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IMPLEMENTATION OF THE EQUIVALENT CIRCUIT METHOD IN INSTRUMENTAL DIGITAL DIDACTICS

Abstract. Instrumental digital didactics is based on the use of various digital means of obtaining, processing, and interpreting empirical data in accordance with the logic of scientific method and engineering design. Appropriate teaching techniques reflect the STEM approach to teaching natural science and engineering subjects. The use of the equivalent circuit created on the NI Multisim platform to investigate the characteristics of electric circuits' components creates favorable didactic conditions. The methodological approaches proposed by the authors are demonstrated by the examples of determining the parameters of technologically advanced devices - photoelectric converter (for example, determining its maximum power point, as well as Fill Factor) and supercapacitor (for example, designating changes in charging and discharging characteristics depending on the type of construction). In such educational projects the parameters of the circuit components obtained by the equivalent circuit method are compared with the specifications of commercial devices available on the market. This approach, on the one hand, demonstrates statistical errors of results to the students, and on the other hand, it is a source of sufficient data for constructing an equivalent circuit of devices without prior experimental research. It is shown that the use of equivalent circuits in a computer simulation environment to replace real electronic and electrical devices, measuring systems and equipment with their virtual counterparts expands the didactic possibilities. Techniques based on the versatile use of digital didactic tools are being actively developed and implemented in the MANLab STEM-laboratory of the National Centre "Junior Academy of Sciences of Ukraine".

Keywords: equivalent circuit; NI Multisim; instrumental digital didactics; STEM; supercapacitor; photovoltaic converter.

1. INTRODUCTION

The problem statement. An important component of instrumental digital didactics (IDD) and today's STEM-oriented educational environment is modern software for modelling and simulating the operation of electronic circuits. In this context, several generations of Multisim software manufactured by National Instruments Corporation® which are used to model and design analog and digital electronics circuits in the educational and research fields are particularly popular nowadays. NI Multisim contains an advanced SPICE-based stimulator integrated with an interactive circuitry environment for instant visualization and analysis of electrical and electronic circuits as well as a device library containing more than 30,000 circuits available in the community. Its intuitive interface and advanced help create comfortable didactic conditions for students to gain knowledge of circuit theory, improve the learning of certain elements of the entire curriculum, and assist in the exploration of a process through changing factors of influence. From the standpoint of training future engineers, NI Multisim helps researchers and designers reduce the number of PCB prototype cycles and, thus, reduce device development costs, create electronics learning opportunities through an interactive, online-optimized touch panel environment, appropriate for any personal computing device.

The software for electrical modelling includes virtual electronic components that can be modified, virtual measuring devices, PCB development tools, and libraries of some basic models of real elements. They are used to design a variety of electronic devices, virtual testing and circuit diagrams debugging. The main features of NI Multisim modelling software can be applied in the STEM-based learning process to combine real and virtual laboratory projects. Moreover, they can be also used for research based on the creation of equivalent circuits of real elements.

Analysis of recent studies and publications. The analysis of the Internet content has shown that the concept of "digital didactics" is often used in various announcements and headlines of digital resources and their parts. R. Krumsvik and A. G. Almås were among the first to substantiate the concept of digital didactics as a means of managing the flow of knowledge in the era of digital society and digitalization of education [1]. A comprehensive study of digital didactics as a means of producing new knowledge was carried out in the works of scientists led by I. Jahnke [2, 3, 4]. In particular, it has been shown that the structure of digital didactics includes learning objectives, learning activities and their evaluation, interactions between an individual and the society, and integration of technology on different levels. F. Perri showed that digital didactical designs significantly change the structure of teachers' activities, as teachers begin to act as engineers of educational tools [5].

S. Pedrosa and T. Tortori were among the first to demonstrate the significant effect of digital didactics on the study of natural sciences based on creativity, interactivity, and interdisciplinary interaction: the use of digital technologies significantly stimulates the learning process if these technologies are successfully combined with traditional teaching methods [6].

It is the aspects of the use of digital technologies in the study of natural sciences at the stages of the real (natural) experiment, measurement (acquisition), and analysis of numerical data that created the basis for the application of the concept of instrumental digital didactics. It is a part of digital didactics and it reflects educational activities involving technical and technological means of gathering and processing empirical data obtained during a scientific experiment. IDD complements the scientific method of conducting research and engineering design with the capabilities of creating interactive computer models, visualizing experimental data, comparing it with theory, and predicting the course of the process.

IDD tools perform the following functions:

- search for the reference literature, documentation of research, modeling of specific tasks, monitoring of academic achievements;
- obtaining empirical data with the appropriate devices (measuring instruments);
- a means of processing the numerical results of the experiment (software for various calculations and data visualization, model building, etc.).

Therefore, in the context of our study, the method of using equivalent circuits in the NI Multisim environment is a practical example of the IDD application**.**

Research on networking resources, such as the Research Gateway and the Google Scholar Search Engine, has shown that NI Multisim has been a popular engineering and training software for over a decade, gradually replacing Electronics Workbench. Considerable didactic experience in using different generations of NI Multisim as a platform for a simulation laboratory for computer-based engineering education was obtained at the Faculty of Electrical Engineering in Gdynia Maritime University. Long-term research led by K. Noga shows that simulation environments create a didactic bridge between theoretical lectures and practical application in teaching students to design, prototype, and test electrical and electronic circuits [7]. Scientific results of P. Ptak [8] demonstrate the effectiveness of methods of teaching engineering disciplines using simulation programs NI Multisim and NI ELVIS. In addition, Lyubomirov et al. have shown that the competence to understand the difference between the properties of real and virtual elements of a circuit will be deeper if laboratory projects incorporate actual measurements of a real electric circuit and a simulation model [9]. In Srikanth et al.'s opinion, educational simulations of electric circuits and their elements based on NI products (Multisim, LabVIEW, myRIO) increase students' perception of theoretical and mathematical models and are effective in organizing project-oriented learning [10].

