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PAPER

Effectiveness of Computer Modeling in the Study of Electrical Circuits: Application and Evaluation

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ABSTRACT

The issues addressed in this study are linked to longstanding shortcomings that have been further exacerbated in the recent practice of studying electromagnetic phenomena, particularly in the context of electrical circuits at the school level. As one approach to address the existing shortcomings, we propose strengthening the physical component in the study of electrical circuit materials. In accordance with this, the research problem can be formulated in the form of the following question: is the pedagogical expediency of incorporating modern microprocessor systems and mathematical modeling to enhance the quality of physical knowledge and the effectiveness of their application in studying electrical circuits? To address the objectives, the research employed the following methods: conducting a pedagogical experiment to assess the effectiveness of computer modeling in studying the physical foundations of electrical circuits, and performing a theoretical analysis of methodological literature. We have developed a methodology for the application of computer modeling and demonstrated its significance in creating conditions for the practical implementation of the research-based teaching approach. The conducted pedagogical experiment confirmed the effectiveness of developed approaches to utilizing computer models in the student's experimental activities. These approaches aim to foster development of intellectual abilities, cultivating a research-oriented mindset, and stimulate student's creative engagement.

KEYWORDS

computer modeling, digitalization of education, future physics teachers, electromagnetic phenomena, STEAM education, laboratory work

1 INTRODUCTION

1.1 Relevance of the study

To meet the demands of modern trends in education, it is imperative to ensure meaningful and methodological continuity in the exploration of physical concepts

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and topics, both within physics courses and special lessons. The analysis of the educational process in schools, focusing on the development of students' understanding of electromagnetic phenomena, particularly electrical circuits, reveals inadequate utilization of the subject of electromagnetism within the framework of practical teaching and understanding. The current form of both the general physics course and its departments, characterized by the formulation of educational material and the comprehension of student training into rigid templates, results in the students' adaptation to superficial preparedness and the accumulation of incomplete knowledge and skills. On the other hand, the modern approach to science aims to empower students to think critically and to utilize their communication skills to organize their knowledge and the environment in which they interact, thereby enhancing the development of the physics course [1–3].

The potentials for schools to equip classrooms with computer technology is expanding rapidly, exceeding the rate at which methodological support for the integrating computer tools with traditional forms of training is being developed [4]. In this context, the educational potential of computer-based training in general, and computer modeling specifically, has not been fully explored. The potential of employing microprocessor measuring systems, computer data processing programs, computer mathematical packages, and simulating computer applications that replicate real objects in the study of the fundamental principles of electrical circuits within the electromagnetism courses is evident. While these resources are increasingly accessible, their systematic utilization requires methodological supportand theoretical justification.

The objective of this study is to provide theoretical justification and implement a methodology for the utilization of computer modeling in the exploration of the fundamental principles of electrical circuits within general physics courses.

The working hypothesis posited that enhance the understanding of the underlying physical processes in electrical circuits, which are imperceptible tohuman senses, it is advisable, firstly, to supplement the full-scale electrical experiment with computer modeling. This integration would unveil the correlation between the mathematical employed for calculations and the actual process. Secondly, computer modeling is utilized to foster a whole and an interconnected understanding of the processes considered in different disciplines that share a common physical basis. Thirdly, the inclusion of search samples methods is advocated. This method is challenging to implement on real electrical facilities but can be readily executed through the utilization of modeling computer programs.

Recognizing the importance of a demonstration experiment in the study of electrical circuits, it should be noted that it should perform not only educational, but also developmental functions. It should facilitate the development of student's thinking abilities, observation skills, and creative imagination.

1.2 Literature review

The need to work in this direction is determined despite the ongoing discussion regarding the utilization of new information technologies in education since the turn of the last century. There are sections within which methods of using modern computer tools are yet to be established.

The analysis of scientific literature pertaining to the designated topic shows that many researchers are working in this field. However, their work is highly specialized, and their experience can be adopted only in a general sense [5–8]. The development of specific methodological techniques for incorporation of modern information technologies in teaching electrical circuits, the study of which is rooted in physics under the section of "Electromagnetism," is both necessary and relevant.

Computer modeling, as a pivotal educational method enabled by computers, includes opportunities that can be harnessed to deliver more effective explanations of the physical foundations of electrical circuits within general physics courses. We can summarize these opportunities as follows [1,2]:

- Enhancing the accessibility of the provided training material and easing the burden on educators by reducing the course load;
- Simulating challenging experiments in a virtual laboratory, enabling students to experience more fundamental physics-electromagnetic experiments through virtual modeling;
- Encouraging students's active participation in the learning process, promoting independent thinking, and fostering an increase in self-directed work.

Making the above-mentioned arrangements is necessary and important for understanding the iintricacies of Electromagnetic Physics. The primary reason for this is that electroanetic phenomena are events that cannot be directly observed, and can only be conceptualized and understood through the use of models. Secondly, some electromagnetic experiments require stringent safety measures due to the potential risk of electrical shock. As a result, students are often unable to conduct these experiments themselves and are limited to the role of observers. Another reason is the level of mathematical complexity involved in expressing electromagnetic phenomena and their voluminous nature. For example, differential and integral calculus, operator methods, Fourier transformations, and other advanced mathematical concepts are required. This situation leads to the fact that difficult mathematical tasks are performed and difficulties are encountered in processing the data obtained. Finally, when all these difficulties are added to the necessity of simplifying electromagnetism in accordance with pedagogical teaching, the burden of the course becomes even more demanding in terms of comprehension and assimilation.

