New Circuit Simulation Applets for Online Education in Power Electronics

A. Müsing
U. Drofenik
J. W. Kolar

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A. Müsing, U. Drofenik, J. W. Kolar

Power Electronic Systems Laboratory, ETH Zurich, ETH-Zentrum / ETL H18, CH-8092 Zurich, Switzerland

muesing@lem.ee.ethz.ch

Abstract-This paper presents new online simulation applets based on Java technology. The applets are integrated into a series of student exercises which accompany the introductory and advanced lecture courses in power electronics at the Swiss Federal Institute of Technology Zurich. Furthermore, the new applets are available via the educational project iPES which is a free collection of Java applets for educational purposes. iPES has been translated into 12 languages and has currently more than 10,000 visits per month. The novel online simulation applets are easy to use and allow an unlimited simulation of converter topologies. The concept of embedding a circuit simulator in the form of a Java applet into a public accessible homepage allows the creation of power electronic and electrical engineering courses that are easy for students to access, highly flexible and require small administrative efforts for the lecturer. The paper will discuss the technical details of the online simulation project and will show how the integration of the online simulator significantly improves the educational value.

I. INTRODUCTION

Many typical engineering problems are quite complex, show dynamic behavior and a large number of different states. It is difficult for a lecturer to describe complex interrelationships and parameter dependencies solely via verbal description and static pictures. In power electronics, current conduction paths depend on diode and switching states, and PWM control adds another level of complexity. The student often finds it difficult to understand how a system works if he is mainly passively following a lecture in the classroom.

Exercises that accompany the lectures' contents give students the ability to deepen the acquired knowledge. Traditionally, the student first calculates curves and waveforms analytically and analyzes the states of a power electronics circuit and the related current paths with pencil and paper. This active involvement of the student strongly contributes to his learning success.

However, many circuit topologies and control strategies are so complicated that it is necessary to perform computer simulations to analyze details of the converter system. Furthermore, it is desirable to encourage students to verify analytic calculation results via numeric simulations.

In the industry, the detailed simulation of systems is a standard procedure, and the demand for graduates that are familiar with applying software tools makes it essential to include numeric simulation in the lectures and exercises. Therefore, simulation is an excellent final step to the traditional analytic approach in engineering education, allows the analysis of more complex systems, and promotes general understanding.

Unfortunately, power electronics simulation software is expensive and student versions of commercial simulation software are very limited in usage. Computer work places are often scarce in academic institutions, considering the large number of students attending a course. There is also a considerable effort required of the teacher or instructor to keep the simulation software and supplied models updated and ready for the student exercises.

In 2001, the Power Electronic Systems Laboratory (PES) at ETH Zurich introduced the free "Interactive Power Electronics Seminar" (iPES) [1] – [4], which is a web-based collection of interactive Java animations discussing and explaining important details of power electronic converters. iPES permits the manipulation of certain preselected parameters of a circuit topology, model or control system, and the observation of the resulting changes of internally coupled parameters. The first version of iPES applets can be changed and manipulated only within given boundaries.

Due to certain applet limitations and user-feedback, the Power Electronic Systems Laboratory went one step further and integrated a fully functional power electronics circuit simulator into iPES in 2010. This free online simulator, developed in cooperation with a company specialized in power electronics simulation software, is called "GeckoCIRCUITS" [5].
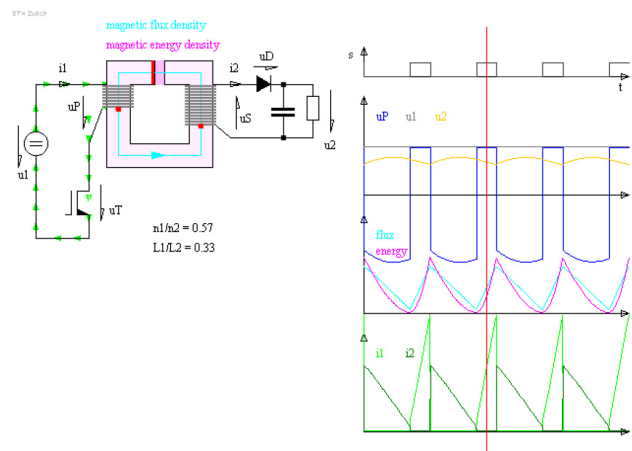

Fig. 1. iPES-Applet "Flyback Converter – Magnetic Components" [6] with current path animation. The applet allows the modification of the transformer winding numbers and air-gap width. Waveforms and distributions of the magnetic energy are updated immediately.

