Integration of Measurement and Simulation in Power Electronics Laboratory

Zeljko Jakopovic*, Viktor Sunde† and Fetah Kolonic*
* Faculty of Electrical Engineering and Computing, Zagreb, Croatia
† Faculty of Engineering, Rijeka, Croatia

Abstract—**The paper presents integrative approach for educational power electronics laboratory, where measurements and simulations are equally used in laboratory exercises. Hardware and software part of laboratory are described, with typical examples deeply explained. Te best properties of measurement and simulation are used to reach final goal – better understanding of power electronic circuit behavior. Proper balance between measurement and simulation is the key for interesting and useful laboratory exercises. First results are promising, students evaluation of described laboratory is very good.**

I. INTRODUCTION

As written in many papers and books on power electronics, power electronics is very difficult and complex technical area for students. In education of power electronics, a proper balance between different teaching methods is requested, with final goal – development of student skills. There are many interesting and good papers describing current state and trends in education of power electronics [1, 2, 3, 4, 5].

Very important part of power electronics education is appropriate laboratory. But all educational institutions are not able to provide to their students modern power electronics laboratory with a variety of circuits and measurement instruments. Relatively large funds are requested for such demands.

One possible way of solving this problem is virtual laboratory, enabling expensive devices and equipment to be on one place, while large number of student can access the laboratory from distance. There are attempts to develop such virtual laboratories for power electronics [6]. But according to our opinion, such virtual laboratory is appropriate only for relatively simple circuits and simple measurements. Flexibility of virtual laboratory is also not large.

At our Faculty, we have started from existing old power electronics laboratory with 5 modeling benches for SCR based power electronics circuits, having in mind that we have only limited funds for laboratory modernization. We have searched the literature, had talks with colleagues, and finally decided to develop here described solution of power electronics laboratory with integration of measurement and simulation.

Why integration of measurement and simulation? The answer is in the fact that exclusive application of only measurements or only simulation has many drawbacks. Application of only measurements on power electronics components and circuits requires expensive measurement equipment, and there is no large flexibility in ability to change parameters of analyzed device. For example, it is hard to have in laboratory load inductors from 1 mH to 1 H value, to show the students the influence of load inductance on the circuit's behavior.

Only application of simulation is not satisfactory solution. Students have to know how the real world looks like, what are real world effects in power electronics. They need to know why one should be very careful during building of simulation model and during analyzing of simulation results.

Only simultaneous usage of measurements and simulation in educational power electronics laboratory gives synergy, new quality in power electronics education. Simulation enables simple analysis of large number of power electronic circuits, simple change of parameters in large span, and huge possibilities of result analysis with virtual measurements. Application of computers in measurements enables reading of measurement results for comparison with simulation results. Students are than standing in front of a question: what is the cause of a difference between measurement and simulation results? Searching for the answer, students are requested to change the simulation model or its parameters, eliminating differences between measurement and simulation results. In such a way they are developing their skills, slowly growing to be engineers.

II. DESCRIPTION OF POWER ELECTRONICS LABORATORY

Our Laboratory for power electronics at Faculty of electrical engineering and computing in Zagreb consists of two parts strongly connected, hardware part and software part of a laboratory. In development of both laboratory parts we were strongly limited with funds, but final results are promising.

A. *Hardware Part of Laboratory*

Hardware part of power electronics laboratory is based on the old modeling benches dedicated for SCR based power electronic circuits, mainly line converters. The old synchronization units were changed with modern SCR driver/control boards from ENERPRO. With this newer SCR driver/control boards it is possible to implement several control schemes, but this option is not used in basic course. Modern power electronics is obviously MOSFET and IGBT based, so the next step was the development of control unit for autonomous converters based on MOSFET and IGBT power switches. For the first phase we have chosen analogue technology for generation of power switches control signals. Developed control unit (Fig. 1.) is able to generate control signals for dc-dc converters as well as dc-ac converters with several

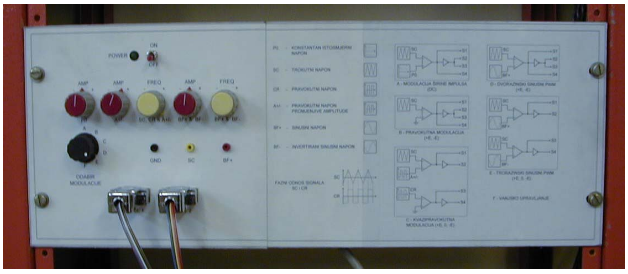

Fig. 1. Control unit for generation of control signals for converters based on IGBT and MOSFET switches.

types of modulations (square wave, quasi square wave, unipolar and bipolar natural sine PWM). In the second phase we are planning implementation of digital technology for the control of our power switches, enabling realization of more complex control schemes.

