ISSN 2683-345X
journal homepage: http://ijiemjournal.uns.ac.rs/

International Journal of Industrial Engineering and Management

2025 / ARTICLE-IN-PRESS / 380

Original research article

Multi-Functional Test Benches for Electric Drive Instructional Laboratories

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ABSTRACT

Laboratory based hands-on classes are essential in electrical engineering education. The market available laboratory equipment for basic training courses in the field of electric drives and automation features mainly low power range. Lack of installations with industry standard rated power components in order of several kilowatts predestined collaboration between Moscow Power Engineering Institute and ABB Russia. As a result, a joint instructional laboratory of electric drives was designed for training both students and industry partners. It allows to safely conduct experiments with DC, synchronous and induction machines of 5.5 kW installed power with a variety of corresponding sensors, power converters, programmable logic controllers, relays and protection devices. This paper deals with design aspects of such a laboratory and illustrates the available functionality for experiment conduction and the corresponding results visualization. The flexibility of the laboratory equipment enables to train various aspects of real mid-power range hardware operation within several disciplines hosting approximately 300 students yearly.

ARTICLE INFO

Article history:

Received January 7, 2024
Revised October 29, 2024
Accepted January 23, 2025
Published online March 28, 2025

Keywords:
Engineering education;
Educational technology;
Electrical engineering;
Electric drive;
Motor;
Control system

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1. Introduction

Modern electric drives enable to increase efficiency in a vast variety of industry applications. By 2030 the electric drive market is expected to exceed 200 billion USD from 121.81 billion in 2021 [1]. There is a special demand for mid-power range electric drive power systems (1 – 37 kW) sharing about 75% of the entire world market [2]. Moreover, the extensive control abilities over electric drives fit well the IoT concept further increasing the demand for specialists in the electric drive field.

Laboratory based hands-on classes are essential in electrical engineering education providing the trainees with practical skills required for professional activity in the industry [3]. The core of practical activity comprises series of controlled assignments usually

Published by the University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia.

https://doi.org/10.24867/IJIEM-380

referred to as laboratory works where students conduct experiments under academic staff supervision [4]. Primary, the laboratory works are designed to help students to underpin the theoretical knowledge obtained from lectures, tutorials, and self-studies. Another objective of students' practical activities in the laboratory environment is the improvement of their project management skills including experiment planning and preparation, defining appropriate methods and means to prove the theoretical provisions or practical approaches, as well as teamwork.

The study of electrical machines, power electronic converters, and drives requires practical demonstration. During the hands-on classes the students are expected to demonstrate the ability to build an experimental setup, collect instrumentation readings, and analyze the operational behavior of the laboratory equipment including electrical machines, power electronic converters, control systems (relays, PLCs, industrial network communication), various sensors. This requires the laboratory equipment to be highly flexible to support students' active learning using performance observation and practicing in the interaction with the equipment and instruments.

In the first instance, the flexible laboratory equipment has to offer a large variety of hardware configurations providing an arrangement of a particular test setup according to the engineering curriculum. On the other hand, the increased flexibility when operating the mid-power range systems imposes additional safety requirements to protect not only the students, but also the equipment itself – in the event of mistakes and errors that a trainee can make.

Many education equipment manufacturers offer quite a wide range of electrical engineering test workstations for instructional laboratories including electrical machines and drives [5]. The main drawbacks of the offered equipment are high cost, specific design, and low-rated power. For example, the rated power of electrical machines and drives produced by Lucas-Nulle [6] and Leybold and Feedback [7] for laboratory investigations is 300 W for educational/test purposes and 1 kW to represent the industrial installations. Obviously, such a low-power rating is related to the demanding health and safety requirements and procedures applied to the educational workshops. Though low-power equipment is easy to manufacture and install in a laboratory environment, it is not fully appropriate for practical learning to achieve the educational goal. The performance of low-power electrical machines and drives is very different in comparison to the higher-power machine class typically installed in industrial applications due to the very different parameter ratio. Also, the difference in power consumption for demonstrative experiments such as direct online starting, soft starting, and frequency converter induction motor starting is insignificant for low-power machinery, whereas the difference for real, more powerful industrial equipment can be 10 times more.

Following the demand for laboratory equipment having higher rated power and to reflect the specific industry needs, several papers [8]–[11] suggested and discussed various test rigs for learning and research purposes. The papers mentioned above mainly deal with the development and design of test benches for the investigation of electric vehicle systems. The testing equipment reported in [8] is based on a DC motor and designed for the study of an electric wheel control system. The report provides the specification of the test equipment and details of the hardware implementation. The test bench proposed by Rassolkin et al. [9] implemented a control system for two motor drives with ABB ACS800 frequency converters designed for electric vehicles. The paper presents the structure of the test bench and analyses the power performance of the hardware. Prior research explored the concept of laboratory to investigate an innovative control system electric traction system [10]. The setup in Electrical Actuators Laboratory at the Technical University of Munich consists of an induction motor and PMSM controlled using MATLAB software [11]. The paper also discusses the improvement of the student knowledge through both the practical approach and the laboratory equipment commissioning. Prior research investigated the synchronous generator control system in the micro-grid concept for investigating the electric machines and drives [12]. This equipment is mainly used by academic staff as a demonstration test bench. However, it is designed to provide a possibility for several students to explore the machinery operation. Previous study explored the development of the test bench for investigation of power electronics, grids, and drives [13]. However, it shows limited flexibility in the reconfiguration of the circuit for tests. Therefore, all the above discussed papers suggest laboratory equipment designed for specific purposes and do not provide the option of practical activities for a large number of students.

The master students' test benches used in the course of "Control Systems of Electric Drives" in the Moscow Power Engineering Institute were considered in [14]. This equipment was designed according to high safety standards and allows composing many control strategies using freely configurable elements inside the control system of specially designed frequency converters. The equipment is very specific and not suitable for bachelor students as it offers enhanced allowance in tuning the control.

Lack of installations with industry standard rated power components in order of several kW predestined collaboration between the Moscow Power Engineering Institute and ABB Russia in building flexible and safe mid power range laboratory benches with maximal rated power 5.5kW suitable for installation in the university considering the load on bearing structure of the building. The cooperation of industry and university helps to fulfil both educational demand and introduce best industrial equipment to the students [15]. As a result, an instructional laboratory was developed, which is considered in this paper.

