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Online Laboratory Sessions for the Education of Electrical Machines and Drives

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Abstract—This paper presents a method to implement online laboratory sessions for education in Electrical Engineering on subjects related to electrical machines and drives. The assignments for the laboratory sessions consist of: the preparation homework, where students have to study relevant theories; the development of circuit simulations; and the participation on a practical session online. For the latter, the students have to implement remotely various models in a physical setup based on the results of their homework tasks. After taking the assignments, the students should be able to: set up circuit simulations of electrical machines and drives; to implement relevant control of motor drives in a physical setup; and finally, to interpret the differences between the simulation and experiment results. Detailed design of the physical setup, the assignments, the relevant Information and Communication Technology (ICT) facilities are presented and discussed in this paper. An example and the feedback of applying it in a master level course is presented. The experience gained so far shows that the proposed online laboratory sessions can be used as supplementary educational resource to existing online education platforms.

Index Terms—online education, electrical machines, electrical drives, laboratory setup, massive open online courses

I. INTRODUCTION

Online education has been a trend in modern higher education. Massive Open Online Courses (MOOCs) have enabled any people with Internet connections to access high quality learning materials from top universities [1]–[3]. All over the world, the fast development of Information and Communications Technology (ICT) and various online learning platforms, e.g. edX, Coursera and the websites of various universities, have dramatically changed the way of teaching and learning higher education subjects relevant to Electrical Engineering. Apart from the wide coverage and easy access, modern online education platforms also provide possibilities to blend online courses into traditional higher education on campus. The well developed online platforms and digitization of study materials actually boost the interactive learning via online forums and the concept of “flipped classrooms”, where the instructor serves as a coach and mentor.

In the meanwhile, the education on Electrical Machines and Drives (EMD) is also undergoing transition on university campus, mainly driven by the demands from emerging applications, technology development and digitization. Traditionally the EMD education is often divided into several aspects:

- Steady state models of electrical machines;

- Dynamic models of EMDs;
- Control of EMDs;
- Design of EMDs.

Numerous excellent classic textbooks with the development of sophisticated theory have been written on each one of these aspects, e.g. [4]–[6]. However, many students in this digital age who are used to gather information via multimedia instead of blackboards may find the mathematical derivations in the books not appealing to them. More recent published textbooks or learning materials try to introduce theories in a more intuitive way by “digitalizing” the learning process. The effort includes, but are not limited to, posting online readers, adding online animations and incorporating computer simulations [7]–[13]. On the other hand, because of new applications including renewable energy and transportation electrification, EMDs are taught more often as components in larger systems, e.g. wind turbines or electric cars, instead of an individual subject. Examples include the two chart-topping MOOCs on electric vehicles delivered by Chalmers University and Delft University of Technology (TU Delft) [14], [15]. This trend should be considered by educators when designing EMD courses.

Being a traditional electrical engineering subject, practicals or laboratory sessions have always been essential parts of the learning process of the EMD education. In modern universities, students are often asked to do experiments on back-to-back setup based on commercial EMDs. Steady state characteristics and dynamic performance of different types of EMDs are measured in numerous laboratory sessions to validate the knowledge practised in classrooms. However, the instant interaction between the practical and the theory parts is somehow limited.

Remarkable work has been done to bring EMD practicals into online education. Concepts and practice of introducing remote and virtual laboratories into the education of power electronics, EMDs and other electrical engineering subjects have been continuously researched since the beginning of the 21st century [16]–[21]. Previous researches have focused on how to implement the remote laboratory setup using ICT facilities. However, there are limited discussions on interaction between lectures and online laboratories in these existing researches. How online laboratories contribute to online education or higher education and how to integrate them into

the existing EMD courses are not widely investigated.

This paper tries to compensate the gap by presenting the thoughts on applying online laboratory sessions in a existing EMD curriculum. Assignments are designed to link the theory learning with online practicals. A physical EMD setup, associated software and ICT platform to implement the assignments are presented. Then a practical example is used to show how an online laboratory session is used in teaching and how it is evaluated by students. The methods and platforms proposed in this paper can be used not only in general EMD subjects, but are also applicable in system oriented courses, e.g. emulation of electric vehicle power trains, which is appealing to wider online learners.

II. DESIGN OF ASSIGNMENTS

To keep students engaged in the active learning process, assignments based flipped classroom strategy is used in this paper to combine it with online laboratory sessions. Table I shows of an example course schedule for the Field Oriented Control (FoC) of Permanent Magnet Synchronous Machine (PMSM) designed based on this strategy. The schedule lasts for one week, and includes three interactive sessions and three assignments. One of the assignments is based on an online laboratory session. An interactive session is scheduled before each assignment.

