Enhancing Digital Learning in Electrical Machines Practical Course Using a Cutting-Edge Desktop Virtual Laboratory for DC Motor Simulation

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***Abstract* – This study investigates the development and efficacy of a virtual DC motor laboratory aimed at enhancing practical learning in electrical machines. Key aspects of the literature review emphasize the increasing adoption of digital simulations in education and the effectiveness of virtual labs in technical training. The primary research question is whether the virtual simulator can achieve learning outcomes comparable to traditional physical laboratory tools. Hypotheses posit that students using the virtual DC motor laboratory will demonstrate equivalent learning outcomes compared to those using traditional teaching aids. The study employs a quasi-experimental design following the ADDIE model for development, with a sample size of 32 students—19 in the control group and 13 in the experimental group.**

Results indicate significant improvements in learning outcomes across both groups, with no statistically significant difference observed between the virtual simulator and traditional methods in post-test assessments. These findings underscore the equivalence of virtual and physical tools in enhancing practical learning in electrical machine practice. Virtual labs offer scalable solutions for educational institutions seeking to modernize their curriculum, crucial in preparing students with relevant skills for the evolving demands of the workforce in electrical engineering and related fields.

***Keywords* – Effectiveness, electrical machines, digital learning, quasi-experimental, virtual laboratory.**

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1. Introduction

Vocational education plays a role in producing skilled workers who can encourage economic growth. Through this program, students are provided with the technical knowledge and real-world skills they need to succeed in the world of work. The aim of learning in vocational education is to prepare individuals to face challenges and demands in the workplace with adequate competence [1], [2], [3]. Vocational skills can be developed to align with the requirements of the labor market. Vocational education emphasizes competency development, equipping individuals with the skills, knowledge, and attitudes needed to meet the demands of the labor market effectively [4]. Student skills include cognitive, affective, and psychomotor competencies that form complete expertise in a particular field [5]. Mastery of skills in vocational education is supported by learning practical courses.

Laboratory and workshop facilities to support practicum learning are still lacking in terms of quantity and quality and are left behind in technology. In the 21st century, it is necessary to design teaching aids that are cost-effective, flexible, up-to-date, and more functional and to use virtual technology [6], [7], [8].

Driven by digital transformation, the integration of cyber-physical systems, and the proliferation of the Internet of Things, the 21st century is revolutionizing both industry and education, creating smarter factories and more interactive, technology-driven learning environments [11]. Learning with digital media is a future necessity in designing vocational learning. Virtual tour technology in factories can present an industrial atmosphere in the classroom; virtual reality can present a real environment in cyberspace; and virtual laboratories can present a laboratory and workshop environment through digital platforms and other digital media technologies [12].

The rapid development of technology makes interaction unlimited in space and time. Conventional learning in the classroom has been replaced by technology-based online learning. The focus of developing future education is emphasized on intelligent computerized classes with the application of artificial intelligence (AI), online learning, internet of things-based examination, virtual reality (VR), and augmented reality (AR) [12], [13], [14].

An organization undergoes a "Digital Transformation" when new business models and digital technologies are applied. One practical application of digital transformation is the integration of learning technology and state-of-the-art software-based approaches into the learning process. The digital transformation of education leads to digital learning. With the use of computers, tablets, and other information technology tools, digital learning makes tailored learning possible [19]. Theoretical courses are very effective when combined with digital technology because they do not require laboratory training to acquire skills, but the implementation of practical laboratory courses for skills training is still a challenge in digital technology-based implementation [7].

The electric machine course presents abstract concepts, making it challenging to grasp both theoretical and practical aspects. Electrical machinery, being an empirical science, relies on laboratory experiments to establish parameters and enhance comprehension of the abstract concepts surrounding electric machines [20], [21], [22], [23], [24], [25], [26], [27]. Practical learning of electric machines is proof of the theoretical concept of the energy conversion phenomenon through a series of laboratory tests or experiments. The facilities and infrastructure for the practical learning of electric machines consist of a set of teaching aids for electric machines equipped with instruments for measuring electrical and mechanical quantities. If a series of trials or laboratory experiments are carried out online, at least the learning media used as a substitute for a physical laboratory must be relevant or compatible so that they can be used to carry out a series of trials or experiments to test the characteristics of electrical machines.