In the next section the main design aspects of the test benches are considered, the component selection, the design solutions, features and working principles are substantiated. Then a description of some special experiments possible to be carried out on the equipment is given and the educational results are discussed.

The mid-power range electric drive power systems laboratory with industry-standard control, measuring and even cable mounting features complying the additional safety requirements described in the paper provides the master students and industry partners with a powerful tool for enhanced experiment flexibility expediting their qualification growth.

2. Design Considerations of the Test Benches

The test benches at the laboratory of electric drives should comply with the following requirements:

- a set of electrical machines of 4 different types commonly used in industry. The power rating should be in between 1 and 37 kW;
- the rated power rating of electrical machines is limited by the permissible load to the floors of the building (not more than 100 kg per motor);
- implement features to the reduce the power grid load;
- the electrical machines should be supplied from various types of power sources including modern power electronic converters to demonstrate different operation modes;
- the student should be able to compose the schematics of experimental setup and connecting devices in any possible way;
- the equipment should be protected from short-circuiting that student can make accidentally;
- the safety should be at the highest level making the electrical shock probability nearly zero.

These requirements were the basis for selecting the components of the benches and for design concept.

2.1 Selecting Electrical Machines

The most common electrical machine used in industry is a Squirrel Cage Induction Motor (SCIM). It can be start up directly from the grid without any power electronics for the simplest case. Its version with wound rotor (WRIM) was very popular before the wide spread of frequency converters. Nowadays these motors are used in high-power applications with non-regulated drives requiring high start-up torque. Moreover, the wound rotor allows to explain the rotor resistance variation impact on the speed-torque curve of the motor. High-performance industrial drives are based on Permanent Magnet Synchronous Motors (PMSM), which can operate under Field-Oriented Control (FOC) or Direct Torque Control (DTC) being fed from frequency converters. And Direct Current Electrical Machines (DCM) are rarely used in new industrial projects. However, they are very well suited for the explanation of the electromechanical energy conversion principle. This set of electrical machines was selected for the test bench implementation.

The rated power of the motors was selected to be 5.5 kW. The weight of each motor is below 100 kg and the construction of two coupled electrical machines can be fit into the standard 1.8-meter side-lying cabinet. The pair of motors should be supplemented by a torque sensor and a tahogenerator. Signals from both devices are to be connected to a computer-based oscilloscope.

The design of the test bench should allow to investigate electric drives based on any of the four electrical machines in the system. For this reason, the four types of drives are paired. When one electric drive is being investigated, the other one operates as a load and vice versa.

After analysis of the best candidates the direct current motor type CD2007P-2 was selected. It has rated speed of 1750 rpm which does not fit the standard speeds of induction machines in Russia because of using 50 Hz grid frequency. Therefore, it was decided to couple DCM with PMSM type BSM100C-6250 having rated rotational speed of 2400 rpm at 600 V in the DC-link of the frequency converter. Its peak output torque and power thrice higher than rated one of the DCM. Higher rated speed of the PMSM in its turn allows to explore field-weakening mode of DCM. The PMSM has a resolver which is used for control and its signals are available for students as well with a help of the computer oscilloscope. This side of the testbench is so-called DC-side due to presence of the DCM.

Another side of the test bench contains coupled induction motors. Rated speed of 1000 rpm was selected because it is the maximum speed for wound rotor induction motors currently manufactured in Russia. The SCIM type M3AA132MC was chosen. It can operate in both 690 and 400 V networks, which allows to investigate its speed-torque curve in wide range when feeding machine with lower voltage. The tahogenerator and the torque sensor are installed as well. The SCIM is equipped with an incremental encoder and its signals are available for students with a help of the computer oscilloscope. This side of the test bench is so-called the AC-side because the AC electrical machines are under investigation.

The assembly of the test bench is shown in Figure 1. Two 1.8-meter cabinets are side-lying with the motors inside. The frontal doors of these cabinets have windows protected by glass, and the operation of the machines can be observed directly. All power supply, power electronic converters, measuring, and control equipment are placed into smaller vertical cabinets for DC- and AC-sides respectively, and attached on top of the cabinets with machines. Countertops are organized to allow students making records, placing wires and tools for assembling circuits, and so on.

Totally laboratory is equipped with three test benches having DC and AC sides. So, six teams of the students can conduct experiments simultaneously. Normally the team consists of 4 students sharing different responsibilities: managing experiments, assembling the circuits, controlling the drives, acquiring data using the oscilloscope, processing the results, and so on.

2.2 Mutual Loading of Machines

Each electrical machine of the test benches can act like a motor under test or a load. To ensure the possibility of load over the entire speed range, the full set of possible speed-torque curves under supply parameter variations should be considered.

2.2.1 DCM and PMSM

The DC-side contains PMSM and DCM. The DCM can be regulated as follows:

- variation of the supply voltage;
- variation of the armature resistance;
- variation of the flux (field weakening).

Figure 1. Photo of the test bench. The side with DCM and PMSM is shown. From left to right cabinets with: relays, PLC and touchscreen, sensors and computer oscilloscope, DCM with DCS800, indicators and assembly box, PMSM and ASC800.

Any combination of these parameter variations is inefficient and cannot be recommended for use in practice. Figure 2 shows the operation area of PMSM and a set of speed-torque curves of the DCM. The DCM is CD2007P-2 which parameters and speed-torque curves can be found in [18]. The PMSM is BSM100C-6250 which parameters and speed-torque curves can be found in [19]. The set of speed-torque curves of the DCM, including rated parameters' curve, curve in a field-weakening mode, curve for voltage regulation, and curve for additional resistors in the armature winding [20], lies inside the operational area of PMSM, which should be controlled by a frequency converter using DTC method. This means that it is possible to examine the behavior of the DCM in any operation mode. On other hand, being supplied from a controlled rectifier the DCM can load PMSM in some limited area. Due to the fact that speed-torque curves of PMSM under DTC are artificial, the properties of DTC can be studied by limiting its parameters such as maximum torque and speed and applying load with the DCM of smaller power.

