

Undergraduate Power Electronics Laboratory – Applying TSMST Method

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Abstract

This paper presents a TSMST (Theory – Simulation – Measurement – Simulation – Theory) method for power electronics laboratory. The method successfully integrates theory, simulation and measurement, thus enabling better integration of student's knowledge and better usage of inadequate number of laboratory hours. Students are attracted with relatively simple tasks to be solved and modern, but economical laboratory equipment. A significant part of the assignments can be made at home, thus lowering the pressure on students to finish the tasks on time. The proposed method is described on three basic examples explaining characteristic phases of the TSMST method.

Key Words: Modelling, Power electronics laboratory, Simulation, TSMST teaching method

I. INTRODUCTION

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]-[21].

If there are no hardware laboratory possibilities, only software lab is proposed [2]. Software tools are becoming more advanced, but real lab facility cannot be eliminated. It is a global opinion that for successful power electronics education the student must get a sense of real power electronics circuits. However, it is not an easy task to organize it. The problem based approach is nowadays one of the most advised solutions [1],[21]. This approach solves specific power electronics learning problems: most students have finished a course in power electronics, but they have not completely grasped the implications of the interactions that occur among the source, the load and the power electronic converter. The problem based approach requires strong interaction of students and the appropriate higher-level knowledge. Power electronics education should not be only focused on detailing each particular structure of a power converter. It is much better to give a student a global perspective based on methodological approach [7].

Modern technologies are influencing power electronics labs, of which FPGA based solutions are one of the most economical solutions [17]. Virtual and distance labs have lately

also been in the focus [12], [15], [18]. In our opinion virtual and distance lab is interesting and attractive solution, but our experiences are not in favor for this approach. Modern E-learning methods are widely used for power electronics education [19]. There are educational papers with very similar approaches as ours [3], [5], [7], [8], [13], [20], suggesting the use of simulation and measurement in the laboratory.

One huge problem caused by implementation of Bologna declaration in our institution is relatively small number of laboratory hours. Students are supposed to study at home, but there is no lab there! We have to adapt our laboratories and methods taking into account all these premises.

II. SOLUTION SELECTION

We have analyzed the best literature from the field of power electronics education, our budget, targeted student knowledge, available laboratory hours and our plans for the next 10 years. Finally we have selected an integrated modular approach for our lab which enables simultaneous simulation and measurement (Fig. 1) [4],[6],[16].

In the same room there are 5 modeling benches, 5 modern digital scopes and 5 computers. All computers are connected to LAN and to Faculty informatics infrastructure. This solution enables efficient interactive simulation and measurement.

Why integration of measurement and simulation? The answer is in the fact that exclusive application of only measurements or only simulation has many drawbacks. The 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 the analyzed device. For example, it is difficult to have in the laboratory load inductors ranging from 1 mH to 1 H value to show students the influence of load inductance on the

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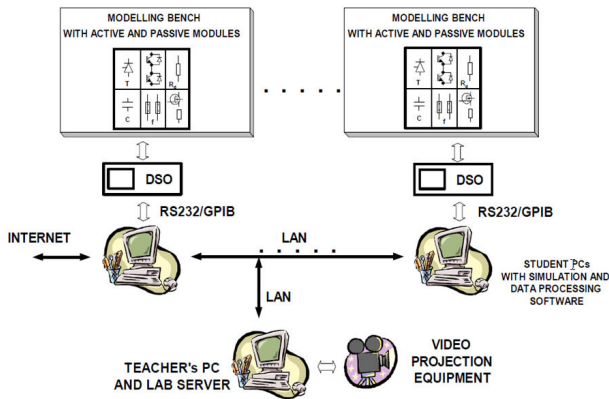


Fig. 1. Interactive modular laboratory for power electronics.

circuit's behavior. The application of only simulation is not a satisfactory solution either. Students have to know what are real world effects in power electronics. They need to know why one should be very careful during building of a simulation model and during analysis of simulation results. Only simultaneous usage of measurements and simulation in educational power electronics laboratory gives synergy and new quality in power electronics education. Simulation enables simple analysis of large number of power electronic circuits, simple change of parameters in a large span, and huge possibilities of result analysis with virtual measurements. The application of computers in measurements enables reading of measurement results for comparison with simulation results. Students are then facing a question: what is the cause of a difference between measurement and simulation results? In the process of searching for the answer, students are requested to change the simulation model or its parameters, thus eliminating differences between measurement and simulation results. In such a way they are developing their skills, slowly growing to be engineers.

