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How the COVID-19 changed the hands-on laboratory classes of electrical measurement

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ABSTRACT
This article depicts how COVID-19 affected practical teaching at Czech Technical University in Prague, Faculty of Electrical Engineering, Department of Measurement. It introduces the subject of Electrical Measurement and its hands-on laboratory classes. The course applies to more than 100 undergraduate students per semester. Since COVID-19 mainly affected the teaching of the hands-on laboratory courses, the article narrates how the COVID-19 lockdown has changed classes. An experience with the rapid transformation of lectures during the lockdown focusing on the hands-on laboratory classes is discussed, and the improvements that have been done to preserve its objectives, but also to adapt them to another possible lockdown, and the need to switch to the distance teaching, is revealed. The changes have been inspired by the results of a survey carried out among more than 250 students. The outline of the laboratory tasks transformation with an emphasis on the possibility of switching the real face-to-face measurement to the distance teaching remote lectures is described. The change includes reducing the number of laboratory tasks taught while preserving most of the objectives. All 11 new laboratory tasks are described in detail, and it is discussed how the possible change from hands-on to remote classes will affect every task.

Section: RESEARCH PAPER

Keywords: COVID-19; laboratory class; measurement; distance teaching

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1. INTRODUCTION

The COVID-19 pandemic suddenly paralyzed universities all around the world. It affected face-to-face education and dramatically changed the way of teaching. During the COVID-19 lockdown, universities switched to distance teaching and cancelled face-to-face education. Face-to-face education has its specifics, and it supports interaction between student-student or student-lector interaction to promote better engagement, motivation, and study results [1] – [4]. Moreover, practically oriented universities (e.g., Engineering, Health Care, etc.) lost their capability to educate students hands-on. It means all hands-on classes were required to move exclusively to the distance from and fully employ online education, which challenged educators to adapt and transform all the courses. The impact of switching to distance teaching is perceptible to both students and teachers, and many questions have arisen about keeping the education quality [5] – [9].

COVID-19 stroke hard at the Czech Technical University of Prague, Faculty of Electrical Engineering, Department of Measurement, where the need to switch to the distance form has been done practically from day to day. One of the subjects affected most by distance learning was Electrical Measurement and its laboratory classes. Electrical measurement is a compulsory subject in Electronics and Communications and Biomedical Engineering and is available for all the faculty students in both Czech and English. The course is taught to undergraduate students and applies to about 100 students per semester.

The Electrical Measurement subject introduces different measurement methods of electrical and physical quantities like voltage, current, power, frequency, resistance, capacitance, or inductance. It is explained together with principles of their correct application and accuracy estimation. The subject also introduces the basic principles of electronic measuring instruments like multimeters, oscilloscopes, or spectral analyzers and explains the fundamentals of magnetic measurements and essential information concerning measurement systems.

Since the laboratory class is primarily hands-on activity, switching to the distance form has been different from conventional classroom-based teaching. The lecturers had to react to provide non-interrupted lectures while maintaining the quality quickly. According to [10], most students appreciated flexibility and quick reaction. Laboratory exercises, on the contrary, often required a complete redesign of the measuring tasks to enable remote access and control of the measuring process. Practically oriented courses are most often conducted in laboratories, with the assistance of lecturers. Solving the hands-on laboratory classes' learning process requires much more than online learning [11]. Since specific laboratory skills (e.g., the connection of the electronic circuit or handling the equipment) are harder to deliver in online teaching, a partial redesign of the laboratory classes must be done [12]. The paper from the times before the pandemic describes remote laboratories explicitly. In [13], laboratory classes are categorized into three types of laboratory exercises:

a) Development Lab: students address specific design questions and verify that the design works as intended.
b) Research Lab: addition to theoretical knowledge.
c) Educational Lab: students apply theoretical knowledge in order to gain practical experience.

At the same time, the authors admit that remote laboratories cannot replace all of the experience gained by face-to-face laboratories. Another paper [14] performed a literature review of “Hands-On, Simulated, and Remote Laboratories,” where the authors, for remote laboratories, concluded that the more significant the computer-student interface is, the easier the task is to perform online. This supports articles [15] and [16] describing the methodology based on the simulation software, which is supplemented, if possible, with remote hands-on experiments. The advantage was that the students could compare the simulated and hands-on results. The main disadvantage was that only one student at a time could be connected and booked in advance for the remote laboratory. A different approach is used in [17] or [18]. Both articles describe the teaching of electronics using pre-prepared kits. These kits have been physically sent directly to students to be able to perform all experiments at home. Every kit comprises a microcontroller, necessary electrical components, and a breadboard with assembling guidance.