It should be noted that the use of simulation programs to study the characteristics of future nano generation electronic circuits that are still in the experimental phase is of utmost importance for learning activities. Such a technologically and didactically attractive nonlinear passive element that can store the previous resistance value is a memristor [11]. Inamuddin et al. [12] demonstrate an interesting example of developing an emulator of this device and studying its characteristics using multi-band modelling.

The study also showed that NI Multisim application now goes beyond the simulation of electric circuits and can be used to describe and model processes in solid mediums or biological systems in which current does not actually flow in defined circuits, for example, for interactive predictive simulation of flows in reservoirs (in particular, layered, heterogeneous, anisotropic media, etc.). For instance, W. Chin & X. Zhuang [13] cite the results of modelling flows in professional quality in the Ni Multisim environment, performed by secondary school students in the framework of an educational program funded by some of the world's largest energy companies.

The research of didactic features of the study of electricity and the basics of electronics, in particular with the use of simulation programs, for example, NI Multisim 11.0, is one of the activities of the STEM-laboratory of the National Academy of Sciences of Ukraine "Junior Academy of Sciences of Ukraine". Some of the techniques tested by Atamas et al. are designed in the form of a workbook [14] and are available freely as instructions on the online resource stemua.science [15]. Among the didactic developments, the list of which is being constantly updated, educational methods of modelling and research of the amplifier (definition of its characteristics within sound frequencies), the generator of a sinusoidal signal (determination of its frequency and comparison with the calculated one), the bridge rectifier of an alternating current, voltage multiplier (comparison of the calculated amplitude value of the alternating voltage and the value of the output constant voltage of the multiplier with the one measured during the simulation) are posted on stemua.science [14]. Note that each project is accompanied by process charts that include, among other things, step-by-step procedures for using Multisim 11.0, as well as data table templates for processing the results of the experiment.

The process of modelling of electronic devices with further study of their characteristics in this software environment requires the involvement of experimental data and statistical error analysis with relevant software, such as Microsoft Excel. In particular, the purpose of the laboratory project "Study of the oscillatory circuit" is to compare the calculation of the resonant frequency and the quality factor of the oscillatory circuit with the results obtained in the process of modelling using the program Multisim 11.0 [15]. For example, M. Djalal and H. Hr [16] demonstrate a technique for studying the amplifying properties of a transistor, in particular, establishing the dependence of the gain on currents of the simulated electrical circuit.

Our research has shown that, despite the popularity of NI Multisim and other similar software products as a means of special engineering training, the didactic principles of their use for teaching young people of school age have been studied very little. Particular attention in this context should be paid to teaching techniques based on the STEM approach, which include, in addition to conducting a full-scale experiment with real devices in electrical circuits, the design procedure, and the analysis of equivalent substitution schemes.

The article's goal. The aim of the article is to demonstrate practical experience on the didactic applications of electrical modeling environments and to present STEM-oriented teaching methods, which are based on the creation and study of equivalent circuits of technologically advanced devices.

2. RESEARCH METHODS

In the conducted pedagogical research theoretical and empirical methods were used. Theoretical methods include a conceptual and comparative analysis of approaches to the study of physical and engineering disciplines using STEM-approach, relevant information on the problem, innovative pedagogical experience and generalization of our own extensive experience. Empirical methods are, first of all, pedagogical experiments, as well as observational methods (direct, indirect, including observation), psychodiagnostics methods (conversations with teachers and students) and praximetric methods (chronometry, analysis of completed research works). In addition, the study used physical experimentation, computer simulation and analysis of theoretical data, such as the physical and technical characteristics of the devices being investigated.

At the previous stage, the authors have checked the technical characteristics of each device and training methods based on their use. So, for modelling and research of the equivalent circuit of the photovoltaic converter in Multisim 11.0, its configuration and parameters were taken from literature sources. The obtained data were transferred to the Excel environment and I-V curve for photovoltaic converter and dependence of its power on voltage were built. According to these characteristics, the main parameters of the photovoltaic converter were determined: open circuit voltage U_{voc}, V, short-circuit current I_{csc}, A, voltage and current at the maximum power point U_m and I_m, respectively, Fill Factor (FF),%. In order to determine the suitability of the obtained equivalent circuit of the photovoltaic converter for use in virtual training studies, the experimental parameters obtained were compared with the values of their commercial counterparts.

Preliminary testing of the equivalent circuit technique to study the characteristics of supercapacitors was carried out using their three models (EECF5R5U105 (Panasonic) 1F 5.5V, SE-5R5-D105VYV (KAMCAP) 1F 5.5V, ESHSR-0005C0-002R7 (NESSCAP) 5F, 2,7 V), a training set for electric circuits, a digital measuring complex with voltage and current sensors, an adjustable power source, and a multimeter. The digital measuring system software was used to obtain charging and discharging characteristics. As a result of the testing, equivalent supercapacitor replacement circuits were built, the parameters of which were not reported to the students. Equivalent circuits of substitution were modelled in Multisim 11.0. Comparison of the charging and discharging characteristics of the supercapacitors obtained in the virtual and the real experiment was the basis for the conclusion about their suitability for further didactic development as a research project. The technical documentation of the supercapacitors, which is freely available on the network, was also analyzed. The purpose of this analysis was to determine whether the technical documentation contained data (eg, Rated Capacitance, Rated Voltage, Internal Sequential Resistance (ISR), and Maximum Leakage Current) that are sufficient to build an equivalent circuit of a supercapacitor without conducting preliminary experimental studies.

Didactic approbation of the educational research projects "Research of the supercapacitor and construction of its equivalent circuit" and "Study of the issue of reconciliation of electrical load with the photoelectric element" was carried out with the participation of students of 8 - 11 forms, who participated in the project "Summer Physical and Technical Schools" in 2016-2019. As a result of the test, the students built equivalent circuits for the same supercapacitors that were used by the authors during the pre-test. After conducting the research, the parameters of equivalent circuits obtained by the students were compared with those obtained during the testing. The procedure for the defence of research results included, in addition to the presentation, answers to questions on the research. The level of assimilation of the processed material was evaluated based on completeness of the answers to the questions.