As a methodology for conducting exercises, the TSMST method is defined as the most appropriate solution for our demands. The method can be shortly described as:

- **T**(heory) – apply theoretical knowledge to solve initial problem and prepare for the exercise,
- **S**(imulation) – make basic simulation model and obtain ideal (idealized) waveforms,
- **M**(easurement) – make laboratory model and conduct required measurements, compare results,
- **S**(imulate) – rearrange simulation model for better description of the real circuit, simulate,
- **T**(heory) – make final conclusions, use additional literature for further enhancements.

The TSMST method is basically designated and tested for relatively simple power electronics circuits, not for complex power electronic systems. Successful application of the TSMST method on the complex power electronic systems would require preparation of complex and accurate simulation models in advance, as well as interactive analysis and explanations of such complex models during exercises. The burden of the tutors would be increased significantly in such a case.

Theoretical knowledge needed for TSMST based exercises

is acquired on regular lectures, eventual additional facts can be found in defined and accessible literature.

The laboratory infrastructure and TSMST details are described in more detail in the following chapters.

III. LABORATORY INFRASTRUCTURE

Our Laboratory for power electronics consists of two parts strongly connected, hardware part and software part. In the development of both laboratory parts we were strongly limited with funds, but final results are promising.

A. Hardware Part of the Laboratory

The hardware part of power electronics laboratory is based on the old modeling benches dedicated for SCR based power electronic circuits, mainly line converters. The bench was fully revitalized, with new SCR driver/control boards as well as self-developed control unit for IGBT based PWM circuits [16]. A modular approach is applied, almost all components are mounted on modules (except heavy inductors). It is very easy to assemble different power electronic circuits. Fig. 2 shows modeling bench and basic power switch modules, SCR and IGBT.

The power switches (SCRs, diodes and IGBTs) are mounted on heat sinks with protection circuits. The described power switch modules are reliable and safe for usage in educational power electronics laboratory. For the measurements modern and relatively cheap digital scopes from TEKTRONIX, series TDS2000 are used. These scopes are very simple to use.

B. Software Part of the Laboratory

It was not an easy decision to select appropriate software as the base for modern power electronics laboratory, but finally SIMPLORER [22] from ANSOFT (now ANSYS) is selected as the best solution for our idea of an integrated laboratory.

SIMPLORER is a multidisciplinary simulation tool developed by the experts 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 perfectly coupled simulators (circuit simulator, control block simulator and state simulator) so a user sees them as a single tool. The set of libraries is well suited for power electronics needs (different complexity levels of power switches, from ideal to dynamic 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 [4] and sophisticated control of simulation,

- existence of prepared virtual instruments and possibility to build special virtual instruments needed for measurements in power electronics,

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



Fig. 2. Modeling bench with SCR and IGBT modules.

C. Connecting Hardware and Software

We have chosen RS-232 connection and WAVESTAR software for connection between the scope and the PC [23]. This is a slow connection, but for educational laboratory transfer speed is satisfactory. The WAVESTAR software is simple and efficient solution for acquiring measured data from TEK scopes. The galvanic isolation between the digital scope and the computer is also provided with an additional device.

D. Basic Exercises

The laboratory is dedicated for basic power electronics courses, for undergraduate students. For all power electronics circuits modeled on test benches, there is an appropriate simulation model in professional and student version of SIMPLORER. There is a list of possible basic groups of laboratory exercises:

1. Basic Power Electronics Switches
2. Basic Power Electronics Circuits
3. AC/AC Conversion – Single Phase Voltage Controller
4. AC/DC Conversion – Mid-point Line Converters
5. AC/DC Conversion – Bridge Line Converters
6. AC/DC Conversion – Application of Line Converters
7. DC/DC Conversion – Switching Converters (single switch)
8. DC/DC Conversion – Switching Converters (H-bridge)
9. DC/AC Conversion – Resonant and Square Wave VSI
10. DC/AC Conversion – Sinusoidal PWM VSI

