Smart-scaled RES Equipment as a Practical Tool for Teaching Students

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***Abstract*—A smart-scaled photovoltaic and fuel cell didactic equipment is presented as a practical higher education tools for learning about these Alternative Energy Sources. This didactic equipment is used at the Faculty of Electrical Engineering, Computer Science and Information Technology Osijek (FERIT), Croatia as a part of a curriculum in the course Applied Power Electronics. The didactic equipment is described, and selected laboratory exercise experiments are presented. A few topic examples, with which the students are dealing at the exercises are given. Furthermore, student's knowledge evaluation has been done in the terms of conducted knowledge tests before and after performed laboratory exercises. Finally, the result of the student's survey is presented.**

Keywords—photovoltaic, fuel cell, didactic equipment, education tool, alternative energy sources

I. Introduction

The production of electricity from Renewable Energy Sources (RES) such as Photovoltaic (PV) and Alternative Energy Sources such as Fuel Cell (FC) systems is constantly increasing [1]. A major cause of this tendency is a global energy crisis and climate change, with which conventional fossil fuel sources are becoming increasingly difficult to cope [2]–[4]. Repercussion of such trend is a growing awareness and interest among students of technical professions to learn more about RES. In addition to theoretical knowledge of PV and FC systems, for better training of future engineers, a practical part of learning is necessary. This implies recording PV cell and FC electrical characteristics, various PV module and FC connections, studying the effects of shading in the case of PV system, etc., on the real systems. However, laboratories for practical learning about PV and FC systems are relatively expensive and impractical, primarily due to the cost of the main and additional equipment, as well as the complexity of using such systems due to dependence on external weather conditions (rain, cloud shadings, etc.) [5], [6]. Besides the PV systems weather dependency, weather conditions also indirectly apply to the FC systems due to the hydrogen production method, which is usually via electrolysis. The power needed for electrolysis is usually obtained through the PV power plants [7]. Together with the constant increase of RES integration in the world, and predicted global penetration of hydrogen technology as presented in [8], next generation students need to have better knowledge of the cogeneration between these two RES technologies. As an alternative approach to learning about PV and FC systems, scaled systems for practical learning are imposed [9], [10]. In this paper, a smart-scaled PV and FC didactic equipment will be presented together with their capabilities. Few examples of student's tasks will be shown. At the end of the paper, a survey taken on students will be presented to show the results of using such approach in teaching students.

II. Smart-scaled Didactic Equipment

Presented smart-scaled didactic equipment (Fig. 1 and Fig. 2) serves as a didactic equipment intended to provide a basic knowledge of PV and FC systems for students [11]. The equipment is scaled and adjusted to laboratory conditions which makes it safe and portable for using. The mistakes in electricity connections, although undesirable, are allowed due to protection circuits in the system which is great feature when working with many students. The unique feature of both didactic equipment is connectivity to the computer and the dedicated software application. This feature can be used in class with large number of students where the computer can be connected to the projector and teacher can show students the procedure of characteristics recording, the influence of different parameters on the system, etc., in real time. The cost of described didactic equipment goes from several thousand euros up to about ten thousand euros per single system.

A. Photovoltaic Didactic Equipment

The PV didactic equipment consists of a PV board that contains all the necessary components to build an island PV system.