3. THE RESULTS AND DISCUSSION

Equivalent circuit in STEM didactics. An equivalent circuit of a real element is an electrical circuit consisting of a set of idealized elements that fully reproduces the properties of the real element and provides the specified functional properties of the structure [17]. Dictionaries define the equivalent circuit as a simple RLC circuit whose power reproduces (duplicates) the power of a more complex circuit or network. However, equivalent circuits can be more complex, reproducing the nonlinearity of the source circuit parameters applied to various DC and AC simulations. The main advantage of using equivalent circuits is the ability to detect and investigate changes in the properties of an element of an electric circuit, depending on its internal parameters, such as internal resistance, which cannot be changed in a real element. For example, they are indispensable in the design of devices for describing the parameters of bipolar transistor elements. In the case of simple applications, for example, when the transistor is used as a key, this is not necessary: creating a certain potential at the base of the transistor effectively determines the closure of the other part of the circuit. However, when using a transistor as an amplifier, there are many nuances to consider, which can be done on the basis of equivalent circuits. For example, the equivalent circuits of the Hybrid-pi[1]take into account the sequential supports and capacitances of the "base-emitter" and "base-collector" junctions, which affect the frequency characteristics of these devices, in particular, their input and output impedance and how they are polarized in the circuits. Another example that demonstrates the effectiveness of using equivalent circuits is the availability of the ISR in the capacitors. Thus, in the process of creating electrical circuits, assuming the ideal characteristics of the capacitor and taking into account only its capacity, without taking into account its own resistance, can lead to undesirable effects in electrical circuits with real elements. For

[1]https://en.wikipedia.org/wiki/Hybrid-pi_model

example, power supply units in the output capacitors may experience voltage ripples as a result of its decrease in the ISR. In addition, capacitors have a parameter of the sequential inductance ESL (Equivalent Sequential Inductance), which is especially important when designing electrical circuits with electrolytic or film capacitors to avoid ripples and unwanted effects in the frequency characteristics of the circuits.

An example of equivalent circuits modelling is the creation in the NI Multisim environment of a model photovoltaic converter (Fig. 1) that provides a possibility to perform virtual experiments to study the characteristics, in particular to determine IVC and the position of the maximum power point. The methodological aspects of the realization of this task are reflected in the research paper “The investigation of adjustment of photovoltaic cell electric load”, which is relevant to modern renewable energy, presented at stemua.science.

Equivalent circuit of the photovoltaic converter shown in Fig. 1 contains a photocurrent source I1, diode D1 and resistors R1 and R2. The photocurrent density of I1 is in the range of 28… 35 A/cm^2 and is almost equal to the short-circuit current density for modern commercial photovoltaic converters. Diode D1 models the p-n junction of the photovoltaic converter. For this purpose, in the NI Multisim environment a virtual diode is selected and its two parameters (saturation current and ideality factor p-n junction) are set. It is taken into account that the saturation current density of p-n transitions of modern photovoltaic converters averages 10^{-10} A/см^2 [18], and the ideality factor of p-n transition of modern silicon mono- and polycrystalline photovoltaic converters is usually within 1.2 … 1.3 [18]. In addition, the specific value of the R1 resistance, depending on the design and purpose of the photovoltaic converters, may range from 0.1 to several Ω·cm^2 [18], [20]. In modern high-quality photovoltaic converters, the value of the parallel (shunt) resistance of R2 is usually more than 1 kΩ·cm^2 [19], [20]. Based on the above, parameters of an equivalent circuit photovoltaic converter with standard dimensions 156×156 mm and an area of approximately 240 cm^2 (taking into account the form of "pseudo-square") may be as follows: photocurrent - 8 A; saturation current - 24nA; sequential resistance - 4.2 mΩ; parallel resistance - 40 Ω.

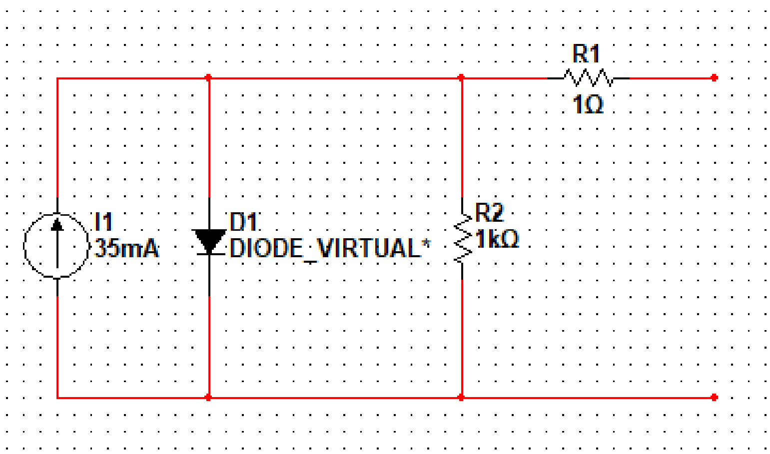

Fig. 1. Example of an equivalent circuit of the photovoltaic converter in NI Multisim environment (parameters are calculated for 1 cm^2)

Equivalent circuit of the photovoltaic converter was modelled in Multisim 11.0 with the specified parameters. The circuit also includes variable load resistance R3 and virtual meters - voltmeter and ammeter. For typical configurations and element parameters, this equivalent circuit of the photovoltaic converter contains a photocurrent I1 source, diode D1, sequential resistance R1, and parallel resistance R2 (Fig. 2).