Every year, there are about 110 master course students attending three different level power electronics courses at ETH Zurich. The amount of students and exercises provides a significant administrational challenge. Therefore, a combination of conventional exercises, online simulations embedded in dedicated HTML pages and additional classroom simulation courses was found to be the best solution for both students and teachers.

II. INTERACTIVE POWER ELECTRONICS SEMINAR

A. The Basic Concept

One of the problems in studying and teaching power electronics is the large number of possible reactions of a system to parameter changes. Another difficulty in understanding power electronics topologies is that conduction states typically go through a sequence of different states even during steady-state operation. The traditional way of presenting such challenging content is by a sequence of slides showing a single system state displaying the behavior of the circuit for a particular set of parameters.

A main idea of iPES is to provide Java-based animations where a time marker ("time slider") can be dragged by the student via the mouse, where the time marker position directly shows the related system state. See the screenshot in **Fig. 1** of a Java-applet in iPES which shows a flyback converter and its magnetic component. The time slider is the vertical red line in the waveform diagrams. According to the position of the time slider the current flow of the associated path in the topology is animated employing little moving arrows.

Another basic idea of the iPES applets is to offer the possibility of the manipulation of various system parameters via a graphical user interface, which allows for showing directly the resulting time and frequency behavior of the system. This feature allows demonstrations of tendencies of a converter system such as the effect of a boost inductor inductance on the current ripple. The online applet of the flyback converter allows to change the winding numbers and air gap length of the magnetic component. The magnetic energy density within the magnetic component is shown in magenta.

A second example of one of the many iPES applets is shown in **Fig. 2** where the basics of inductance are explained. The student can change the diameter and the distance of the wires, and experiment with the impact of these two parameters on the magnetic field, energy distribution and the resulting inductance.

One important idea in the iPES applets is that the student can only change a small number of parameters, ideally 1- 3, and experiment with the effects of such changes. By limiting
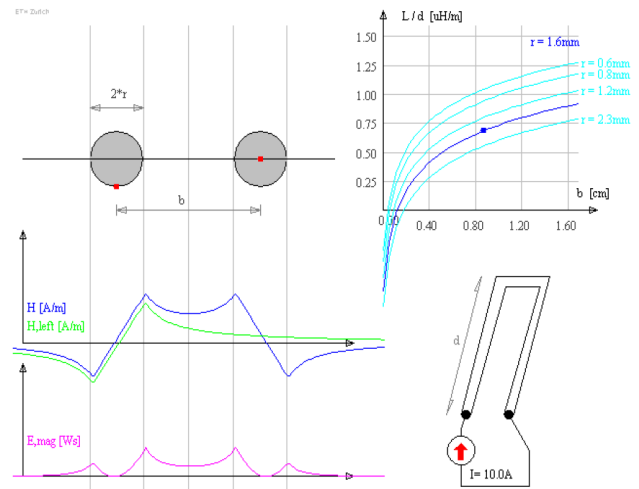

Fig. 2. iPES-Applet "Magnetomotive Force (MMF), Inductance, Magnetic Flux" [7] for demonstration of the magnetic fields and inductance of a wire. The student can change the diameter and the distance between the two wires. The curves of magnetic field strength, the magnetic energy density and the inductance in the graph are updated immediately.

the number of parameters the student is forced to concentrate on certain details of the topology. With a small number of parameters the student can get a quick grasp of the underlying concepts, which improves his/her studying. It was considered important not to overwhelm the student with too many features implemented in one applet.

Compared to traditional teaching approaches, this way of learning promotes the active involvement of the student who is free to decide on the speed of progress while going through the learning matter. This fosters an individually optimized learning pattern. Another important advantage of the free web-based iPES concept is that the student can study at home.