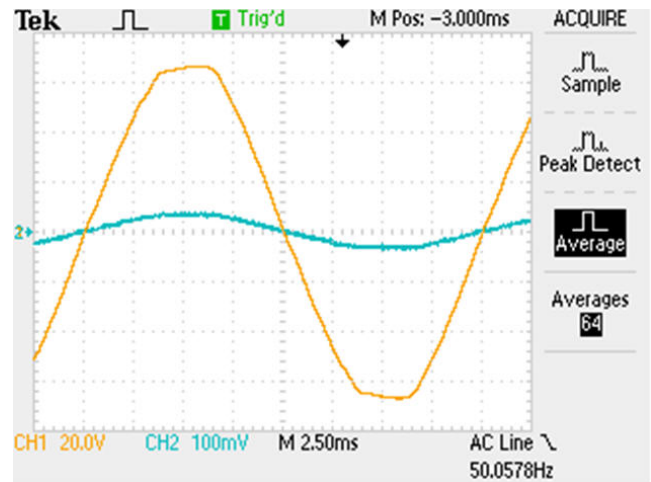


Fig. 3. Measured laboratory grid voltage and current under resistive loading.

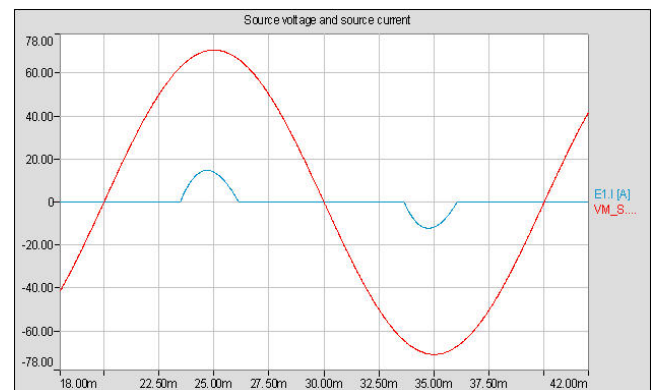


Fig. 4. Simulation results for grid voltage and current obtained on a basic model.

IV. USED METHODOLOGY

As mentioned before a whole variety of power electronics circuits can be modeled for measurement and simulation. Due to time limitation, only fundamental circuits and measurements are selected for the exercises. This section describes methodology for analysis of fundamental power electronics circuits with the application of the proposed TSMST method.

A. Case I – Diode rectifier with capacitive load

A diode bridge rectifier with capacitive load is the most commonly used power electronic circuit, it belongs to the Basic Power Electronics Circuits group of exercises. However, the influence of this circuit on power grid is not well known. A large number of educators (those who are not from the field of power systems) are not aware of the problem. This simple circuit enables us to establish the connection between the theory and real life.

T(heory)- In lectures, ideal waveforms of diode bridge rectifier with capacitive load are briefly analyzed. Students expect that grid voltage is sinusoidal, but we show them that measured grid voltage (Fig. 3, with resistive loading) in the lab is distorted. The question is why? Laboratory exercise should give the answer.

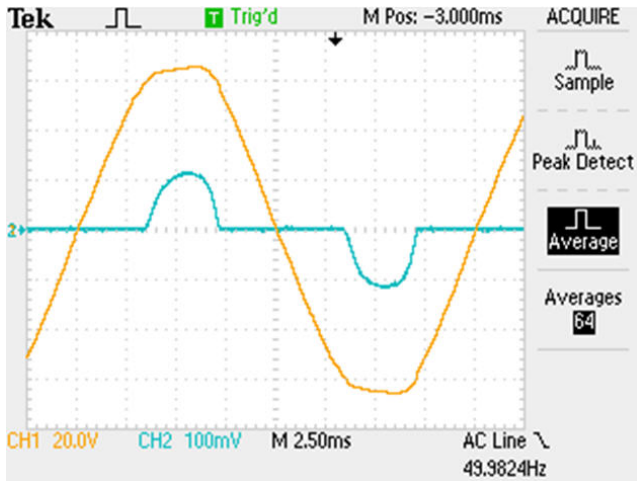


Fig. 5. Measured laboratory grid voltage and current (diode bridge rectifier with capacitive load).