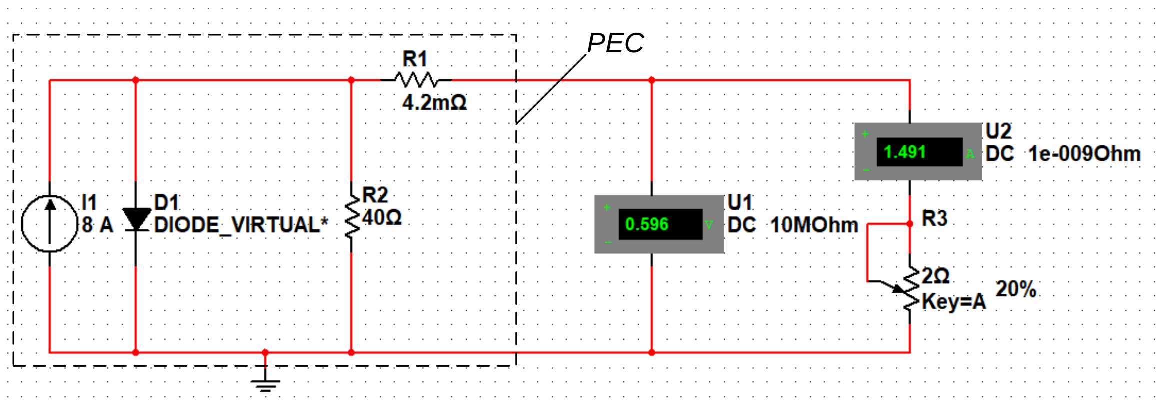

Fig. 2. Equivalent circuit photovoltaic converter with an area of 156×156 mm in NI Multisim 11.0

After modeling the equivalent circuit in the NI Multisim 11.0 environment, the I-V curve of this photovoltaic converter is built (Fig. 3), which determines its main parameters: no-load voltage, short-circuit current, voltage and current at maximum power, and Fill Factor.

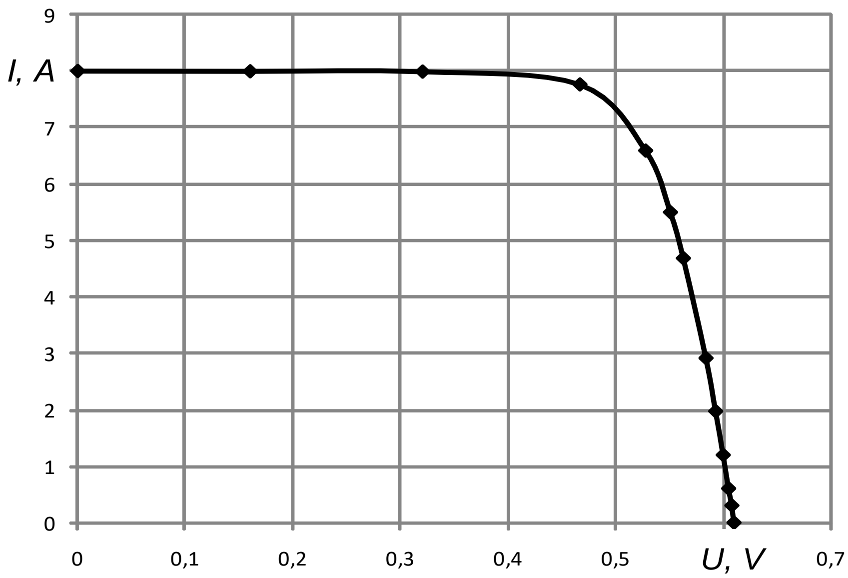

Fig. 3. I-V curve of the photovoltaic converter according to the simulation results in Multisim 11.0 and built using Microsoft Excel

To determine the optimal load of the photocell, it is necessary to determine the position of the point of maximum power. For this purpose, the Excel environment can be used to calculate the power of the photovoltaic converter, multiplying the voltage by the current at each point of I-V curve, and build a graph of power versus voltage (Fig. 4). According to this graph, with sufficient accuracy for educational purposes, it is possible to determine the maximum photovoltaic converter power (≈ 3.65 W) and the voltage (≈ 0.49 V) corresponding to the maximum power, and then calculate the current, which will turn out to be 7.45 A for this point. According to Ohm's law, the optimum load resistance can be determined for the circuit section (in this example it is 0.0658 Ω).

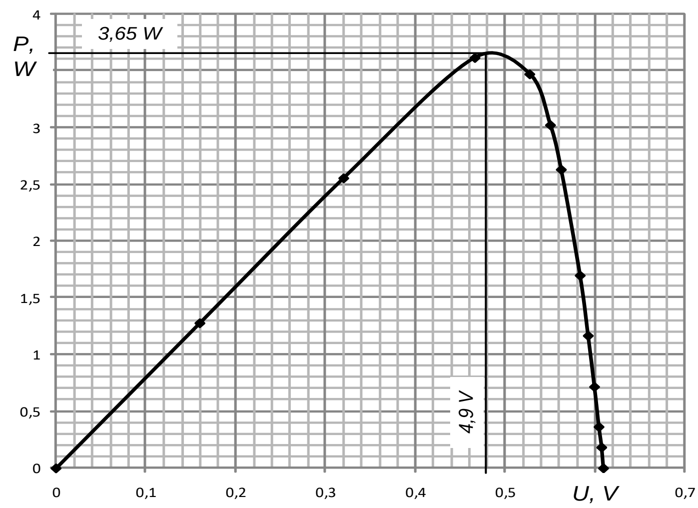

Fig. 4. Dependence of P=f(U) for the photovoltaic converter

An important characteristic of a photovoltaic converter, which is always specified in the technical documentation of this device, is the Fill Factor (FF), which is determined by the formula:

$$FF = \frac{U_m \cdot I_m}{U_{voc} \cdot I_{csc}} = \frac{P_m}{U_{voc} \cdot I_{csc}}, \tag{1}$$

where U_m and I_m – respectively voltage and current at maximum power point; P_m is the maximum power of the photovoltaic converter; U_{voc} – open-circuit voltage (voltage in the absence of a load corresponding to a point on the IVC at which the current is 0 A); I_{csc} – short-circuit current, (current at 0 Ω load resistance and 0 V voltage) [21]. Thus, in our example, we determined the maximum power (3.65 W), voltage, and current at maximum power (0.49 V; 7.45 A), as well as the Filling Factor of the I-V curve (74.9%).