TABLE I
EXAMPLE ASSIGNMENT BASED COURSE SCHEDULE: PMSM FoC.

Interactive Sessions	Assignments
Theory explanation: PMSM FoC	1. Digital modelling of PMSM and inverter; 2. Simulation of FoC and controller design/tuning.
1. Feedback on modelling and simulation results; 2. Explanation of hardware implementation.	1. Online laboratory session; 2. Reflecting on experimental results and report writing.
Results discussion and feedback	Review and reflection

A. Interactive Sessions

Interactive sessions are used to explain the theory and to give feedback to the students. On campus the interactive sessions can be held in lecture rooms or computer rooms if computing/simulation tools are needed. The teacher can interact with the students via a presentation, Q&A session and demonstration. The students can also interact with peers via discussions.

In the online platform, the interactive sessions can be a combination of recorded videos, students forum and online simulation tools. In order to make the explanations more interactive and to keep students engaged, interactive computing platforms can be used to present the mathematical derivations, the modeling process and the simulation results.

Figure 1 shows an example of interactive simulation of the direct online start-up of an induction machine based on the open source platform JupyterLab [22] and its MATLAB kernel [23]. Students are able to interact with the lecturer by

running MATLAB codes on the webpage and by submitting their assignment reports in form of an interactive practice. They are also able to practice and check their assignments on the webpage after the interactive sessions. Experience about this practice at TU Delft has shown that the interactive computing platform makes the teaching more efficient by speeding up the assignment checking, the self-study and the knowledge transfer.

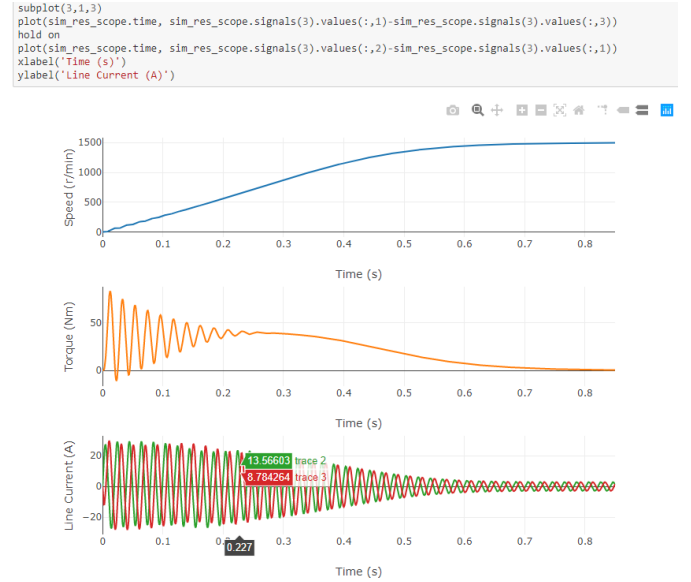


Fig. 1. Interactive modelling and results plotting in JupyterLab.

B. Assignments

The assignments should be designed in an incremental way to build up the knowledge framework and confidence of the students. A flow from theoretical analysis, computer modelling and simulation to laboratory experiments and results reflection are proposed. The effort of transforming the simulation models to the experimental setup should be minimized by checking the milestones after each assignment and by giving proper feedback in the interactive sessions.

In the particular example shown in Table I, milestones are set on the development of models, the tuning of controllers, and the ending of the laboratory sessions. Interactive sessions are interleaved in between to check the progress and to give instant feedback. The model-based design approach will be used for the modelling, simulation and deployment of the controller to the hardware.

III. ONLINE LABORATORY SETUP

To implement an online laboratory session, a setup to host the session is needed. Compared to a conventional educational setup, it requires not only a hardware setup, but also software and ICT platforms.

A. Hardware Setup

The hardware setup should meet the following requires:

- It should provide the flexibility of monitoring, measurements, and even the programming of control;
- It should be able to run safely in unattended mode;
- It should be able to post an alarm in case of emergency or catastrophic failure (component destruction, fire, smoke, etc.).

A back-to-back electrical machine setup can be used for the online laboratory sessions of the EMD. Because of their wide applications, an Induction Machine (IM) and a PMSM can be used, as the example shown in Figure 2. The two machines are coupled to each other mechanically via a coupling.