The most complex approach, which can be applied to the class of Electrical Measurement, is described in [19]. The authors divided the learning process into five steps.

1. Preparation for online labs: The explanation of the topic basis and short, simple multiple choices test to pass.
2. Pre-lab: Developing of understanding of critical points from theory.
3. In-lab: Measurement, processing, presentation, and uncertainties.
4. Post-lab: Performing calculations, making conclusions, and understanding the concepts in a science and engineering context.
5. Marking: Grade distribution, analyzing comparison with face-to-face lectures.

The article describes the challenges associated with distance teaching lectures on Electrical Measurement and hands-on laboratory classes and indicates changes in the post-COVID-19 era. The paper is organized as follows. Section 2 introduces the class of Electrical Measurement and its lectures. Section 3 describes its laboratory class during the COVID-19 lockdown and shows the student's feedback results. Section 4 focuses on how COVID-19 changed the laboratory class and its tasks.

2. LECTURES OF ELECTRICAL MEASUREMENT CLASS

As COVID-19 strikes suddenly, all the given lectures had to be quickly transformed into a distant form. The universities offered online courses and teaching classes before the pandemic. Still, it never happened that the whole year had to be taught in a distant form without personal contact or consultations for all students [20], [21]. When the lockdown occurred, the lecturers could not even get to the classroom to provide the lecture. Therefore, rapid actions had to be taken to preserve the classes. It was shown the best and only tolerable way how to continue in lectures almost continuously is to record the lessons in advance. The lecture can be offered, if there is no possibility to attend the university (i.e., lockdown or quarantine), as a recorded presentation in suitable software (i.e., MS PowerPoint or similar), where tools like a pointer, marker, or drawing, and other features are available.

In this case, recording the lecture in advance and allowing the students to watch the video with the lecture before the originally scheduled time showed as the best solution. In this way, the students can prepare their questions or topics for a discussion, and at the originally scheduled time, the lecturer is available for remote consultation with all participants.

The survey pointed out the power of choice to watch a pre-recorded lecture and use it as study material. The anonymous survey was conducted through 269 bachelor program students (approx. 75% of men, the average age of the respondents was about 21 years) in the second year of the study (third semester). The first survey question, "Was the opportunity for you to watch a pre-recorded lecture a benefit?" shows in Figure 1.

An essential aspect of recorded lectures was the availability of the lecturer to be 'online' at the scheduled time of the original schedule to offer the lecture again and to discuss all the problems raised through the pre-watched video. The survey results for the second question: "Was the opportunity for you to discuss a lecture with the lecturer online at the scheduled time a benefit?" is in Figure 2.

The student survey showed an important finding, which has to be considered to improve lectures, not only during the lockdown. The recorded lectures can also be used during face-

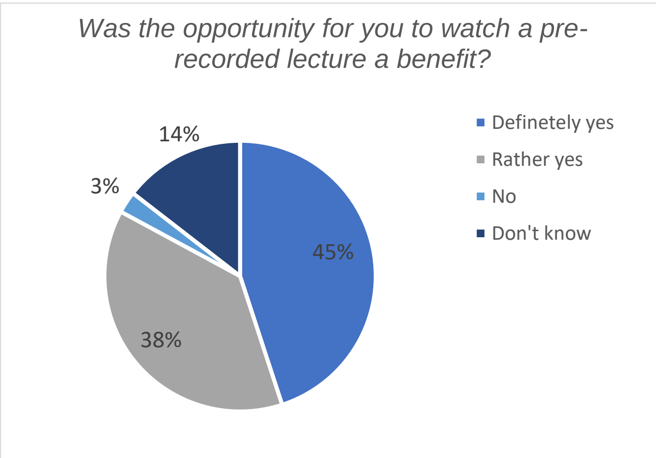

Figure 1. Survey results "Was the opportunity for you to watch a pre-recorded lecture a benefit?".