Comparison of the basic parameters obtained by modeling and investigating the equivalent circuit of the photovoltaic converter with the performance of their real counterparts with dimensions of 156×156 mm, gives grounds to conclude that the equivalent circuit corresponds to some average commercial photovoltaic converter that can be used for educational research, for example, to perform the research project "Study of the coordination of electrical load with a photocell". Further development of our proposed technique can be, for example, the study of the dependence of the position of the point of maximum power on the magnitude of the sequential and parallel resistances. It is also possible to simulate and study a solar battery made of several such devices, as well as other electronic products and elements, based on the equivalent circuit of a single photovoltaic converter.

Features of the supercapacitor as a didactic tool. A supercapacitor, or ionizer, is an electrochemical device, a capacitor with an organic or inorganic electrolyte, with a double electrical layer at the interface between the electrode and the electrolyte as the covers of the capacitor. From the scheme of the symmetric supercapacitor structure (Fig. 5), it can be seen that a double electrical layer is formed at each of the two electrodes. Therefore, in fact, a supercapacitor consists of two double electrical layers connected in series through a liquid conductive electrolyte with a certain resistance, which can be charged like the covers of a conventional capacitor. In addition, these devices have a leakage current, or self-discharge current, due to the peculiarities of their structure and the imperfection of electrochemical processes. According to their characteristics, supercapacitors occupy an intermediate position between the capacitor and the chemical current source [22].

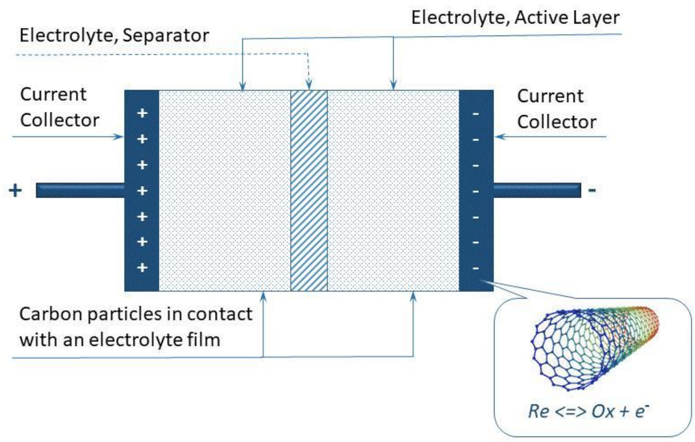

Fig. 5. Scheme of supercapacitor structure

Obviously, a special role in the functioning belongs to the electrodes. They are usually made using porous materials such as activated carbon, foamed metal, or new carbon material, graphene [12]. Synthesized and modified materials with specified (desired) properties based on graphene, in particular, graphene oxide, fullerenes and carbon nanotubes (from zero to three-dimensional, from microporous to mesoporous (Fig. 5, right, bottom)) best meet specific design configurations requirements of modern supercapacitor devices and architectures for electrochemical energy storage [23]. Electrodes made of such materials have a very large specific surface area per unit mass, and therefore a large area of the double electrical layer, due to which supercapacitors have a large electrical capacity.

The main physical and technical advantages of supercapacitors over conventional batteries are the much higher charge/discharge currents and large cyclic life (up to 1 million charge-discharge cycles), and the main disadvantage is less power consumption than batteries. This determines their use as independent energy storage, additional storage of electric energy as components of batteries together with electrochemical batteries, smoothing capacitors for rectifiers [22], [23], [24]. Supercapacitors are also used as stand-alone power storage devices – backup power supplies for motherboards, microprocessors, and storage devices. They are also effective in cases where high energy consumption is not required, but high charging and discharging currents are important, for example in internal combustion engine starting systems, uninterruptible power supply systems, peak power equalization systems, electric vehicle braking systems, etc. Supercapacitors can also be additional elements in renewable energy storage devices: their use together with electrochemical batteries can significantly expand the range of current loads of the drive and improve the operating conditions of the electrochemical batteries.

Importantly, the design of the morphology supercapacitors significantly increases the number of applications for a wide range of potential solutions, including related electronics, commercial gadgets, hybrid electromobiles, stationary and industrial frameworks.

Educational research of the supercapacitor and construction of its equivalent circuit. The method of equivalent circuits is effective in measuring the electrical characteristics of new synthesized structures for electronic devices. A striking example is the study of the structure of carbon supramolecular structures with a hierarchical architecture. In particular, the potential intervals of capacitive and pseudocapacitive energy accumulation at the interface with the electrolyte were identified, and the relationship between the porous structure, electronic properties of nanoporous carbon, and capacity at the interface between the electrolyte was investigated [25].

Consider another example of the use of equivalent circuits in our educational research project "Research of a supercapacitor and construction of its equivalent circuit", located in the section "Research projects" of the educational portal stemua.science. Note that the equivalent circuit reflects the capacitance of each double electrical layer separately. This design demonstrates not only the properties but also the structure of the supercapacitor, which is a didactic advantage compared to the circuit with fewer elements, which we present in [24]. To create a model, students experimentally determine the total capacity of the device, internal resistance, and leakage resistance, using a real supercapacitor and a digital measuring system. This procedure can be performed according to the method of laboratory project "Capacitor Research" [14].

A further development of this project may be the study of changes in the charging/discharging characteristics of the supercapacitor when reducing/increasing its internal resistance. It is known that the internal resistance of a real supercapacitor is almost impossible to change without damaging it, so in this case it is advisable to investigate its equivalent circuit, created, for example, in NI Multisim (Fig. 6).

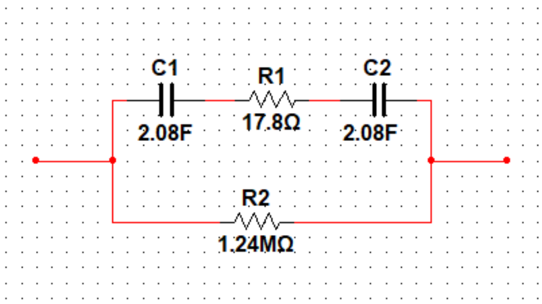

Fig. 6. Equivalent circuit of the supercapacitor in NI Multisim 11.0

For this purpose, it is convenient to simulate two equivalent circuits - one with the actual internal resistance, and the other - with changed (doubled or halved). At the same time, one should measure the charging and discharging characteristics in parallel, using a dual-channel oscilloscope.