Creating a virtual laboratory to facilitate the practical instruction of electric machines in vocational education is the aim of this research project. The scope of electric machine practice is limited to the material of DC motors only. This study discusses the procedures for developing multimedia-based instructional materials, starting with needs assessment, planning, design, development, implementation, and evaluation. Reviews of development results and implementation results in practical classes are described in the discussion chapter. This study is expected to contribute to vocational education in the 21st-century digital learning era.

2. Method

This study followed the ADDIE development procedure outlined by Lee Owens [28]. Developing a multimedia-based learning environment for electrical machine applications is the aim of this project. Congruently, Figure 1 depicts the development process.

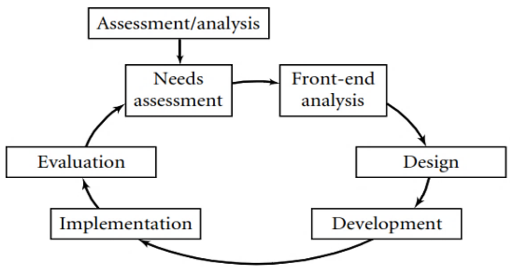


Figure 1. Multimedia instructional design process [28]

Needs assessment and front-end analysis are included in the initial steps in the analysis phase. Needs assessment evaluates the gap between current and desired conditions, thereby establishing instructional objectives. Front-end analysis utilizes various data collection techniques to narrow the disparity between the current and desired conditions. In the design phase, instructional design specifications are created, encompassing well-crafted multimedia specifications, multimedia navigation structures, and implementation methodologies. The development phase is the stage in making learning multimedia products.

Computer-based multimedia learning is used to determine the next basic specifications. Storyboards, videos, and graphics animations are created, and initially, computer-based systems are developed, tested, and reviewed. The implementation phase involves integrating computer-based multimedia into the learning process. The pretest is given before implementation, while the post-test is given after the application of computer-based multimedia products. The evaluation phase is the most important. The effect of using computer-based multimedia was analyzed for its effectiveness. Responses and changes in behavior are measured and analyzed to improve sustainability [28]. All stages are carried out serially and sequentially until the product is ready for mass application.

2.1. Data Collection

Data was gathered through the utilization of a performance questionnaire. In the electric machine practice course, pertaining to DC motors, students demonstrated their learning achievements by successfully conducting tests on variously connected direct current electric motors following the correct procedures. There were five different types of DC motors: series, shunt, short compound, long compound, and separately excited DC motors. For each type of motor, a performance assessment of five items is carried out so that the overall DC motor test performance items consist of 25 items. Table 1 shows the assessment guide of the performance assessment questionnaire.

Table 1. Guide to the performance assessment

Indicator	Descriptor	Item Number	Score
Assembling the test circuit of a DC electric motor	Able to assemble a DC electric motor testing circuit properly and correctly.	1	3 - the circuit is correct. 2 - the circuit has several errors (e.g., the measuring limit on the measuring instrument does not match). 1 - short circuit
Testing direct current electric motors according to the correct procedures	Able to start a DC motor with the correct procedure.	2	3 - the DC motor is operated independently with proper procedure. 2 - DC motors are operated independently with the correct procedure under the direction of the Lecturer. 1 - can't run a DC motor.
	Can describe the characteristics of *n=f(Ia)*; *Ta=f(Ia); n=f(Ta)* correctly	3	3 - data is parsed correctly. 2 - the data has some errors (e.g., errors in meter readings). 1 - data cannot be parsed.
	Be able to calculate the efficiency of a DC motor correctly	4	3 - the efficiency is calculated correctly. 2 - there are several calculation errors (e.g., the unit of measurement is not according to the calculation standard). 1 - unable to calculate efficiency.
	Able to stop a DC motor with the correct procedure.	5	3 - the DC motor is operated independently with proper procedure. 2 - DC motors are operated independently with the correct procedure under the direction of the Lecturer 1 - can't run DC motor.

2.2. Data Analysis

The DC motor virtual laboratory is utilized for practical learning in electrical machine courses. To evaluate the effectiveness of this virtual laboratory as a learning tool, a quasi-experimental method was employed, featuring a pretest-posttest control group design [29]. A pre-test is given prior to the start of the learning process, and a post-test is carried out at the end to evaluate the efficacy of the learning intervention. The quasi-experimental design has two class groups. There is a control class and an experimental class in the two classes.

