

APPLICATION OF INDUSTRIAL FREQUENCY CONVERTERS FOR PROJECT-ORIENTED EDUCATION OF CONTROLLED ELECTRICAL DRIVES

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Abstract: In the perspective of current trends in engineering education, aiming at meeting industry requirements, especially in the field of power electronics and motion control, the article presents a way of teaching electric drive control in undergraduate engineering programmes using experimental setups with AC motors equipped with industrial frequency converters. The setups consist of two motors: induction and PMSM (each one can act as a motor or a load machine) and a number of other elements necessary in contemporary drive systems: speed sensors, temperature sensors and braking resistors. While using such setups students can learn about various issues related to AC motor control, both in terms of scalar and field-oriented control methods in all three drive operating modes: torque, velocity and position control. The laboratory setups allow students to familiarize themselves with such detailed issues as: vector control without a speed sensor, various ways of voltage control in a DC input circuit of the voltage inverter during motor braking or the influence of the type and value of load torque on drive system operation. Classes can have a classical form or they can be taught in the open-laboratory system.

Keywords: *education, controlled electrical drives, ac motors, control algorithms, designing*

1. INTRODUCTION

The properties of AC motors allowed them to dominate most of industry branches [1]. This is particularly due to the fact that as a result of growing requirements of the society, resulting from increasingly higher living standards, it became necessary to take into consideration the decreasing fossil fuel deposits and the need to generate power from renewable energy sources and save conventionally generated power by its high-performance processing in drive systems used in various industrial and municipal equipment.

As a result of the necessity to ensure the operation of electric drives with fluent speed changes, they have to be fed by frequency converters. The increasing popularity of AC

motor drives means that for many years there have been a continuous need for engineers with power electronics and motion control (PEMC) qualifications. This is why the issue of engineering education related to controlled electrical drives in such courses as Control Engineering and Robotics, Electrical Engineering and Mechatronics has gained significantly in importance.

In the last two decades, some important changes in engineering education have occurred resulting from the implementation of standardisation in Europe (Bologna process) [2–4]. In consequence, a need arose to concentrate specialist education addressed to undergraduate studies (Bachelor of Engineering Degree), graduate studies (Master Degree) and postgraduate studies (doctoral studies – PhD).

PEMC qualifications related education, similarly to many other engineering specialisations, are difficult to obtain within undergraduate studies due to necessity of getting acquainted students with the fundamentals of higher mathematics, physics, chemistry, social and humanistic sciences as well as courses in the major area of study. The time which can be devoted to specialisations in Poland becomes very limited in the course of 3 or 3.5 year engineering study. PEMC encompasses a few disciplines, such as electronics (analogue and digital), power electronics, electromechanical power conversion and control theory. Employers expect that an engineer specialised in PEMC would know the fundamentals of the design of analogue and digital systems, power electronic system control and digital signal processing as required by drive systems [2, 3]. However, the variety of systems and topologies on the one hand, and the limited time frame on the other, lead to a number of problems in passing specialist knowledge at appropriate level to students as well as making it impossible to teach them everything. In consequence, it is necessary to define the scope of indispensable knowledge to be taught very carefully, the same applies to the process of transferring this knowledge to students.

In the case of engineering specialisations, laboratory classes play an especially important role as they provide not only a practical demonstration of the issues discussed during lectures, but also allow students to familiarize with technologies specific to a given specialisation (discipline) as well as control and measurement apparatus. It is essential that didactic laboratories are supplied with the latest technology equipment which will also be used by students in their future industrial practice [3–9]. It is a well-known fact that laboratory equipment and its continuous updating requires high expenditures and, hence there is a natural trend to replace classical laboratories based on hardware with computer laboratories in which various types of simulation software is used in the educational process [10]. Moreover in many cases, the large-scale nature of engineering education leads to significant difficulties related to the access to classical laboratory classes and, in consequence, the idea of open-laboratory [2] or remote learning [8, 9] has been introduced. Apart from this, for many years there has been an ongoing discussion on the strategy of practical education – whether it is better to take a problem-oriented or project-oriented education approach [2].