In Fig. 7 there are two equivalent circuits for measuring the charging and discharging characteristics of the two supercapacitors: SC1 has an actual internal resistance R4 = 17.8 Ohms, and SC2 has twice the internal resistance R1 = 35.6 Ω. The test devices are connected to separate power supplies via the same 39 Ω R3 and R6 resistors. Switching keys S1 and S2, makes the devices charge through these resistors, and switching the keys back leads to discharging through the same resistors. The oscilloscope has two channels: channel A - for CC1 with normal internal resistance, and channel B - for CC2 with increased internal resistance.

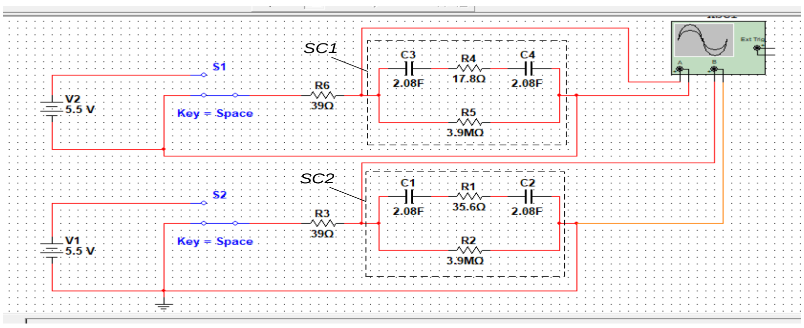

Fig. 7. Scheme for measuring charging and discharging characteristics of two supercapacitors with different internal supports

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To obtain the charging and discharging characteristics, one has to open the window of the oscilloscope, set the offset "-2" on channel B, and run the simulation of the circuit. After starting the simulation, switch keys S1 and S2 to charge. Next, wait until the voltage on the supercapacitor stops rising, and switch the keys to discharge. When the voltage drops to 0 V - stop the simulation. The charging and discharging characteristics of supercapacitors can be compared using oscilloscope tools (Fig. 8). Note that to perform this study, synchronous switching of keys is not essential. In the case of other projects, where there is a need for synchronous switching of keys, they can be replaced by a circuit built using relays, which are also available in the library Multisim 11.0.

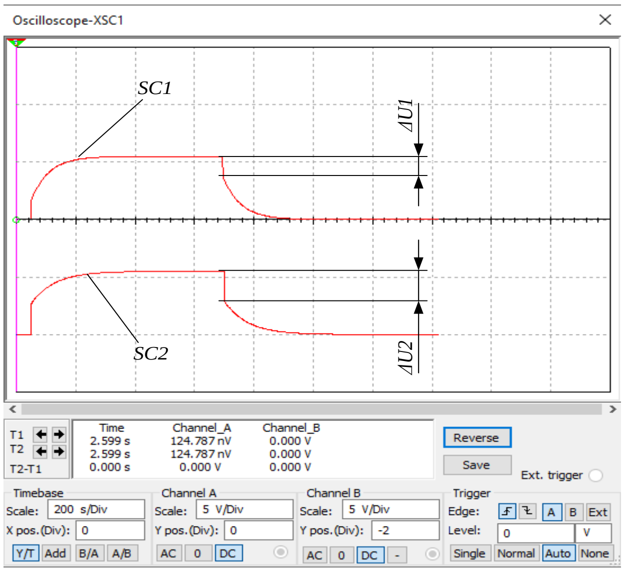

Fig. 8. Graphical dependency U=f(t) for equivalent circuits of the supercapacitors in NI Multisim 11.0

The obtained characteristics differ from each other, in particular, by the values of voltages ΔU1 and ΔU2 during the transition to the discharge mode (ΔU1 and ΔU2 increase along with the internal resistance). These values can be determined for both supercapacitors using oscilloscope tools that students master during the laboratory workshop [14]. One can determine the exact values of voltage and time with the oscilloscope using the buttons T1 and T2 in the lower left part of the oscilloscope window (Fig. 8). In addition, the NI Multisim 11.0 oscilloscope provides a possibility to save graphs as a text document ("Save" button in the oscilloscope window).

The authors' analysis showed that the technical documentation available for free contains technical data sufficient to build an equivalent circuit of the supercapacitors without prior experimental research. Therefore, if it is not possible to perform measurements using a real device, then its equivalent circuit can be built based on the passport data of any such industrial product. The nominal capacitance of this supercapacitor is 5 F, so the capacitances of the double electrical layer of positive and negative electrodes in the equivalent circuit will be $C1+C2=2\cdot C = 10$ F, as demonstrated in the research project "Research of the supercapacitor and construction of its equivalent circuit» [14]. After assembling the equivalent circuit in the Multisim 11.0 environment, it can be investigated by changing both the internal (internal resistance, leakage resistance) and external (load resistance) parameters of the electrical circuit.

Experiments with a real supercapacitor are carried out using laboratory equipment, a digital measuring system and software (Fig. 9).

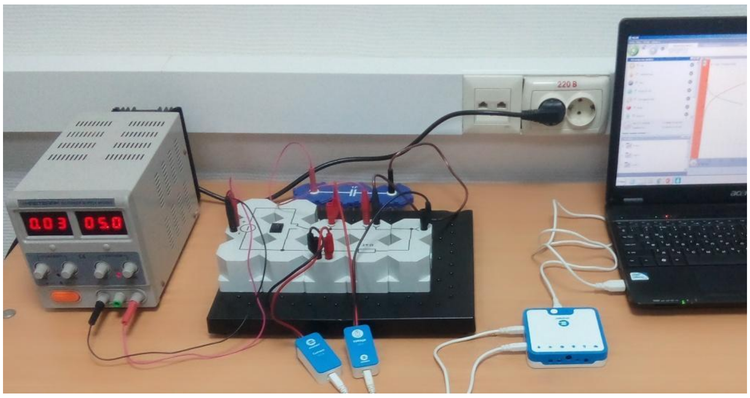

Fig. 9. Experimental setup for measuringcharging / discharging characteristics of the supercapacitor

The data obtained in the software environment of the digital measuring complex are presented in the form of graphical dependence *U*=*f*(*t*) and *I*= *f*(*t*) (Fig. 10), which makes it possible to determine the parameters of the equivalent circuit. At the same time, in the NI Multisim 11.0 environment, an equivalent circuit supercapacitor is built and the charging / discharging characteristics are measured (Fig. 8). The comparison of the graphs leads to the conclusion about their identity, which confirms the correctness of the model and gives grounds for further virtual studies (change of serial and parallel internal resistances, load resistance, supply voltage, etc.).