2.2.2 SCIM and WRIM

The induction machines have a similar number of options to regulate their performance. They are variation of supply voltage, variation of frequency with simultaneous change of supply voltage, and variation of resistance in the rotor windings. From industry applications the following operation conditions are well-known:

- direct start and operation from the grid;
- direct start of the WRIM with resistors in the rotor windings;
- soft-start of SCIM and operation from the grid;
- operation of SCIM from soft-starter at low loads;
- dynamic braking of induction motor (any type);
- operation from frequency converter under v/f-constant control or DTC;
- WRIM operates as a DC-excited synchronous motor;
- WRIM operates as a doubly fed induction motor.

Second, fifth, and seventh cases require the use of WRIM as the motor under test. In these cases, the SCIM is fed from the frequency converter under DTC and can serve as a load. It can operate as a speed or a torque source in all 4 quadrants. Eighth case has limited implementation. It requires use of frequency converter to feed the rotor windings. But as the frequency converter is used for a drive, then SCIM can operate as a load only in the braking mode being supplied with direct current. In this operational mode it has huge losses in the rotor, that's why bachelor students are not allowed performing this experiment. In other cases, use of WRIM as a load is

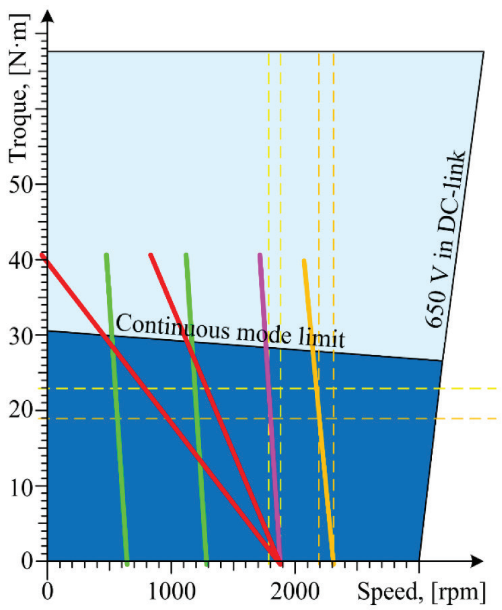


Figure 2. Operating region of PMSM (generator mode) and a set of speed-torque curves of DCM (driving mode): dark blue–area of continuous operation of the PMSM; light blue–area of short-term operation mode of the PMSM; magenta–rated speed-torque curve of the DCM; orange–speed-torque curve in the field weakening mode; red–set of speed-torque curves with additional resistance in the armature winding; lime–set of speed-torque curves for various armature voltages.

required. For that purpose, the WRIM can be used in a braking mode supplied from DC source with additional resistors in the rotor windings. The set of its mirrored speed-torque curves is shown in Figure 3. Being fed from the regulated current source the maximum braking torque can be adjusted. The critical slip can be varied by adding resistors into rotor winding. Thus, the entire speed and torque range can be covered.

2.3 Selecting Power Electronic Converters. DC-side.

The controlled rectifier is an industrial standard for adjustable speed DC drives. ABB Company has DCS800 converters containing a bipolar bidirectional 3-phase bridge rectifier for an armature winding and an unipolar and unidirectional 3-phase bridge rectifier for a field winding. The control system can operate in closed-loop or open-loop modes and supports field-weakening operation. The simplified circuit diagram of DCS800-S2 is shown in Figure 4. It contains a line filter with fuses and two bridge rectifiers.

In order to explain classical control methods for DCM such as direct online starting with current limiting by means of resistors in the armature winding, the 240 V DC voltage source is implemented as well. It is made of a transformer, controlled bridge rectifier, and LC-filter. It is assembled in the power supply cabinet and common for all test benches in the laboratory. The current limit is set to 100 A allowing to perform any kind of experiments at three test benches simultaneously.

The use of DC voltage supply for the DCM allows not only to explain the speed-torque curves with resistor in the armature winding, but the efficiency of this type of drive compared to the drive with controlled rectifier and energy consumption during starting. Due to simplicity of the DCM the evaluation of useful power and losses can be done easily. While the WRIM has the same principle of regulation and starting its analysis is more complex because of cost when 3-phase current and voltage waveforms should be considered. Unlike the efficiency of the DCM which can be visually evaluated in any operational point and during starting from the waveforms of voltage, current, and speed.

The PMSM can be controlled only from a frequency converter with DTC or FOC. ABB Company is supporting DTC, and due to the fact, that driving and regenerative modes of both drives are to be investigated the regenerative frequency converter ACS800 was selected. Its simplified circuit diagram is shown in Figure 5. It contains an input line LCL-filter and two inverters: one operates with the grid and another feeds the motor.

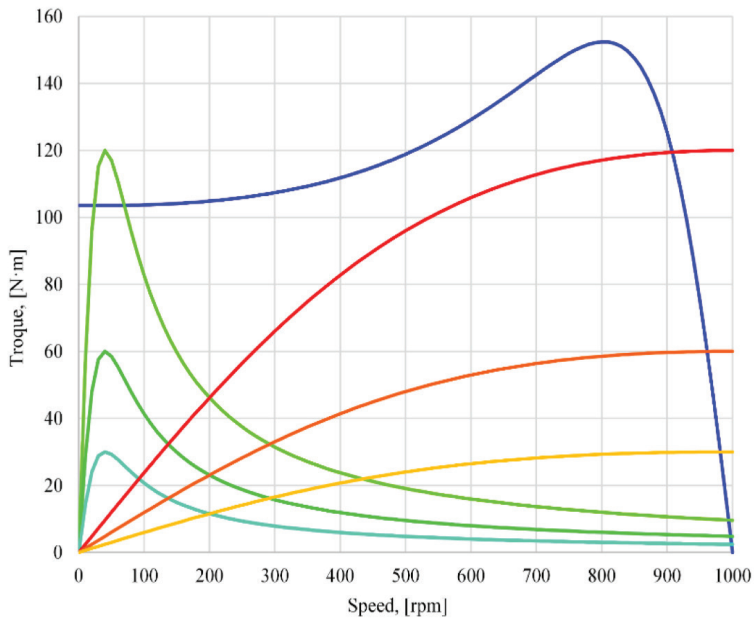


Figure 3. WRIM is loading SCIM in braking mode: blue–rated speed-torque curve of the SCIM under test; red to orange–mirrored speed-torque curves of WRIM with additional resistors in the rotor windings with different excitation currents flowing in the stator winding; lime to cyan–mirrored speed-torque curves of WRIM without additional resistors in the rotor windings with different excitation currents flowing in the stator winding.