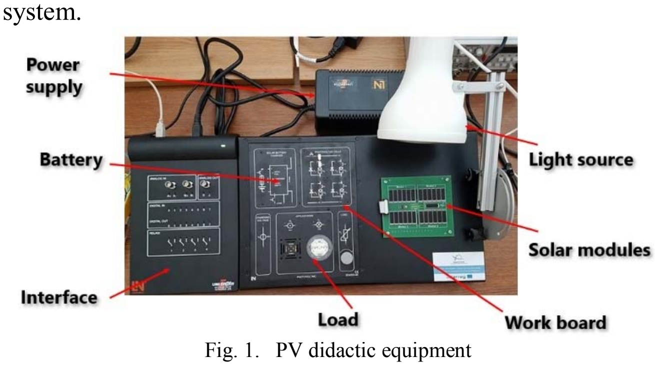

Fig. 1. PV didactic equipment

The main parts of PV system (Fig. 1) are a power supply, an interface that connects to a computer via a USB cable, and a work board. On the work board students can connect parts of the PV system at their will. PV system consist of a 24 PV cells placed on the work board, and they are physically connected to four PV solar modules. The work board also contains various loads such as fan, LED lamp and potentiometer to emulate an inductive, capacitive and resistive type of loads. Furthermore, the system contains a battery as an energy storage device, and a special lamp light source to imitate the Sun. The dimensions of the PV didactic equipment are 560x270 mm.

B. *Fuel Cell Didactic Equipment*

The FC didactic equipment consists of three main sections: electrolyzer with hydrogen and oxygen tanks, fuel cells stack, and connections section (Fig. 2). Hydrogen and oxygen tanks are filled with distilled water and closed with expansion vessel lid. The gases are produced via electrolyzer which is supplied by 0 – 2A DC current source. The gas segment of each tank is connected to the fuel cells stack with tubes. The fuel cells stack contains two fuel cells rated at 1W, each with max. voltage of 0.9V. Fuel cells can be used individually or can be connected in parallel or series. The connections section consists of electrolyzer, FC and load connection terminals. Here, the user can connect fuel cells to the various loads at will. Load section provides few different types of loads: incandescent bulb and variable resistor as resistive, and a DC motor as an inductive type of load. Dimensions of a FC didactic equipment are 420x280 mm.

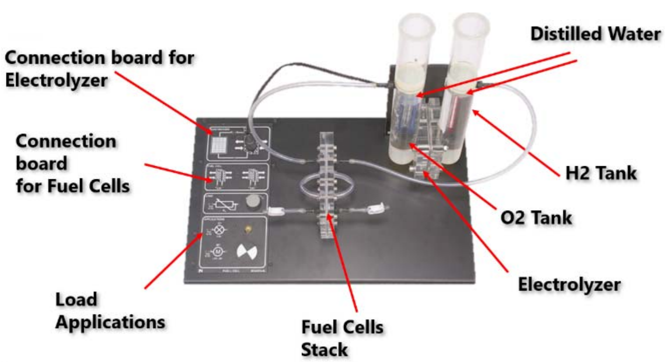

Fig. 2. FC didactic equipment

C. *Software*

The software installed on computer controls and monitors both didactic equipment. The two main windows of the software for PV didactic equipment are shown side-by-side in Fig. 3. Left window is dedicated for characteristics recording, where the user can choose which parameter will be shown on *x-axis* and which on *y-axis*. The parameters which can be recorded are voltage, current, power, irradiance and temperature. This allows students to learn about various parameters relations and dependencies. On the right side (Fig. 3), an irradiance and temperature meters are shown, which are used for real time monitoring of these two parameters. When using the software of FC didactic equipment (Fig. 4), user has options to choose to record voltage, current and power for both, *x-axis* and *y-axis*. The right window in Fig. 4 is for electrolyzer current adjustment.

Once characteristics are recorded, user can save the data as a figure or as *.csv file for further data processing in different software. When the class is held in demonstration manner, the computer is connected to the projector and measurements are displayed in real time (Fig. 3 and Fig. 4), and in this way students can iterate with the teacher about records.