To effectively integrate computer modeling into the study of the physical foundations of electrical circuits in general physics courses, it is crucial to develop a comprehensive pedagogical approach and methodology. This approach should address the specific pedagogical aspects related to the problem at hand. According to references [1,2,9–11], three approaches to the integration of computer technologies in teaching practice have been identified. The first is computer use training, also called computer awareness training, which focuses on computer literacy and understanding the nature of computers. The second approach emphasizes the exploration of computer as independent information tools. Lastly, the third approach entails the use of computers or microprocessor technology as technical tools for problem-solving across various educational domains.

We position our activities within the framework of the third approach, which involvesthe development of experimental educational activities for the study of electrical circuits. These activities involve the integration of computer modeling alongsidetraditional teaching methods.

To comprehend the role and significance of experiments, including in-situ, computational, and demonstration approaches within the educational process, it is crucial to initiate an analysis of modern learning objectives [12]. The experimental method in the learning process is the main tool for developing the core competencies of future physics teachers (students) [13]. In the present era, with the advancements in computer technology, there exits a significant opportunity to broaden the scope of the educational experiments and further promote the research methodology of teaching [14].

Thus, when addressing the tasks typically associated with electromagnetic phenomena, we emphasize the inclusion of physical component in them, striving to subordinate their solution to the development of a research-based teaching methodology. This approach encourages the active engagement of students' creative activities, with the goal of acquiring knowledge through active inquiry rather than passively receiving it in a ready-made.

In contrast to previous studies that have primarily defined approaches to computerizing the teaching of general physics, this work goes beyond by developing tools and methodological foundations for the use of computer models. The objective is to ensure continuity, meaningfulness, and methodological coherence in the study of the physical foundations of electrical circuits.

2 MATERIALS AND METHODS

2.1 The goals and main methods of research

The study employed the following research methods:

- Theoretical analysis of the problem, which involved studying philosophical, psychological, physical, and methodological literature;
- Analysis of the theory and methodology of teaching the section of general physics "Electromagnetism";
- Analysis of the theory and methodology of teaching the material of secondary schools, the study of which is based on "Electromagnetism";
- Conducting a pedagogical experiment and analyzing its results in order to determine the effectiveness of using computer modeling in the study of the physical foundations of electrical circuits.

The criteria used to evaluate the effectiveness of the proposed methodology included the level of knowledge formation, the level of self-regulation, the degree of formation of research skills and abilities, and the degree of independence among students.

The level of knowledge formation was assessed through the method of element-by-element analysis, which enabled the determination of the quality of assimilation of individual components of knowledge within their system. The level of formation of students' knowledge was quantitatively assessed using the coefficient *K*.

$$K = \frac{n}{N} \tag{1}$$

where “*n*” is the number of tasks solved by the student and “*N*” is the total number of proposed tasks during the control tests.

To test the null hypothesis, the Wilcoxon-Mann-Whitney criterion was used, the use of which is permissible for independent samples where the studied property of objects is continuously distributed and measured on at least an ordinal scale.

To ensure that the recorded differences are the result of the application of the proposed methodology rather than other factors, the Kolmogorov-Smirnov statistical hypothesis testing criterion was employed.

2.2 Experimental base of the study and the stages of the study

The effectiveness of the methodology was evaluated during the formative stage of the pedagogical experiment, While the feasibility and practicality of integrating computer modeling with traditional forms of training sessions were further examined during the ascertaining and search stages.

The general characteristics of the pedagogical experiment are presented in Table 1.

Table 1. General characteristics of the pedagogical experiment

Formative Experiment		
Tasks of the Stage	**Methods**	**Result**
1. Assessing the extent of students’ understanding of the teaching material on electrical circuits. **2.** Developing methodological recommendations for students regarding the use of new computer technologies in their educational work. **3.** Approbation of the developed methodology. **4.** Determining the effectiveness indicators of the developed methodology.	**1.** Analysis of the results of preparation, laboratory tests and data processing. **2.** The scaling method. **3.** Conducting control sections. **4.** Implementing experimental teaching.	**1.** The methodology for preparing, conducting, and processing data from a full-scale physical experiment integrated with a virtual computer experiment has been tested. **2.** Criteria for evaluating the effectiveness of the proposed methodology have been established. **3.** The research hypothesis has been confirmed.

A total of 93 students from schools No. 20 and 21 in the Turkestan region, Republic of Kazakhstan, took part in the formative experiment. The experiment was conducted over a period of time from 2020 to 2022 and included four academic 10th grade. In the academic year, 2020–2021 a control group of 26 students were formed, while a training group consisted of 23 students. In 2022 two additional groups were identified: experimental group of 21 students and a control group of 23 students. The educational achievements of students in both pairs of groups were assessed and analyzed using uniform statistical methods, which revealed that the students in the experimental groups outperformed the students in the control groups in terms of the studied properties.

It should be taken into account that the purity of the experiment with the first pair of groups was higher, since the control group was trained in the complete absence of computer developments considered in the study. In contrast the second pair of groups studied simultaneously and had access to information about new methods and computer-based learning tools. Here, therefore, the results of a control group involving 49 students from the period 2020–2021 will be presented here. In the experimental group, students acquired knowledge on electrical circuits using computer models in accordance with our methodological system, while the control group followed a traditional lesson organization approach.