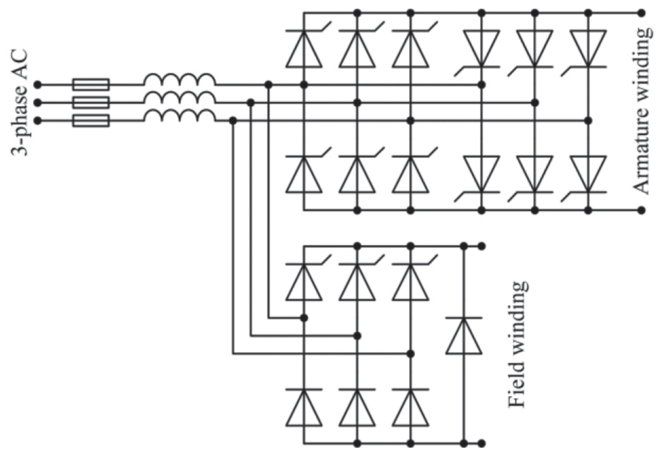


Figure 4. Simplified circuit diagram of DCS800-S2

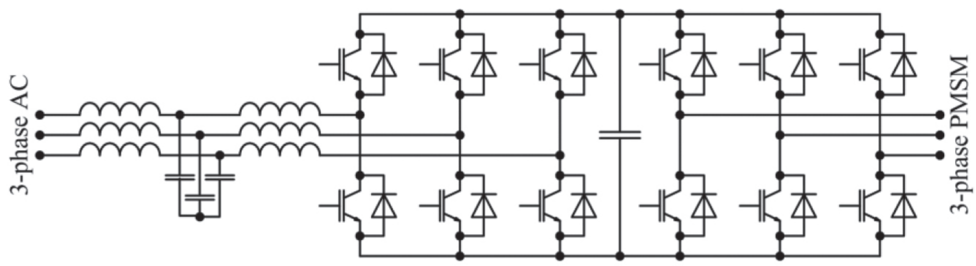


Figure 5. Simplified circuit diagram of ACS800

2.4 Selecting Power Electronic Converters. AC-side.

At the AC-side an ACS880 was chosen to drive the SCIM. It is conventional frequency converter with a diode bridge rectifier and a braking chopper. A DCS800-S1 containing only single unipolar unidirectional controlled rectifier was chosen to excite the WRIM in the braking mode. And a soft-starter PST30-600-70 was selected for the experiments with voltage regulation of the SCIM.

The measurement system is presented with measuring devices, which are used to control the experiment, and a computer digital oscilloscope, which writes the processes in the test bench for postprocessing. The first set of devices is ammeters and voltmeters, which indicate voltages, currents, torque from the torque sensor, and speed from the tahogenerator. The classic mechanical versions with dial indicators were selected. The use of the dial indicators helps to understand the limits of the measured value and its deviation in time during the experiment. Their indication is more intuitive for students than the representation given by digital ammeters and voltmeters.

The test bench has a power meter ANR96, which can measure active, reactive, and apparent powers, cosφ, make an FFT analysis of the supply voltage and consumed current. It has an LCD display and can indicate digits, vector diagrams, FFT, and waveforms of the measured signals.

The test bench has the closed-loop Hall-effect current sensors, current transformers, and voltage sensors. Their primary circuits are available for commutation by the students and secondary circuits are connected to the digital computer oscilloscope. These sensors are configured for measurement in a 3-phase network.

The computer digital oscilloscope is made of analog-to-digital converter having PCI interface and installed into computer. It has 16 channels of 12-bit ADC able to measure up to 400 000 samples per second for one channel. For *N*-channels the maximum rate is decreased *N* times. This sampling rate is high enough to measure pulse-width modulation in the output voltage of the frequency converter. The lists of the signals, which are connected to the oscilloscopes, at the DC-side and the AC-side are presented in Table 1 and Table 2 respectively.

Table 1. The connections of the signals at the DC-side

№	Signal name	№	Signal name
1	Temperature of the PMSM winding	9	Torque sensor signal
2	Temperature of the DCM winding	10	Speed from the tachogenerator
3	Analogue output of ACS800	11	Signal from the current transformer in phase A
4	Analogue output of DCS800-S2	12	Signal from the voltage sensor between B and C
5	CANL signal of the CAN network	13	Signal from the voltage sensor between A and B
6	CANH signal of the CAN network	14	Signal from the current sensor in phase A
7	Sine signal of the resolver	15	Signal from the current sensor in phase B
8	Cosine signal of the resolver	16	Signal from the current sensor in phase C

Table 2. The connections of the signals at the AC-side

№	Signal name	№	Signal name
1	Temperature of the SCIM winding	9	Torque sensor signal
2	Analogue output of ACS880	10	Speed from the tachogenerator
3	Analogue output of PST30-600-70	11	Signal from the current transformer in phase A
4	Analogue output of DCS800-S1	12	Signal from the voltage sensor between B and C
5	CANL signal of the CAN network	13	Signal from the voltage sensor between A and B
6	CANH signal of the CAN network	14	Signal from the current sensor in phase A
7	A signal of the incremental encoder	15	Signal from the current sensor in phase B
8	B signal of the incremental encoder	16	Signal from the current sensor in phase C

2.5 Circuit Assembling Principles and Safety Issues

The main principle of the test bench organization is that all the considered equipment is available for interconnection. Students can connect it in any possible way like it is usually done inside the cabinets of low voltage equipment. Figure 6a shows the photo of the assembly box at the DC-side.