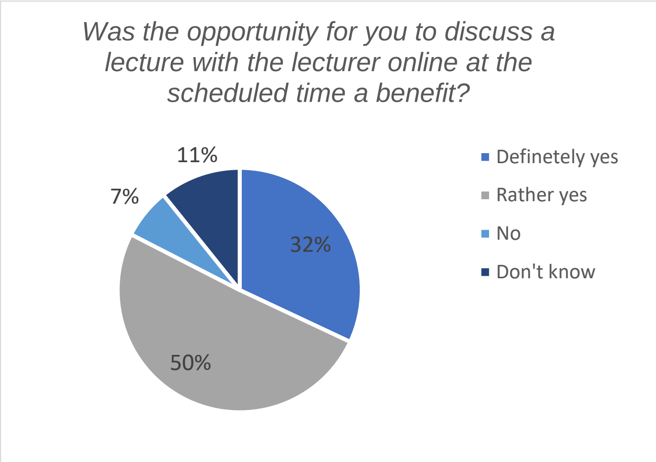

Figure 2. Survey results "Was the opportunity for you to discuss a lecture with the lecturer online at the scheduled time a benefit?".

to-face classes to support students who need to repeat the problem or cannot attend the lecture. This was also verified during the first "face-to-face" semester after the COVID-19 lockdown, as an excellent complement to face-to-face lectures. On the other hand, the possibility of watching recorded lecture could dramatically decrease the number of students who attends the face-to-face lecture. Therefore, all the lectures of the Electrical Measurement Class are available only during the examination period on the YouTube channel of the Department of Measurement. Moreover, to help the students in orientation in lectures and topics, all the lectures were divided into sub-topic to decrease the length of the individual videos.

3. LABORATORY CLASS OF ELECTRICAL MEASUREMENT DURING THE COVID-19 LOCKDOWN

The Laboratory class of the subject is focused on hands-on measurement method tasks of various electrical quantities and their evaluation. It shows the students the several measurement methods for the given topics and clarifies the most suitable techniques for specific measurements. Moreover, it also draws attention to possible measurement systematic errors that may be unknowingly made.

Before COVID-19, students had to perform real hands-on measurements of 17 laboratory tasks and complete reports from all the measurements. Every task had multiple parts to be done, and a student had to connect several schematics to get the measurement results. When COVID-19 struck, and the university was closed almost immediately, the question arose how to maintain laboratory teaching even in a distance form. The crucial requirement was to continue uninterrupted with the hands-on laboratories. As the quickest solution and keeping the learning tolerable, the pre-recorded tasks measured by the teacher and offered to students to watch were considered as a compromise between continuing in teaching and, at the same time, providing at least part of the practical experience. Pre-recorded laboratory tasks cannot substitute hands-on experience. However, on the other hand, quick response and some compromise are crucial for preserving even hands-on-type classes. This way, students can watch pre-recorded tasks anytime and every week, prepare the reports and discuss and present the achieved results during the originally scheduled class. During the online meeting, the main idea of the task was explained again, discussed, and theoretically explained again.

There are different ways to handle hands-on distance teaching, for example, to secure remote access to the laboratory where the tasks will be already connected [22] – [25] or use batch-mode remote-controlled laboratories, like the Virtual Instrument Systems in Reality [26], [27]. However, in classes with significant numbers of students and lots of tasks to be carried out, it demands lots of measurement instruments. It is also insisting on personnel preparing new sets of tasks every second week. It is worth to mention synchronizing the remote access to perform the tasks for all the students can be challenging in such a short time. Moreover, in some of the tasks, there is a need to reconnect the schematics during the measurement. All these requisites were taken into account.

How COVID-19 affected the Electrical Measurement subject shows the statistics of the success rate of the students. During the times before COVID-19, the subject's average success rate was slightly more than 85 %. When COVID-19 strikes and the class have to change from face-to-face hands-on laboratories to a distance form in the first fifth of the semester, the success rate of the class was over 92%. It is given by the fact that the assessment requirements were decreased. Nevertheless, the success rate during the COVID-19 lockdown (at CTU, it has been the following two more semesters) dropped to 84% and 83%, respectively, for the classes that study the subject for the whole semester in a distance form.

Moreover, the average student grade of the class varied from 2.04 (average from the last three semesters before COVID-19) to 2.54 during COVID-19 (three semesters), where 1.00 is equal to the A grade, and 3.0 is equivalent to the E grade according to the European Credit Transfer and Accumulation System (ECTS).

