E-laboratory in the Field of Electrical Drives

H.Hõimoja* A.Rosin* T.Möller* M.Müür*
* Tallinn University of Technology/Electrical Drives and Power Electronics, Tallinn, Estonia

***Abstract*—Modern information and communication technologies have changed the concept of conducting laboratory experiments and learning the theories behind them. New terms like "distant learning", "remote laboratories", "virtual learning environments" etc have emerged. To follow the mainstream and improve practical aspects of given education, the TUT has started designing its own remotely controlled electrical drives laboratories where students can make experiments on real objects. Designing a remote laboratory presumes finding solutions to problems regarding technical, didactic, security and financial requirements as well as the integration into a wider distant learning environment. These requirements give a basis for laboratory structures and methodology.**

Keywords—Education methodology, electrical drive, test bench, virtual instrument.

I. INTRODUCTION

Energy technologies remain essential regardless of currently prioritized sciences, therefore academic education and practice training in this field to produce qualified specialists is a must for modern society. A traditional university training course consists not only of lectures, but also of exercises, laboratory and industrial practice. The laboratories' primary task has been promoting specific skills and knowledge, at universities also scientific dimension is added, while further development of technology is unthinkable without experimental part.

Local laboratories have been the most common way of experimenting and relating theoretical knowledge to real objects. Unfortunately they possess some limitations related to fixed time and place as well as the number of experimentation sets and participating students. Empowered by information and communication technologies (ICT), the new approach is to conduct remote experiments at a distance from the actual experimental setup over the World Wide Web (WWW). Existing software and hardware needs to be adapted to suit tutors' and students' needs, the schedule should be more flexible and allow repetitions [1]. Remote learning features should be applicable both in academic and industrial context like in the form of complementary courses. Remote laboratories have been already utilized in several universities all over the world; the feedback has been mainly positive [1], [4]. Encouraged by different success stories, the TUT has decided to introduce its own electrical drives remote laboratory; the background and considerations are discussed in the next chapters of current paper.

II. PRESENT SITUATION

Existing electrical drives laboratory equipment at the TUT has been partly procured in 1950's - 1960's and therefore become obsolete. Laboratories carried out so far are in most cases outdated and do not correspond to the requirements of modern labor market. For example, the current experiments in general course of electrical drives comprise:

Taring the load machine

Here the DC motor no-load losses and relationship between armature current and torque are estimated.

DC motor characteristics

This experiment includes DC motor speed control with armature voltage regulation, series resistance in the armature circuit and field weakening. Electrical and mechanical values are measured or calculated and compared with theoretical ones.

Induction motor characteristics

Here the motor speed, voltages, currents and electrical power of a squirrel-cage induction motor are measured at different loads. Based on the results, speed, efficiency and power factor as a function of the load are represented graphically and compared with theoretical values.

Induction motor transients

Using an oscilloscope, induction motor speed and current transients starting from standstill are recorded and compared with theoretical graphs.

Getting acquainted with a frequency converter

Here the students learn to parameterize a frequency converter, test different acceleration-deceleration profiles and braking modes.

As seen, four of five laboratories described above are solely motor-based, though the motor is only a part of a drive system. Obviously, there should be more experiments regarding design and control, including sensors, power converters and controllers. These considerations were the main starting point when planning the renewal and upgrading laboratory experimentation sets.

III. CONSIDERATIONS WHILE UPGRADING ELECTRICAL DRIVES LABORATORIES

A. Objectives

First of all, main objectives while selecting new equipment must be defined:

1. Developing a remote laboratory to support learning and R&D activities in the electrical drives and power electronics disciplines.

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2. Increasing quality of teaching at the TUT and its colleges.
3. Complementary training for industry specialists.

Based upon those objectives, new ideas can be generated.

B. *Questions to be answered*

Different electrical drives courses are included in the curricula of two TUT departments:

- department of electrical drives and power electronics;
- department of mechatronics.