B. Acceptance and Users

The educational platform iPES went online in August 2001. Today, it has been translated into 12 languages (in alphabetical order: Arabic, Chinese, Taiwan-Chinese, Dutch, English, Farsi, French, German, Italian, Japanese, Korean, and Spanish). There are up to 500 visitors per day and on average more than 10,000 visits per month. The distribution of the users is shown on the map in **Fig. 3** which has been created from a free online-statistics tool. Other projects of web-based educational interactive animations have been developed in Java but also other Internet technologies like Flash, e.g. [9] – [14].
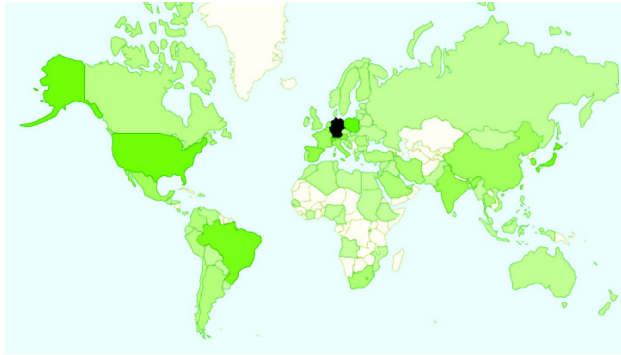
Fig. 3. The figure shows the global distribution of iPES-visitors based on 10,000 visits per month from more than 100 countries. The color intensity indicates the number of visitors per country. 30% of the visitors are from Germany (1st), 5% are from Japan (2nd).

C. Shortcomings and Criticism

Applets in iPES allow only a small number of parameters to be changed by the user. This gives the previously discussed advantages concerning the educational effect. Another reason for the restrictions is that parameter changes have to be simulated numerically, but the user experience should be an immediate effect. The underlying numerical simulations therefore have to be very fast, e.g. long-term transients in converter systems with low damping caused by a parameter change by the user have to be calculated extremely fast.

The technical solution when implementing the iPES applets was to accept numerical inaccuracies by employing large numerical time steps and adding artificial damping resistors. Then, the parameter changes result in waveform changes that are felt as "immediate" due to the fast but inaccurate simulation. The relationships and tendencies are all correct, but the values might show errors up to 10%. Numeric values are therefore not given in many iPES applets. After having gained experience and understanding in power electronics with the educational iPES-applets, many users (especially teachers and instructors) have asked for "real" circuit simulation and for much more flexibility. Introducing numerical simulation in power electronics education would show the students that converter systems, when e.g. considering parasitics or non-ideal switches, might behave differently compared to the textbook example and the iPES-applets. This was the motivation to integrate online circuit simulation into the iPES platform.

III. ONLINE SIMULATION WITH GECKOCIRCUITS

A. How do GeckoCIRCUITS applets work?

GeckoCIRCUITS [5] is a circuit simulator specialized for the simulation of power electronics systems with the following features:

- Easy to learn and use
- Very fast and numerically stable
- Multi-domain: Electric - Thermal - EMI
- Easy and fast calculation of junction temperatures
- No installation required

GeckoCIRCUITS is written in the Java programming language which allows it to run online as "Java applet". This would not be possible in this form if it was written in C/C++. When the online user opens the webpage, the web-browser automatically loads the Java executable from the server and hands the Java executable to the so-called Java Runtime Environment (JRE). The JRE has to be installed, the executable is then running on the user's computer – and not on the server. Currently, 92% of the visitors of the iPES homepage have Java preinstalled and enabled in their web-browser.

B. Technological Limitations of Circuit Simulation Applets

In the following paragraph, the five main limitations in using a Java applet as circuit simulator are specified, and it is shown how these shortcomings are resolved in Gecko-CIRCUITS. Please note that those limitations are only present in the online version of the software, whereas the standalone (non-applet) version allows full simulation capability similar to any other commercially available software.

(1) The Java program must be downloaded over the Internet. There are limits as to how long the user is willing to wait for a download. Therefore, large programs in the form of Java applets will not be accepted by most users. It is essential to keep the program size small. The circuit simulator GeckoCIRCUITS has currently a total size of 1.4 MB which takes less than a few seconds to download with a fast Internet connection.