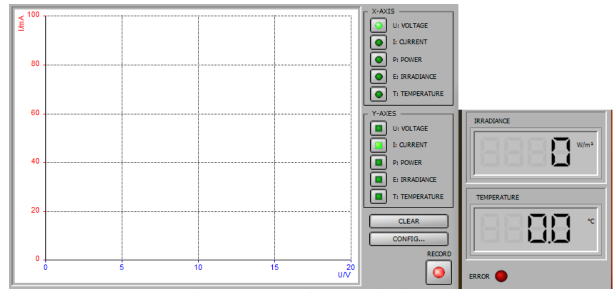

Fig. 3. PV software windows

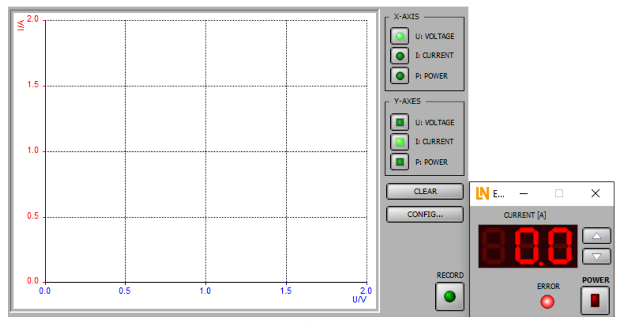

Fig. 4. FC software windows

III. Practical Measurements

In this chapter, a few practical measurement examples for both, PV and FC didactic equipment will be presented. These practical examples are chosen to show the possibilities of both didactic equipment regarding to the real-world issue cases, and they are part of the curriculum in Applied Power Electronic course for graduate students.

A. *Practical Examples on Photovoltaic Didactic Equipment*

First example will show the influence of incidence angle of the light source on electricity production. The Sun travels from East to West and because of this, the Sun irradiance varies through the day. Most of the PV modules are fixed and due to different irradiance of the day, the *i-v* and *p-v* characteristics of the PV module will be different for every chosen time of the day [12]. It is worth to mention that besides variable incidence angle of the Sun, the irradiance of the PV module also greatly depends on the weather conditions. Although simple at first glance, weather influential factors can be unpredictable, which sometimes makes it difficult to estimate an electricity production for a given day [13]. Fig. 5 and Fig. 6 shows *i-v* and *p-v* characteristics for incidence angle of $z = 90°$ and $z = 30°$, respectively. Fig. 5 and Fig. 6 clearly shows the difference in electricity production for different incidence angles. Irradiance is fixed in both cases and amounts to $E = 1000\ \mathrm{W/m^2}$.

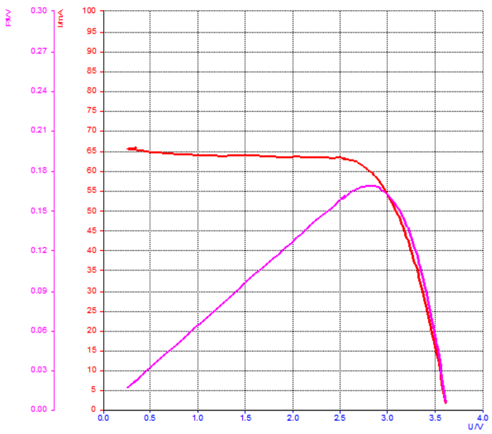

Fig. 5. The *i-v* (red) and *p-v* (pink) characteristics of one PV module for incidence angle of the Sun of $z = 90^\circ$

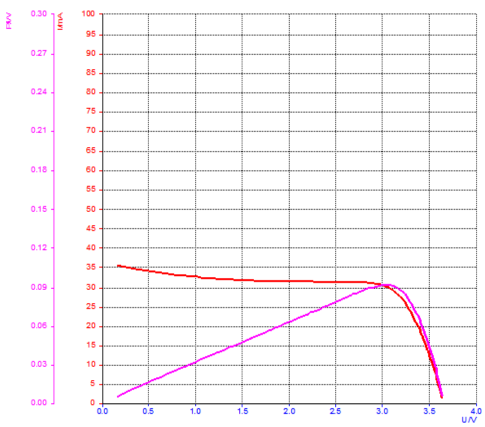

Fig. 6. The *i-v* (red) and *p-v* (pink) characteristics of one PV module for incidence angle of the Sun of $z = 30^\circ$

The Fig. 5 and Fig. 6 represents the Sun at noon, and at early morning/evening, respectively. In this way, students can experiment with different incidence angles together with different irradiances and obtain additional knowledge of influential parameters dependencies.