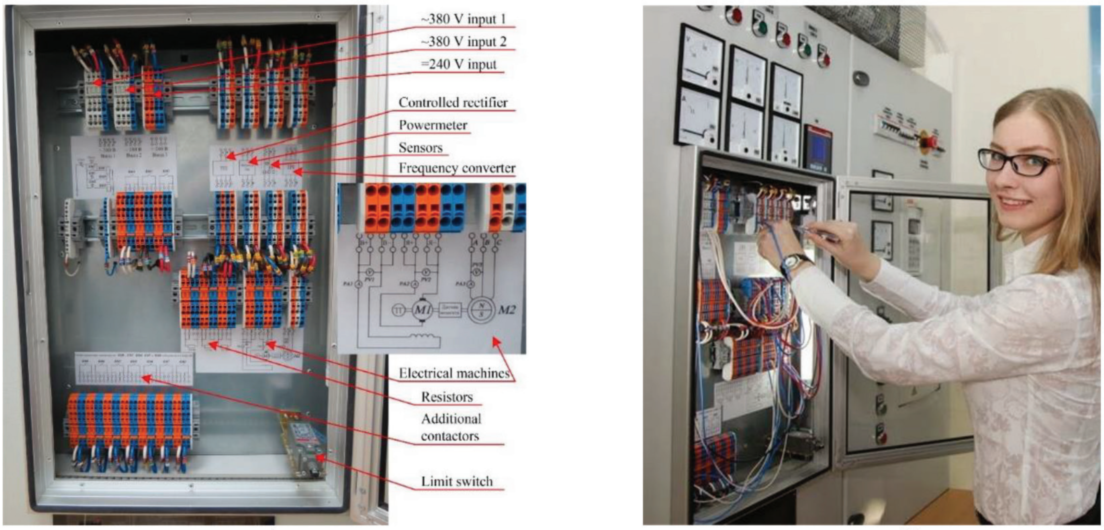
Connection to each terminal of the motor, power converter, or any other device is made using spring pluggable terminals with 3 connection points. Three connection points were selected because in this case it is possible to assemble any topology of the target circuit. Students are using terminated wires with cross-section of 4 or 6 mm^2 to connect the circuit for their experiment. Spring contacts are served with a flat screwdriver. The collection of the circuit is shown in Figure 6b, which is similar to the way it is done in industry and gives student an important skill.

The assembly box has a door, which should be closed after the circuit is collected and the experiment is going to be performed. Its position is controlled by the limit switch, which affects the protection circuit of the testbench. If power supply is switched on when the door is opened, then the protection switches off the power and raise an alarm attracting supervisor of the laboratory. This way the most important safety feature is implemented, and the contact of the student with the wires is prevented.

When students are assembling the circuit for their experiment, they can do mistakes including short circuiting. Short circuits are normally protected by circuit breakers and rarely harm the equipment. However, there is one fault that had occurred several times over last 25 years while students use frequency converters. It is confusion between input and output of the frequency converter when connecting motor and grid.

This mistake is caused by an equal number of connections: three at the input and three at the output. By feeding the frequency converter to its output the inrush current is charging DC-link capacitor and is not limited. As a result, inverter blows up.

To overcome this problem protection was suggested which diagram is shown in Figure 7. The output of the frequency converter is detached from connectors reachable by students with contactor switches. The power supply to the contactor's coil is connected to the inputs of the frequency converter. Thus, if the power supply is accidentally connected to the output of the frequency converter it remains disconnected



a) b)

Figure 6. Assembly box at the DC-side – a); Assembling electrical circuit for experiment – b)

by the contactor switches. If the supply is connected correctly, the contactor switches go to the conducting state and do not affect the operation of the frequency converter.

The presented topology was implemented in every instructional test benches at the department of Electric Drives MPEI and helps to avoid the malfunction of the frequency converters for more than 15 years.

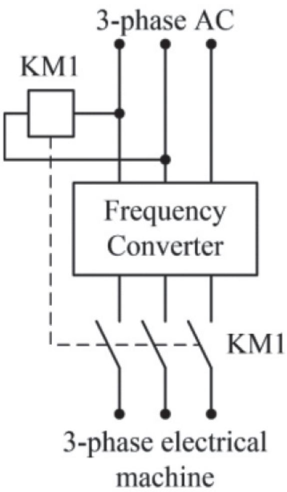


Figure 7. Frequency converter protection from connecting its outputs to the power mains

3. Performing Experiments

Students obtain several tasks to carry out during the semester. These tasks depend on their specialization and the subject taught. Students gather into small teams of 2-4 persons and prepare their experiments. They should picture the schematics for the experiment, write down the sequence of the experiment, and explain the expected experimental results. Two tasks for the DC-side of the testbench will be considered here.

3.1 Examining Direct On Line Starting

3.1.1 Task

Perform the following actions:

- perform the direct on line starting of the DCM using timing relay circuit for resistor shunting in the armature winding;
- tune the timing relays to make approximately equal peak current when resistors are shunting;
- evaluate the energy consumed by the drive from the grid and obtained kinetic energy of the motor.

3.1.2 Electric Circuit Designing and Assembling

The field winding of the DCM can be connected directly to the DC voltage source as there is no need to adjust flux. Moreover, the motor should be excited upon startup as depicted in Figure 8a.

The on line starting of the DCM requires utilization of the current limiting resistors. They can be shunted by contactors governed from the timing relays during acceleration of the drive. The assembly box contains connectors to the preassembled circuit of contactors equipped with timing relays which should be fed by the AC power supply. The circuit can be turned on by pressing SB1 button and KM1