(2) Most users will already have the Java Runtime Environment (JRE) preinstalled, so there is no need for any additional installations. A large number of users are not willing to perform complicated installations in the web-browser to make a Java applet work. Therefore, a Java applet is practically limited to the features which are available in the standard JRE. This means that features such as 3D graphics will not be accessible to most users. However, Gecko-CIRCUITS works well with the standard JRE.

(3) The default RAM memory size of Java applets is currently limited to 64 MB, which enforces the circuit simulator applet to handle the limited memory resource with care. Memory storage of simulation data for visualization requires GeckoCIRCUITS to compress simulation results with advanced algorithms, especially when small simulation step-widths and a long simulation time were chosen by the user. The GeckoCIRCUITS applet therefore applies a difference compression algorithm [15] together with a lossy GZIP algorithm to reduce its data amount in RAM memory. With these compression algorithms, a data reduction factor of 10 and more can be achieved in average. Therefore, detailed circuit simulations with, for instance, 10 ns step-width resolution and a mains period of 20 ms are possible without a Java RAM memory overrun. If a simulation demands still more memory than available after data compression, GeckoCIRCUITS prints a warning message, and subsequently overleaps simulation time steps for memory storage.

(4) The most important restriction is the default inability of a Java applet to access the hard disk. Therefore, a Java applet cannot do harm to the client computer, cannot manipulate or destroy data, or spy on user data on the hard disk. This
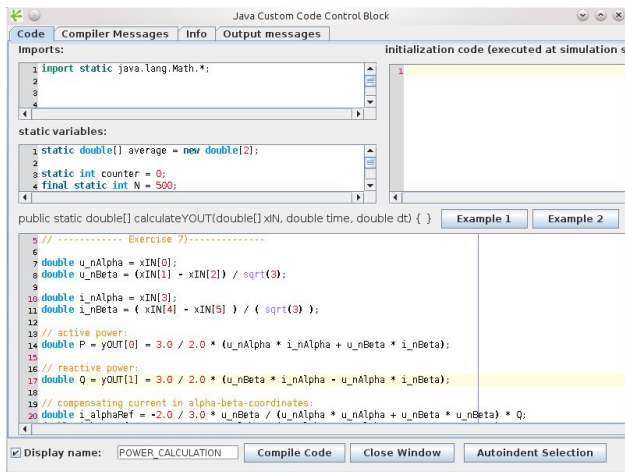
Fig. 4. Dialog window of the JAVA code-block in GeckoCIRCUITS.

guarantees strong security for the user and is a main reason for the success of Java as an Internet language. On the other hand, a Java applet cannot read a file or load a model from the user's hard disk, and it cannot save models locally. Therefore, the online version of GeckoCIRCUITS does not permit the loading or saving of models locally. It only accepts prepared models that are stored on the server. However, this is sufficient for educational purposes.

(5) The functionality of one important GeckoCIRCUITS feature, the "Java code-block", which is a highly flexible Java programming interface, is, due to technical reasons, only usable with restrictions in the online version of Gecko-CIRCUITS. The code-block (see **Fig. 4**) allows for example to describe logical control structures like "if-then" statements in Java programming language. The JAVA-block is executed at each solver time step and the input signals are then processed according to the Java code in the block, and output signals are calculated and applied to the output pins of the block. For complex control or calculation tasks, an equivalent control built from discrete blocks would result in an overly cluttered and complicated model. Due to its simplicity and efficiency, the Java-block quickly became highly popular among GeckoCIRCUITS users.

A key property of the Java block is the compilation of the internal Java code in order to achieve acceptable simulation speed. The Java compiler is part of a library "tools.jar" of the Java Development Kit (JDK), which is included in the typically preinstalled standard JRE, and with 13 MB this library is too large to be delivered together with the applet over the network. However, to be able to run simulation models in applets that require the code-block functionality, the compiled binary classes were included in the simulation models. Then, the only restriction is that the user is not able to change or recompile the code when GeckoCIRCUITS runs as a Java applet.