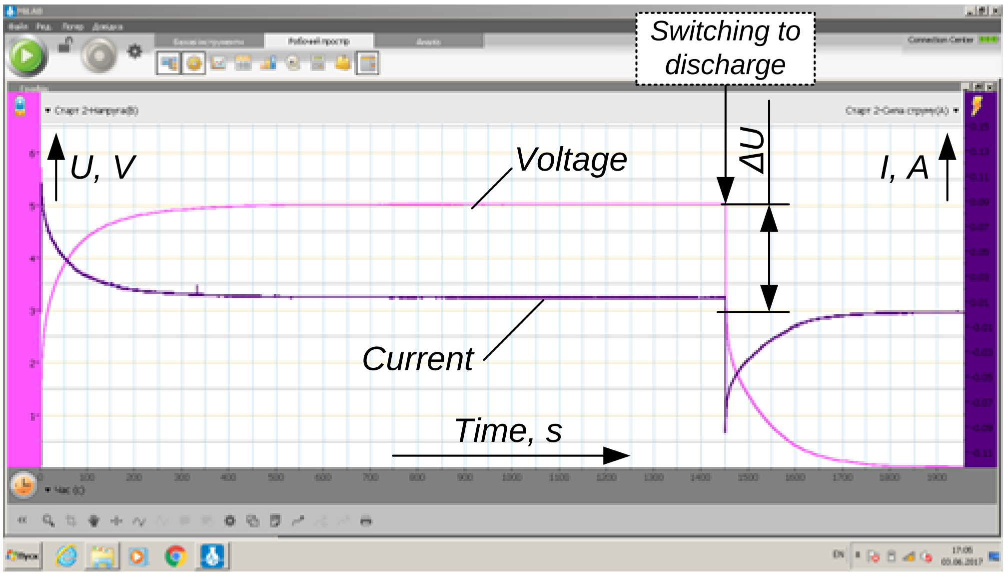

Fig. 10. Experimental graphical dependence of U=f(t) and I= f(t)
for supercapacitor in MiLab environment (screenshot from PC screen)

Equivalent circuits are an important component of IDD, which creates opportunities for the improvement of planned school laboratory work from being composed of educational activities according to a certain algorithm to the one that involves educational research (Fig. 11).

The suggested method of conducting research using equivalent circuits was tested in the activities of summer schools of the National Center "Junior Academy of Sciences of Ukraine", involving students from different regions of Ukraine. The parameters of the equivalent schemes obtained by the students turned out to be quite close to the parameters obtained by the authors during the approbation, and the discrepancy between them did not exceed 10%, which is quite justified for school educational research. A comparison of the charging and discharging characteristics of the supercapacitor obtained by virtual and real experiments showed their identity. During the defence, students confidently answered the questions on the topic of the study, indicating a high level of assimilation of the material they processed during the experiment and preparation of the presentation. This experience confirmed the effectiveness of using the equivalent circuits of supercapacitor in laboratory classes of different complexity levels.