While the control class uses electrical machine teaching aids in a real laboratory, the experimental class uses a virtual laboratory for DC motor applications. The quasi-experimental model is shown in Table 2.

Table 2. Quasi-experimental design [29]

Class	Pre-test	Treatment	Post-test
Control	O_1	X	O_2
Experiment	O_3	-	O_4

Symbol explanation:
O_1: the pre-test results of the control class.
O_2: the post-test results of the control class.
X_1: treatment using a virtual laboratory of DC motor.
O_3: the pre-test results of the experimental class.
O_4: the post-test results of the experimental class.

Each class undergoes a pre-test before the learning process begins. Following the learning treatment administered to both classes, a post-test is conducted for each. The Mann-Whitney test is employed to assess two unrelated variables, such as the pre-test results of the control and experimental classes, as well as the post-test results of both classes. Conversely, the Wilcoxon test is utilized for two related variables, namely the pre-test and post-test results within each class. The gain value test determines the effectiveness of the learning treatment, derived from the pre-test and post-test scores. The average normalized gain (N-gain) is calculated using the formula provided [30], with Table 2 presenting the classification of gain values.

$$g = \frac{Spost - Spre}{S\,max - Spre} \quad (1)$$

Symbol explanation:
Spre: pre-test scores
Spost: post-test score
Smax: highest possible score
g: gain score

Table 2. Gain value classification [30]

Nilai <g> (n)	Criteria
0,00 - 0,30	Low
1,31 - 0,70	Moderate
0,71 - 1,00	High

3. Results of Learning Media Development

This section discusses the development results, which consist of the analysis stage, the design stage, and the development stage. The implementation and evaluation phase are presented in the next section.

3.1. Assessment Phase

Preliminary studies serve as the foundation for the development of virtual laboratory of DC motor. These studies are comprised of two essential components: needs analysis and front-end analysis. The preliminary studies have been conducted following the prescribed procedure in this development process. [31].

3.2. Design Phase

The formulation of the virtual laboratory of DC motor delineates multimedia requirements, educational frameworks, configuration parameters, targeted performance, methods for product testing, and approaches for product implementation within the learning context. The desired multimedia specification is that it can be installed on a computer with a Windows operating system. Learning structure or DC motor practical lesson plan. Product tests were carried out to assess the performance of the virtual laboratory of DC motor including integration or performance tests, computer multimedia tests by experts, electrical machine material test carried out by experts, as well as investigating student perceptions.

3.3. Development Phase

Virtual laboratory of DC motor is developed in two dimensions on a computer screen. The operation of the virtual laboratory of DC motor is demonstrated through a user interface that combines static and dynamic visuals. A virtual console box with buttons mimics an operator's interface to the machine, along with a pop-up window display that functions as a help center or module.

The multimedia technical architecture is planned, created, and implemented as a constituent master chart of each flow of data and information communication between the computer program and devices involved. The system architecture is illustrated in Figure 2, with the program code developed according to technical flow diagrams and a data and information communication flow architecture. The change execution buttons are specified for each possibility. Internal integration of display contents is made through writing program code. The computational process of the DC motor testing model was made using Simulink Matlab [26]. All types of DC motors from the Simulink model are generated in code in the form of *.dll (dynamic link library) files. Integration testing is performed by the developer on each technical diagram flow when writing program code. The integration testing method is carried out by a black box test [28].