C. The User Experience

The online simulator is very simple to use. If Java 1.6 is preinstalled, the user just has to visit the according webpage where the applet is located. Java will be loaded automatically

which takes a couple of seconds the first time an applet is opened within a browser session. GeckoCIRCUITS is then loaded automatically, and an orange rectangle is displayed on the webpage. The text inside the rectangle tells the user to open GeckoCIRCUITS with a mouse click. An example of this is shown in the screenshot in **Fig. 5**. After loading the GeckoCIRCUITS applet, the user can immediately start a simulation, and the scopes for visualization of transient waveforms show the simulation results. This is a "real" accurate simulation, not a visualization of tendencies as implemented in iPES. The user can now freely change all parameter values, add and delete components, or he can build completely new models with different topologies. There are no limitations concerning number of nodes and elements. The main limitation from the user's point of view is the inability to read from or write to the hard disk. Therefore, simulation models that were changed by the user cannot be saved, and simulation results cannot be written to the local hard disk either. The user has to make screenshots to document the simulation results.

D. From the Instructor's Point of View

For the preparation of the online applets, the following feature was implemented in GeckoCIRCUITS: the course instructor builds the simulation model on a standalone version of the software. After testing and model verification, the instructor is able to create a new executable Java applet by using the built-in "Save-as-Applet" feature. Thus, a new GeckoCIRCUITS.jar file is written to the hard disc, which
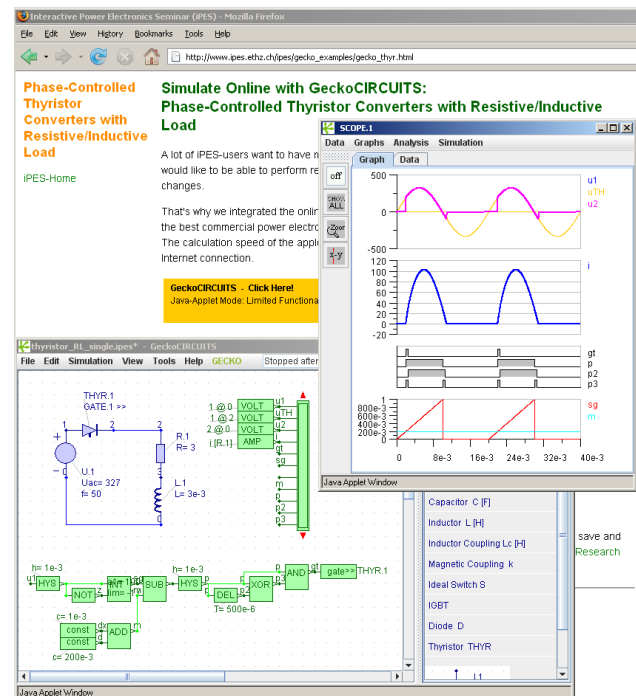

Fig. 5. Online simulation in iPES. The screenshot shows the iPES webpage with a simple example (single-phase thyristor rectification with RL-Load, [15]). The model can be simulated immediately within the web-browser and without any installations on the computer.

has the prepared simulation model embedded in its binary code. Subsequently, the instructor just has to copy the applet to the web server to make it accessible for his students.

A simple implementation of a student course would then be to create a set of HTML pages, one page for each exercise. In each page there would be GeckoCIRCUITS embedded with the according model or topology for the specific exercise. Several examples of such a course can be found at [17].

The HTML page allows the addition of explanatory text describing the content of the exercise. The main advantage is the very simple centralized administration of the Gecko-CIRCUITS applets in the described online implementation. A whole course then consists of a set of web pages and GeckoCIRCUITS applets. The teacher has full control of the content of the course, and easily administers all models in the student course. All this can be easily assembled with little knowledge of HTML, Java and Internet technology.

POWER ELECTRONICS COURSE AND STUDENT EXERCISES AT ETH ZURICH

A. The Simulation-Platform "Gecko" in Education

Originally, GeckoCIRCUITS was developed for the PhD research program at the Power Electronic Systems Laboratory (PES), ETH Zurich, due to various restrictions of commercial power electronic simulators. From the educational point of view it has been very important to make GeckoCIRCUITS easy to use to reduce learning time and increase productivity.