The second example which will be presented is the shading effect, which is common issue in PV arrays with PV modules connected in series. The problem occurs when PV array is not equally shadowed and thus every PV module in array will behave differently in terms of electricity production (shaded PV modules will consume the power instead producing it). This will yield with unwanted consequences which besides no electricity power production (if one PV module in series is shaded, no electricity power is produced by that series), introduces additional losses and heat to the PV modules, which can damage them [14], [15]. The students in this way can learn why and how to deal with this issue. Four PV modules are connected in series as shown if Fig. 7 for this experiment. In one point in time of characteristic recording, one PV module is shaded by the hand. Although the voltage of the PV array remains the same, this phenomenon will result with sudden current sag to the current amount produced by the shaded PV module. This problem is solved with a bypass diode built into every PV module, which if shading occurs, conducts the electricity (and bypass affected PV module) and thus prevent PV modules from heating and damaging [16]. Recorded characteristics for this experiment are shown in Fig. 8.

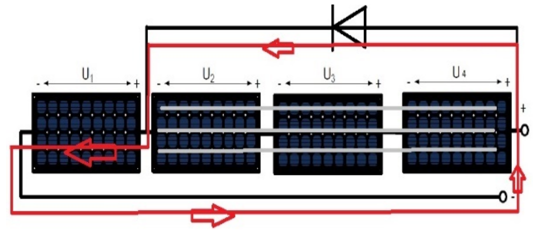

Fig. 7. PV modules shading experiment

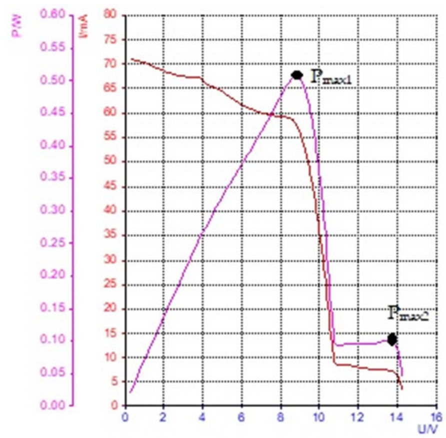

Fig. 8. The *i-v* (red) and *p-v* (pink) characteristics of series PV array

In the Fig. 8, two points are marked, $Pmax_1$ as maximum power point with no shading which amounts to 0.5W, and $Pmax_2$ as maximum power point with shading effect which amounts to 0.125W.

These two practical examples are part of the laboratory exercises attended by students. Other experiments which students conducts on the PV didactic equipment are series, parallel and series-parallel connections experiments, influence of irradiance and temperature, experiments with battery storage unit, etc.

B. Practical Examples on Fuel Cells Didactic Equipment

In addition to the experiments conducted on the PV didactic equipment, students also conducting experiments on the smart-scaled FC didactic equipment, with similar approach. Two chosen FC experiments will be shown in this section. First experiment deals with FC in parallel connection. At first, *v-i* and *p-i* characteristics of a single FC are recorded (Fig. 9). Once the characteristics are recorded, students reconnect the didactic equipment to different connection arrangement (in this case in parallel connection). Recorded characteristics for paralleled FC are shown in Fig. 10. The maximum current of approximately 1A for single cell can be read from the characteristic in Fig. 9. It is expected that produced current will be doubled in the case of two identical fuel cells connected in parallel. Fig. 10 shows that produced current in the case of parallel fuel cell connection is between 1.6A and 1.7A. This phenomenon can be explained with the way that fuel cells are connected to the hydrogen and oxygen tanks. The tanks are first connected via tubes to first fuel cell and then junction is made to the second fuel cell. This kind of connection will result with higher gas pressure on the first, and lower on the second fuel cell, which for consequence will yield with unequal electricity production of individual cell. This kind of issues are discussed with students when they finish the experiments and presents the results.