3 RESULTS

3.1 Methodology of development and use of computer models

We consider the physics of electricity and magnetism as a discipline, the purpose of which is to teach how to mentally visualize and understand the nature of electricity. The path to a deep and lasting understanding of the processes occurring in electrical circuits is long and requires dedicated intellectual effort. It is impossible to provide a revolutionary breakthrough here at the expense of any technical innovations. However, sensory perception is always inextricably linked with the cognitive activity of the mind.

Considering the limited sensory perception of electricity by individuals, it is crucial to approach "old" tools and means of circuit research with care and reverence. These tools have evolved alongside the development of universal concepts about electricity. The students must master the experience accumulated by humankind over the years. Therefore, it becomes necessary to continuously expand and enhance the arsenal of tools and methods for the study of electricity.

The dialectical combination of evolutionary and revolutionary principles should consist skillfully introducing new technologies into the teaching methodology of electromagnetic phenomena while preserving traditional methods and means.

The first aspect of optimizing student's independent work in the study of electromagnetic phenomena within general physics courses is the incorporating computer tools for performing and verifying calculations into teaching methodology. There are various widely used tools for performing calculations, such as "MATLAB" and "MathCAD" mathematical packages, as well as spreadsheet software like, "Excel". However, most of the students lack computer literacy and that remains the major challenge.

The teacher responsible for designing the curriculum, cannot assume that students are fully prepared to use mathematical programs for electrical calculations. Students who are learning how to use these tools may find themselves confused by unusual formulation of the problem and new notations. In such cases, they rely on guidance from the physics teacher to help them perceive a familiar physical or mathematical problem in an unfamiliar electrical problem. Seeking explanations from computer science teacher or a mathematics teacher for such explanations may not be feasible. Therefore, it can be concluded that a physics teacher should be aware of modern software developments and actively incorporate them into the educational process while designing the curriculum.

Thus, the proposed methodology follows a specific approach: the content of electromagnetism covered in the lesson is closely linked with the solution of a practical problem, and the explanation is based on the concepts introduced in the school physics curriculum. The challenges associated with the dynamic and visual representation of the studied processes are effectively addressed with the help of computer modeling. The creation of a virtual model of the circuit being studied in real-time during the lesson, with the help of mathematical programs, serves to establish interdisciplinary connections, connecting together the laws of physics, computational tools of higher mathematics, computational methods of theoretical electrical engineering, and objects of study of special courses. By combining mathematical modeling tools like "MATLAB" and "MathCAD" with the use of ready-made simulators of electrical processes such as "Workbench" and "Micro-Cap," the integration of computer technology becomes a powerful tool for optimizing classroom time. The teacher's visual and effective use of computer technology serves as a role model and inspires students to use modern scientific tools for both their educational and professional endeavors.

For example, recommending the use of the MATLAB software package for solving systems of linear equations may not be feasible for many individuals due to various reasons. Some may not have access to a computer, while others may not have the specified program installed. Some others may find the interface of the program window to be "unfriendly" leading to difficulties in using it effectively [14]. A 100% success rate can be achieved when the teacher has carried out the appropriate work to adapt students to this specific software product. By installing "MATLAB" on computers of the computer class and providing electronic guidelines in the form of an M-book, the use of this program cannot only be recommended but also mandated [15].

With such an approach, the student is not exempt from the work of analyzing the initial scheme, choosing contours and composing equations, that is, from that part of the work that directly concerns the physical foundations of the circuit and requires knowledge of laws and rules. But all the routine work on calculating determinants is transferred to the machine, which achieves a double effect: firstly the execution time of the calculations is reduced, and secondly, the chances of mathematical errors are eliminated. However, there remains a need to check calculations for errors when composing systems of equations. Such errors can be associated with both inattention and misunderstanding of the educational material. To detect errors of this kind, the operation of the calculated circuit can be simulated using software packages such as "Electronic Workbench" or "Micro-Cap," etc. It should be noted that in addition to the verification function, the use of a virtual circuit model deepens the physical perception of electromagnetic processes and provides a better grasp of the relationship of the mathematical model and its real counterpart.

For example, to validate the accuracy of the equations, it is necessary to include them in the virtual circuit using the "Electronic Workbench" program (Figure 1).