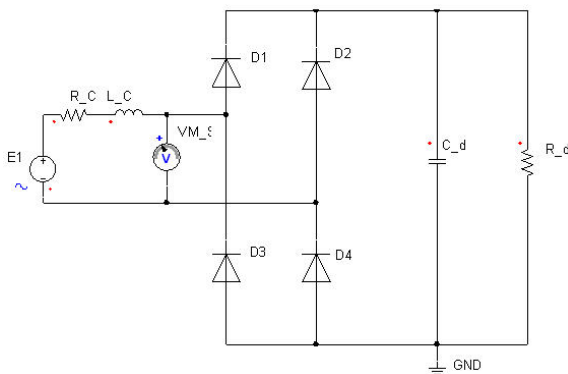


Fig. 6. Modified model of a diode bridge rectifier with capacitive load.

S(imulation)- Students are also requested to build a simple working simulation model of a diode bridge rectifier with capacitive load and to obtain idealized waveforms. They should make initial simulations (Fig. 4) and prepare possible answers. Simulations on the basic model are not giving distorted grid voltage waveform.

M(easurement)- Laboratory model of a diode bridge rectifier with capacitive load is assembled on the bench, according to printed instructions and with a help of the assistant. The focus is on the grid waveforms (voltage and current). The measured grid voltage and grid current (Fig. 5) are transferred from the scope to the PC and compared with ideal (Fig. 4) waveforms. The fact that voltage distortion is in phase with the current flow could help in finding the answer. The voltage distortion is larger when grid is loaded with diode bridge rectifier with capacitive load than in the case of resistive loading.

S(imulation)- After discussion, students are aware that impedance (L_C , R_C) should be added to the basic simulation model, but the values of R , L , C components are to be estimated. After solving this task, a modified model of the diode bridge rectifier with capacitive load is obtained (Fig. 6) with simulation results (Fig. 7) in a good agreement with measurement (Fig. 5).

T(heory)- The reason for grid voltage distortion is revealed.

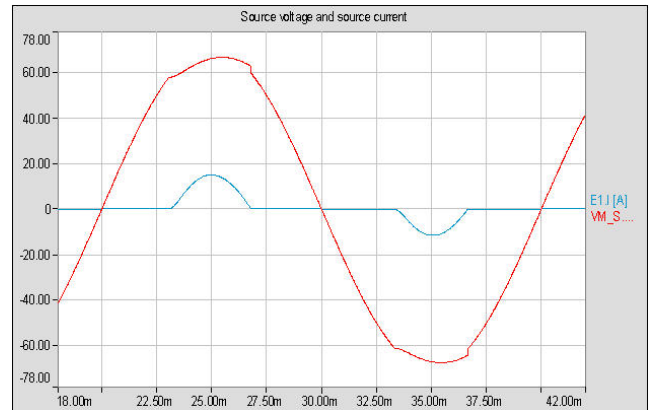


Fig. 7. Simulation results for grid voltage and current made on a modified model.

The faculty grid voltage is distorted because many rectifiers with capacitive load are connected to it. Now, we can explain students that there are solutions for this problem based on modern power electronics (PFC, active power filters).

B. Case II – Phase controlled rectifier

Although phase controlled rectifiers are becoming obsolete in modern power electronics, they are still in use and their behavior should be analyzed by students, especially their influence on the power grid. The rectifier load is of inductive type.

T(heory)- In lectures, ideal waveforms are briefly analyzed, single phase controlled rectifier operation is discussed. The waveforms of interest are on the grid side (grid voltage and current), load side (load voltage and current) and on SCRs (voltage and current). Before laboratory exercise, students have to prepare themselves by solving relatively simple examples as a homework. They are also requested to build a simple working simulation model of a phase controlled rectifier and obtain idealized waveforms of interest.

S(imulation)- Students are also requested to build a simple working simulation model of a phase controlled rectifier and obtain idealized waveforms of interest before approaching the laboratory.

M(easurement)- In laboratory, students have to build a model of the phase controlled rectifier on the bench, according to printed instructions and with a help of the assistant. After successful circuit assembling, the measurement starts. The focus is on the grid waveforms. Measured grid voltage and grid current (Fig. 8) are transferred from the scope to the PC and compared with ideal (or idealized) waveforms from lectures and simulation. The differences should be noticed and analyzed. The main difference is in voltage distortion due to the commutation.

S(imulation)- After discussion, students are aware that reactance (L_k) should be added to the basic simulation model, but the value of inductance is to be estimated. After solving this task, a modified model of the universal phase controlled converter is obtained (Fig. 9), thus enabling successful description of commutation effects (Fig. 10). The resulting modified simulation model has many other possibilities for an upgrade



Fig. 8. Measured laboratory grid voltage and current (single phase controlled rectifier with inductive load).