Remarkably, students having electric drives and power electronics as their main subject have previously undergone electrical machines' courses with corresponding laboratories, thus an unnecessary duplication might occur while laying more stress on a driven motor than the whole drive system, whereas mechatronics students have only basic knowledge of electrical circuits and electromechanics. Consequently, before undertaking next steps, one must find answers to following questions:

1. To whom is this project targeted?
2. What types of experimentation sets are needed?
3. What can be taught on these sets?
4. What experimentation sets are commercially available?
5. Is there any existing equipment that can be integrated into new installations?

As defined in objectives, the main target group consists of TUT's, its colleges' and institutes' students both in B.Sc., M.Sc. and PhD levels (0). Industry specialists can also participate in the courses; localized Web user interfaces enable involvement of foreign partner universities in the framework of student and knowledge exchange.

Following new demands, a state procurement to furnish the new drives laboratory was announced in June 2007. The aim was to provide courses with up-to-date laboratory benches with modern power conversion and control systems, at least three of the newly procured benches are planned to be connected to the Internet.

IV. AN OVERVIEW OF WEB-BASED LABORATORIES

A. *Virtual and remote laboratories*

One can distinguish between two basic types of Web-based laboratories:

- virtual laboratories;
- remote laboratories.

TABLE 1. REMOTE LABORATORY TARGET GROUPS

Target group	Trainees per year
TUT department of electrical drives and power electronics	120
TUT department of mechatronics	50
TUT Virumaa College	175
TUT Kuressaare College	30
TUT Institute of Sustainable Technology	20
Estonian industry	25
Total	420

A good example of a virtual laboratory is *MatLab*'s embedded Web server, developed by *MathWorks* which enables simulations to be carried out remotely using a Web browser. Distant Web-based *MatLab* experiments have already been implemented at some universities [2]; unfortunately the software producer has discontinued this product. Wolfram Research company has its own *webMathematica* software package, which enables online calculations and visualizations of previously defined processes, where the user can check the outcome by different input values. Well-known *MathCAD* software has also its own remote Web interface [3]. Simulations are undoubtedly the cheapest and safest way to model the processes in existing systems, including electrical drives. There is no physical threat to laboratory equipment like overloads, short circuits, etc.

As the students must have real world experiences, the virtual labs based solely on simulations are less than a half of a solution. While arranging multiple experiments is expensive and even impossible in full scale, a more advanced way is to conduct real experiments in laboratory, which are remotely controlled and monitored by students using standard Web tools. The provision of remotely controlled experiments accessible over the internet or university intranet can potentially address the issue of access to practical exercises in a number of ways [4]:

- By giving access to experiments over a longer time frame and at times preferred by students.
- By sharing expensive resources between institutions.
- In giving access to safety critical and expensive equipment with reduced risk.
- By offering improved access for disabled students.
- By facilitating greater access to experimental work in distance education.

Usually the Web-based laboratories are a combination of both basic types, where the outcomes from real experiments can be compared to simulation results.

B. *Application areas*

The increasing popularization of distance learning as well as the availability to as many students as possible is the main reason for adoption of remote laboratories. Four application areas have been pointed out [1]:

1. Shared remote laboratories can be established to access a single expensive or rare experimentation set that is only available at a distant university.
2. Localized remote laboratories allow to carry out experiments according a more flexible schedule and place or to repeat a missed laboratory session.
3. Distant remote laboratories are mainly used in distant education to replace difficult to attend classroom experiments.
4. Technical review laboratories allow industry specialists to test new products without attending traditional workshops and seminars.

C. *Requirements*

The design of a properly functioning remote laboratory assumes fulfilling a set of requirements. These demands are mostly derived from practical experience and divided into four main categories [5]:

1. Technical requirements state the local equipment to be maintenance-free during the remote experiment. The installation should support full real-time feedback regarding control commands.
2. Security requirements pose demands mainly on the software. The installation must be protected against wrong commands, exceeding allowable limit values and network attacks.
3. Didactical requirements define student-tutor interactions. Every student's results and solutions must be recorded for evaluation purposes, the files and folders must be private, their access controlled by means of individual username and password.
4. Financial requirements above all state the end user software to be as common and license-free as possible, in this respect the usual Web browser is a perfect solution. Locally applied software and control apparatus should also be commercially available and cost-efficient.