Power switches (SCRs, MOSFETs and IGBTs) are mounted on heat sinks with protection circuits. Together with plexiglas front plate, this forms power switch module to be inserted into appropriate slots of modeling bench. IGBT module is new development, based on 50 A SEMIKRON IGBT/diode module and SEMIKRON SKHI 22 driver circuit. Described power switch modules (Fig. 2.) are reliable and safe for usage in educational power electronics laboratory. Fig.3. shows the whole modernized modeling bench with inserted power switch modules and passive components.

For the measurements we are using modern and relatively cheap digital scopes from TEKTRONIX, series TDS2000. These scopes are very simple to use, have nice color screen and students simply like them.

B. *Software Part of Laboratory*

It was not an easy decision to select appropriate software as the base for modern power electronics laboratory. We have tried many software tools, but finally we selected SIMPLORER from ANSOFT as the best solution for our idea of integrated laboratory. Professional version of this software is very expensive, but ANSOFT is offering university plans, and what is the most important, there is student version of SIMPLORER. Student version has very large modeling capabilities and is free of charge

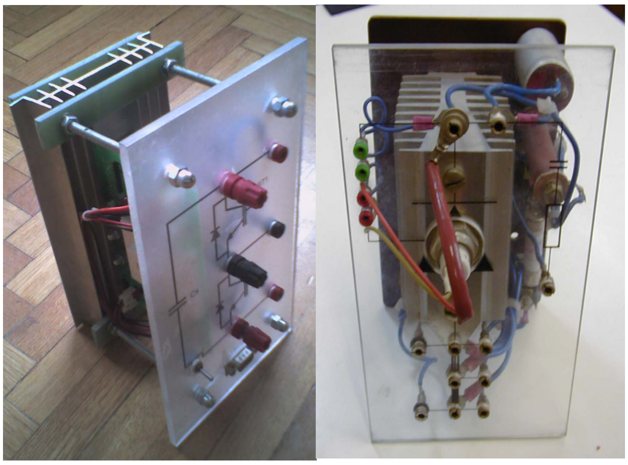

Fig. 2. Power switch modules (IGBT/diode – left and SCR – right).

Fig. 3. Modernized modeling bench with inserted power switch modules and passive components.

for student use. This fact enables student work at home and good preparation for laboratory exercises.

Let us shortly present main features of SIMPLORER. SIMPLORER is multidisciplinary simulation tool developed from the people grown in the field of power electronics and it is dedicated and suited for power electronics and surrounding fields, such as electrical drives. SIMPLORER is based on 3 different simulators (circuit simulator, control block simulator and state simulator) perfectly coupled and user sees only one tool. Set of libraries is well suited for power electronics needs (different complexity levels of power switches, from ideal to dynamic models) and contains even simple and more complex DC and AC machines models. Additional tools enable data processing, magnetic design, frequency analysis and what is really important, interfacing with other well known simulation tools, such as MATLAB/SIMULINK. Some properties of SIMPLORER important for our laboratory are:

- support of event driven systems (state simulator) enables interactive simulations [7] and sophisticated control of simulation. Teacher or student can easily choose initial set of conditions (e.g. to choose ideal or real converter) and system parameters. Parameters can be changed during simulation and students can see immediately the effects of circuit parameter change, e.g. change of control angle α or duty cycle D.

- existence of prepared virtual instruments and possibility to build special virtual instruments needed for measurements in power electronics. Average and RMS values (normal and sliding in defined period) of simulated variables are easily obtained, FFT analysis is possible during simulation and afterwards, power factor measurement can easily be realized,

- several possible complexity levels of power switches, ideal, static models, dynamic models,

- integration with additional software tools for magnetics and rotating machines (PExprt, RMexprt).