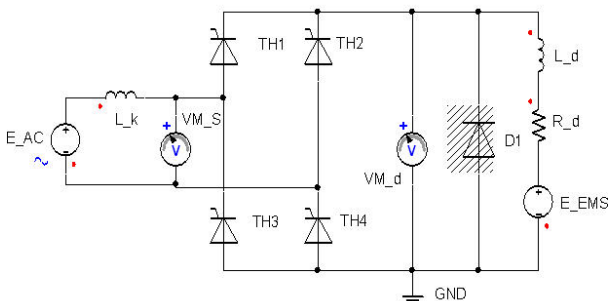


Fig. 9. Modified model of a universal single phase controlled rectifier.

(influence of freewheeling diode, automated estimation of control and output characteristic etc.).

T(heory)- After finishing all the requested measurements, students are analyzing the results and discussing the remaining differences, using knowledge from lectures and additional materials. The laboratory report should include all the explanations that were not discussed during laboratory exercise.

C. Case III – Step-up DC/DC converter

A step-up DC/DC converter is a representative of power electronics circuits with fully controllable switches. There is an option with either MOSFET (compact version) or IGBT switch. There are no control possibilities on the circuit. This is the case for investigation of the influence of real components on the circuit behavior.

T(heory)- As usual, ideal waveforms are briefly analyzed and step-up DC/DC converter operation is discussed. The waveforms of interest are controllable switch voltage and current, inductor L voltage and current and output capacitor C voltage and current. The preparation of students through solving the simple examples as a homework is assumed. One of the tasks is to calculate the required duty cycle D_x for obtaining a ratio of 2 between the output and input DC voltages ($V_0/V_i = 2$).

S(imulation)- Students have to build their own simple working simulation model of a step-up DC/DC converter and obtain idealized waveforms of interest. All used component models

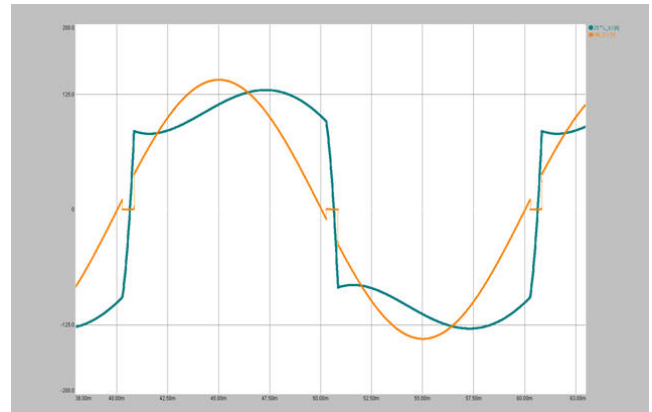


Fig. 10. Simulation results for grid voltage and current made on a modified model of a universal single phase controlled rectifier.

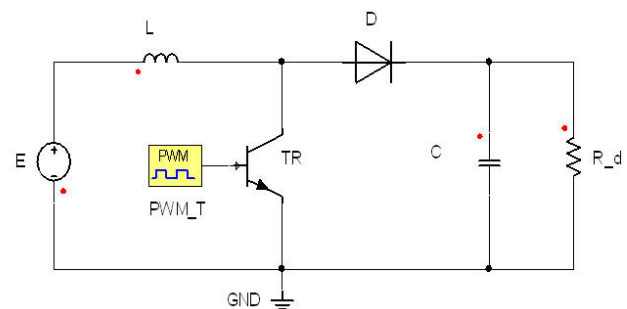


Fig. 11. Basic simulation model of a step-up DC/DC converter.

are ideal, without losses (Fig. 11). The simulated results for the basic model are in Fig. 12 (inductor voltage and current, output voltage)

M(easurement)- In the laboratory, students have to build a model of the step-up DC/DC converter on the bench, according to the printed instructions and with a help of the assistant. After successful assembling, the measurement starts under the same conditions as in simulation, for calculated duty cycle D_x . The focus is on the inductor L waveforms. The measured inductor voltage and current (Fig. 13) are transferred from the scope to the PC and compared with ideal (or idealized) waveforms from lectures and simulation. The differences should be noticed and analyzed. The main difference in this case is in the amplitude of the output voltage V_0 , whose measured value (72 V) is lower than simulated (80 V). There is also a strong AC component in the DC source voltage. Students should find out the reason for these effects and implement the required changes into simulation model. Obviously the main reason is in the circuit losses (switch losses, parasitic components).