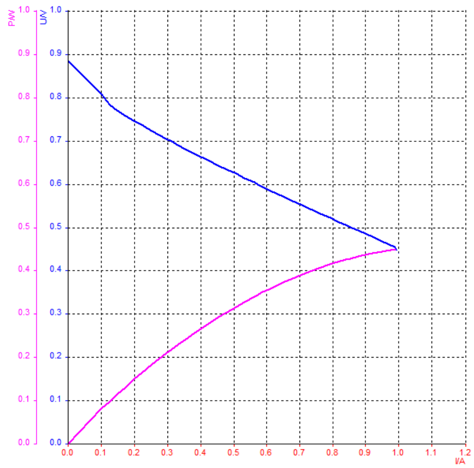

Fig. 9. The *v*-*i* (blue) and *p*-*i* (pink) characteristics of single fuel cell

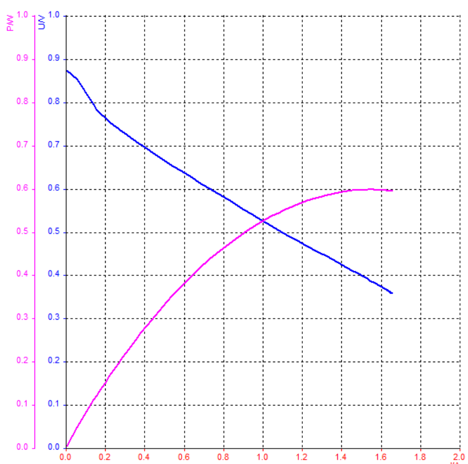

Fig. 10. The *v*-*i* (blue) and *p*-*i* (pink) characteristics of two paralleled fuel cells

The second chosen experiment example is determination of FC efficiency. In this experiment, students are introduced to the procedure of FC efficiency calculation. FC converts chemical energy of hydrogen and oxygen to electrical energy. The fuel cell efficiency can be calculated as the ratio between electrical and chemical work [17].

$$\eta_{fc} = \frac{W_{el}}{W_{ch}} = \frac{U \cdot I \cdot t}{H_{\mathrm{H2}} \cdot (\Delta V)} \quad (1)$$

where are: W_{el}[J] – electrical work, U[V] – voltage, I[A] – current, t[min] – time, W_{ch}[J] – chemical work, ΔV[l] expended volume, H_{H2} – caloric value of hydrogen which amounts to $H_{\mathrm{H2}} = 11920\,\mathrm{kJ/m^3}$. As in every conversion process, losses are inevitable. Besides the conversion losses, hydrogen is a gas with very small molecules, and as such it can diffuse even through solid materials such as storage tanks, pipes, seals, etc. This needs to be considered in FC system design and evaluation [18]. Every storage element continually loses a small amount of hydrogen. This is called the "leakage rate". The leakage rate must be considered when FC efficiency is measured and calculated due to connections between tanks and fuel cells. Leakage rate calculation procedure is as follows. First, the hydrogen tank needs to be filled with the gas and initial value of hydrogen needs to be recorded. After certain amount of time (in this example five minutes) the amount of hydrogen is recorded again. The difference in the two amounts equals to leaked hydrogen. The leakage rate q_l is obtained as ratio between leaked hydrogen and elapsed time, and in this case it amounts to:

$$q_l = \frac{\Delta \mathrm{H_2}}{\Delta t} = \frac{4\mathrm{ml}}{5\mathrm{min}} = 0.8\ \mathrm{ml/min}$$

Once leaking rate is obtained, students reconnect the FC didactic equipment for the fuel cell efficiency determination. First, certain amount of the hydrogen needs to be produced by the electrolyzer. After that, the fuel cell is connected to the constant power load where current and voltage are measured via virtual instruments. Electrolyzer is then turned off and the time is measured. At this point, fuel cell consumes the hydrogen from the tank. After certain amount of time (three minutes in this example), the final hydrogen volume is recorded. Important key in this experiment is constant power load. This experiment is repeated three times for accuracy and results are recorded as shown in Tab. I.