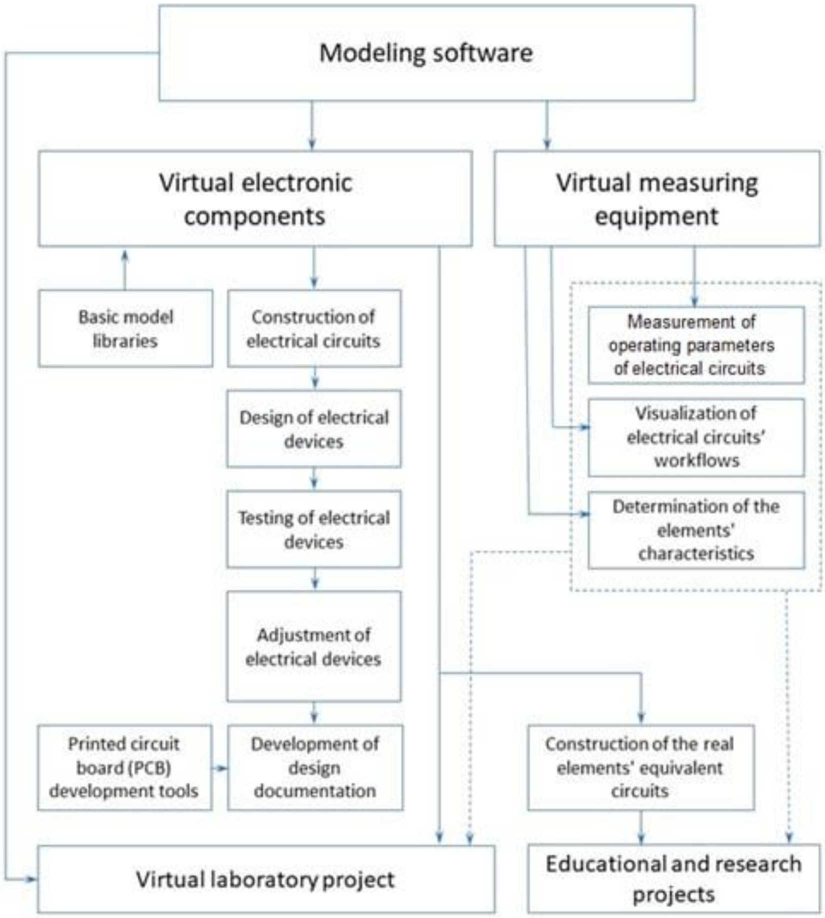

Fig. 11. Modelling software in IDD

4. CONCLUSIONS AND PROSPECTS FOR FURTHER RESEARCH

Computer simulation of equivalent circuits is an important and convenient engineering and didactic tool in STEM training, as it provides a possibility to identify, investigate, mathematically accurately describe the properties and take into account the processes occurring in a real element of an electrical circuit. An important feature of methods using equivalent circuits is the possibility of conducting research projects, which can not always be carried out using real electronic and electrical devices with real measuring systems and equipment. Such circuits for electronic components can be obtained both from previous experimental studies and from open source passport data. Therefore, simulation of equivalent circuits, as shown with the example of photovoltaic converter and supercapacitor, can be both a complement to experimental studies and an independent research.

The article provides only a few examples of didactic application of equivalent circuits based on the use of the NI Multisim package. The NI Multisim software environment can also be used remotely, for example, by means of one of the versions installed in the STEM-laboratory of MANLab. Remote access is carried out via Team Viewer in accordance with the laboratory projects schedule using the tools provided [15]. Students can create schematics on a single circuit board while in remote access, which optimizes the use of time in the lab. In addition to NI Multisim, other simulation programs can be used in the didactics of modeling and research of simple equivalent circuits, such as EveryCircuit, which is free and adapted for smartphones and other gadgets.

Development. Our future plans will focus on the development of methods of embedding the research projects in the training programs. In particular, such projects would involve the applications of the equivalent circuits to study certain technologically advanced devices, such as supercapacitors, photovoltaic converters, inductors and other electronic components in accordance with their documentation and simulations performed in the computer environment. One of the tasks can be an experimental comparison of the characteristics of virtual and real objects in order to investigate the differences between them and to provide the relevant justification.

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ВИКОРИСТАННЯ МЕТОДУ ЕКВІВАЛЕНТНИХ СХЕМ В ІНСТРУМЕНТАЛЬНІЙ ЦИФРОВІЙ ДИДАКТИЦІ

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Анотація. Інструментальна цифрова дидактика ґрунтується на використанні різноманітних цифрових засобів отримання, обробки та інтерпретації емпіричних даних за логікою наукового методу та інженерного проєктування. Відповідні методи навчання відображають STEM-підхід до викладання природничих та технічних предметів. Використання еквівалентних схем заміщення на платформі NI Multisim для дослідження характеристик компонентів електричних ланцюгів створює сприятливі дидактичні умови. Запропоновані авторами методичні підходи продемонстровано на прикладах визначення параметрів технологічно перспективних пристроїв – фотоелектричного перетворювача (наприклад, визначення його максимальної точки потужності, а також коефіцієнта заповнення) та суперконденсатора (наприклад, виявлення залежності зарядних/розрядних характеристик від типу конструкції). У таких навчальних проєктах параметри компонентів схеми, отримані методом еквівалентної схеми, порівнюються зі специфікаціями комерційних пристроїв, доступних на ринку. Цей підхід, з одного боку, демонструє учням походження і величину похибок, а з іншого, є джерелом даних, достатніх для побудови еквівалентної схеми пристроїв без попереднього експериментального дослідження. Показано, що використання еквівалентних схем у комп'ютерному моделювальному середовищі для заміни реальних електронних та електричних девайсів, вимірювальних комплексів та обладнання їх віртуальними аналогами відіграє важливу дидактичну роль: виконання планових лабораторних робіт на їх основі може бути розвинутим від пояснювально-ілюстративного до дослідницького методу навчання. Методики навчання з використанням різноманітних цифрових дидактичних засобів активно розробляються та впроваджуються у STEM-лабораторії МАНЛаб Національного центру «Мала академія наук України».

Ключові слова: еквівалентна схема заміщення; NI Multisim; інструментальна цифрова дидактика; STEM; суперконденсатор; фотоелектричний перетворювач.

ИСПОЛЬЗОВАНИЕ МЕТОДА ЭКВИВАЛЕНТНЫХ СХЕМ В ИНСТРУМЕНТАЛЬНОЙ ЦИФРОВОЙ ДИДАКТИКЕ

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Аннотация. Инструментальная цифровая дидактика основывается на использовании различных цифровых средств получения, обработки и интерпретации эмпирических данных по логике научного метода и инженерного проектирования. Соответствующие методы обучения отражают STEM-подход к преподаванию естественных и технических дисциплин. Использование эквивалентных схем замещения на платформе NI Multisim для исследования характеристик компонентов электрических цепей создает благоприятные дидактические условия. Предложенные авторами методические подходы продемонстрированы на примерах определения параметров технологически перспективных устройств – фотоэлектрического преобразователя (например, определение максимальной точки его мощности, а также коэффициента заполнения) и суперконденсатора (например, выявление зависимости зарядных / разрядных характеристик от типа конструкции). В таких учебных проектах параметры компонентов схемы, полученные методом эквивалентной схемы, сравниваются со спецификациями коммерческих устройств, доступных на рынке. Этот подход, с одной стороны, демонстрирует ученикам происхождение и величину погрешностей, а с другой, является источником данных, достаточных для построения эквивалентной схемы устройств без предварительного экспериментального исследования. Показано, что использование эквивалентных схем в компьютерной моделирующей среде для замены реальных электронных и электрических комплектующих, измерительных комплексов и оборудования их виртуальными аналогами играет важную дидактическую роль: выполнение плановых лабораторных работ на их основе может быть развито от объяснительно-иллюстративного до исследовательского метода обучения. Методики обучения с использованием различных цифровых дидактических средств активно разрабатываются и внедряются в STEM-лаборатории МАНЛаб Национального центра «Малая академия наук Украины».

Ключевые слова: эквивалентная схема замещения; NI Multisim; инструментальная цифровая дидактика; STEM; суперконденсатор; фотоэлектрический преобразователь.