This article presents a concept of using industrial frequency converters in teaching electrical drive control, in particular to undergraduate students as well as the introduction of the project-oriented learning and the „quasi-open laboratory concept”, on the example of the Controlled Electrical Drives Laboratory at Wroclaw University of Science and Technology (WUST) and didactic setups developed for this laboratory.

In the next section, one presents the assumptions which had to be met by a sample specialist laboratory to ensure the achievement of particular didactic outcomes which would allow to meet the PEMC related requirements of employers. Section 3 states the assumptions to be met by a basic didactic setup in this laboratory so as to enable the introduction of project-oriented education. The following chapter gives the description of a drive system as well as the electrical rating and the parameters of its particular elements. Section 5 describes possible applications of the setup in a didactic process, including converter programming and a sample class plan. The article is completed with a short summary.

2. PROJECT-ORIENTED VERSUS PROBLEM-ORIENTED LEARNING AND A QUASI-OPEN LABORATORY CONCEPT

The role of laboratory classes in technical education is obvious, engineering education would be impossible without them. Laboratory classes offer a practical presentation of theoretical knowledge presented in lectures and also complement it. Over the years, three approaches to laboratory classes in technical studies have been developed: hands-on approach, remote laboratory or virtual laboratory [2, 11].

The hands-on approach is a laboratory with a particular location, equipped with laboratory setups composed of measurement apparatuses and various devices and driver elements, or complete training systems [3] which are tested during classes. Students participate in classes at particular times and conduct some earlier defined experiments. Usually, laboratories are dedicated to particular subject groups encompassing lectures, sometimes project classes or laboratories. This approach is called the building-block approach [5–7]. Complex systems are divided into subsystems (smaller fragments) students learn about in specific courses.

In the case of a remote laboratory, students can log in to a laboratory on the Internet from any location and using a web-based interface gain access to an appropriately configured laboratory setup to perform certain, strictly defined experiments [8, 9]. Laboratories taught in this way are an element of remote learning, their advantage is the possibility of repeating an experiment even a few times by a student, which is usually impossible in the hands-on approach. A limitation here is the fact that students can conduct only strictly defined types of experimental research.

The difference between the virtual laboratory and the remote laboratory is the fact that in the former there is no real equipment and measurement apparatus. Laboratory

systems are modelled using appropriate, usually dedicated software [10], which contributed to significant cost savings in comparison with the above discussed solutions. Recently a new trend has appeared to use advanced software for real-time simulations (RTS) [12, 13]. This is particularly important in the case of very complex systems, such as distributed power electronics systems cooperating with renewable energy sources. However, the use of such systems means that students do not have an access to real equipment and cannot gain any practical experience.

The basic limitation of universities using real laboratories are high costs. In consequence, two main trends can be observed: design and construction of own setups or cooperation with industry and the construction of experimental setups using state of the art equipment, allowing to conduct experiments and educate students in accordance with the requirements of industrial partners [14].

The latter solution was adopted during the modernisation of the Controlled Electrical Drives Laboratory at WUST, which provides education in the field of power electronics and drives, specialization *Automation of Machines, Vehicles and Devices* and *Industrial Electrical Engineering*. The setups described in the next chapter were designed and constructed in cooperation with Lenze Poland. The setups allow to educate students in both classical laboratories, hands-on approach type, and also using the project-based approach which is a trend in modern engineering education considered the best by numerous specialists [9, 15–17]. This form of education offers students an opportunity to integrate a few basic fields of theoretical knowledge they familiarized with earlier and to gain new project related and practical experience in their specialization. This is especially significant in such specialization as power electronics and drives as it combines the issues related to power electronics, analogue and digital electronics, electrical machines, fundamentals of electric drive systems, measurement techniques, signal processing and control theory and techniques.

3. DESIGN ASSUMPTIONS OF THE DIDACTIC SET-UP

This chapter describes laboratory setups designed in cooperation with an industrial partner – Lenze Poland [18] using various industrial frequency converters made by Lenze. The setups in the Controlled Electrical Drives Laboratory at WUST encompass two AC motors: induction and permanent magnet synchronous motor (PMSM). Each of them is fed by its own industrial frequency converter [19], and can be the subject of classes while the other one generates load torque as the emulator of a loading machine. Additionally, the setup is equipped with appropriate control and measurement apparatuses (cf. the next section).