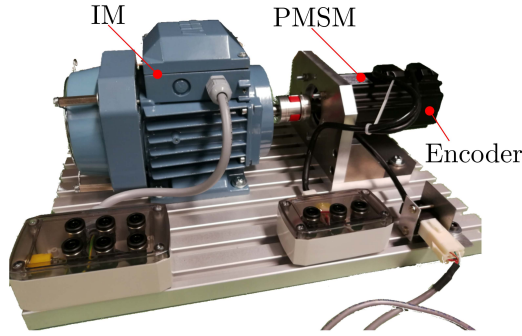


Fig. 2. Back-to-back IM and PMSM electrical machine setup.

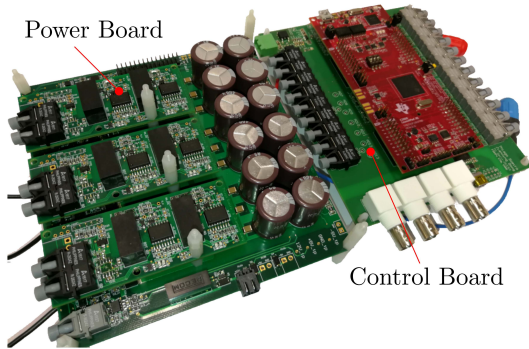


Fig. 3. Power, gate driver and control boards of the remote laboratory setup.

A power electronics converter can be used to drive either one of the two machines is designed. Figure 4 presents the main circuit schematics of the power electronics hardware. As it can be observed a conventional two level voltage source inverter is implemented. For the power semiconductors, three hard-parallel SMD packaged 900 V Silicon Carbide (SiC) MOSFETs are used per necessary active switch. This ensures operation with high power efficiency even at high operating switching frequencies. Additionally, only natural convection PCB mounted heat sinks are necessary for the thermal management of the devices junction temperatures. A 200 MHz dual core Micro Controller Unit (MCU) from Texas Instruments assembled in a LaunchPad development kit is used. A master PC can be used to control the operating modes programmed in the MCU through a USB communication link which is electrically isolated by a XDS100v2 debug probe.

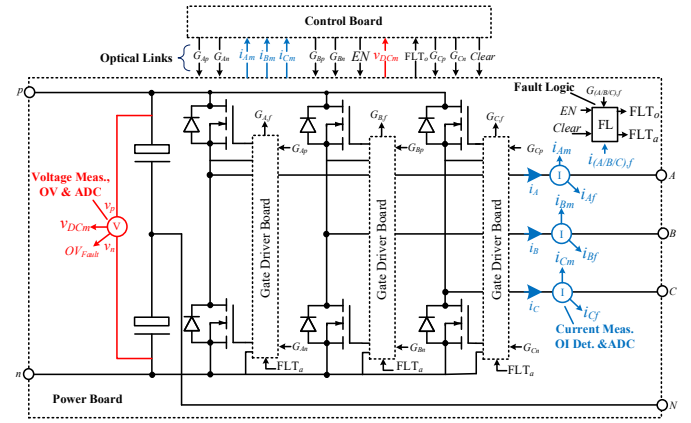


Fig. 4. Main circuit schematic of the traction inverter setup.

Additionally, to achieve a high Common-Mode Rejection Ratio (CMRR) and also for human safety reasons the control and the power boards are interconnected through optical fiber links. All the necessary Analog-to-Digital Conversions (ADC) of the inverter required measurements, namely the AC terminal currents and the DC terminal voltages, are performed in the power board using 10 MHz delta-sigma modulators. The measured data is transmitted to the available sigma-delta filter channels of the MCU through a 50Bmd fiber optic transmitter.

In order to avoid a catastrophic failure of the power converter, over-current and over-voltage protections are implemented in both, the hardware and the MCU software. In addition, each MOSFET gate driver employs fast DESAT (DC shoot-through can be interrupted in less than $2\mu s$), UVLO and Miller current clamping. A Fault Logic (FL) unit implementing D-type flip-flops and digital logic ports process each individual fault information, provide fault debug data (for easy problem identification) and execute hardware actions such as the necessary safe shutdown of the system. Additional safety measures can be added to the hardware setup, e.g. monitor the temperature of the motors and drives using thermometer or infrared webcam.