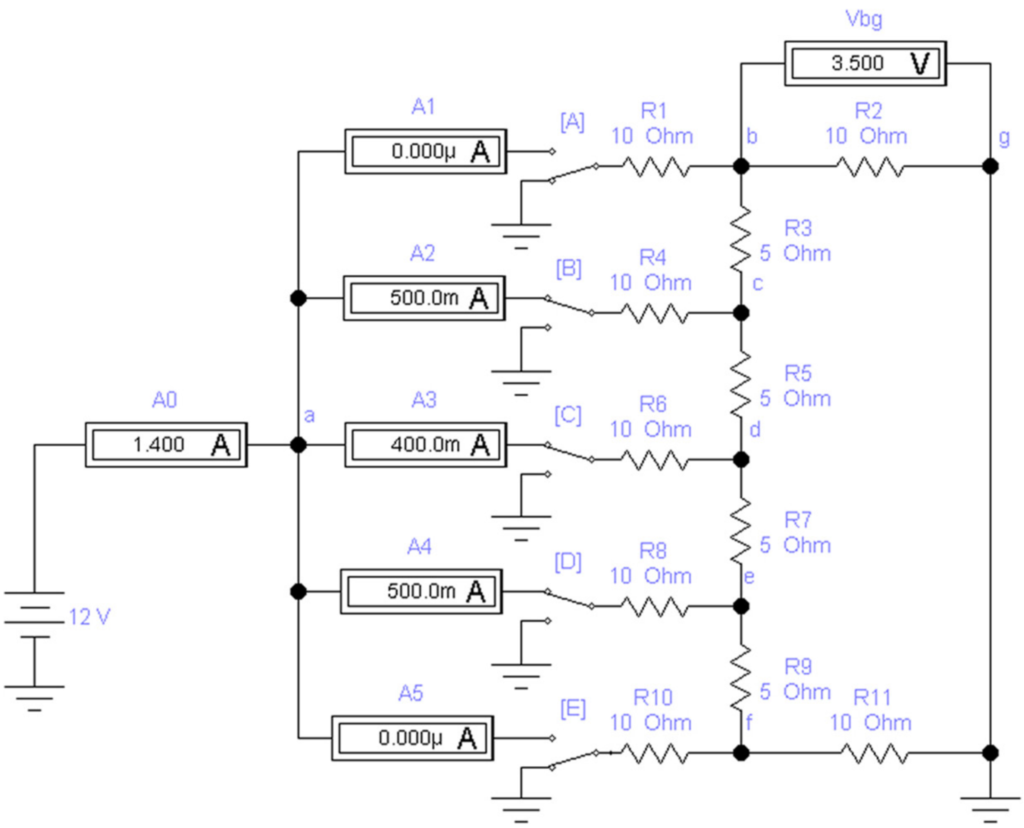

Fig. 1. Installation diagram of a complex electrical circuit assembled from resistors R1÷R11

In this version, the connection states of the keys A, B, C, D, and E are marked with the logical digits “0” (the circuit is connected to the ground) and logical “1” (the circuit is connected to the current source) and written in the order above, which is equal to the number 01110(2) in the binary counting system, that is equal to the number 14(10) in the decimal counting system, i.e., 01110(2) = 14 (10).

In this version, the A and E keys are connected to the ground. Keys B, C, and D are connected to the current source. Enter the following values of the EMF source and resistors R1÷R11 (Figure 2), connect the circuit to the current source, and record the readings of measuring instruments in Table 2.

Table 2. Readings of measuring instruments

No	A	B	C	D	E	U_{bg} мВ	A_0 мА	A_1 мА	A_2 мА	A_3 мА	A_4 мА	A_5 мА	$R_ж$ Ом
0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	1	250	800	0	0	0	0	800	15
2	0	0	0	1	0	500	800	0	0	0	800	0	15
3	0	0	0	1	1	750	1200	0	0	0	600	600	10
4	0	0	1	0	0	1000	800	0	0	800	0	0	15
5	0	0	1	0	1	1250	1400	0	0	700	0	700	8.57

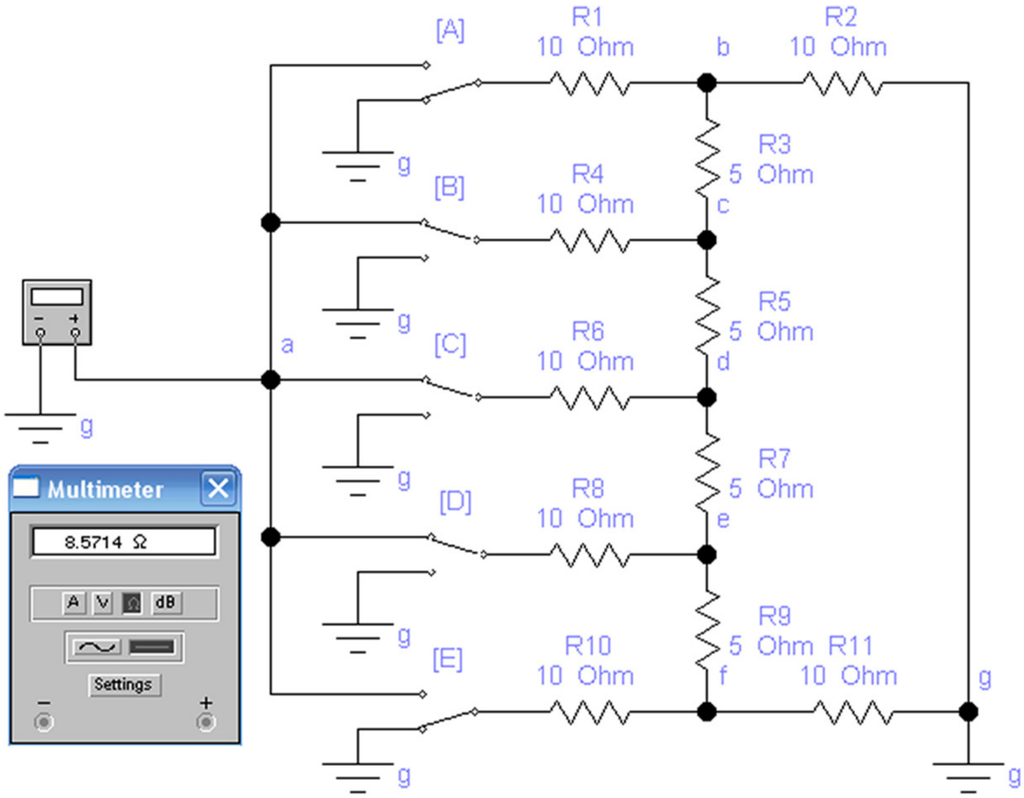

Fig. 2. Total resistance of a complex electrical circuit constructed from resistors R1÷R11

In order to prove the results obtained, we perform calculations. To do this, we convert the mounting scheme into a basic one.