TABLE I. MEASUREMENTS

Measure	I [A]	U [V]	ΔV [ml]
1.	1.0	0.43	18
2.	1.0	0.45	19
3.	1.0	0.44	20
Average	**1.0**	**0.4**	**19**

After results are obtained, students are calculating fuel cell efficiency by the expression (1) with leaking rate consideration in total hydrogen volume consumed, as:

$$\eta_{fc} = \frac{W_{el}}{W_{ch}} = \frac{U \cdot I \cdot t}{H_{\mathrm{H2}} \cdot (\Delta V - q_l)} = \frac{0.44 \cdot 1.0 \cdot 180}{11920 \cdot (19 - 2.4) \cdot 10^{-3}}$$

$$\eta_{fc} = \frac{79.20}{197.9} = 0.4002 \approx 40\%$$

Finally, the efficiency of embedded fuel cells can be calculated and by the above calculation, the FC efficiency is around $\eta_{fc} = 40\%$. Besides fuel cell efficiency calculation, students also determine the electrolyzer efficiency and finally, the whole system efficiency. The real efficiency at last can be obtained if the hydrogen tanks compression process and transportation is included in the equation.

IV. Evaluation

The aim of laboratory work is to learn about specific issues through the practical work as opposed to deal exclusively with theory or simulation. The PV and FC exercises are part of a curriculum in the course Applied Power Electronics at the FERIT. The constant penetration of RES in electricity production demands a wider range of occupations to be familiar with it. At FERIT, the students from three different elective modules; Sustainable Power Engineering, Industrial Power Engineering and Automotive Computing and Communications are attending the Applied Power Electronics course.

A. Knowledge Tests

According to the conducted tests, the overall results are similar for all three elective modules. In total, 50 students have solved the tests and took the survey on working with smart-scaled PV and FC didactic equipment. In the test, students did have nine tasks to solve in limited time of 20 minutes.

The entrance test (T1), exit test (T2) and post data processing test (T3) are created specifically for this research. The entrance test is given to the students prior to the laboratory work to check their input level of knowledge about the PV and FC topics. The questions are formed in such manner to be closely related to the practical issues. For example, one such question was as follows: *"The i-v characteristic of single PV module (Fig. 11) is recorded. The irradiation amounts to* $E = 750\,\mathrm{W/m^2}$*, and the PV module temperature equals to* $\theta = 40\,°\mathrm{C}$*. What is the tendency of the short-circuit current* I_{sc}*, open circuit voltage* U_{oc}*, and the voltage in maximum power point* U_{MPP}*, if irradiation E increases to* $E = 1000\,\mathrm{W/m^2}$*, with new PV module temperature of* $\theta = 60\,°\mathrm{C}$*".*

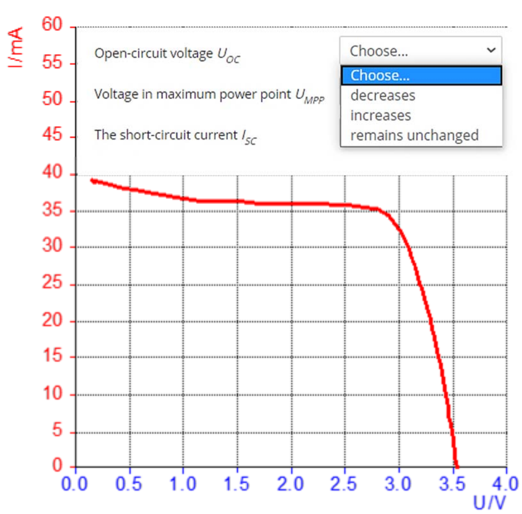

Fig. 11. Recorded *i-v* characteristic for initial parameters of PV module with offered questions and answers

Students choose the correct answer from the drop menu as shown in Fig. 11. To answer this question correctly, students must be familiar with the PV module *i-v* characteristic dependency on irradiation and temperature.