In addition to GeckoCIRCUITS, a 3D thermal solver (GeckoHEAT) and a 3D electromagnetic solver (GeckoEMC) are in development. These additional simulation programs will permit coupled multi-domain simulations in power electronics with the goal of optimizing converter systems not only in respect of electric behavior but also covering important issues such as thermal design and electromagnetic noise. GeckoHEAT and GeckoEMC will be available in spring 2012 and will also be integrated into education at PES.

Students who do their master thesis in power electronics at PES are using GeckoCIRCUITS for circuit simulation. Furthermore, GeckoCIRCUITS is used for the lectures' exercises. Three different levels of power electronics courses are offered at ETH Zurich:

In the basic course for 5th semester students, the fundamentals of power electronic circuits are covered. Within the 13 exercises of the basic course [17], three introductory computer exercises familiarize the students with the application of the simulation tool GeckoCIRCUITS. These computer exercises are conducted at the university's classroom computers, and teaching assistance is given during the exercise course.

The subsequent lecture "Power Electronic Systems I" for 7th semester master students delves into the details of power electronics circuits, for instance the non-ideal switches, current commutation, switching losses and snubber circuits. This lecture includes another set of 13 exercises.

The exercises of both the 5th semester and 7th semester course are given as PDF-files, and simulation models that describe the converter system are available through the
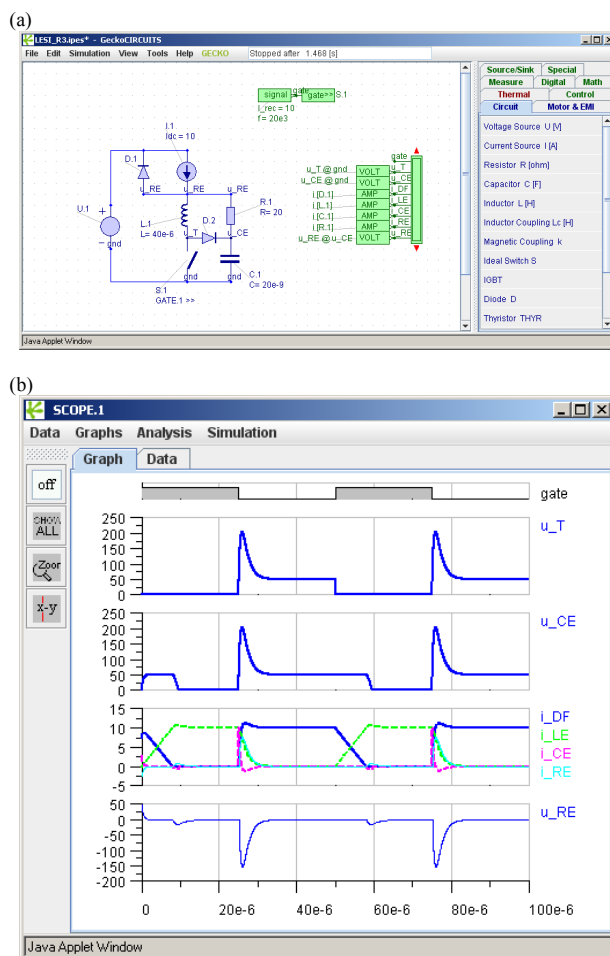

(a)

(b)

Fig. 6. Screenshot of an exercise example from the 7th semester master course in advanced power electronics. The example is about a snubber network for power switches, see [16].

online-version of GeckoCIRCUITS. Students have to solve the exercises in written form, and GeckoCIRCUITS is used to understand the various aspects of the problem and to validate their calculated exercise results.