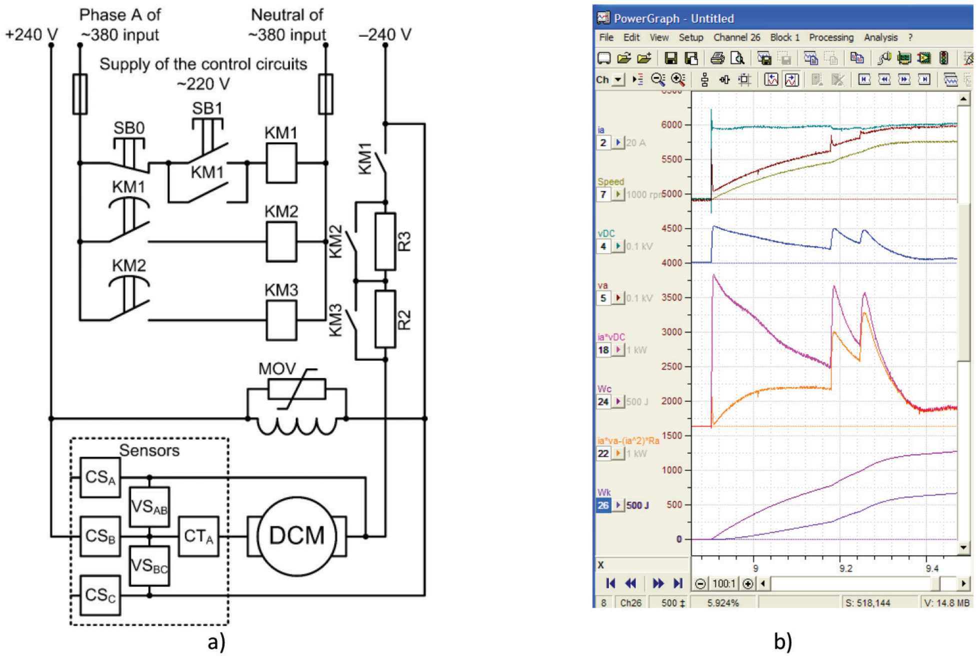


Figure 8. Direct on line starting of the DCM a – Electrical circuit: CSA, CSB, CSC are the current sensors, VSAB and VSBC are the voltage sensors and CTA is the current transformer. b – trnansients observed.

will be closed. The KM2 and KM3 contactors are closing by the command of the timing relays, which can be adjusted. This circuit is commutating the armature winding of the DCM which includes two serial resistors. These resistors will be shunt by the contactors during starting.

The measurement of all required variables can be done by a “Sensors” block, which contains three current sensors, two voltage sensors, and a current transformer. One voltage sensor is connected to measure the DC voltage supply, another one measures the armature voltage. The armature current is measured as well.

According to the task it is needed to estimate the consumed energy during starting and the kinetic energy that the motor obtained. The first one can be evaluated using:

$$W_c = \int_0^{T_s} i_a v_{DC} \, \mathrm{d}t, \tag{1}$$

where i_a is the measured armature current, v_{DC} is the measured supply voltage, T_s is the time of acceleration to the rated speed.

The kinetic energy can be estimated through the energy delivered to the motor with respect to the one lost in the armature winding as:

$$W_k = \int_0^{T_s} \left(i_a v_a - i_a^2 R_a \right) \mathrm{d}t, \tag{2}$$

where v_a is the measured armature voltage and R_a is the expected armature resistance. These calculations can be done using data from the digital oscilloscope implementing numerical integration methods or by composing functions for postprocessing the results in the oscilloscope software.

3.1.3 Experimental Results

The experimental results for the direct online start of the DCM with the current limiting resistors are shown in Figure 8b. Eight channels of a digital oscilloscope depict the processes in the electric drive. Four of them are taken from the sensors and four of them are calculated from the measured ones.

The tuning process of the timing relay can be justified by the oscillogram of the current transient (blue curve in Figure 8b). It can be seen that the current peaks are approximately equal. The motor speed, supply voltage, and armature voltage are measured as well. Their scales are shown in the left part of the figure in units per division. The main scale of the plot is shown for the selected unit—kinetic energy.

The measured values are used to calculate (1) and (2). At first the integrands are to be evaluated forming channels 18 ($i_a v_{DC}$) and 22 $\left(i_a v_a - i_a^2 R_a \right)$. Then these curves are integrated into consumed and kinetic energies, which are depicted by channels 24 and 26 respectively and represented in joules. All these calculations are performed by means of computer software and can be configured by the students.

The obtained results showed that one half of the consumed energy during direct online start is wasted into losses. Equation (2) does not take into account load torque, which is small but still exists. That's why the kinetic energy continues growing after acceleration is finished. Students can estimate the load torque and make the correction to the kinetic energy equation in order to obtain more accurate result.

3.2 Examining Operation of the DCM fed from the Controlled Rectifier

3.2.1 Task

Perform the following actions:

- design the circuit for investigation of the direct current motor drive fed from the controlled rectifier under rated load;
- examine the grid current waveform and the total harmonic distortion in the grid current under different speeds and loads;
- the armature voltage and current should be compared with the ones from the grid.

3.2.2 Composing and Collecting the Circuit for Experimental Setup

The DCM is fed from the controlled rectifier connected to the grid. The experimental setup measures the grid current consumed by the drive using the current sensor C. The waveform of the motor current and voltage can be measured using current sensor B and voltage sensor AB. The connection is shown in Figure 9. The load of the DCM is performed by the PMSM fed from the regenerative frequency converter.

3.2.3 Experimental Results

The first part of the experiments should show the dependence of the grid current harmonic composition from the load. The controlled rectifier is well-known for its poor total harmonic distortion (THD) in the consumed currents. The experiments are conducted under idle load and 1000 rpm and under load of 10 A in the armature winding. The load was provided by the PMSM fed from the bidirectional frequency converter. The current waveforms and their fast Fourier transforms are shown in Figure 10. It is clearly visible that the rectifier consumes current with a large amount of higher harmonics. The bigger is the load, the smaller are higher harmonics with respect to the fundamental one.

After that analysis of the armature voltage and current can be done. Their oscillograms are depicted in Figure 11. The speed reference was set to 1000 rpm. The left plot corresponds to idle load and the right plot is given for 10 A of the armature current. In both cases the DCM is operating with a discontinuous armature current. It has a tendency to become continuous with the growth of the load. At 1000 rpm controlled rectifier works with the high commutation angles due to relatively small back-EMF of the DCM. Thus, the armature voltage is changing a lot during conducting mode. When the armature current is zero the armature voltage is equal to back-EMF, which is purely visible in Figure 11a.