C. *Connecting Hardware and Software*

As the basic idea of our laboratory is integration of measurement and simulation, it was important to find a solution for simple and cheap connection between the digital scope from measurements world and the computer from virtual, simulation world. We have chosen RS-232

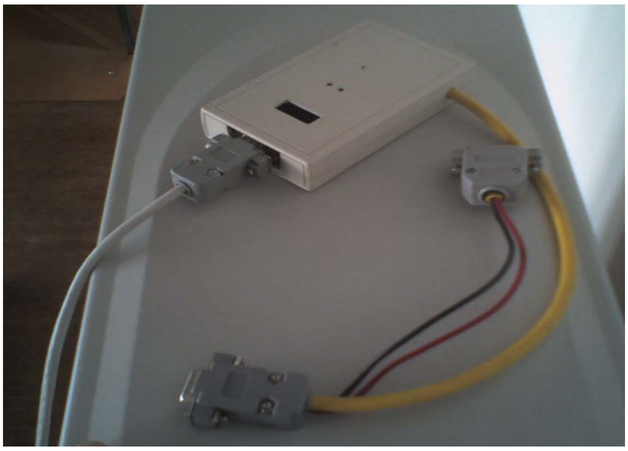

Fig. 4. Interface board with galvanic isolation for connecting digital oscilloscope and computer.

connection and WAVESTAR software. This is slow connection, but for educational laboratory transfer speed is satisfactory. WAVESTAR software for acquiring measured data from TEK scopes is simple and efficient solution. It enables transfer of waveform data and screenshots from the scope. Also control of all scope functions is possible from PC console. Transferred data can be saved in different data formats for the use in simulation software.

One additional problem has to be solved. Galvanic isolation between the digital scope and the computer. Simple interface board powered from computer side was developed, Fig. 4.

III. Basic Exercises

Laboratory is dedicated for basic power electronics course, for undergraduate students. At the time of attending power electronics course, students have not finished control course. This is the reason why there are no control problems in basic exercises. For all power electronics circuits modeled on test benches, there is appropriate simulation model in professional and student version of SIMPLORER. There is a short overview of basic laboratory exercises.

1. Basic Power Electronics Switches

Students are prepared for work in laboratory. Basic information about simulation software and modeling hardware is given. Simulation of semiconductor switches behavior. Switches are modeled at different levels, as ideal switch, as a *real* switch with static characteristic and as *real* switch with dynamic model realized as SPICE-like model or behavioral based model. This model hierarchy is really good feature of SIMPLORER software. Demonstration of measurement on real IGBT switch with *R* and *RL* load is provided at the end of exercise

2. Basic Power Electronics Circuits

Basic power electronics circuits are half way rectifiers and phase controlled rectifiers loaded with *R* and *RL* loads, as well as loads with counter EMF. Freewheeling diode effect is investigated. During simulation it is easy to provide circuit parameter change and to see the effects of this change.

3. AC/AC Conversion – Single Phase Voltage Controller

In this exercise circuit behavior with different load types is investigated. For the first time automatic simulative measurement of control characteristic $V_{Oeff} = f(\alpha)$ is introduced.

4. AC/DC Conversion – Mid-point Line Converters

Single- and three-phase mid-point line converter circuits are investigated as basics for all line converter circuits. Special care is dedicated to commutation effects, mains voltage distortion and automatic simulative measurement of control and load regulation characteristic of converter. Different types of load are used (*R, RL, RLE*). During real measurement on benches, it is interesting to see student's surprise seeing line voltage distorted, not sinusoidal as in books.

5. AC/DC Conversion – Bridge Line Converters

Single- and three-phase bridge line converter circuits are investigated, controlled and half controlled. Freewheeling diode effect is investigated again. Comparison of semiconductor switches loading in different circuit configurations is conducted.

6. AC/DC Conversion – Application of Line Converters

In this exercise, application of line converters for the 4-quadrant control of DC electrical drives is shown. Until now, loads on modeling benches were passive. Introduction of motor load is very interesting to the students, this is real load, it rotates. It is not dangerous, because small motor (50 V, 40 A) is used. Speed reversal process is explained and demonstrated.

7. DC/DC Conversion – Switching Converters (single switch)

Operation of DC/DC switching converters without galvanic isolation is investigated. Buck, boost and buck-boost configurations are available, but measurement is made on boost converter. Both CCM and DCM operation modes are used and transition between them is demonstrated. This exercise analyzes effect of real components on converter behavior, influence of losses on power switches and passive components can be clearly seen and measured.

8. DC/DC Conversion – Switching Converters (H-bridge)

H-bridge topology is introduced as 4-quadrant DC/DC converter. Unipolar and bipolar modulations are explained and compared. FFT of load voltage and current is calculated. Speed reversal process of small DC motor is again demonstrated and results are compared with those obtained with line converter.