The didactic setup should allow students to learn about scalar and vector control methods, both with reference to induction motors and PMSM and their variants. Students should also learn the fundamentals of sensorless control principles [20].

The design assumptions for the didactic setup for testing the control methods of drive systems with AC motors, used as an educational tool in teaching students about controlled electrical drives in undergraduate studies were as follows:

- The setup should be equipped with elements used in modern, industrial drive systems with AC motors.
- The setup should allow one to investigate control systems with both induction motors and PMSMs.
- Each motor should be fed by its own, industrial frequency converter.
- Both motors should be equipped with a winding temperature measurement device.
- Both independent and simultaneous operation of motors should be possible.
- Load torque simulation should be possible on each motor. Additionally, it should be possible to generate various values and types of load torque: passive, active, fan-type, etc.
- Both converters should be equipped with braking resistors in the case of the generator operating mode (the necessity to control voltage in the DC link).
- The setup should be equipped with control panels to ensure convenient user access to switches, inputs and outputs, both analogue and digital ones.
- The setup should be equipped with an easily accessible safety switch in case of emergency.
- There should be a possibility to program frequency converters at the computer software level to enable the waveform analysis of particular drive variables online, including also the internal variables of the control system.
- There should be a possibility to control the frequency converter in a selected industrial real time network.
- Computer software should allow to select a wide spectrum of control systems, including both scalar and vector control systems. There should also be a possibility to work in a sensorless mode.
- The setup should be mechanically stable and portable at the same time.

4. THE DIDACTIC SET-UP WITH AC MOTORS

For the purpose of fulfilling the assumptions listed in the previous chapter, the didactic setup was designed and constructed (Fig. 1). Its main part consists of two AC motors with identical frequency converters to feed them. On the left, there is an induction motor, 1.1 kW. It is additionally equipped with an incremental encoder with a resolution of 128 impulses per revolution, HTL standard, and an induction fan supplied separately (it is possible to use single-phase and three-phase supply). Both elements are hidden under the motor casing. The right motor is a PMSM, 1.0 kW. The motor is

equipped with a dedicated resolver to measure speed and mechanical position. The induction motor has a KTY winding temperature sensor, while the PMSM is equipped with KTY + 2×PTY sensor system.



Fig. 1. The didactic set-up

The shafts of both motors are coupled with an electromagnetic coupler – this solution allows two student groups to work at one setup simultaneously – for example when they familiarize themselves with the set-up and the software. A switch located on the control panel enables the connection of the coupler and the joint operation of both motors. To ensure the correct operation of the coupler, the setup is also equipped with a 24 V DC supply. Both motors are controlled by Lenze frequency converters (TopLine). They are programmed at the level of the software – Lenze Engineer [19] (cf. sect. 5.1).

Additionally, the setup is equipped with a communication module which allows controlling the operation of one of the converters using the industrial real time network Profibus. For the purpose of controlling the voltage value in the DC bus, both converters are equipped with external braking resistors. Such a solution allows one to test each motor both in the motoring and generating operation mode. The software also allows one to select other braking types (cf. sect. 5).1.

To enable students to gain easy access to all converter inputs and outputs, special control panels were developed (Fig. 2). The panels are the result of engineering diploma works conducted in the Department of Electrical Machines, Drives and Measurements of the Faculty of Electrical Engineering, Wrocław University of Science and Technology (mostly realized using the open-laboratory concept). The panels are equipped with such devices as: inverter switches, external fan and coupler switches, potentiometers,

analogue input and output BNC concentric connectors, microswitches or D-Sub connectors of the converter. The panels are designed in such a way that they ensure as much universality as possible, hence e.g. potentiometer connectors are BNC connectors. Such a flexible solution can allow to connect the converters, for example with rapid prototyping systems or PLCs (setting frequency, torque, speed or position from an external source). Both frequency controllers are powered by separate sources and this is why each of them has separate safety switch.