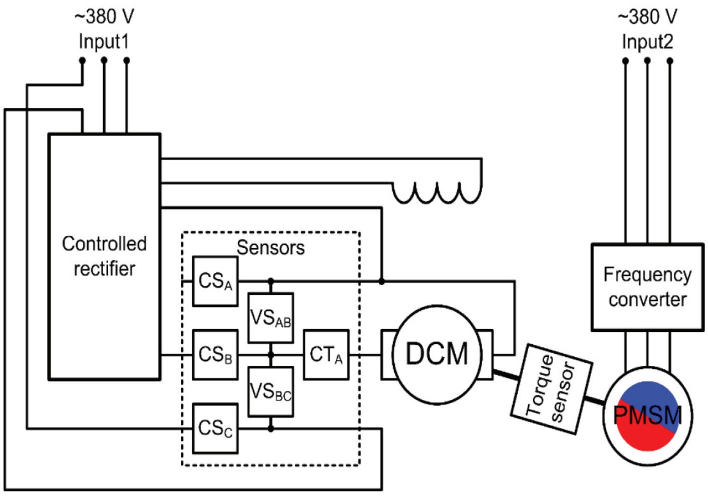
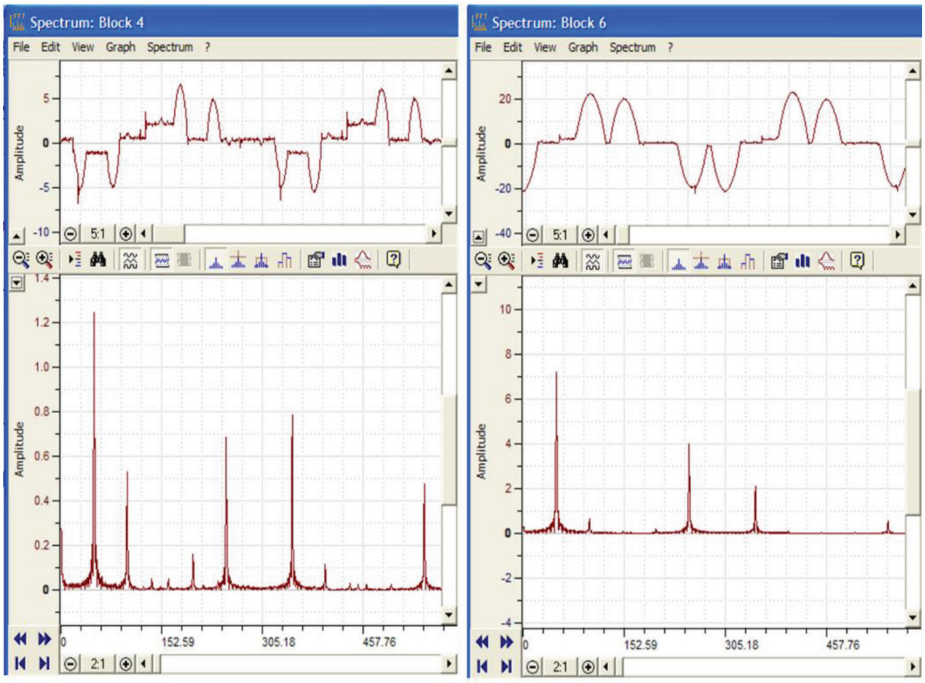
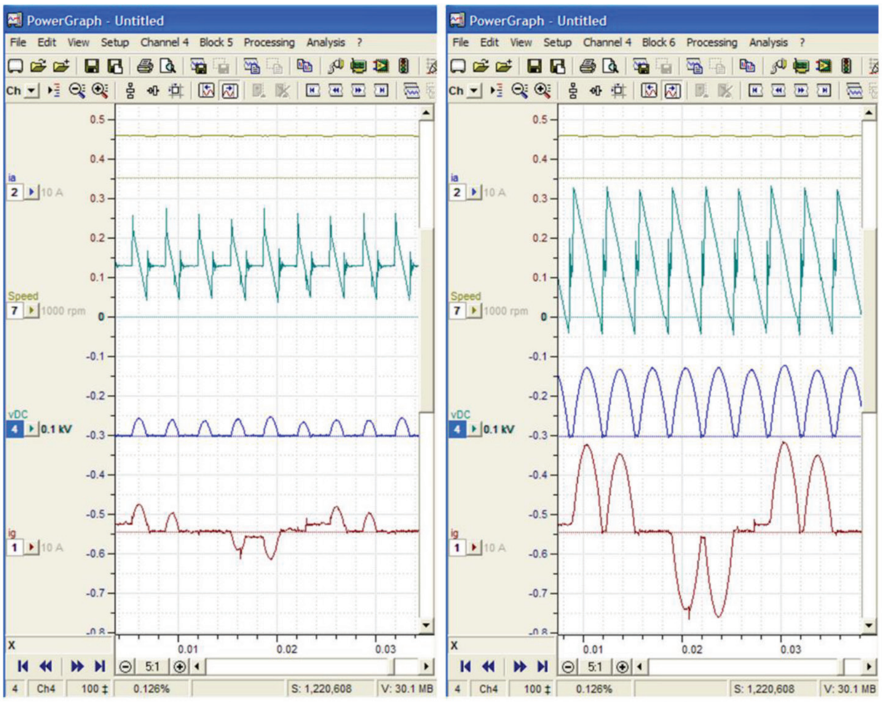


Figure 9. Circuit for experiment with DCM fed from a controlled rectifier



a) b)

Figure 10. Input current of the controlled rectifier: a—at 500 rpm, no load; b—at 1000 rpm, 10 A load



a) b)

Figure 11. Operation of the DCM fed from controlled rectifier. From top to bottom: speed, armature voltage, armature current, grid current: a—idle mode at 1000 rpm; b—10 A load at 1000 rpm.

4. Operation Experience

The new test benches were put into operation in 2014 replacing the legacy ones developed in 2005. These old test benches were an improved version of the ones used 25 years before. This section provides an analysis of the difference in operation and educational process for both solutions. The previous version of the test benches has a 1.9 kW DC motor and 1.4 kW WRIM. The induction motor can be fed from a frequency converter. The direct current motor can be fed from the DC grid of 110 V and from an LC-resonant current source. A two-channel digital oscilloscope is available. The circuits for experiments should be assembled using wires with socket connectors.