Clearly, the subject had to be changed to the future in case of another lockdown and to reflect the student survey. According to the feedback, the main issue was the number of tasks and receptivity of the reports from the tasks, which can demotivate the students. The results from the survey are in the following figures. One of the survey questions was: "Was the number of tasks optimal for you?". Results are shown in Figure 3.

Figure 4 presents the results for the question, "Were the recorded videos an adequate substitution for hands-on classes?". Surprisingly, the results of the situation that arose were not conclusive.

Another question, "Were the recorded videos beneficial, or would you prefer a different method? " revealed the students' satisfaction with the chosen method. According to almost 80% of all subject students, the pre-recorded videos of all the tasks

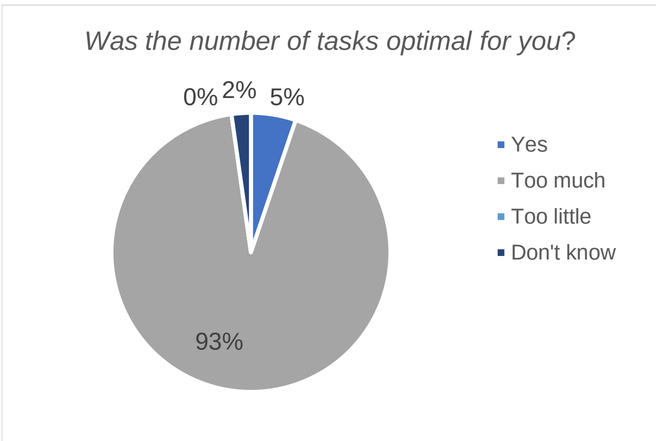

Figure 3. Survey results "Was the number of tasks optimal for you?".

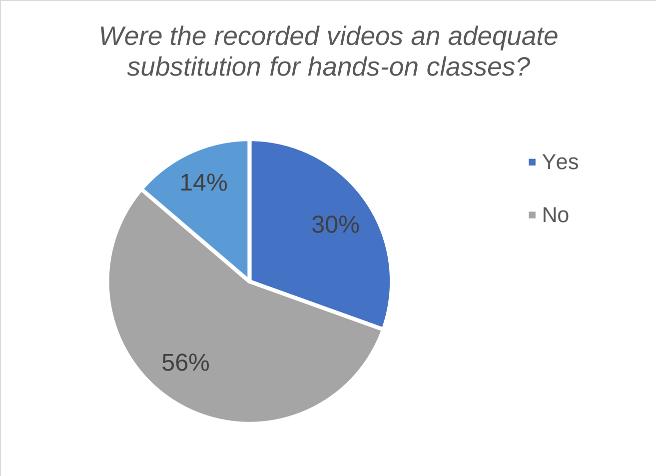

Figure 4. Survey results "Were the recorded videos an adequate substitution for hands-on classes?".

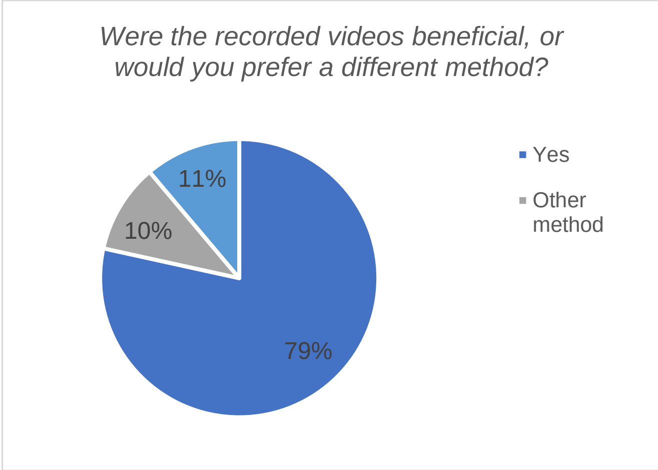

Figure 5. Survey results "Were the recorded videos beneficial, or would you prefer a different method?".

were an adequate substitution for considering the COVID-19 lockdown situation. The results are shown in Figure 5.

The other part of the survey, where the students had space to express what they liked and did not like, indicated the direction in which the subject should be improved. The majority of the students addressed the repetitive reports of the tasks.

The survey results and the overall feelings of the subject led to the need to change the number of tasks and content compression into a smaller number of tasks while preserving the subject's content. The survey also showed how the teaching during the COVID-19 lockdown was appropriate and substitutes the hands-on laboratory class well under the given circumstances.