All these demands cannot be satisfied simultaneously, so some compromises must be made excepting security. For example, communication over HTTP is not as fast as over TCP/IP, but the latter has some access problems regarding software and ports disabled by firewall.

V. Remote Laboratory Structures

There are several approaches to the definition of a remote laboratory; one of the most generalized architectures can be described as consisting of core components [5], [6]: HMI, physical process, applications, didactical content and client software with user interface (Fig. 1).

HMI is the central element communicating with all other components, driving the signals and allowing students to perform various experiments. Usually it is an interface program running on a server computer.

Physical process can be any remotely controlled physical device or process, including also data acquisition and control functionalities.

Applications mean the tools and services for human communication, collaboration, production, etc. They deal

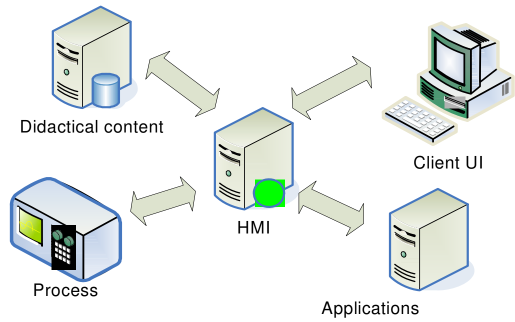

Fig. 1. Core components of a remote laboratory

with the communication between the laboratory and students. The didactical content consists of the textual, audio, video or animated instructions and exercises.

A. *The four dimensions*

Whatever an approach to a remote laboratory structure might be, one can describe it four-dimensionally [7]:

1. Remote manipulation dimension includes necessary functionalities between controlled object and HMI to remotely manipulate the system under research.
2. Didactic dimension corresponds to the educational viewpoint, regarding teaching methodology.
3. Communication dimension deals with the interaction between laboratory counterparts, including students, tutors and administrators.
4. Administration dimension features schedule management, access control and site maintenance.

B. *Methodical structure*

Carrying out a set of remote laboratory experiments, each experiment can be roughly divided into eight parts with approximate durations (Fig. 2):

1. Methodical preparation - up to 1 hour
2. Registration and authentication - up to 15 minutes
3. Theoretical preparation - 2 hours
4. Local activities and experiments - 2 hours
5. Preparation assessment - up to 30 minutes
6. Remote experiments - up to 3 hours
7. Final report - up to 1 hour
8. Final assessment - up to 30 minutes

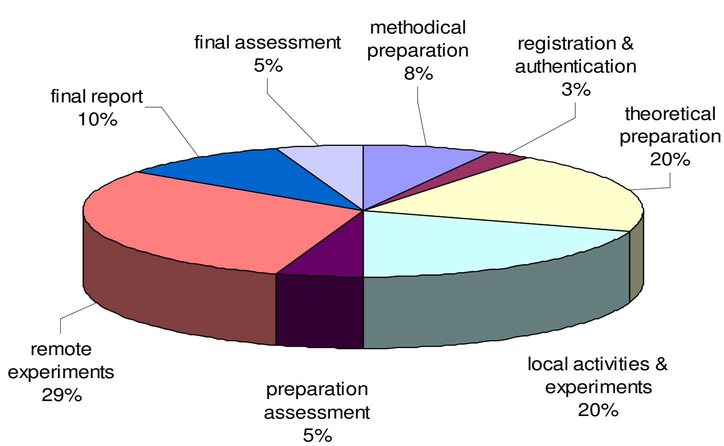

Fig. 2. Methodical structure

So the overall maximum duration of an experiment will be about 10 hours, 80% of which shall be done over the Internet.

C. *Hardware and software structures*

To guarantee fast and effective maintenance, the hardware components should be as simple and available as possible [8]. The Web-enabled PLC used in designed remote laboratory environment has data acquisition interface, allowing it to be connected to an experimentation set's (Fig. 3):

1) voltage, current and movement sensors;
2) actuators in the form of converters;
3) measuring instruments.