According to the positive student feedback, the online simulation is extremely helpful to understand and solve the exercises. For the teachers it was very easy to administer the course in this way. Changes in the content of the exercises can be performed quickly and with minimum effort. **Fig. 6** and **Fig. 7** show screenshots from examples of the 7th semester course that are web-based, where the latter example describes the dimensioning of a PFC boost converter with a snubber circuit utilizing the nonlinear switch capacitances. Due to the nonlinear capacitances, the exercise cannot be solved solely by analytic calculations. Furthermore, the required maximum simulation step width of 100 ns enforces the memory optimizations as described in Section III B to store the simulation results in memory. The switch control is implemented in a Java code function, since an implementation with discrete control elements blocks would result in a very large and confusing model.
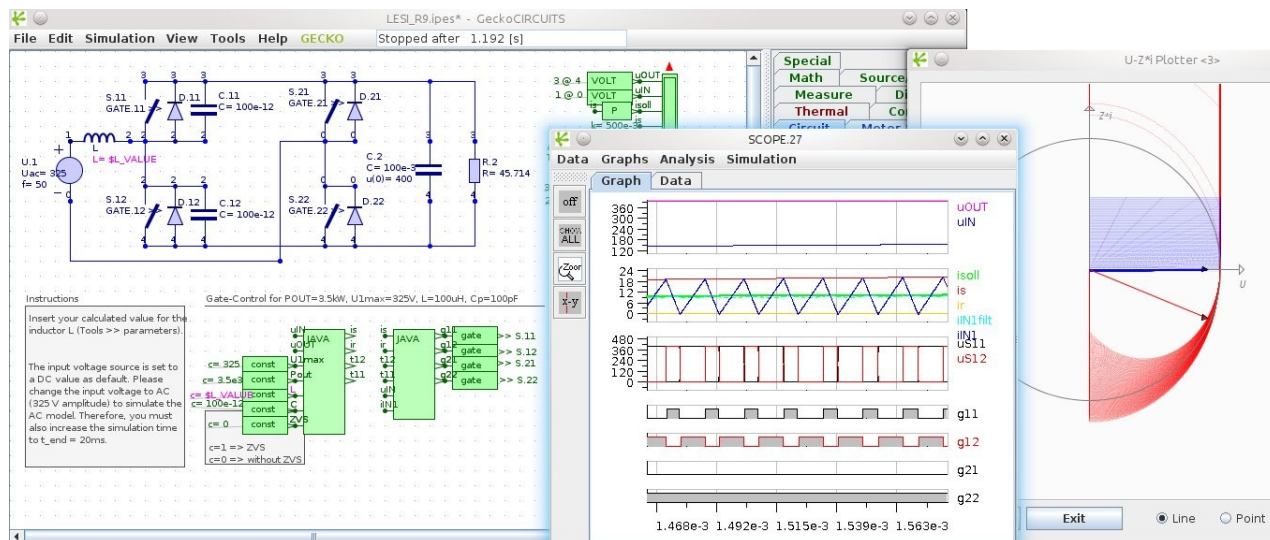
Fig. 7. Screenshot of a GeckoCIRCUITS online exercise: The nonlinear parasitic switch capacitances are utilized as snubber circuit. The online simulation models contain short instruction texts to explain the basic applet functionality and tasks. The figure on the right shows a voltage-impedance vector plot to visualize the dynamic behavior of the snubber circuit.

The advanced level course "Power Electronic Systems II" mainly covers the control of power electronic systems and drives. Since control implementations and the interaction between converters and electric machines are difficult to describe and understand solely by analytic equations, the exercise set for this advanced course includes a combination of analytic exercises and simulation/computation tasks [17].

CONCLUSIONS AND OUTLOOK

The Interactive Power Electronics Seminar (iPES) provides Java Applets that are limited to a few variable parameters. This makes sense from an educational point of view, especially when teaching basics in power electronics. iPES is very useful in demonstrating behavioral tendencies of power electronics circuit, but does not perform numerically accurate simulations. In order to allow unlimited simulation, the circuit simulation program GeckoCIRCUITS has been integrated into the iPES-platform as an online simulator. This novel online simulator is very easy to use, and optimized for power electronics. User acceptance is very high because no installations are needed. The online simulator allows setting up power electronics courses which are very easy to use, simple and highly efficient in maintenance and administration. Power electronic courses at the ETH Zurich are performed using this kind of online simulation.

In the future, additional improvements will be implemented into the online version of GeckoCIRCUITS. For instance a dynamic current path animation will enhance the educational value for the students. Based on the simulated current values, the actual circuit state and commutation path will be visualized in the circuit schematic. Moreover, new online simulation applets of additional lectures, such as e.g. "Electrical Drive Systems", are planned to be made available in the future.

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