Fig. 2. Photo of the control panels

The motors are mounted on a strong, steel frame and the remaining elements are mounted on the back wall of the setup.

The nominal data of the two AC motors are presented in Tables 1 and 2. The converter parameters are presented in Table 3 and all other parameters in Table 4.

Table 1. Nominal data of the 3-phase induction motor (Lenze)

Power, kW	1.1
Current, A	5.50Δ/3.20Y
Voltage, V	200Δ/345Y
Frequency, Hz	120
Velocity, rpm	3490
Power factor	0.77
Efficiency, %	81.4
Degree of protection	IP 54
Class of insulation	F
Temperature measurement	TKO/KTY83-110
Operation type	S1
Type	MFFMAIG0761-32C1C

Table 2. Nominal data of the 3-phase permanent-magnet synchronous motor (Lenze)

Power, kW	1.0
Torque, N·m	2.3
Current, A	2.3
Maximal current, A	10
Voltage, V	320
Frequency, Hz	270
Velocity, rpm	4050
Degree of protection	IP 54
Class of insulation	F
Temperature measurement	KTY + 2×PTC
Type	

Table 3. Nominal data of the frequency converters Lenze 8400 TopLine C

Power	1.1
Input frequency, kW	50/60
Input current, A	4.4/3.6
Input voltage, V	400/500
Class of insulation	IP 20
Output frequency, Hz	0–1000
Output voltage, V	0–400/500
Output current, A	3.2/2.6

Table 4. Nominal data of the remaining elements of the designed drive systems

Clutch	Electromagnetic, Intorq 14.105.08.30, 20 W, 24 V _{DC} , 15 N·m
Braking resistor	Lenze, $P = 200$ W, $R = 180 \Omega$, $U_{\max} = 800$ V
Measurement of induction motor speed	Incremental encoder, 128 imp./rev., HTL
Measurement of synchronous motor speed	Dedicated resolver
Fun of the induction motor	Supply: 1 phase, 3 phase, $f = 50/60$ Hz, $P_{\max} = 31$ W
Communication module	Lenze Profibus, E84AYCPMV

5. APPLICATION OF THE DIDACTIC SET-UP TO STUDY THE FUNCTIONING OF CONTROLLED ELECTRICAL DRIVES

5.1. APPLICATION OF THE CONVERTER SOFTWARE IN THE DIDACTIC PROCESS

Student's work with the Lenze Engineer computer software consists in two stages: project establishment including defining all components of the drive system and appropriate software execution. Sample screenshots are presented in Fig. 3. Figure 3a shows one of the

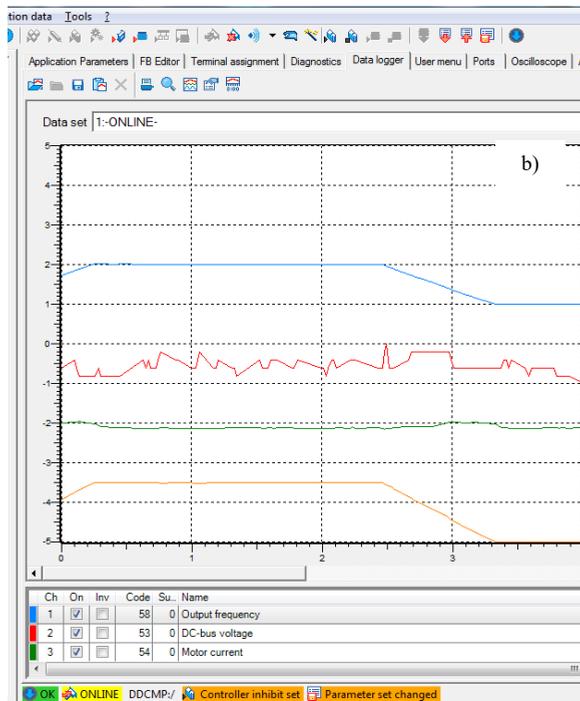
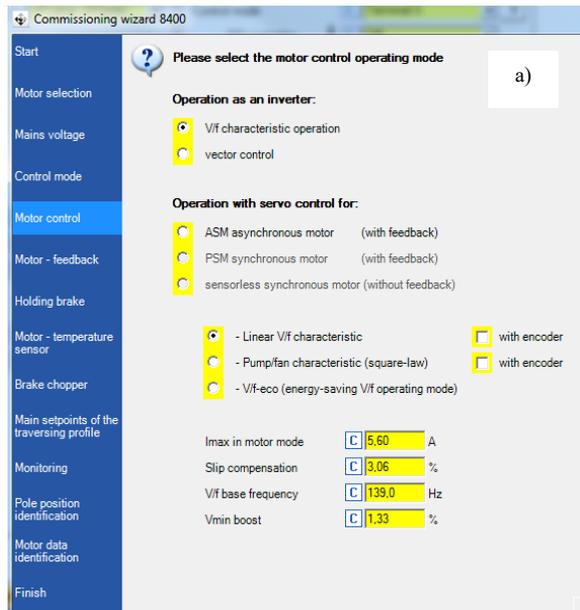