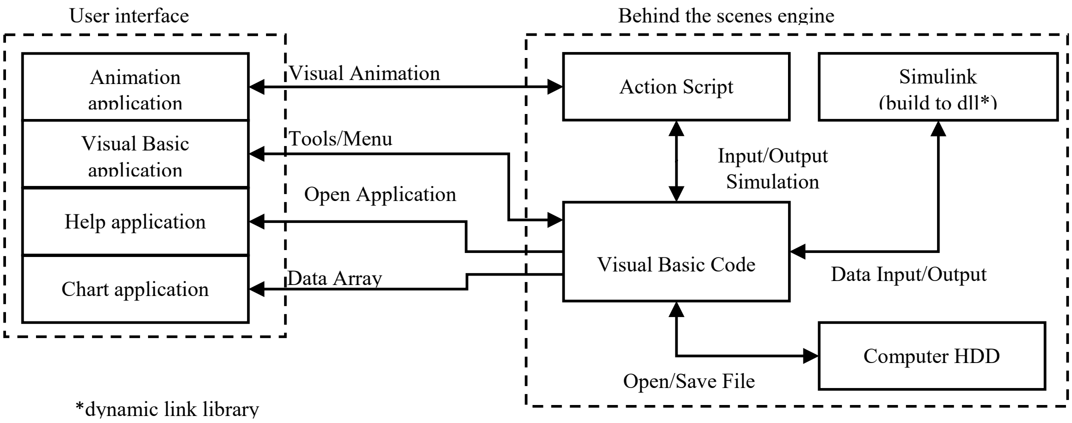


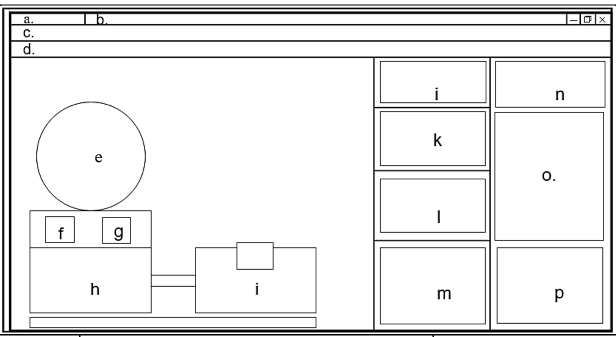
Figure 2. Computer-based system architecture of virtual laboratory of DC motor

User interface requirements are outlined in the storyboard chart. The storyboard contains an image of a chart or window display design (windows form) accompanied by an explanation of each part or icon. The display design consists of the main window display and supporting windows.

The primary window exhibits the core visual representation of the virtual laboratory for direct current electric motors. The auxiliary window showcases the help feature. In Table 4, a comprehensive storyboard chart is presented.

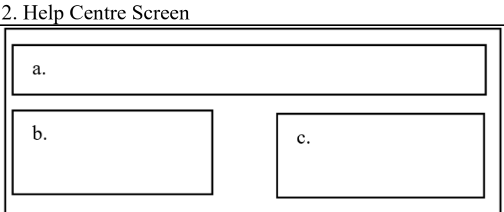
Table 4. Storyboard of the development of a virtual device for a direct current electric motor laboratory

1. Main Screen



No	Component	Description
a.	Application logo	Contains the application logo.
b.	File location	Contains the location of files opened from computer storage.
c.	Menu bar	The navigation menu bar consists of tabs such as file, edit, simulation, and help center.
d.	Tools bar	The navigation button bar includes functions for file opening, saving, establishing connections, removing connections, selecting motor types, starting simulations, stopping simulations, recording data, clearing data, and accessing the help center.
e.	Torsimeter	Serves to indicate the amount of torque.
f.	Field Rheostat	Serves to adjust the generator's magnetic field
g.	Tacho generator	Serves to measure the speed of the motor.
h.	DC Generator	Direct current generator as a load on the motor under test.
i.	DC Motor	Direct current motor as the motor under test.
j.	Instrument	Current and voltage analog meter.
k.	Field Rheostat	Serves to adjust the motor's magnetic field.
l.	Loading Resistor	Serves as a load on the generator.
m.	Power Pack	As a variable direct voltage power source and a fixed direct voltage.
n.	Wiring Diagram	Serves to display the motor connection wiring diagram.
o.	Textbox	To display test results data that cannot be displayed by analog instruments.
p.	Characteristic Chart	To display the characteristic curve from the test results of direct current electric motors.

2. Help Centre Screen



No	Component	Description
a.	Navigation button	Functions as a shortcut command to move to the next page or the previous page.
b.	Instruction list	Lists of instructions for using the application program.
c.	Instruction description	Explain the description in narrative and illustrated pictures.

The initial version of the virtual laboratory of DC motor interface has been successfully developed, including the initial appearance of the application program when it is first run, the display of the electric machine unit, the display of measuring instruments, image display of direct current electric motor testing circuit, the display of characteristic curve data, and the display of instructions for use. Figure 3 shows the splash screen display, which is the initial display the first time the program is run. The splash screen contains information, including the application program name, year of manufacture, developer name, application version, and affiliation.