S(imulation)- After discussion, students are aware that resistances (R_L , R_C) and real static characteristics of power switches should be added to the basic simulation model, with the values to be estimated. New, larger duty cycle D_y is required to compensate the losses. The estimation of D_y is also a task. An AC source should be also added in series with the DC source to describe eventual ripple in DC source voltage. After solving these tasks, a modified model of the step-up DC/DC converter is obtained (Fig. 14), thus enabling successful description of the effects of losses (Fig. 15). The

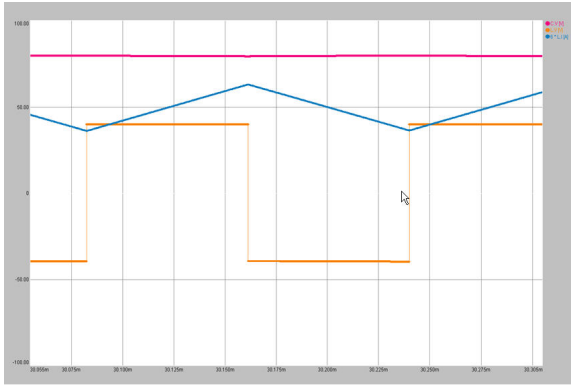


Fig. 12. Simulated results for the basic model. (voltages 50 V/div, current 8 A/div)

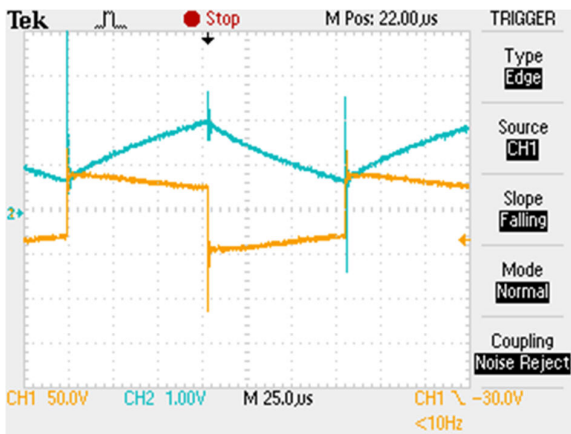


Fig. 13. Measured inductor voltage and current of the step-up DC/DC converter ($D_X = 0.5$).

comparison of the modified circuit simulation results with the measurement results (Fig. 16) shows good agreement, but points out that not all effects are described with the new modified model.

T(theory)- The task of the last exercise part is to find out what new modifications should be made to cover these effects as well. This is a task for advanced students given as a homework after exercise. Our simulation package SIMPLORER enables also implementation of dynamic power switches models instead of simple static models. The change of power switch model levels (with addition of appropriate parasitic inductances) leads to a better description of details during switching phase.

V. CONCLUSIONS

This paper describes a TSMST (**T**heory – **S**imulation – **M**easurement – **S**imulation – **T**heory) method used in power electronics laboratory at a bachelor level. Since the number of laboratory hours is significantly reduced during forming of a new undergraduate study according to Bologna declaration, the most adequate solution has to be found. The small number of laboratory hours has to be optimally utilized, not for countless measurements on various power electronic circuits, but for solving specific problems on simple examples, thus enabling the establishment of connection between ideal circuit models and real world effects. The TSMST method starts from

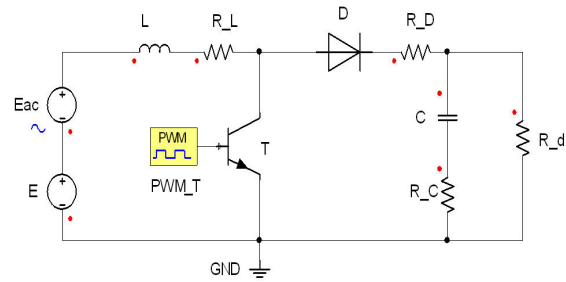


Fig. 14. Modified model of a step-up DC/DC converter.

