to be used during traditional lectures. It was found out however, that these animations could be very well used for self-study purposes provided a good instruction and clear assignments were given.

2.1 Shift from teaching oriented towards learning oriented education: problem analysis from a learning point of view

By the end of last century engineering educators began to realize, that the demands from industry had changed. There should be more emphasis in skills and (deep) understanding...
rather than knowledge. This is reflected in the change in curricula (Petty 1999) as well in the engineering criteria such as the ABET criteria (http://www.abet.org). These changes were largely discussed in the SEFI Annual Conference in Copenhagen (SEFI 2001). For existing programmes, curricula and courses the shift from teacher to learner oriented education implies a redefinition of the objectives of education. Traditionally, the main objective was that students acquired knowledge. The assessment was based on testing whether students could reproduce the acquired knowledge. Presently, the main objective of teaching is the development of student skills. This means that the teacher is a coach in the process of the students’ development. Obviously, this has its implications on assessment as has been discussed a.o. by McDOWELL (1999).

These actual objectives for a particular area/course should be derived from a reconsidered analysis. As an example: the original problem, defined as “it is difficult to explain the switching sequence and the consequent voltages and currents in a static converter” (teacher oriented) will be changed into “the student has difficulties in understanding the switching sequence and the consequent voltages and currents in a static converter” (student oriented). Obviously, a more detailed problem analysis is required. The educator has to carry out this analysis using as much information from students as possible. This will lead to requirements for a solution that has to be designed and implemented consequently. The final goal is to create an environment in which the defined problem is solved. Obviously, there are many boundary conditions that have to be taken into account such as

- prior knowledge and skills
- facilities
  - human: staff
  - material: laboratories, rooms, ICT-support systems
- available time for students, both in terms of hours and of schedules.

This latter issue is becoming increasingly important. Nowadays, students often cannot follow courses simultaneously. Due to other activities, they want to devote time to their studies when it suits them individually. Therefore, any solution should allow for individual action, regardless when or where. Finally, eventual learning methods should be such that students indeed are able to learn and do assignments, in other words: an appropriate instruction in the learning material remains to be essential.
3. Designing an educational infrastructure for some topics in power electronics

3.1 Problem analysis

A general problem in electrical engineering is the fact that it deals with rather abstract notions such as current, voltage, resistance, capacitance etc. These electrical quantities and phenomena are not directly observable and can only be made observable (usually: visible) by means of measurements. This is all the more so in the area of power electronics.

It has been found, that students who are faced with the principles of power electronics have problems in understanding and dealing with the high complexity of these systems. This complexity becomes evident by the high dimensionality and the dynamics of these systems. The main features of such systems are the large number of simultaneously occurring variables i.e. voltages and currents, in particular:

- the way they vary with time
- their polarities
- their mutual dependency (in particular the causal relations)
- their relation to the state of the circuit.

Particularly, in three-phase systems this becomes apparent. The systems become too complex, therefore by teaching a step down approach is used. In the first step only the principles are explained and later the real world effects (stray effects, noise) are added. This is in agreement with philosophy of modelling.

Teachers may clearly discuss all the phenomena involved during lectures. However, even if computer animations are used, students cannot grasp the details in a short time, since the teacher only once or twice shows examples or animations. There remains a need for repetition and exercises.

As a side problem, students tend to get de-motivated by this complexity. This leads to the undesirable situation, that the discrepancy between the number of students in electronic power engineering and the demands from industry for engineers in this field is increased.

3.2 Requirements for a solution: learning support system

On the basis of the problem analysis discussed above, it was identified that a possible solution should meet two (design) criteria:

- a learning support system should be developed that allows students to acquire a, possibly deep insight into the complex and dynamic interactions of a number of parameters in power electronic systems
- the focus of learning should be on the electrical phenomena themselves and not on the problems inherent in measurements
- the learning support system should be structured in such way that it is faced with increased complexity (hierarchical approach)
- due to the multi-dimensional character of the systems, a high degree of interactivity should be provided e.g. if simulations or computer-animations are used, students should have the possibility to freeze the time or even reverse the time so as to study the causal relation between different phenomena and states of the circuit under study
- the system should give a qualitative impression of level of different quantities
- the learning support system should be accessible, independent of time and place
- an appropriate instruction in the usage of the system should be provided
– students should get motivated to study these systems in more detail, so as to become skilled in designing such systems themselves
– the system should allow for self-assessment of student learning
– the system should allow for including assignments as well as individual assessments.