9. DC/AC Conversion – Resonant and Square Wave VSI

First laboratory term dedicated to inverters includes investigation of resonant inverters with serial resonant load and voltage source inverters (H-bridge topology) without modulation. FFT of output voltages and currents is calculated and compared for both inverter solutions.

10. DC/AC Conversion – Sinusoidal PWM VSI

Second laboratory term dedicated to inverters introduces voltage source inverters with natural sinusoidal PWM. Both unipolar and bipolar modulations are investigated, with comparison of their harmonic spectra. Influence of change of M_a and M_f parameters is analyzed,

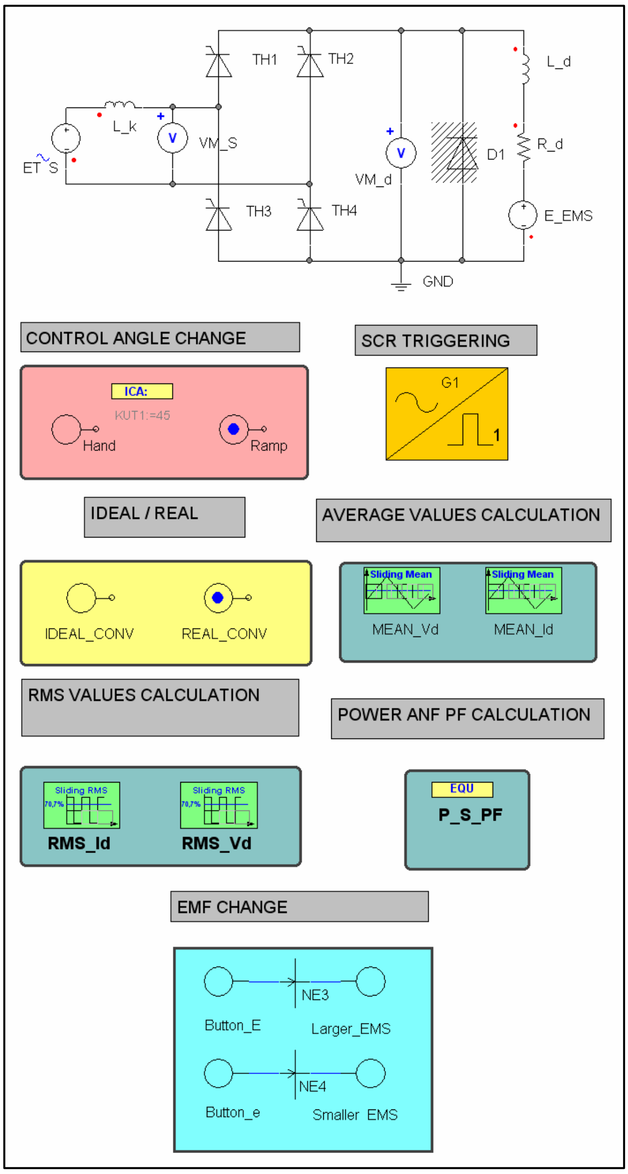

Fig. 5. SIMPLORER worksheet for interactive simulation of single phase bridge line converter.

as well as synchronous and asynchronous modulation. Overmodulation effects are presented.

IV. Typical Exercise Examples

Two typical examples of basic exercises are illustrating the idea of our integrated laboratory. Only basic features and possibilities are described. There is not enough time on basic course to use all possible features of simulation models.

A. Single-Phase Bridge Line Converter

Simulation model of single-phase bridge line converter is made to be as universal as possible and to enable successful comparison with real laboratory model of the same converter. Fig.5. shows SIMPLORER worksheet for simulation of single-phase bridge line converter.

Let us explain interesting features of SIMPLORER model. Two possible types of load are modeled, ideal current source load (not shown on picture) and *real* RLE type of load. Topology of the circuit can be easily modified using "*Do not add to SML*" option. Application of this option can be seen on Fig.5. as shadowed free-wheeling diode. If element is shadowed, it is not included in the model. It is very efficient way of modifying topology, or even control law.

One can see many Petri net elements, belonging to the state simulator of SIMPLORER. We are using intensively this feature for sophisticated control of simulation, especially for interactive change of parameters. In line converter example, with change of active states, one can select if ideal or *real* circuit is modeled, or if control angle is set up by hand, or it is controlled by ramp generator. In the same way one can change values of load parameters.