As a rule, modern mathematical packages and programs for designing electrical equipment have excessive capabilities that may exceed the needs of students. Therefore, to prevent computer technologies from becoming an additional burden, the use of such programs should be guided by the teacher's methodical instructions. Creativity and additional research in the "MATLAB" or "Electronic Workbench" environment should be the personal responsibility of the student (Figure 3). The teacher's role is to enhance the execution of calculation tasks and compensate for the lack of personal communication with the student. The guidelines should be designed with the goal of achieving a specific task in mind, rather than containing a description of the capabilities of the prgrams and transcripts of all menu items.

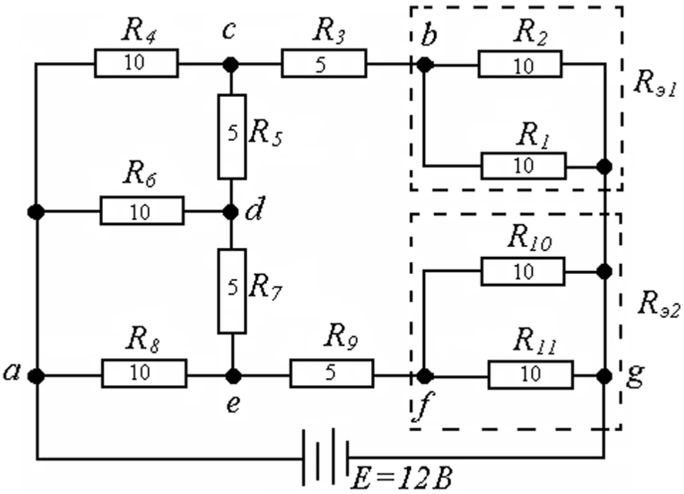

Fig. 3. Basic scheme of a complex electrical circuit constructed from resistors R1÷R11

There are no resistors connected in parallel or in series in this circuit. So we get an equivalent circuit diagram in Figure 4.

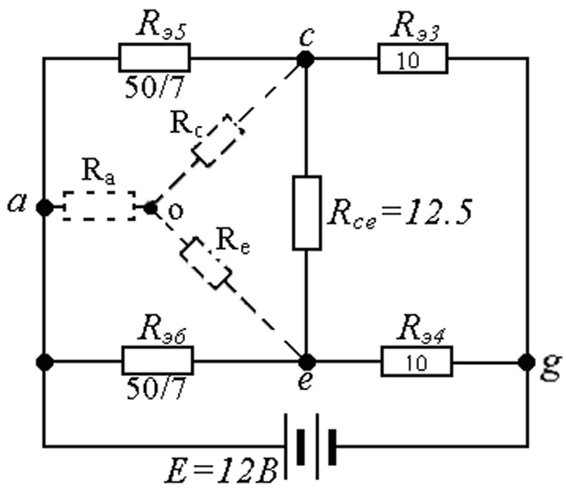

Fig. 4. An equivalent circuit diagram is shown in Figure 3

In this scheme, we convert the resistors $R_{э5}$, R_{ce}, and $R_{э6}$ connected by a rectangular circuit to an asterisk circuit that is equivalent to it, and find the values of the resistors using the formula below.

$$\frac{R_{ac} \cdot R_{ae}}{R_{ac} + R_{ae} + R_{ce}} = \frac{R_{э5} \cdot R_{э6}}{R_{э5} + R_{э6} + R_{ce}} = \frac{\frac{50}{7} \cdot \frac{50}{7}}{\frac{50}{7} + \frac{50}{7} + \frac{25}{2}} = \frac{\frac{2500}{7 \cdot 7}}{\frac{375}{7 \cdot 2}} = \frac{40}{21}$$

$$\frac{R_{ac} \cdot R_{ce}}{R_{ac} + R_{ae} + R_{ce}} = \frac{R_{э5} \cdot R_{ce}}{R_{э5} + R_{э6} + R_{ce}} = \frac{\frac{50}{7} \cdot \frac{25}{2}}{\frac{50}{7} + \frac{50}{7} + \frac{25}{2}} = \frac{1250}{375} = \frac{10}{3} \tag{2}$$

$$\frac{R_{ae} \cdot R_{ce}}{R_{ac} + R_{ae} + R_{ce}} = \frac{R_{э6} \cdot R_{ce}}{R_{э5} + R_{э6} + R_{ce}} = \frac{\frac{50}{7} \cdot \frac{25}{2}}{\frac{50}{7} + \frac{50}{7} + \frac{25}{2}} = \frac{1250}{375} = \frac{10}{3}$$

Thus, using Ohm's law, it is possible to determine the voltage and current on each resistor.

The developed electronic guidelines for self-preparation in laboratory work take the form of an interactive M-book that guides the student's actions during the study of virtual electrical circuits. The sections of the guidelines are aligned with the stages of a full-scale experiment, therefore, the work performed under their guidance can be considered as a training on a simulator before engaging with a real object. In this case, the program "Electronics Workbench" serves as a simulator.

The essence of the proposed methodology for performing calculation tasks is to leverage computer technology to alleviate student's routine mathematical calculations and instead focus on formulating computational experiments. The purpose of the methodology is to redirect the student's efforts and attention from computational operations towards the study of electromagnetic phenomena proper as a means of research.