B. Software Platform

A flexible software platform should be used to interact to the hardware setup and to minimize the effort of the transition from the simulation assignment to the hardware deployment. MATLAB embedded coder can be used to achieve this. The controller can be designed and tuned based on the simulation models implemented in MATLAB/Simulink. The same model can be used for automatic code generation and programming of the MCU. The Environment Controller block can be used to switch the inputs between the simulated target and the MCU peripherals, as shown in Figure 5.

To interact with the controller running in the MCU, a graphic user interface (GUI) running on the PC is needed to minimize the number of parameters the students have to manipulate. For safety reasons, the interface also limits the

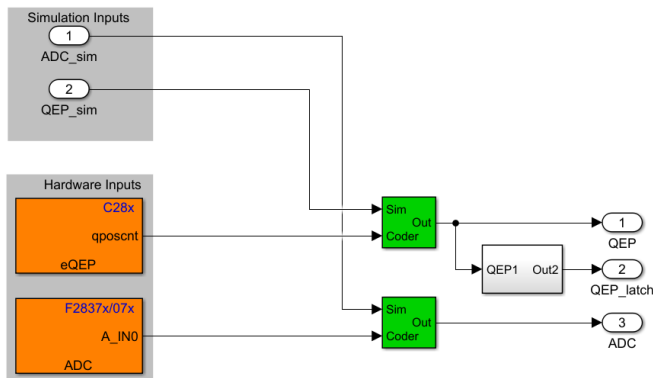


Fig. 5. Switch inputs between simulation and hardware.

value range the students can enter for each parameter. Similar feature of data range limits is also implemented in the MCU. To monitor variables with high dynamics, e.g. voltage/current waveforms, rotor position, noise and vibration, an oscilloscope with remote operation feature are recommended to be used. Non-measurable variables, e.g. current/flux linkage in dq or $\alpha\beta$ reference frames, can be sent to the oscilloscope via the digital-to-analog converter (DAC) ports included in the control board.

C. ICT Platform

The following requirements are defined for the ICT platform of the online laboratory:

- Students should be able to enrol the online laboratory sessions using the standard university enrolment system;
- Students should be able to access the online laboratory without installing any extra software.

To arrange the enrolment of the online laboratory a web based scheduling platform is developed. The lecturer imports a class list into this platform. The students could use the campus id login system to access the platform to schedule an available time slot.

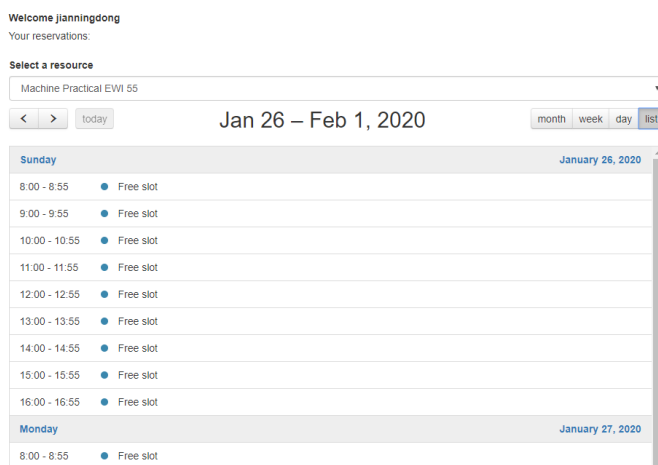


Fig. 6. Example scheduling system of the online laboratory.

A web browser can be a solution to prevent the need for students to install extra software packages to interact with the laboratory setup. A straightforward way is to run the GUI in a host PC interacting with the control board. The students access the PC via remote desktop. Remote desktop software such as Apache Guacamole [24] can be used to feed the remote desktop connection to the students via a browser.

IV. PRACTICAL EXAMPLE

A pilot online laboratory session was made and tested in the MSc course ET4291 Control of Electric Drives at TU Delft in the semester of 2018-2019. There were in total 12 students participating in the pilot. Each student was able to enrol for the 55 min time slots using their campus *id* via the remote lab web page. The learning objectives of the assignments are: after completing the assignment and laboratory session, the students should be able to

- Perform digital modelling and simulation of an electrical drive system;
- Tune the PI controller of an electrical drive system.
- Explain the differences between simulation and experiment by identifying the non-ideal factors/components in a real electrical drive system;
- Validate the electrical drive performance using steady state calculation;
- Model flux weakening control and implement it in simulation.

A. Implementation

The topic of the online laboratory session is “scalar control of an induction machine with speed feedback and slip compensation” [12]. Prior to the laboratory session, assignments on the design and implementation of the controller, modelling and simulation of the drive, and hardware deployment have been completed, checked and discussed in the interactive session.