The PLC can communicate with control objects over Ethernet or using digital and analogue I/Os. A visual image of the installation is obtained via a webcam set.

Some data monitoring and plotting can also be realized over frequency converter's or soft starter's remote HMI, where IP addresses and other network parameters can be specified, the HMI is also used for local control, monitoring and parameterization, like defining IP addresses. Simulation and other auxiliary programs are stored in an application server, the SQL server houses various databases and processes queries. Firewall router protects the installation from outer intrusions. To conduct a remote experiment, the user needs to perform following steps [9]:

1. Connecting the webpage of the remote laboratory.
2. Authorization and registration.
3. Selecting the desired and available experiment.
4. Displaying corresponding Web pages.
5. Conducting a remote experiment.
6. Terminating the session with logout.

Local configurations at the laboratory site are carried out using manufacturer's own application software, like HMI parameterization and PLC programming. All laboratories are planned to have Web-based instructions, which can be linked to interactive calculation and simulation programs hosted inside an application server and assembled in Java or other programming environment.

VI. Planned Experiments

The e-lab project includes seven experimentation sets, all these enable local experimentation and remote preparatory learning. Sets with remote control and monitoring are marked in the list below with italics:

1. Self-commutated converter.
2. Frequency converter drive with asynchronous motor.
3. Servo drive.
4. Stepper motor drive.
5. *Frequency converter with vector control.*
6. *Soft starter.*
7. *Torque control bench.*

Covered topics are explained in the next subchapters.

A. *Self-commutated converter*

IGBT fundamentals.
Control principles: PWM, DC chopper controller in 1-, 2- and 4-quadrant operation.
Low-frequency AC voltage PWM.
Circuits: step-down controller, H-bridge, inverter.
Resistive, capacitive and inductive loads.
Suppressor, link and free-wheeling circuits.
Control characteristics and operating graphs.
Computer-assisted measurements.
Fourier analysis of harmonics.

B. *Frequency converter drive with asynchronous motor*

Fundamentals of inverters with voltage and frequency control.
Analysis of U/f ratios.
Stator resistance compensation.
Characteristics of the inverter-fed drive.
Computer-assisted parameter setting and animation.

C. *Servo drive*

Computer-aided commissioning and parameter setting of a linear axis servo drive.
Positioning and sequence control.
Setting parameters of the position and speed controller using industrial software.
Investigating the effects of various controller settings.

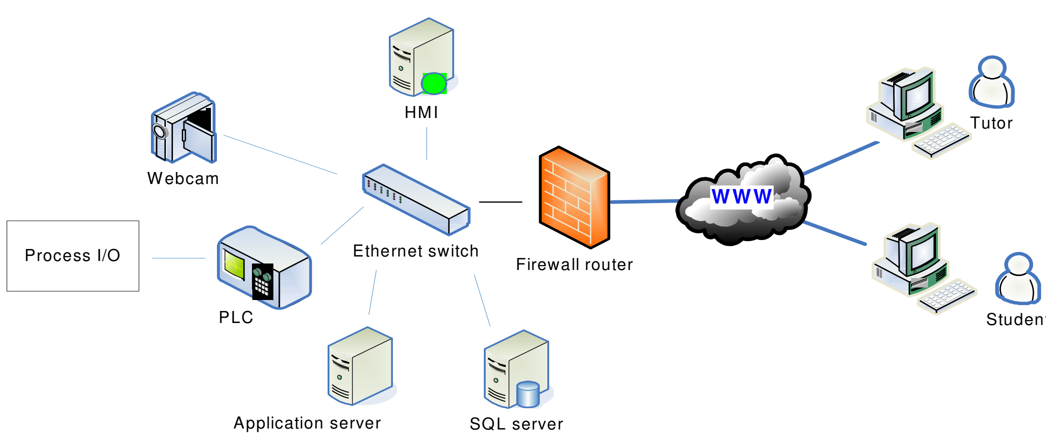

Fig. 3. Hardware structure

D. Stepper motor drive

Stepper motor fundamentals.
Introduction to CNC programming.
Speed and position control.
Influence of different acceleration-deceleration ramps.