4. LABORATORY CLASS OF ELECTRICAL MEASUREMENT AFTER THE COVID-19 LOCKDOWN

As stated in the previous section, the laboratory classes had to be redesigned to preserve the content taught in the subject and can be effectively conducted even during the lockdown period. Repetitiveness was a factor often mentioned by the students. The laboratory supervisors accepted that a thorough understanding of the principles demonstrated by the measurement experiment is way more important than gaining skill through excessive repetition of the same drill steps. Moreover, most repetitive measurement tasks are fully automated today in professional environments.

Therefore, the number of tasks has been reduced from the original 17 real measurement tasks to 11 new real measurement tasks. This step will increase the motivation of the students to complete the course successfully. Moreover, some new tasks have been designed to minimize the number of instruments used, reduce the wiring diagrams, and fulfill the need for modern measurement applications in the industry [28] and [29]. In this way, in case of pandemics and lockdowns, the newly designed tasks could be easily modified for remote laboratories.

Article [30] stress the lack of coherent learning objectives for laboratory classes and how this limits their effectiveness. The authors proposed the learning goals for instructional laboratories and suggested future research.

The learning objectives of all tasks have been considered and worked on to motivate the students and to meet all intended educational objectives. The new tasks are:

• Measurement of non-sinusoidal voltages with multimeters and digital oscilloscope with a probe - a task shows students principles of a voltage measurement using different principle multimeters and an oscilloscope using the oscilloscope probe. The effective values of non-harmonics voltages are explained for True RMS and Rectified Mean principle voltmeters. Moreover, the compensation of the oscilloscope probe is shown. Through the measurement, students reveal the limitations of "cheap" multimeters in the measurement of non-harmonics voltages and compare the measurement error of such instruments with the True RMS instrument. Since all the multimeters can be set before the measurement and only the measured signal is changed, this part of the task can be done remotely in the case of distance teaching. In the case of a scope probe compensation, in a distance form, students have skipped this part and only theoretically derived the condition of a correctly compensated probe.

• Measurement of DC currents – a task that explains various methods to measure correctly small and large currents. It introduces a current-to-voltage convertor with an operational amplifier (OA) and shows the methodological error of measurement with multimeters with non-zero inner resistance. In the case of small currents measurement, the experiment pointed out the importance of knowledge of ammeters' real inner resistance and, by calculation, shows the possibility of great measurement error compared with the "ideal" current-to-voltage convertor with an OA. It also explains the contactless measurement of large currents using a clamp meter without breaking the circuit during the measurement. The task has been re-designed to minimize the reconnection of the circuit. Therefore, the small current is measured on two ranges of one ammeter in the case of distance teaching to show the increasing inner resistance with the lower ranges.

• Measurement of small DC voltages – a task that explains the measuring amplifiers with OA's, its actual features like voltage input offset, input resistance, etc. The measurement uncertainties are also explained. The students have to measure the output voltage of the thermocouple with small inner resistance. The difference between inverting and non-inverting amplifiers with the OA is shown. Students calculate and experimentally verify how the output voltage affects the load caused by the amplifier's input resistance. Moreover, it is demonstrated by the measurement of how the input offset voltage of the OA can affect the resulting uncertainty. In the case of distance teaching, students have to measure only inverting amplifier, and for an uncertainty calculation, the catalogue value of the input offset voltage is used.

• Frequency dependence of multimeters for sinusoidal and rectangular waveforms – task explains the principle of frequency dependency of multimeters input circuits, its cut-off frequency, bandwidth, and effects of higher harmonics for rectangular waveforms. For instance, the article [31] compares simulations (virtual lab) and remote experiments with straightforward experiments dealing with the frequency characteristics of real instruments. In this task, students have to measure the frequency bandwidth of four different voltmeters, one laboratory and three "cheaper" voltmeters, hand-held included. The resulting frequency characteristics are then discussed. In a distance form, the task is unchanged since most instruments can be controlled remotely while the camera captures the hand-held.