Average and RMS values of voltages and currents are calculated during simulation, and used for the calculation of real and apparent power, as well as power factor. These are virtual instruments. There are basically two ways of displaying results, classical one with whole window displaying all results during simulation, and *View element*, where scope-like display on worksheet with animated symbols is used.

What is difference between ideal and *real* converter model? On the worksheet one can see only two states, but with definition of each state, one can define precisely what properties of real world to include in the model. In this simple case ideal converter has ideal switches without losses and no commutation inductance, while *real* converter has switches with only static losses and real commutation inductance. This is important for modeling real world effects.

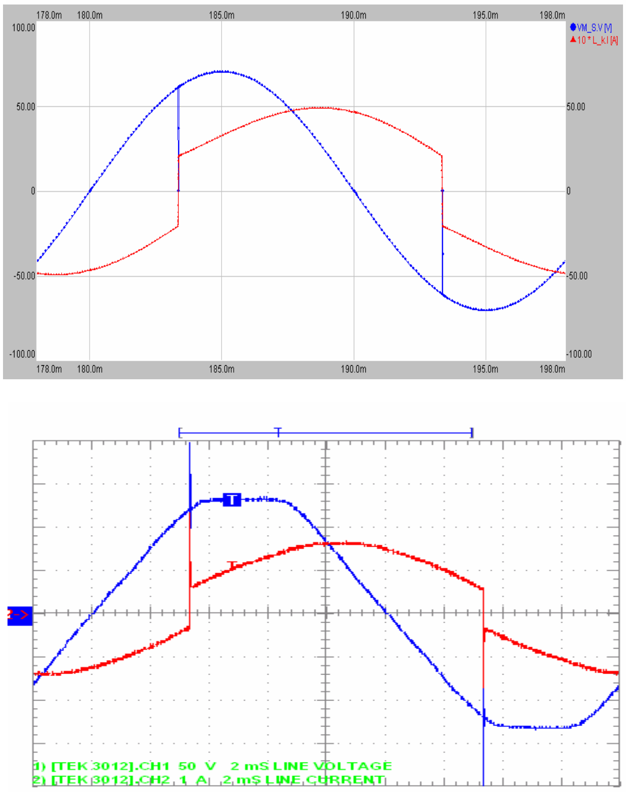

Fig. 6. Comparison of measured (lower picture) and simulated (upper picture) line voltage and current waveforms of single phase bridge line converter.

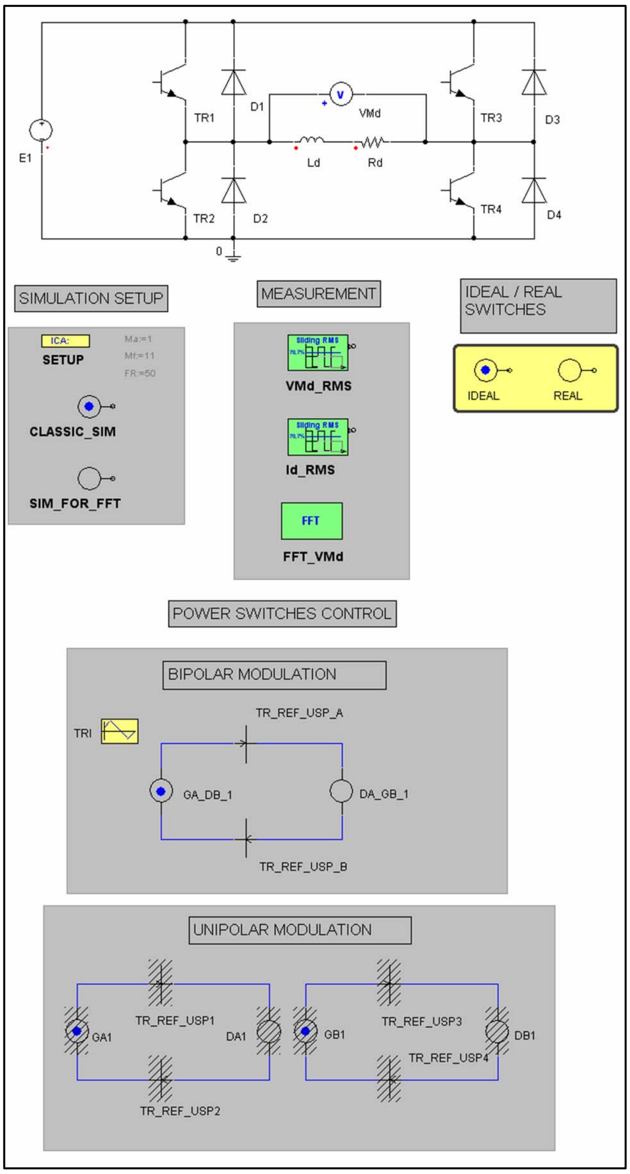

Fig. 7. SIMPLORER worksheet for interactive simulation of single phase bridge PWM inverter.