3.2 Results of the pedagogical experiment

The effectiveness of the proposed methodology was evaluated based on criteria such as the level of knowledge formation, the level of self-regulation, and the degree of formation of research skills and abilities, as well as the degree of independence of students.

The assess the level of knowledge formation, the experimental and control groups underwent an evaluation using the formula (1), which was based on the results of a control assignment on the topic of "Electric current and resistance."

Students were presented with 5 tasks to assess their theoretical knowledge and 5 to evaluate their practical application of the acquired knowledge. In the control work task, students were required to demonstrate their knowledge and actions in the following areas:

1–5: Understanding the values associated with sinusoidal current. The image of sinusoidally varying quantities by vectors on the complex plane. Inductance, capacitance, and active resistance in a sinusoidal current circuit. The triangle of resistances and the triangle of conductivities. The use of vector diagrams in the calculations of electric circuits of sinusoidal current.

6–10: Draw two current sinusoids with different amplitudes and equal, but opposite in sign, initial phases. Explain how, by connecting a capacitor to the input of a passive two-pole, to determine the sign of the load angle. Illustrate your answer. Show the triangle of conductivities and the triangle of resistances of the branch, the voltage and current of which are represented by vectors. Check with the help of a vector diagram whether the current in the circuit is correctly determined.

The results of the control work are summarized in Table 3.

Table 3. The results of the control work

Elements of Analysis	Number of Correct Answers (%)	
	Experimental Group	Control Group
1.1	91.3	84.6
1.2	86.9	84.6
1.3	82.6	80.8
1.4	73.9	69.2
1.5	69.5	61.5
2.1	65.2	46.1
2.2	52.2	46.1
2.3	60.9	53.8
2.4	65.2	61.5
2.5	69.6	61.5

As can be seen from Table 3, the students of the experimental group achieved high results for each task. It was found that when performing theoretical and practical tasks, students of the control group experienced difficulties in mastering electrical circuits through traditional methods. And the students of the experimental group, who had the opportunity to engage with computer programs during classes, showed a good understanding of the topic. The data in this table serves as evidence that the use of computer models affects the development of theoretical knowledge and practical skills among students.

The numerical expression of competence calculated by the formula (1) is presented in Table 4.

Table 4. The numerical expression of competence

Coefficient K	Rank Coefficient R	Experimental Group		Control Group	
		Number of Students	%	Number of Students	%
0	1	0	0	1	4
0.2	2	0	0	1	4
0.3	5	2	7	3	11
0.4	8.5	2	7	0	0
0.5	12.5	3	13	3	11
0.6	19	4	14	3	11
0.7	25.5	2	7	4	14.5
0.8	31.5	0	0	6	26
0.9	36	2	7	1	4
1.0	43.5	8	28	4	14.5

Upon analyzing Table 4, it can be noted that the experimental group has a relatively higher number of students achieving the highest score, while the number of students with the worst indicators is relatively lower. However, based on the given table alone, it is impossible to judge exactly the reliability of the data obtained. To access the reliability and make a more accurate judgement, it is necessary to test the null hypothesis, which suggests that there is an equal likelihood of the experimental group outperforming the students of the control group and vice versa. In other words, with the accepted significance level a = 0.1, the level of competence of the students of the two groups is the same.

To test the null hypothesis, the Wilcoxon-Mann-Whitney criterion was used. This criteria is suitable for independent samples where the studied property of objects is continuously distributed and measured on a scale that is not lower than ordinal.

According to the results of the ranking of the objects of the entire studied population, the sum of the ranks was calculated for the objects of the experimental sample:

$$S = \sum_{i=1}^{n} R(x_i) \tag{3}$$

where $R(X_j)$ is the rank attributed to the *i*-th object of this sample, *n* is the number of objects of any sample.

$$S = 611.5 \tag{4}$$

The value of the criterion statistics is calculated using the following formula:

$$T = S - \frac{n(n+1)}{2} \tag{5}$$

Based on Table 4, it can be observed that 47 out of 49 elements in the set have the same rank values. This indicates that the accuracy of the final conclusions will be reduced if no correction is made in the formula for calculating the critical value of the criterion statistic. The correction is made by introducing a value into the formula:

$$W_a = \frac{n_1 \cdot n_2}{2} + X_a \cdot \sqrt{\frac{n_1 \cdot n_2 \cdot (n_1 + n_2 + 1)}{12} - \sum \frac{k^3 - k}{12}} \tag{6}$$

where X_a is the quantile of the normal distribution, assumed for $a = 0.1$ to be equal to 1.28; n_1 and n_2 are the number of elements of the first and second samples, *k* is the number of members of the series having the same rank value.

$$W_a = \frac{23 \cdot 26}{2} + 1.28 \cdot \sqrt{\frac{23 \cdot 26 \cdot (23 + 26 + 1)}{12} - 236} = 359.8 \tag{7}$$

According to the decision-making rule, the null hypothesis is rejected at the accepted significance level if

$$T > W_{1-a} (W_{1-a} = n_1 \cdot n_2 - W_a) \tag{8}$$

$$W_{1-a} = 23 * 26 - 359.8 = 238.2 \tag{9}$$

Since 335.5 > 238.2, one can be 90% sure that the results indicating the positive impact of the proposed methodology on the level of competence of students are reliable.