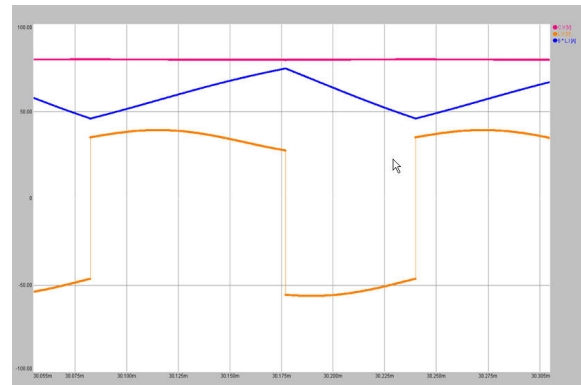


Fig. 15. Simulated results for the modified model. (voltages 50 V/div, current 8 A/div)

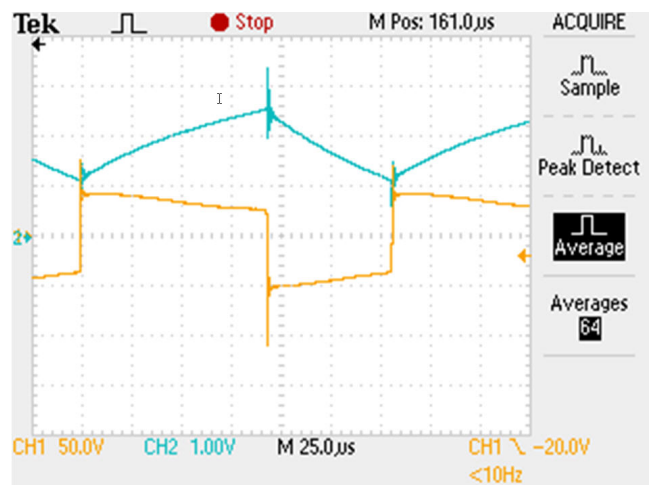


Fig. 16. Measured inductor voltage and current of a step-up DC/DC converter ($D_Y = 0.6$).

fundamental theoretical background obtained during lectures and from preparation for a laboratory. This theoretical knowledge is then used for interpretation of simulation results and comparison with measurement results. The required correction and adaptation of a simulation model and model parameters forces students to integrate their existing knowledge and to acquire additional knowledge needed for solving the problem. The laboratory infrastructure needed for implementation of TSMST is economical, adapted to current financial situation in the university and industry environment. The obtained results are promising.

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Zeljko Jakopovic was born in Zagreb, Croatia, in 1959. He received his B.S.E.E., M.S.E.E. and Ph.D.E.E. degree from Faculty of Electrical Engineering and Computing, University of Zagreb, in 1981, 1992 and 1997, respectively. He is currently professor at the Faculty of Electrical Engineering and Computing, University of Zagreb. His areas of interest are modelling and simulation in power electronics, active power factor correction and converters control techniques as well as introduction of modern power electronics education methods. He has been author and coauthor of many papers published in journals and presented at the national and international conferences. He is the member of Korema and IEEE (PEL, IA).



Viktor Sunde was born in Orah, Vrgorac, Croatia on April 4, 1959. He received the B.S. degree and M.S. degree from Faculty of Electrical Engineering, University of Zagreb in 1984, and 1992 respectively. He received the Ph.D. degree from Faculty of Electrical Engineering and Computing, University of Zagreb in 1999. From 2009 he is Assistant professor at the Faculty of Electrical Engineering and Computing, University of Zagreb. He is the author and coauthor of several papers published in scientific journals and proceedings of international and domestic conferences. His research interests include power electronics, technology of electronic and electrical components, modeling and simulation power electronics systems.



Zvonko Bencic was born in Senj, Croatia, on April 23, 1940. From the University of Zagreb Faculty of Electrical Engineering, he earned the B.E.E. in Electronics in 1963, then continued his studies with the University of Zagreb Faculty of Natural Sciences and Mathematics, earning M.Sc. in Solid State Physics in 1969. He received his Ph.D. from the University of Zagreb Faculty of Electrical Engineering in 1988. From 1994 he is employed at University of Zagreb Faculty of Electrical Engineering and Computing as full professor. Dr. Bencic's published works include one textbook, four handbooks, 8 textbook materials and three textbook translations. Through his career Dr. Bencic has been honored for his research activities and professional duties. He is a member of Croatian Academy of Engineering, Croatian System Society, Electrotechnical Society Zagreb and senior member of The Institute of Electrical and Electronics Engineers.