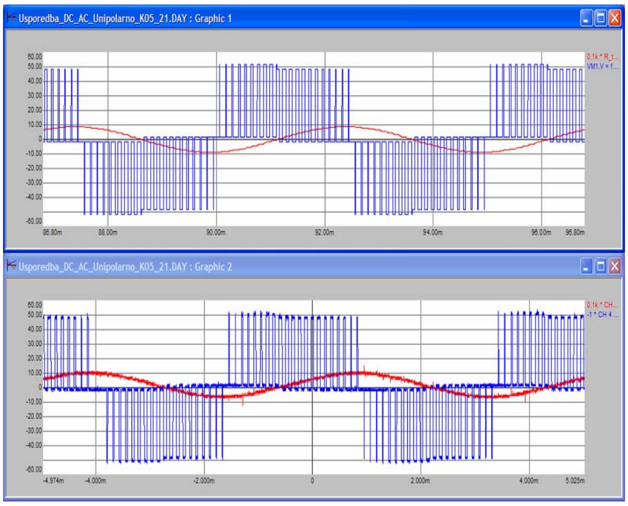

Fig. 8. Comparison of measured (lower picture) and simulated (upper picture) load voltage and current waveforms of PWM inverter.

In case of line converter, students are simulating at first ideal converter. Then, during measurements, they can see voltage distortion on measured line voltage. They return back to simulation, trying to find reasons for the distortion. After selecting *Real Converter* option, student can see that commutation inductance causes voltage drops during commutation. Fig.6. shows measured and simulated results of line current and voltage for single-phase bridge line converter.

Another interesting and useful feature of simulation is possibility to make virtual measurements that are not easy to perform in educational laboratory, e.g. output and control characteristic of line converter. With simulation it is possible to perform for ideal and real converter case.

What is difference between professional and student version of simulation model for this circuit? Only virtual instruments are not included in student version, all other main features are included.

B. *PWM Inverter*

Simulation model of single-phase bridge PWM inverter also universal and enables successful comparison with real laboratory model of the same converter. Fig.7. shows SIMPLORER worksheet for simulation of single-phase bridge PWM inverter. Typical structure of the simulation worksheet can be seen. Again ideal and *real* (static model) switches can be selected.

In this case, modulation is defined with Petri nets, in the same logical way as it is explained in textbooks. Two types of sinusoidal PWM are selectable, unipolar and bipolar. Selection is made by using "*Do not add to SML*" option. Modulation parameters (M_a, M_f) can be freely changed. Comparison of simulated results with measurement shows really good agreement, Fig. 8, if *Real type* power switches are selected. Without expensive instruments FFT of output voltage and current can be calculated, using numerical features of SIMPLORER.

V. Typical Exercise Course

Before accessing laboratory, students have enough hours of lectures dedicated to specific area. On the dedicated Web-pages students can find all required materials for laboratory exercise, preparation for the exercise, instructions for measurement and simulation, instructions for report writing, and finally files with simulation models to be used on exercise.

As preparation for the exercise, students are requested to answer the questions, to solve some numerical examples, and to make some initial simulations. This makes work in laboratory more efficient.

During the exercise, students are firstly making measurements and after that they are comparing measurements results with results obtained with ideal model simulation.

The next step is appropriate change of model structure or model parameters, to obtain more accurate simulation model, able to describe behavior of real power electronics circuit.

Finally, results of measurements and simulation are transferred to electronic form of laboratory report.

VI. CONCLUSION

Integration of measurement and simulation in power electronics laboratory, while maintaining proper measure of both methods, gives new quality to educational laboratory for power electronics. Simulation offers flexibility, easy change of parameters, topologies and control laws, while measurement gives important information on behavior of real circuits. If both methods are used simultaneously, students can apply their knowledge for finding the causes of differences between measured and simulated results. Finally, they can try to build simulation model that accurately describes behavior of real circuit.

Student's assessment of laboratory at the end of semester shows that students are satisfied with integrative approach. Few of them would like more simulations, few of them would like more measurements, but final mark is between very good and excellent.

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