After some considerations it was decided to develop a number of computer animations showing in a systematic and consistent way the interactions of switching states, currents and voltages of different circuits. Systematic and consistent in this case means, that currents and voltages (both polarity and values) are displayed in the same way in all animations. The animations allow for a high degree of interactions with the user. The animations can be run either via an internet link or using a CD-ROM. Assignments and assessment can be done over the Internet. A limited number of lectures are given. The main role of these lectures is the introduction of the backgrounds of power electronics and the usage of the computer animations.

4. Designed interactive animations

A learning system fulfilling the abovementioned criteria is developed. Three from the mentioned criteria need an additional discussion before a final design is made.

4.1 Accessibility

The learning support system should be accessible, independent of time and place and therefore the used learning software tool in the designed interactive animations must be independent from the operating system of the computer, without complicated installing of software and plug-ins and which can be available via Internet, too. Java applets and HTML are a perfect choice for all requirements.

4.2 Possible visualization of currents and voltages

One of the reasons that circuits are hard to understand is the fact that the voltage and current is not directly visible and must be measured indirectly via meters and oscilloscopes. For power electronic circuits the data to be displayed are the circuit topology and the behaviour of the circuit variables (e.g. voltage, current, power, stored energy). These data are traditionally displayed as two separate diagrams (circuit schematic and plot of the waveforms). Animating the circuit variable plot emphasizes the dynamic nature of circuit behaviour. Merging both graph and plot data in a single graphical object will improve understanding of how circuit behaviour relates to circuit topology. Advantage of the animations above the measurements is that the waveforms are clear without the hindrance of the measurement noise. For understanding of the principles the stray effects are omitted in the first step to limit the complexity of the circuit and later added as they form limitations in the design. Insertion of a short film section is one possibility of how to introduce this important details.

There are two basic problems to solve with respect to the animations:

1. How to animate current and show the current path and at the same time how to animate the voltage. The state of the power electronic semiconductor switches must be clearly visible too.
2. How to show the power, active and reactive power in one phase but especially in three phase circuits.
The animation is usually two-dimensional and next to the circuit there is a window with oscillogram like waveform representing the time varying voltage, current and power (Drofenik et al. 2001, Bauer and Kolar 2003). There is a possibility that ‘coloured electrons’ moving according to the direction of the current flow visualize the current path. Varying voltages and currents are represented by time varying waveforms. Showing the moving electrons as dots with different sizes the qualitative impression of the level of the current is added. The voltage level could be shown with the length or the thickness of an arrow. Also the use of the different colour of the node by assigning the voltage level as used in (van Duijsen 2001) is a possible way. Another interesting approach is the use of three-dimensional animations of voltages and currents as suggested by Sullivan (2003). The voltage level is shown as the third dimension. The three dimensional animation is surely an original idea and the third dimension gives a possibility to show the voltage on different places in the circuit. However, for more complex systems it is unpractical.

Final choices for visualization have been made as follows:

- **Voltage** is represented by a vertical blue arrow of variable length. The length of the arrow represents approximately the voltage level.
- **Current** is represented by red (blue) and moving dots. The size of the dots corresponds to the magnitude of currents. It is possible to observe how the dot sizes add up (the current values add up) at a node to verify that current law (1st Kirchhoff current law) is being obeyed.

### 4.3 User Interaction

The multi dimensional character of the system requires studying the causal relations between different phenomena and states of the circuit. There are many examples of e-learning tools, where the viewer watches the explanation as a cartoon or movie. Here conversely a high degree of interactivity is requested and many parameters are to be changed. These are e.g. polarity of the voltages, currents, states of the different switches and time sequence. The interactive quantities must be clearly identified. Any action (change in the interactive quantities) has an influence on the rest of the animation. This way the learning system can be used to solve small engineering problems. This is a next step in the education and yields a better understanding of the system.

Finally, the designed learning system allows freezing the behaviour in time, changing interactively the parameters and going back in time and behaviour.