Fig. 3. Lenze Engineer software under: a) project parameter determining, b) execution of the software (transients registration)

steps during the commissioning of the inverter, while Fig. 3b shows exemplary time responses of the output frequency, DC-bus voltage, motor current and motor speed. The responses must be properly identified by the students and then saved and visualized in some external program to be placed in the report.

The first stage allows students to familiarize with all elements of the didactic setup. After the establishment of a new project, they have to make the following steps (commissioning):

1. *Motor selection.* The program allows to select both Lenze motors and any other motor. In the case of the motor made by Lenze, code C86 from the motor nameplate should be entered. This step requires the students to know how the motor stator winding is connected (delta/star) – they can check it individually or they can use a photo attached to the laboratory instruction. The way the windings are connected determines the rated voltage of operation which has to be selected in the program.

2. *Frequency converter voltage selection.* Depending on the type of the converter it is possible to choose between single- and three-phase power supplies with various voltage values.

3. *Selection of the initial meaning of the converter inputs/outputs.* This choice can be modified at any time during the later converter operation.

4. *Selection of the motor control type.* Depending on the type of the connected motor (induction/PMSM), it is possible to choose the appropriate motor control type. It can be both scalar (for induction motors) and vector. In the case of the scalar control, it is possible to choose between linear and parabolic frequency characteristics (pumps/fans) and the energy saving mode. Additionally, it is possible to choose a sensorless mode in which an angular speed sensor is not required. At this point, it is also possible to additionally define basic control parameters, such as a base frequency, active slip compensation factor and maximum current. Fig. 3a presents the screenshot of the control system selection.

5. *Mechanical brake selection.* Although the setup is not equipped with a brake, students learn that there is also a possibility to equip the drive system with such an element.

6. *Selection of voltage value control method in the DC link during braking.* The necessity to choose the said control method makes the students aware of the braking energy processing problem and shows them various solutions. The most popular method is the use of a braking resistor the laboratory setup is equipped with. Among other methods of voltage control, it is possible to distinguish stopping the braking process and maintaining constant speed when voltage exceeds the maximum value. Voltage control methods are illustrated with intuitive graphics presenting speed and voltage waveforms for particular methods. When a braking resistor is selected, it is necessary to determine its data: resistance and power.

7. *Selection of the basic parameters of static and dynamic work,* i.e. the values of reference speeds and as well as acceleration and braking times in relation to the reference speed. Additionally, it is possible to define the time of the so called quick stop.

8. *Selection of a reaction mode to the overload of particular drive system elements: motor, converter and braking resistor.* It is possible to select levels (percentage with reference to nominal values) and reaction modes (no reaction, warning, error).

9. *Identification of system parameters.* This step is particularly important when the used motor does not come from the same manufacturer as the frequency converter and when the vector control method is used (motor parameters are used in state variable and electromagnetic torque estimators [20]). Additionally, the identification program allows one to choose regulator parameters, scalar control characteristic parameters as well as the parameters used during the field-weakening operation.