E. Soft starter

1) Investigation of acceleration-deceleration ramps.
2) Soft start with current limitation.
3) DC dynamic braking features.
4) Voltage, current and speed transients.

The *Altistart 48* soft starter is controlled via PLC's digital outputs and monitored by analogue and digital inputs by means of voltage and current measuring transducers. The settings are viewed and changed over Modbus RTU protocol. For speed acquisition, a tachogenerator has been installed. In Fig. 5 starting curves of a 4 kW asynchronous drive are depicted with following settings:

1) acceleration time $t_{acc} = 2.0$ s,
2) applied torque $T_L = 0.25\ T_N$.
3) no torque boost.

F. Frequency converter with vector control

Comparison of acceleration and deceleration profiles.
Speed, current and torque transients.
Differences between scalar frequency and flux vector control.
Behavior in constant torque and weakened field regions.
Different braking modes: freewheel, ramp stop and dynamic DC braking.

The frequency converter test bench comprises two similar converter-fed 0.75 kW asynchronous drives with mechanically linked shafts, whilst one drive acts as the working machine and the other as load in generating quadrant. The load is controlled with resistive torque reference, which can be made dependent on drive's speed using a PLC subroutine. This way several load characteristics can be simulated. The DC links are connected together to enable reuse of generated energy by the drive in motoring quadrant.

In Fig. 6, the remotely obtained results of an acceleration-deceleration experiment with following parameters are shown:

1) acceleration time $t_{acc} = 2.0$ s,
2) deceleration time $t_{dec} = 2.0$ s,
3) ramp type: S-spline,
4) applied torque $T_L = 0.7\ T_N$.

G. Torque control

Load sharing.
Frequency converter's behavior in master and slave modes.
DC bus sharing.
Driving multiple motors in parallel.

The laboratory stand consists of three *Altivar 71* frequency converters, which are connected to common DC bus and three asynchronous motors with their shafts mechanically linked by pulleys' transmission belt. Remote control and monitoring is similar to vector controlled frequency converter's experimentation set.

The three last test benches can be switched between local and remote control modes. The start of a remote experiment is signaled at the site audibly and visually by a buzzer and strobe driven by PLC's digital outputs.

VII. Data Processing

The SQL server saves time-based values in real time on its storage media. These values can be later downloaded by the user in HTML (Hypertext Markup Language), CSV (Comma Separated Values) or XLS formats to be later handled, especially in Excel worksheets, like shown in Fig. 5 and Fig. 6. After composing the graphs demanded in the task, the trainee sends them to tutor for assessment. During the experiment, a nearly real-time graph is running in the user window for feedback purposes only.