The operation panel of the online laboratory session is shown in Figure 7. A webcam is used to monitor the physical setup. Two speed gauges are used to monitor the set speed and the measured speed, two knobs are used to set the reference speed and the reference flux linkage. Serial communication via USB is used to exchange information between the operation panel and the control board. A YOKOGAWA DLM2000 oscilloscope is used to measure the phase voltage of the IM and the modulation waveform. The YOKOGAWA Wire puller software is running next to the operation panel to control the physical oscilloscope and to monitor the main waveforms.

The operation panel is a GUI created in MATLAB App Designer. The operation panel and the oscilloscope interface are running on the same PC. At the enrolled time slot, the student logged in via the web page will be routed to the remote desktop of the PC. This will be able to interact with the controller and oscilloscope using its own mouse and keyboard.

In the online laboratory session, the students are asked to set three different reference speed, and to measure them. For each reference speed, they should measure the modulation and current waveforms under three different flux linkage settings.

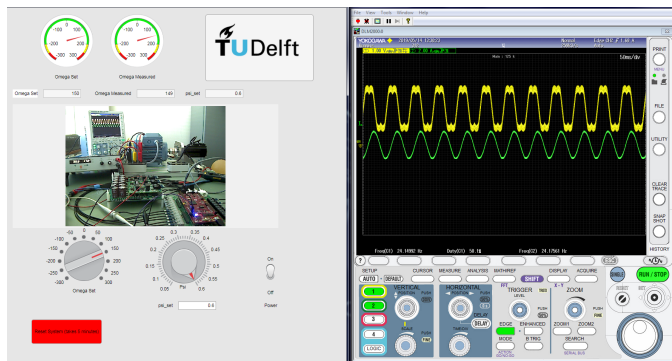


Fig. 7. Operation panel and oscilloscope interface of the online laboratory session.

After the online laboratory session, the students are asked to compare the results obtained with the measurements, the simulations, and the analytical modelling. Results and analysis are to be submitted in a practical report.

B. Results and Feedback

There were collected in total 12 reports from the students. Nine of the students were able to complete the laboratory session on the first try. The remaining students had to enrol to 2 or 3 time slots until they were able to complete the practical report. All the students were able to record the required data and to perform the comparisons among the experiment results, the analytically calculated steady state performance, and the simulation results. All the students were able to qualitatively explain the non ideal behaviours of the electrical drive using the dead band of the inverter, the non modelled losses in the simulation, the mismatch in the machine parameters or the thermal behaviour of the stator/rotor resistance.

Feedback on the course and the online laboratory session is also collected in the report. Most of the students gave an overall positive feedback and two students expected a more challenging laboratory assignment. Most negative feedback is on the non intuitive/physical operation of the setup and the low quality and delays of the video. Typical comments are quoted below:

“The remote lab was fun to do, I had plenty of time which give me the opportunity to play a bit more with the machine and it felt like that helped me understand the machine better.”

“The remote lab experience was the first time that I controlled something that was 2.5 km away from me. It must be continued, but with a clear ban of not pressing the AUTO button of the oscilloscope. Furthermore, some delays were noticed between the values I was setting on the board, and the response from the machine but they were not that important. Generally, a unique and interesting part of a course.”

“It would be helpful and useful if the students had the chance to see all the setup at the lab and understand how the controller, inverter and machine

are connected together and how they interact in practice.”

V. CONCLUSION

The paper presents how online laboratory sessions can be used for the education on electrical machines and drives. A methodology to design assignments is proposed to integrate online laboratory sessions in the active learning process. A practical example is used to show the effectiveness of the online laboratory session. The following conclusions can be drawn from the work presented in the paper:

- 1) The online laboratory is applicable to education of electrical machines and drives. It can be used in higher education on campus, and is also possible to be applied in online education;
- 2) Online laboratory can be scheduled with simulation assignments and interactive sessions to make the learning process active and effective;
- 3) The online laboratory can reduce the amount of supervision hours, which benefits the mass education;
- 4) Apart from the hardware setup, software and ICT platforms are essential to implement the online laboratory.

The application chosen in the paper is electrical machines and drives. However, the online laboratory sessions proposed in the paper and the methodology to implement it can also be applied in other electrical engineering practicals, e.g. power electronics and microgrids. At the moment when the authors are preparing for the final manuscript of this paper, the online platform also provides a solution to practical education and research during the COVID-19 pandemic.

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