The test results analysis shows 11% increase in success rate in exit test compared to the entrance test results (Tab. II). The results are similar for all three election modules. In addition, students solved the third test after the results data processing, where additional increase in success is observed (Tab. II).

TABLE II. Test Results

Test	*Success rate*	*Relative success rate compared to* **T1**
T1	43%	0
T2	54%	+ 11%
T3	69%	+ 26%

B. Survey Analysis

After finished all tests, students took the survey to quantify their experience in working with the didactic equipment. Five statements were given to every student, for which a Likert scale was implemented for preference ranking, ranging from Strongly Disagree (score: 1) to Strongly Agree (score: 5). The survey questions were formed in such manner to cover different aspects of the educational experience:

1) Perceived Usefulness (PU)
   Learning about PV and FC systems with the help of didactic equipment was useful and productive!
2) Perceived Enjoyment (PE)
   Learning about PV and FC systems with the help of didactic equipment was fun!
3) Ease of Use (EO)
   PV and FC didactic equipment is easy to use!
4) Interactivity (IT)
   PV and FC didactic equipment is interactive!
5) Attention on the Topic (AT)
   Didactic equipment improved my concentration and focus on the laboratory exercise topic!
6) Laboratory Work (LW)
   I would like more laboratory exercises to be done with similar didactic systems!

The survey results of all 50 students are shown in chart (Fig. 12), where the responses for each question are averaged.

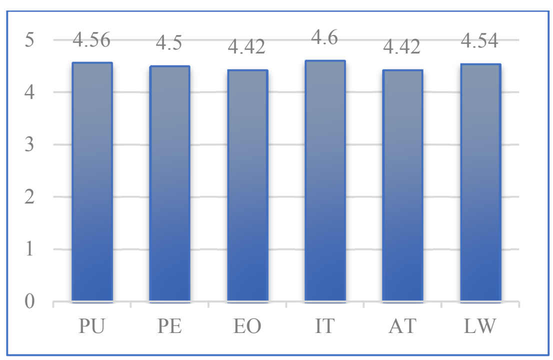

Fig. 12. Survey results by the Likert scale ranging from strongly disagree (score: 1) to strongly agree (score: 5)

The results show that learning with didactic equipment can increase student's interest and attention to the lecture topic and thus make the topic more interesting and enjoyable. A significant notion is the observation of the lecturer where the engagement and collaboration of the students was in visibly higher level compared to different teaching methods such as laboratory demonstrations or simulations. The downsides of teaching with didactic equipment starts to emerge when the group of students (per single didactic equipment unit) is larger than four. In such groups, the students which standing or sitting a little farther away and just observe the experiment processes, are less engaged and interested, and their lecture attention span is significantly lower.

V. Conclusion

In the paper, the usability of the scaled learning didactic equipment in higher education is presented. The results of the student's knowledge test show improved success rate of 11% after the laboratory exercise is done. After the exercise data is processed, students took another test, where the success rate is 26% higher compared to entrance test. These results show the benefits of practical work and the usefulness of scaled didactic equipment as an addition to the theory and/or simulations when the real systems are not obtainable. Students survey results shows satisfactory grades in terms of interest in the given topic, work enjoyment, ease of use and interactivity regarding to the used didactic equipment. The most significant observation of the research was noticeably improved engagement and collaboration of the students in learning, compared to different teaching methods such as demonstrational exercises, simulations or theoretical lectures.

Acknowledgement

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