The criterion of self-regulation accesses the readiness and the capacity of students to independently apply the acquired knowledge. The concept of readiness includes two components: consistency and functionality. The functional component, which is demonstrated through the understanding the essence of intellectual activity involved in completing a task, is based on:

- Knowledge and skills of the students as well as their ability to apply them to solve unfamiliar problems,
- Motivation and student's ability to set goals, which predetermine the entire process of knowledge and skills formation.

Students' self-regulation can be characterized by three levels: Low, C-Medium, B-High.

At the low level students exhibit superficial knowledge and adopt a mechanic and uncreativeapproach to laboratory research. They do not utilize their available knowledge of the research topic to predict the results of experiments. At this level, students are reliant on detailed instructions and constant guidance of the teacher.

The medium level of self-regulation is characterized by the emergence of interest in the subject and the research process. At this level students begin to recognize the interconnectedness of the educational material, viewing it as a whole rather than a sum of individual knowledge. It allows the student to independently and actively perform individual experiments, but does not provide long-term concentration of will and long-term planning of research.

A high level of self-regulation implies a student's readiness to apply their existing knowledge in a new and unfamiliar situation. At this level students are able to formulate problems independently, plan an experiment and predict its results. The research is promoted not due to the administrative activity of the teacher, but due to the student's high degree of autonomy in their research activities. The help of a teacher is required only in cases of extreme difficulty.

The following system was used to evaluate students' self-regulation during laboratory research. For the timeliness of the preparatory work, a $C_П$ coefficient was assigned a value of 1.0 for timely submission of the report and 0.5 for late submission. From 0 to 3 points were awarded for the correctness of the preparatory work, depending on the number of errors in it. Self-regulation at the preparation stage was calculated as,

$$C_П = K_П \cdot O_П \tag{10}$$

where $O_П$ is the grade for the preparatory work.

For activity when working in a group of researchers, a coefficient of $C_И$ was assigned, equal to 1.0 with an active position and 0.5 with passive behavior. From 0 to 3 points were awarded for the correctness of the experiments. Thus, self-regulation at the stage of the study was calculated as

$$C_И = K_И \cdot O_И \tag{11}$$

where $O_И$ is the evaluation of the quality of the study.

The students were evaluated using this system, receiving scores ranging from 1 to 6 points. The low level of self-regulation was put in line with the assessment of up to 2.5 points, the average level ranged from 3.0 to 4 points, and the high level ranged from 4.5 to 6 points. The distribution of the students by their levels of self-regulation is presented in Table 5.

Table 5. The distribution of the continent by levels of self-regulation

The Level of Self-Regulation	Number of Correct Answers (%)	
	Experimental Group	Control Group
H	17	43
C	35	27
B	48	30

Analyzing Tables 4 and 5, it can be concluded that the proposed methods of integrating computer modeling with a full-scale experiment have a positive effect on both the level of knowledge formation and the level of self-regulation among students. At the same time, there is a significant noticeable increase in motivation to perform laboratory research, as evidenced by the distribution of students in the experimental and control groups based on their levels of self-regulation.

The degree of formation of research skills and abilities both the control and experimental groups was tested based on a research assignment. Task topic: to study the effect of the magnitude of the active resistance in a sequential R-L-C circuit on the nature of the transient process. Poetical task plan:

1. Obtaining an oscillogram of the R-L circuit current.
2. Determination of the time constant of the circuit and the inductance of the coil.
3. Obtaining an oscillogram of the R-C circuit current.
4. Determination of the time constant of the circuit and the capacitance of the capacitor, etc.

To successfully complete the proposed task, the following research skills are required:

1. The ability to set a research task and plan an experiment.
2. The ability to conduct an experiment.
3. The ability to analyze the results of the experiment and draw conclusions.
4. The ability to compare the physical and mathematical model of the phenomenon under study.
5. The ability to analyze the model and determine its compliance with the data of a full-scale experiment.
6. The ability to distinguish from experimental data essential and non-essential for the phenomenon under study.
7. The ability to expand the scope of field research by analyzing the data obtained.

The experimental and control groups were tested for the manifestation of these skills during research work. The results are presented in Table 6.

Table 6. The results of testing for the manifestation of the listed skills during research work

Research Analysis Element	The Number of Students Who Have Demonstrated These Research Skills	
	Experimental Group	Control Group
1	87	77
2	83	65
3	65	58
4	78	58
5	74	50
6	61	46
7	65	50

The data presented in Table 6 show that students in the experimental group outperform those in the control group in all criteria for assessing the degree of formation of research skills and abilities. To make sure that the recorded differences are the result of the application of the proposed methodology, and not influenced by other factors, the Kolmogorov-Smirnov statistical hypothesis testing criterion was applied.

The random variable *X* represents the success of a task completed by one student of the group. The property being studied was evaluated on a ordinal scale consisting of seven ranks. When one of the skills or abilities listed in Table 6 was shown, the student received 1 point, otherwise – 0 points. Since the studied aggregates had large volumes, for each sum of points, the absolute frequency of observations – 'f' and the accumulated frequencies of observations were calculated, there is a number of observations having values less than or equal to the values from this sum of points. The empirical distribution functions of task success (*S*) in the experimental (1) and control (2) groups were defined as

$$S_1(x) = \frac{\sum f_1}{n_1}.$$
$$S_2(x) = \frac{\sum f_2}{n_2}. \qquad (12)$$

The results of applying the Kolmogorov Smirnov criterion are presented in Table 7.