4.1 Reliability and Safety of the Equipment

Approximately 4200 students passed through this lab from 2005 to 2020. The ABB laboratory accepted only 1600 students from 2014 to 2022. However, the great improvement in reliability and safety can be evaluated even with a three-times smaller representation.

Each student conducted at least seven 4-hour classes doing experiments for approximately 4 hours per course.

The first issue was with the use of the wires with socket connectors. These wires were used to assemble circuits at the top panels of the test benches. As they are accessible by the hands of the students, double-layer insulation was used. However, this couldn't fully protect the students in case of mechanical wear of the wires and their destruction when assembling or during operation. They were detected 134 damages of the wires during inspections and assembling the circuits and 6 damages during operation. The damages during the operation were caused by the melting and burning of the wires due to the flowing current when the part of the conductors of the stranded wire was mechanically broken. These damages during the operation were the most dangerous because the student could accidentally touch the conductor. Several damages to the sockets on the top panels occurred as well.

The new test benches of the ABB joint laboratory utilize terminated stranded wires for assembling the circuit. This solution showed much higher reliability with 4 mechanical damages of the wire terminals and zero failures of the spring pluggable terminals.

For the last 8 years only 2 malfunctions of the dial indicators and 3 malfunctions of the circuit breaker occurred, which were replaced by technician. All other equipment works properly without need of maintains.

5. Education Results

5.1 Motivation of the Students and Quality of Education

Previous test benches allowed students to perform seven unique experiments common for all the specialties of the electrical engineering faculty. The new test benches have approximately 5 times bigger number of equipment units making it possible bigger variety of experiments to be conducted. These variations were adapted to the specialty of the bachelor student. For example, the students of the electrical apparatus and machines department have the topics of their laboratory works dedicated to the features of circuit breakers, contactors, and machines in the electric drives. The students of the electrical supply department are focused on the power quality and

Table 3. Variation of the Topics for Investigation

№ of work	For the students of Electrical Apparatus Machines department	For the students of Electrical Supply department
1	Investigation and measurement of the speed-torque curve of induction motor	Investigation of the induction motor power factor and efficiency under idle and rated load
2	Speed regulation of the direct current motor using controlled rectifier	Harmonic analysis of the grid feeding controlled rectifier
3	Analysis of the residual current circuit breaker operation for fire prevention with induction motor	Analysis of the inrush current during the direct online start of the induction motor
4	Contactors and timing relays for starting of the direct current motor from DC source via resistors	Exploring direct current measurement using different types of current sensors
5	Investigation of the speed-torque curves of the induction motor fed from the frequency converter	Investigation of the grid voltage and currents in driving and generating modes of regenerative frequency converter
6	Energy consumption when starting the direct current motor using resistors or controlled rectifier	
7	Energy consumption and grid current analysis when starting the induction motor using soft-starter	

how the drives are affecting the grid. The examples of the individual program are presented in Table 3 (only two of them are shown). Only a few laboratory works are conducted with a similar topic, whereas others are dedicated to the specialty of the student being taught. Such targeting of the tasks motivates students because they are doing experiments that are useful for them in the scope of their future specialty.

The presence of various experiments to be conducted helped to renew the tasks and to adjust them yearly with some variations. This limits cheating among students as the drafts are not relevant for the next year and are not transferred between specialties of the same year anymore.

Of course, the motivation of the students was also improved due to the quality and novelty of the equipment. The instructors from other departments have noticed that many of the students improved their skills in designing the electrical cabinets during their future subjects and projects. This occurred due to the organization of the circuit assembling in the laboratory, which principles are similar to the ones used in industry.

5.2 Quality of Education

Graduates were surveyed through the end study period to monitor the quality of the educational process. The results of the survey are presented in Table 4. The main questions were about the feelings of students about involvement in the discipline (it was correlated with attendance), obtained theoretical knowledge applicability in practice at the University, and usefulness of the knowledge gained in the industry. The main parameter which was dominated in this survey is the percentage of employed alumni in the electric drive industry.

A wide percentage of alumni employed in the industry is due to the development of the region's manufactory. Practice on real test benches in the University with a power of several kilowatts helps alums easily adapt to working with real equipment in the industry.

6. Conclusion

The practical investigation of electric drives and other electrical equipment is the important part of electrical engineering education. Most of the instructional test benches presented on the market have disadvantages such as small power and low flexibility. The designed test benches considered in this paper, allow the students to compose experiment connecting equipment in any possible way using industrial standard spring pluggable terminals. The 5.5 kW electrical machines and frequency converters were used, which are closer to the ones commonly used in industry. Proposed test benches have a set of protections, satisfy high safety standards, and provide students powerful measuring system with dial indicators and computer oscilloscope. The documentation for the test benches (schematics, bill of materials, assembling instructions, design considerations and student's guide) in Russian is available at [16].

This instructional laboratory hosts approximately 300 students a year mainly devoted to the bachelor course “Basics of electric drives” and some other

Table 4. Survey of Students

Years	Involvement (attendance)	Obtained theoretical knowledge applicability in practice	The usefulness of the knowledge gained in industry employment	Employed alumni in the electric drive industry
2014	70 %	82 %	97 %	93 %
2015	73 %	83 %	98 %	93.4 %
2016	73 %	81 %	98 %	95 %
2017	76 %	82 %	99 %	96 %
2018	84 %	83 %	98 %	98.2 %
2019	86 %	81 %	99 %	98.7 %
2020	50 %, Covid-19 time	n/a only simulation models in MATLAB	97 %	97 %
2021	70 %, Covid-19 time	n/a only simulation models in MATLAB	98 %	98 %
2022	92 %	81 %	99 %	99 %
2023	98 %	92 %	99 %	99 %

specific courses. The safety and reliability of the test benches were significantly improved compared to the old solution. The variety of tasks and use of novel electrical equipment improved the motivation of students as well.

After pandemic of COVID-19 it was decided to adapt these test benches for remote control providing ability of conducting experiments via Internet connection. The real equipment giving the students a lot of degrees of freedom for experiments, is hardly replaceable with virtual hardware as done in [17]. The solution to the remote access implementation will be discussed in the future papers.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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