The subsequent stage in students' work with frequency converter software is the analysis of drive operation in both dynamic and static states. The main part of the program is divided into a number of bookmarks which, among others, allow to:

- Change the basic elements of a drive system and its parameters (application parameters bookmark). This is the place where all the most frequently used functions were collected: selection of power supply type, selection of control type and its most important parameters, manual control (PC manual control), transmission value, reference speed value or the value of acceptable acceleration/braking. Most frequently it is the PC manual control option to be the first method used by students to check if a drive operates correctly.

- Considerably modify the control system structure (*FB Editor* bookmark). The bookmark enables significant intervention in the converter software and is dedicated only to advanced users (e.g. graduate students). It allows, among others, to create motor torque control system of a motor generating load torque ensuring different torque characteristics: constant, changing in time, changing as a speed function, passive, active, fan-type, etc.

- Check the state of converter inputs and outputs, and define their functions (Terminal assignment bookmark). The bookmark allows one to change the way of using digital and analogue inputs and outputs in the system and their simple conditioning (gain increasing, adding offsets).

- Check the general condition of a drive. The bookmark allows to delete the appearing errors (as long as their sources were deleted), check the most important drive parameters: DC voltage, speed, converter state, temperatures, etc.

- Register waveforms in the system (Data logger bookmark). Sample waveforms are presented in Fig. 3b. Students can also save obtained results as an Excel or MATLAB file and generate waveforms for reports.

- Check selected system parameters from the list of all parameters (All parameters bookmark).

The presented structure and software of laboratory setups allows one not only to do strictly define laboratory tasks such as the ones described in sect. 5.2, as part of laboratory practice conducted according to the hands-on approach, but also to conduct more advanced projects and research experiments in the open-laboratory, available, e.g., for

members of student scientific teams or students working on their engineering diploma or master theses.

5.2. SAMPLE LABORATORY CLASS IN UNDERGRADUATE STUDIES. CONTROLLED ELECTRICAL DRIVES

A sample laboratory class in the Controlled Electrical Drives Course – Fundamentals for undergraduate (engineering) studies, related to the vector control of an induction motor can be as follows:

1. Familiarizing with a setup, identification of its components.
2. Starting a new project in the Lenze Engineer software, performing the steps described in sect. 4.1.
3. Starting the previously prepared program for the torque control of PMSM.
4. Checking the correctness of entered data using the PC manual control option.
5. Familiarizing with the way converter inputs and outputs are defined, e.g., by programming one of the analogue inputs as a set signal and one of the digital inputs as a change in shaft rotational motion. Analogue outputs can be observed using an oscilloscope, digital outputs using LEDs connected to the control panel.
6. Observing drive operation during speed reversals with various types and values of load torque. The registration of waveforms which are later used and analyzed in reports.
7. Completing tests and switching off the setups.

6. SUMMARY

The article discusses selected aspects of educating students of technical studies with particular consideration to education in power electronics and motion control. Special attention was given to engineering education oriented to the needs of industrial employers. The possibility of using industrial frequency converters during laboratory classes on controlled electrical drives in engineering studies is also presented in the paper. There is also a description of a sample laboratory setup in the Controlled Electrical Drives Laboratory at Wrocław University of Science and Technology used to efficiently educate students in this respect.

The setup with software for the converter control allows simultaneous learning of both theoretical fundamentals of modern methods and control systems and their industrial application. The setup allows one to familiarize students with a number of elements used in modern drive systems: various types of motors (induction, PMSM), converters, braking resistors, couplers, temperature sensors, various speed sensors.

The setup enables students to learn both about scalar and field oriented control systems. They can also recognize differences in torque, speed and position control of two

currently most popular types of electrical motors, induction and PMSM ones. They can also familiarize themselves with the idea and operation of sensorless drives. The scope of use of the designed laboratory setups depends on the needs of the didactic process, type of studies, laboratory teacher's and also the interests and invention of students who can also conduct experiments beyond the curriculum of studies and use the described here laboratory setups in their diploma theses or elective courses (scientific teams for students – open-laboratory classes).

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