Table 7. The results of applying the Kolmogorov Smirnov criterion

Total Points	Absolute Frequency in the Sample		Accumulated Frequency		$S_1(x)$	$S_2(x)$
	f_1	f_2	Σf_1	Σf_2		
7	11	8	23	26	1.00	1.00
6	1	1	12	18	0.52	0.69
5	1	0	11	17	0.48	0.65
4	4	1	10	17	0.43	0.65
3	4	7	6	16	0.2608	0.6153
2	2	6	2	9	0.09	0.35
1	0	3	0	3	0.00	0.12
0	0	0	0	0	0.00	0.00

To confirm the non-random nature of the identified best abilities of the students of the experimental group compared to the students of the control group, it is necessary to refute the null hypothesis, which assumes that the success of the research task is distributed stochastically equally in both groups. Additionally, it is important to confirm the alternative hypothesis, which suggests that the students of the experimental group outperform the students of the control group according to the studied property.

To make a decision regarding the acceptance or rejection of the null hypothesis, criteria statistics were calculated using the specified formulas, and Table 8 was compiled to present the results.

$$T_1 = \max\left|S_1(x) - S_2(x)\right|.$$
$$T_2 = \max(S_1(x) - S_2(x)). \qquad (13)$$
$$T_1 = \max(S_2(x) - S_1(x)).$$

Table 8. Decision on the rejection or acceptance of the null hypothesis, the criteria statistics

Total Points	T_1	T_2	T_3
7	0.00	0.00	0.00
6	0.17	–0.17	0.17
5	0.17	–0.17	0.17
4	0.22	–0.22	0.22
3	0.3545	–0.3534	0.3534
2	0.26	–0.26	0.26
1	0.12	–0.12	0.12
0	0.00	0.00	0.00

For the accepted significance level of 10%, we determine the critical value of the Kolmogorov-Smirnov criterion by an approximate formula:

$$W_{1-a} \approx \lambda\sqrt{\frac{n_1 + n_2}{n_1 \cdot n_2}} \qquad (14)$$

$$W_{1-a} \approx 1.22\sqrt{\frac{23+26}{23 \cdot 26}} = 0.3492 \qquad (15)$$

According to the decision-making rules $T_1 > W_{1-a} (0.3545 > 0.3492)$, if the inequality is fulfilled, the null hypothesis is rejected at the accepted significance level, and the alternative hypothesis is accepted. This state of the studied property for objects in the two groups is stochastically different.

When performing the inequality $T_1 > W_{1-a} (0.3545 > 0.3492)$, it can be concluded that the objects in the experimental population are stochastically superior to the objects of the control population with respect to the studied property.

In other words, only in one case out of ten we risk making a mistake, considering that the degree of formation of research skills and abilities among students of the experimental group is higher than among students of the control group.

4 DISCUSSIONS

Kotseva et al., (2019) points out that "a demonstration physical experiment performs an important methodological role in the implementation of the interrelation of the conceptual apparatus of trainees with the empirical basis of physical science and technology, contributing to the penetration into the essence of the phenomena and processes being studied" [16]. In this context, the role of laboratory practice in the preparation of students is extremely important. The creation of modern laboratory work and the development of new techniques for their implementation are highly relevant in ensuring up-to-date education.

In modern methods of teaching physics, a physical experiment is considered an integral part of overall educational process, where theoretical and experimental methods of studying and researching physical phenomena are mutually combined [17–19].

Thus, the analysis of the currently existing computer workshops in physics has shown that they are aimed at the formation of experimental competence of students, including the skills of creating experimental setups and carry out a range of studies using ready-made experimental installations [20]. Indeed, the methodology for the formation of experimental competence in physical education has been well developed, has proven itself as an active form of education, and has given science many talented experimenters [21]. However, the active materialization study of theoretical models is not implemented in these workshops, which prevents students from understanding the physical essence of theoretical models and mastering the relevant theoretical concepts.

The methodology we propose is as follows: preparation for a full-scale study is organized in the form of a training mode of a computer game. The analogue of a voluminous and nuanced game in our case is a real laboratory study, all the features of which cannot be provided with the most detailed methodological instructions. The training consists of performing the main stages of a full-scale experiment on a virtual installation. At the same time, the individual task is compiled in such a way that the test questions are put in an implicit form, and the student, in order to move forward, must find answers to them. For control, based on the results of virtual laboratory work, it is proposed to draw up a protocol that is easy for the teacher to check. It is not difficult to see that if we design electronic guidelines for two different types of independent activity in accordance with the recommendations developed by us, they turn out to be not just similar, but almost identical in form. In our opinion, this is an undoubted advantage of the methodology since it eliminates the artificial division of the discipline into laboratory and practical parts.

5 CONCLUSION

Thus, we have revealed a contradiction between the target settings of physical education for the formation of students on the fundamental basis of electromagnetic phenomena considered in the context of special disciplines and the existing practice of presenting the material section, leveling the value of this basis.

Computer modeling is considered an addition to traditional research tools and tools that have developed with the formation of universal ideas about electricity.

A methodology for the application of computer modeling at the stages of preparation, execution, and processing of laboratory test results has been developed.

The role of computer modeling in creating conditions for the implementation of the research method of teaching in practice is shown. As a result of the pedagogical experiment, the effectiveness of developed approaches to the use of computer models in the experimental activities of students has been proven, with the aim of developing intellectual abilities, forming a research approach, and stimulating the creative activity of students.

Analyzing the tables of experimental data, it can be noted that in the experimental group, there are relatively more students with the highest score and relatively fewer students with the worst indicators.

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