• Frequency and period time measurement by a counter – introduces the principles of measurement of the time and the period, showing the possibility of inaccurate data measurement caused by incorrectly set of a trigger level and principle of averaging. In this task, a counter developed in the late 80s is used since it can best demonstrate the principle of the time and the period measurement. It can allow setting manually the time when the gate is open in case of the frequency measurement, and it allows manually setting the averaging for the period measurement. On the other hand, in the case of distance teaching, it cannot be used since it cannot be controlled remotely. In other words, this task is the most affected by distance teaching. As modern counters work fully automatically, they can't substitute the used counter. Therefore, the task is skipped in case of distance teaching, and only recorded video is provided.

• Single-phase load power measurement – a power measurement task involves an electrodynamic wattmeter, power analyser, and clamp meter. It also explains the measurement current transformer. Students have experimentally checked whether the current transformer has not been overloaded and used it in the measurement circuit to measure the power. The electrodynamic wattmeter measures power consumption. The constant of the wattmeter is explained. Moreover, the power is simultaneously measured by the power analyser and a clamp meter. Students have to measure the THD and power factor. The task is reduced by the clamp meter measurement in the case of distance teaching.

• Sampling principle, digital oscilloscope, and programmable waveform generator – a task with the advanced measurement with the oscilloscope, verification of the sampling theorem, principle of an arbitrary generator, and work with the oscilloscope trigger. The purely hands-on task focused on the skill to handle the instruments. Similarly, like the task dealing with frequency and period time measurement by a counter, this task cannot be handled remotely, and only the recorded video is offered.

• Resistance measurement – complex task explaining the problem of measurement resistances, focusing on small resistances, 4-wire connection, thermoelectric voltages, and series comparison methods, introducing resistance-to-voltage convertor with OA. Students must experimentally verify the different techniques used for the resistance measurement, its limitations (in the case of the resistance magnitude), and its advantages. The task can be measured remotely unchanged.

• Unbalanced Wheatstone bridge - evaluation of resistance change of Pt1000 temperature sensor – the task is showing the principles of Wheatstone bridges, analogue signal processing from resistance sensors, linearity of the voltage and current supply bridge, and linearized bridge with OA. Similarly, like the task of Resistance measurement, students experimentally verify the principle of the bridges and, through data analysis, calculate their linearity. Also, this task can be measured remotely unchanged.

• Digital impedance and admittance meter – laboratory measurement explaining the principle of vector voltmeter, measurement of the real and the imaginary part of a complex voltage, calculation of rectified mean voltage and effective value voltage, measurement using a digital impedance meter. Completing this task, the students understand the principles of the capacitance and inductance measurement and calculation of its serial and parallel equivalent schemes. The task can be measured, if needed, completely remotely.

• Magnetic measurements – a task that introduces the basics of magnetism, measurement of a leakage magnetic field of the transformer, hysteresis loop measurement, and calculation of amplitude permeability. In the first part, students have to experimentally determine the constant of the measuring coil by the Helmholtz coils and then use the measuring coil to measure the leakage magnetic field of a transformer. In the second part, students measure the amplitude permeability of the ring specimen as a dependency on the magnetic field strength. In the case of the distance form, the first part has to be skipped, and only the second part is measured remotely.

All the tasks are taught as real measurements during the face-to-face semester, but in the case of distance teaching, most of the tasks are designed to be transformed into remote laboratory classes. In addition, every task will be complemented by the instructional video to understand the main objectives better and to demonstrate the connection/wiring of the whole measurement circuit.

Apart from reducing the number of laboratory tasks, the repetitiveness of certain measurement types has significantly been reduced by, e.g., decreasing the number of points in which the examined characteristics are measured or evaluating the measurement uncertainty on a subset of measured points only. On the other hand, preserving the number of measuring method principles of a given topic (e.g., in resistance measurement, series comparison method, ohm method, R → U converter method) has been crucial.

Part of each task is home preparation containing several questions that prepare students to understand the measurement's issues better. These questions are awarded extra points added to the final grading to motivate the students.

As mentioned at the beginning of section 4, most laboratory class tasks have been redesigned to prepare them, in case of a need, for a remote laboratory class. For this reason, as a supplement for basic instruments like, e.g., multimeters or arbitrary generators, a set of smart bench instruments with software to connect, control and capture data remotely has been purchased. Each smart bench consists of a smart triple power supply (EDU36311A) and a two-channel oscilloscope with a digital multimeter and waveform generator (EDUX1052G).

All used instruments allow remote access to be controlled remotely. Therefore, the objective of instrumentation, in a limited way, is preserved even in the case of distance teaching.