Figure 3. The virtual laboratory of DC motor opens with this screen

The electric machine unit appeared with two DC machines coupled on the same axis. A DC generator unit complete with instruments for measuring electrical and physical quantities as a load, coupled with a DC motor which will undergo characteristic tests. A screenshot of the virtual laboratory of DC motor and its parts is shown in Figure 4. The torsimeter and tachometer are located on the generator unit, as shown in Figure 4, part number 2. At the top of the application, part number 1, there is a menu bar and navigation buttons such as a button for making a connection, a button for running a simulation, a button for recording data, and a help center button. Electrical instruments such as ammeters analog and voltmeters analog, accessories such as motor starters, shunt rheostats, switches, and load resistors, as well as the power supply, are located on the equipment rack in Figure 4, part number 3. Part number 4 in Figure 4, or the right side, contains a wiring diagram, digital motor-generator parameters such as current, voltage, speed, and torque, as well as graphs of characteristic functions from the results of testing DC electric motors.

Supporting applications, including help centers, can be opened via the help bar menu in the virtual laboratory of DC motor. A screenshot of the help center support application is shown in Figure 5. The help application has three parts: part 1 is navigation, part 2 is a list of help, and part 3 is a description or guide of the selected help. The help center window contains information about the DC motor virtual laboratory, a literature review of DC motor testing, operating guides, and procedures for collecting electric motor practical data.

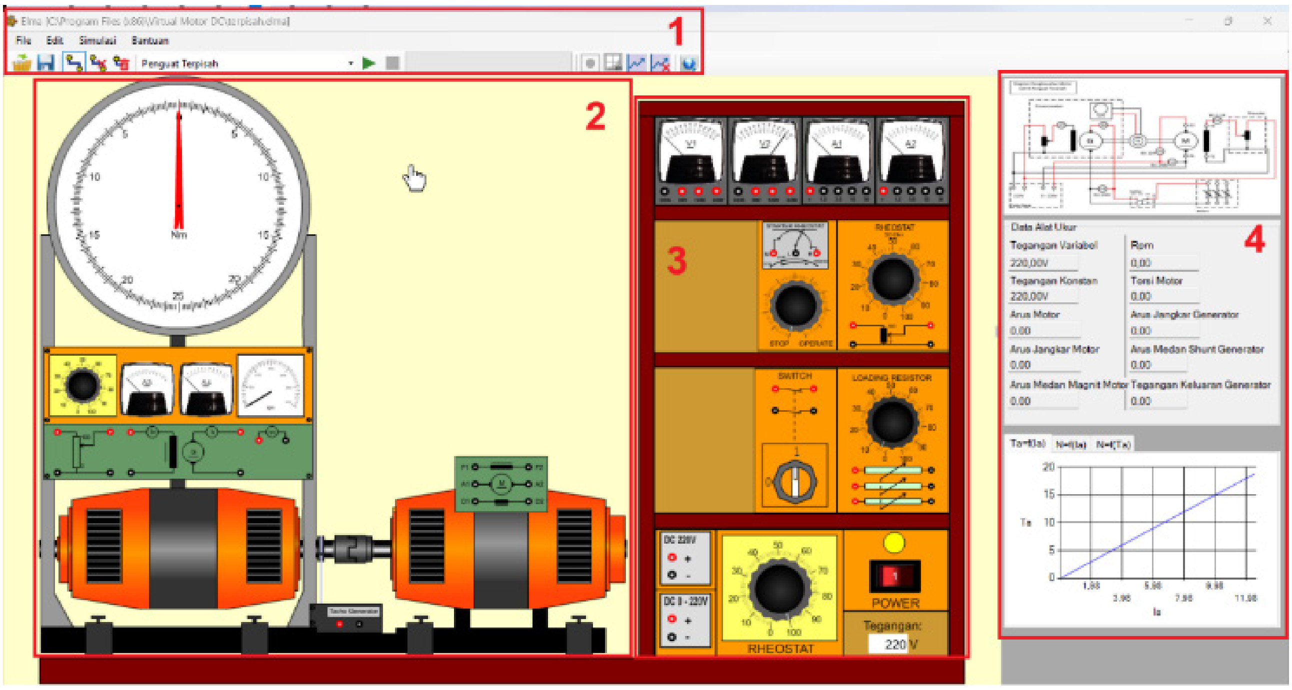


Figure 4. Screen capture of the virtual laboratory of motor DC, including its parts