### 5. Example of an electronic tap changer

As an example of the learning system the electronic tap changer will be discussed. This example shows the design of a power electronic converter for a tap changer. Distribution transformers are equipped with a mechanical tap selector. The position of this tap selector is changed according to the transformer secondary voltage. Hereby, transformer windings are added or subtracted and in this way the transformation ratio is changed. To achieve a continuous control of the transformer voltage and to design a static converter one must be able to change the taps under the full operation of the transformer. By pending at a high frequency between two taps under the full operation of the transformer the continuous regulation of secondary voltage is achieved. This application must be studied on different levels viz. a systems level and a components level. The animations are performed on the different levels too. Top down approach is here selected. The first animation on system level explains the
consequences of the tap positions. Even if the existing transformers are equipped with the taps on the transformers’ primary side, the basic question remains: what is the most convenient place for the tap changer? The student has to understand the consequence of such a choice. This question can be rephrased: Is it more convenient to switch high currents or to block high voltages as the animation in figure 2 shows. The quantified animation of the current (moving dots with different size) gives a fast and visualised answer to this question. The voltage level is also visualised by the length of the arrow.

After the selection e.g. of the primary side is made, the next the student has to understand is the system concept. There are different system concepts available. In the animation (figure 3) different system concepts (phase control, cycle control and PWM (Pulse Width Modulation) are explained. By moving the orange cursor along the time axes, the waveform of the output voltage, switch position and the transformer winding colour is changing. The animation is interactive, the student can move the cursor in any position for all three concepts and the state of the switch is changing. The switch position ‘up’ is visualised by a blue voltage line and to the switch position ‘down’ by a green one (figure 3b). In the same way the transformer windings are coloured.

To follow the top down approach, the next problem is the replacement of the switch depicted in figure 3 as an ideal switch by power electronic devices. The essence of the commutation is that the tap must not be short-circuited and at the same time the transformer has to be connected by one of the two switches. This has to be understood and switches are switching in the way neither to create a short circuit nor an open connection.

To understand the tremendous potential of the interactive animation first the smart commutation (Bauer and Schoevaars 2003) for an electronic tap changer will be explained by classical means (static explanation) and later with the help of an interactive animation (Bauer and Fedak 2003). The smart four-step commutation can be explained with the help of figure 4 using states a . . . e and timing diagram f. The different states in the commutation cycle are determined by the either positive or negative voltage of the $u_{\text{tap}}$ capacitor. In this classical explanation the semiconductor switches that are ‘off’ are black; a colour (blue and red) shows which switches are ‘on’. The timing of the switches is depicted in figure 4f. After four steps from one conducting bi-directional switch SW1, SW2 (figure 4, state 1a) we obtain the second conducting bi-directional switch SW3, SW4 (figure 4, state 1e). If someone wants to understand the operation of the bi-directional switch, he has to follow the diagram f and compare it to one of the states a . . . e. Additionally, the state diagram is usually shown in a different picture.

**SOLID STATE TAP CHANGERS: PRIMAIR OR SECUNDAIR?**

<table>
<thead>
<tr>
<th>TAP CHANGER ON PRIMARY (HV) SIDE</th>
<th>TAP CHANGER ON SECONDARY (LV) SIDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>150kV/10kV 100MVA transformer</td>
<td>150kV/10kV 100MVA transformer</td>
</tr>
<tr>
<td>10kV/400V 500kVA transformer</td>
<td>10kV/400V 500kVA transformer</td>
</tr>
</tbody>
</table>

Figure 2. Solid state tap changer location.
Figure 3. Different system concepts of the tap changed transformer.

It is difficult to follow all this graphs and state diagrams statically without interactivity between them. The result is that during the lectures the students usually get already lost when the second graph is shown. By self-study, it is also difficult and time consuming to follow the changes on three different pictures. Additionally in figure 4 the smart commutation is explained only for one polarity of the voltage.