Although the number of tasks has been significantly reduced, the demands on the measuring instruments are still considerable. Therefore, the tasks will be prepared gradually in groups of two or three, and students will have two or three weeks to complete them. Moreover, in the case of online teaching, the remotely measured tasks will also be captured by the camera to help the students better to understand its principles, schematics, and connections. On the other hand, in the case of pre-recorded videos, the fundamental objectives of teamwork, ethics in the laboratory, and communication are essentially limited in all tasks.

An example of the measuring tasks, "Digital impedance and admittance meter," connected to the smart bench is in Figure 6. A camera continuously monitors the task to help the students be oriented. By this, students can compare the connection with the circuit diagram and see the instruments used. In the following step, students have to connect to the instruments remotely and set the power supply, generator, digital multimeter, and scope. In this case, the measurement is performed in two steps. Firstly, the real part of the output voltage is measured, and the corresponding waveform is displayed. In the second step, the phase difference of 90° has to be set to measure the imaginary part of the output voltage and corresponding waveform.

An integral part of the task, performed and controlled remotely, is a suitable remote access method to the controlling computer or directly controlling instruments if needed. An overview of software technologies presents in the article [32]. It introduces the main characteristic of the remote laboratory and its implementation from the client-server side. On the other hand, the selected method must comply with the institution's IT security policies and not only allow remote access (usually of several students at a time) to the task but must also restrict access privileges to only those students who need to work on the task. Based on this, the proposed solution uses Apache Guacamole open-source platform for a remote desktop gateway primarily used by the IT of CTU in Prague.

This will be supplemented with an interactive calendar, implemented in Moodle, an open-source learning management system, where students register in advance and thus reserve access to a specific task at a time that is convenient for them and complete the task at any time.

All the proposed changes have been incorporated in the winter semester of 2022. The program board has positively received them. Moreover, informal feedback from the students during the first semester taught in the changed form (winter 2022) indicates a step in the right direction. The home preparation helped the students better understand the essence of the experiment, and the reduced number of tasks reduced the student's workload and increased interest in a deep understanding of the discussed topic. Therefore, it is believed it will motivate students to pass the subject successfully.

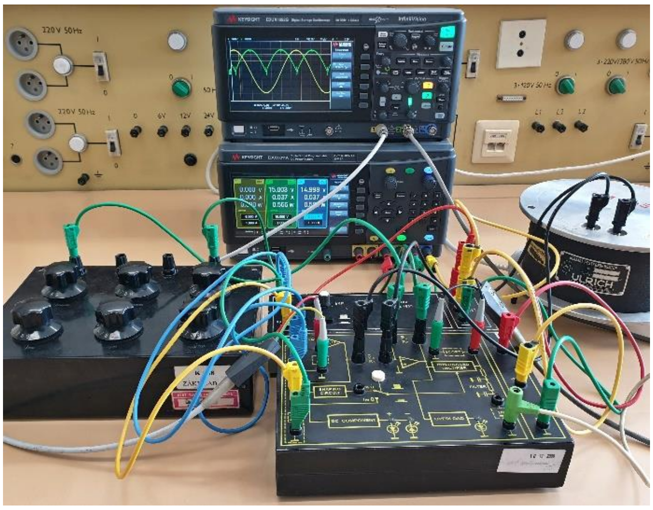

Figure 6. Measurement task: digital impedance and admittance meter prepared for remote measurement.

5. CONCLUSION

The article describes how COVID-19 changed the Electrical measurement subject taught at CTU in Prague, Faculty of Electrical Engineering, Department of Measurement. The Electrical measurement subject is hands-on laboratory class-oriented, and the impact of COVID-19 was radical. It has been shown how the classes were taught in the pre-COVID-19 era and how the COVID-19 lockdown struck it. The fast response and recorded laboratory tasks helped to overcome the lockdown acceptably. The student survey revealed the subject's shortcomings and showed how the laboratories had to change. All the old tasks have been redesigned and reduced to preserve the fundamental objectives.

Moreover, the reworked tasks have been designed with an emphasis put on the possibility of switching to distance teaching. Still, in the case of a distance form, the fundamental objectives of teamwork, ethics in the laboratory, and communication are essentially limited. All the adjustments made to improve the quality of the course have been made to maintain the quality, content, and objectives of the tasks in the case of a possible future lockdown.

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