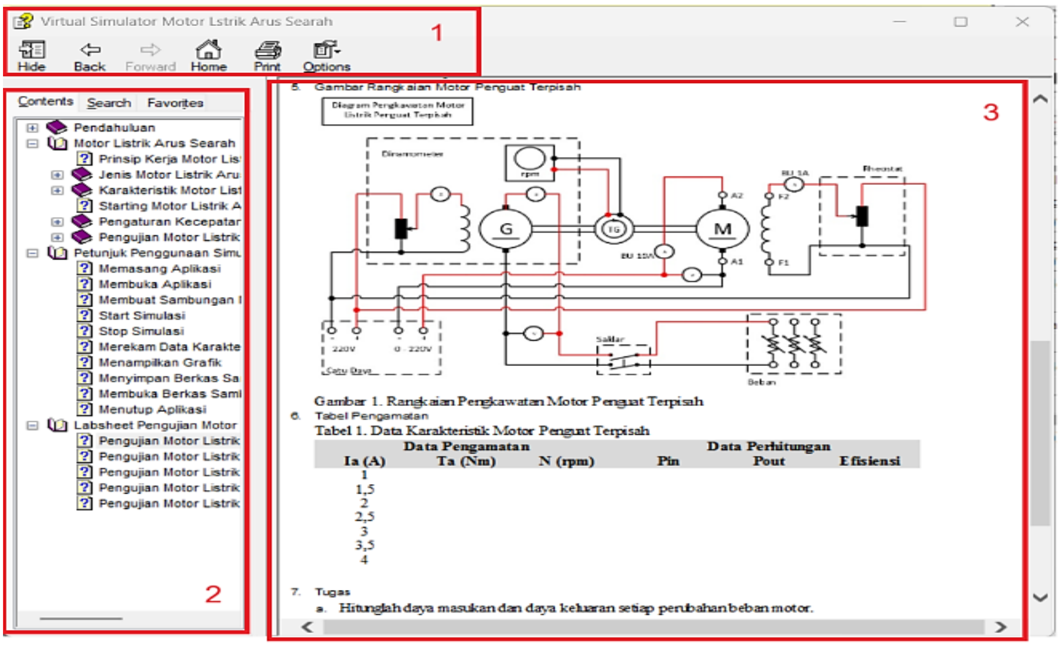


Figure 5. Screenshot of the help center on the DC motor virtual laboratory

Expert-based evaluation was carried out to validate the virtual DC motor laboratory application as a learning media. Criticism and suggestions from experts become material for product improvement. Electrical machine material specialists and computer-based media experts are involved in product validation testing. Expert-based validation has been carried out, and improvements have been made according to expert advice [32].

Furthermore, a perception study was carried out to assess students' opinions regarding the virtual laboratory of DC motor in practical learning of electrical machines. Based on research, students generally have a positive opinion of virtual DC motor laboratories and consider them to be a useful addition to conventional hands-on laboratories. It provides repeated experiments in a secure setting and permits self-paced learning [33].

4. Implementation and Evaluation

The DC motor virtual laboratory is used in practical learning of electrical machines. The location of the implementation is at Universitas Negeri Yogyakarta, Indonesia, more precisely in the Electrical Engineering Education Department. The control class uses conventional electric machine teaching aids, while the experimental class uses the virtual laboratory of DC motor for learning treatments. This research included a total of 32 students as participants, with 19 students assigned to the control group and 13 students assigned to the experimental group. The experimental class's documentation is shown in Figure 6, the outcomes of the work in the experimental class are shown in Figure 7, and the outcomes of the work in the control class are shown in Figure 8.