Figure 4. Smart commutation (classical static explanation).
In figure 5 an interactive animation of the same tap changing is shown. The actual current path is marked by moving coloured points (“positive charges”) and the visual representation of the power switch is different for on- and off-state. The switch which is gated for the respective current direction has a red or a blue colour. Similarly, the current has red or blue colour. The current polarity can be changed by clicking on the current sign $i_{\text{tap}+}$, $i_{\text{tap}-}$. The actual current path is changed by moving the draggable red marker (timing of the switching) on the right side. At the same time the state in the state diagram changes too. This is shown in figure 5a, from the state 1a to a state 1c. By moving the red marker the state of the switches, the actual current path and state diagram change simultaneously. Similarly, by clicking on the voltage polarity the animation changes voltage polarity and the switching pattern accordingly. In figure 5b a special effect of diode reverse recovery is explained. The current direction is depicted by blue dots, whereas the green loop illustrates the reverse recovery circuit of the diode. The green arrow in the state diagram explains that the effect happens at the transition between two switching states. It is an effect of the diode switching off and it occurs only in this particular state. A power electronic student should be aware of this fact. Reverse recovery of the diode plays a role only at certain current and voltage polarities as the students learn. This fact is later questioned during the self evaluation.

6. Evaluation

The tool is accepted by the students with the great enthusiasm. Especially the fact that they can replay part of the lecture at their convenience is highly appreciated, as the polls show. After a first evaluation the need for further explanation of some terms appeared to be desirable in order to make it more suitable for self-study. For self-study the technical terms are explained in sub screens, which appear after clicking on the terms to be explained.

The ‘freeze’ feature and the fact that the operation can be time reversed allow for repeatedly following the system behaviour and capturing many aspects of it. This way everybody can study at his pace. The use of the learning platform results in better study results of the subject.

For purpose of self-evaluation a set of questions is developed. Mentioned reverse recovery of the diode serves as an example of such a question. The student has to set up the operational point the way that this particular effect occurs and has to verify it in the learning tool. Obviously, a lot of knowledge is necessary to do that. This way a small engineering problem is created and the learning platform serves as a practical verification tool.

For the lecturer the learning platform offers a great help and support.
7. Conclusions

Learning platform for power electronic applications is introduced and documented on several examples. Effectiveness of the e-learning and interactive animations is demonstrated on the electronic tap changer example. The principles for interactive solution and visualization of the static and dynamic systems are shown for only a few from the large amount of existing examples. The developed interactive package contains animation covering the entire field of power electronic applications in power systems. The e-learning tool and animation with simulation opens the way to a new unknown experience and better understanding of power electronic applications. Due to the underlying technology the tool is very flexible in use. It simplifies teaching when used with a laptop and beamer in the classroom. It simplifies studying the basics of power electronics for both the student and the engineer who wants to update knowledge at home after work. Interactive animation is very efficient for studying because the student is actively involved. The first experience is very positive.

Acknowledgement

The authors wishes to express their gratitude to Leonardo da Vinci II programme, project INETELE (No CZ/02/B/F/PP-134009) within framework of which the interactive animations were performed.

References

Available online at: http://www.abet.org.

About the authors

P. Bauer, Delft University of Technology, received his Masters in Electrical Engineering at the Technical University of Kosice (‘85) and Ph.D. from Delft University of Technology (‘94). Since 1990 he is with the Delft University of Technology teaching Power Electronics, Electrical Drives and related subjects. Mr. Bauer published over 100 papers in his field, he holds an international patent and organized several tutorials. He is a reviewer of different IEEE proceedings and Journals and member of the International Steering and Technical Committee of several conferences.
Otto Rompelman received his MSc. in Electrical Engineering (1969) and his PhD (1986) from the Delft University of Technology (Netherlands). He has worked in the field of biomedical signal and image processing for about 25 years. He published about 50 papers and book chapters and co-edited two books on the analysis of heart rate variability. As a member of the board of the Faculty of Electrical Engineering TU Delft (1991–1992), he was responsible for the introduction of a new curriculum. Since 1993 he has been active in different projects related to internationalisation and innovation of education in electrical engineering. He has been active in SEFI for about eight years (a.o. as a chairperson of the Curriculum Development Working Group). Since 2004 he is a free-lance consultant for higher engineering education.
TO: CORRESPONDING AUTHOR

AUTHOR QUERIES - TO BE ANSWERED BY THE AUTHOR

The following queries have arisen during the typesetting of your manuscript. Please answer the queries.

<table>
<thead>
<tr>
<th>Q1</th>
<th>Below “Historical development” heading, 2nd paragraph, 5th line, closing bracket is given. But, opening bracket is not given. Please check.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Production Editorial Department, Taylor & Francis Ltd.
4 Park Square, Milton Park, Abingdon OX14 4RN

Telephone: +44 (0) 1235 828600
Facsimile: +44 (0) 1235 829000