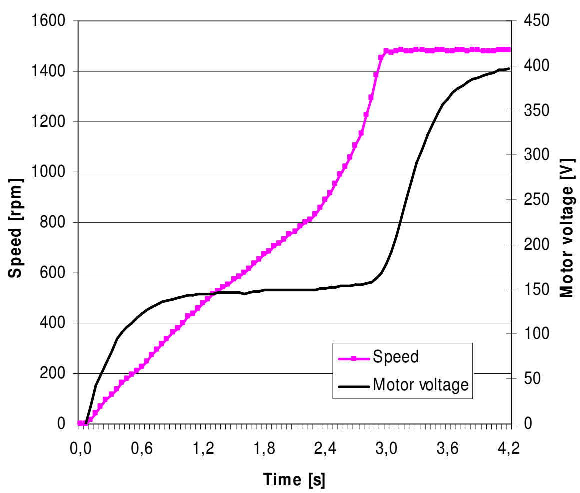

Fig 5. Remotely obtained soft starter curves

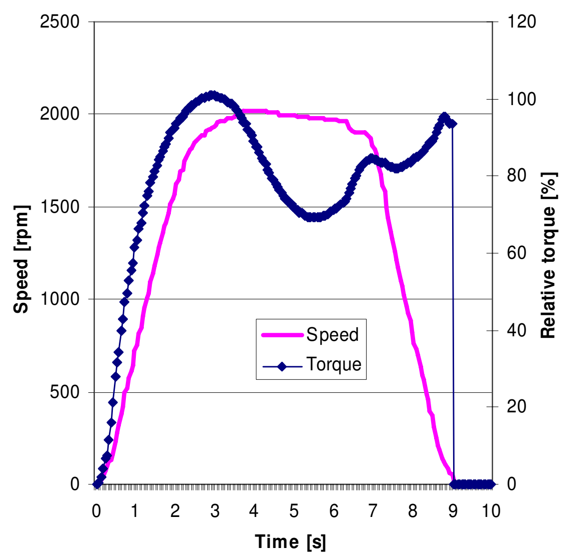

Fig. 6. Remotely obtained frequency converter's speed diagram

VIII. Experienced Problems and Obstacles

Obviously, one could expect a laboratory test bench to cover a possibly wider amount of experiments. These experiments must be safely conducted without permanent local supervision and eliminate any serious human error. As test benches' PLCs are freely programmable, new experiments may be flexibly added to the exercise lists. As for every ambitious project, there have emerged certain major and minor obstacles, described below:

1. Hardware problems are mainly related to I/O scanning capabilities. The data refresh rate is important while recording transients and other short duration processes, however the Modbus protocol used for communication between the master PLC and frequency converter allows the fastest rate of 50 ms. Besides control hardware, the controlled load still remains the issue to be solved. There are thoughts of variable pitch or choked fans.
2. Software obstacles, confusing the end user, are caused by the behavior of Java applets to run correctly only on the Internet Explorer browser. A really user-friendly user environment must be OS and browser-independent.
3. Network constraints mainly consist of bandwidth and security issues. The user expects the system to react and respond without a remarkable time lag, caused by bottlenecks between the installation and the student. Security solutions must protect the installation against unauthorized access and hacking.

IX. Conclusion

Present experiences have shown that the best way to explain theory is not by difficult formulas, but hands-on experiments. Modern tendencies are towards reducing the number of lectures in favor of exercise and laboratory classes, where the students can fix existing and obtain new knowledge through practical results of their personal work. Empowered by increasing broadband Internet connections and software platforms development, many laboratory and exercise classes can be carried out remotely, where theoretical background can be delivered and assessment given by automated program applets.

Present tendency at the TUT implementing e-studies in laboratories has shown that expenditure of time in Web-based courses has paid off. Animated diagrams and exercises help to understand functional principles, so the students are better prepared for real experiments. Thanks to more flexible schedule the working students do not interrupt their courses so easily as before. So it might be summarized that implementing e-labs as a part of e-studies has become inevitable due to increasing amount of extramural and complementary courses as well as the fact that 60% of students must share their time between studies and daily work.

To enhance efficiency, remote laboratories must be integrated into bigger managed learning environments. Laboratory control applets must have links to methodical and theoretical materials, facilitating understanding of performed experiments. In longer terms, the remote laboratories can contribute to [10]:

1) easier understanding the performance of electric, electronic, electro-mechanical and control circuits;
2) by understanding physical phenomena in circuits developing analytical thinking without learning a set of difficult formulas;
3) developing engineering skills through circuit synthesis.

As described, the TUT plans only to conduct remote experiments on AC induction drives. Although these constitute the majority of all drives, remote research of other motor drives, like DC, synchronous or SRM must also not be neglected. In this case, co-operation with our foreign partner universities to mutually utilize the remote laboratory resources would be a solution.

The designed remote laboratory will be fully launched in autumn 2008. Another important part besides machinery, hardware and software installations would be final choice of remote laboratory exercises, preparation of dedicated methodology, composing interactive learning materials and sharing gained experiences with other interested academic and industrial counterparts.

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