Figure 6. The experimental class documentation

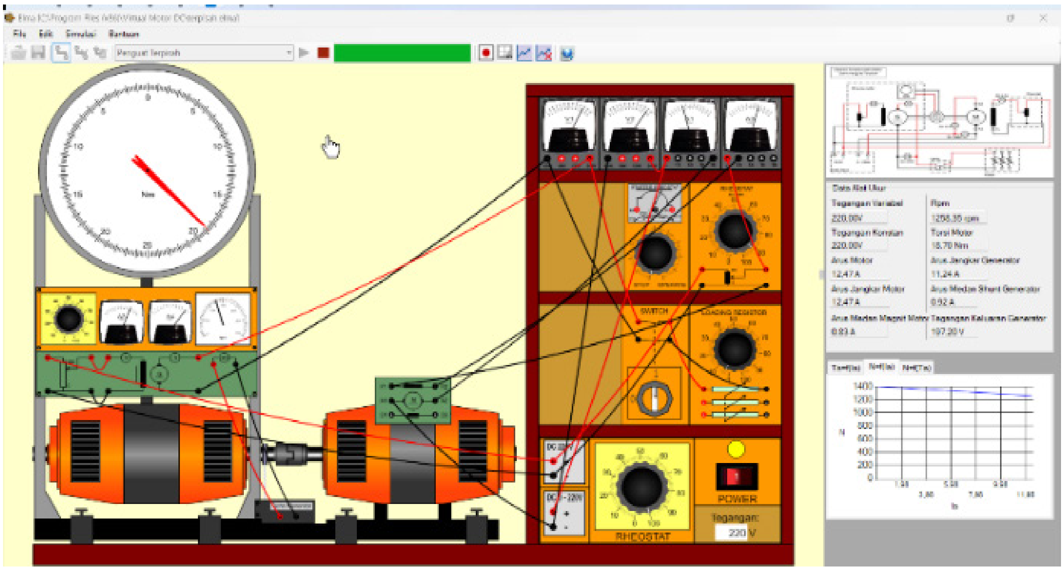


Figure 7. Example of student work results in the experimental class

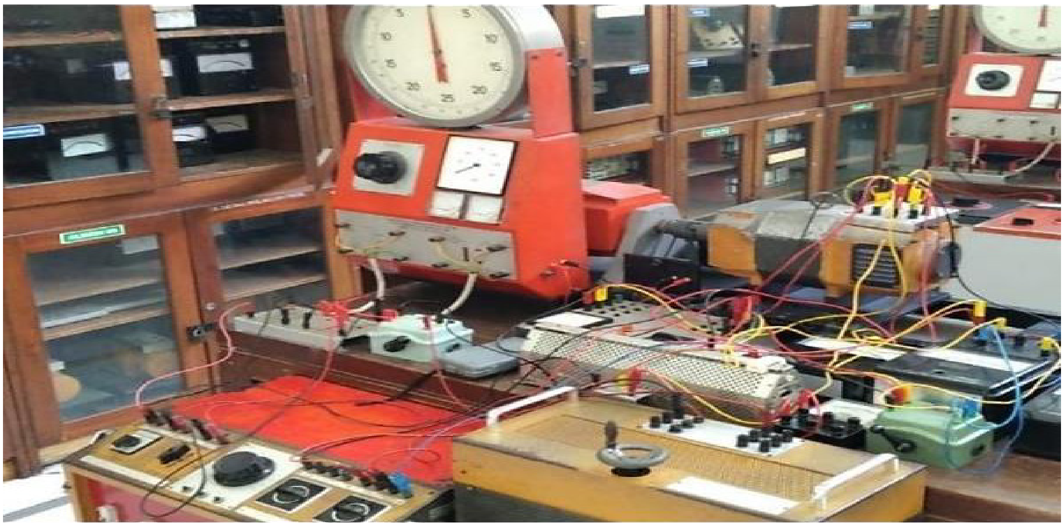


Figure 8. The control class uses real electric machine trainers in the physical laboratory

4.1. Results of Both Classes Pre-Test

A pre-test was administered to both classes prior to the implementation of the learning treatment. The results of the Mann-Whitney pre-test for both classes are presented in Table 5. According to Table 5, the significance value exceeds 0.05. Consequently, it can be inferred that the initial abilities of both classes are comparable.

Table 5. The results of the Mann-Whitney pre-test for both classes

Test Statistics[a]					
	Pret-test of separately	Pre-test of Shunt	Pre-test of Series	Pre-test of short compound	Pre-test of long compound
Mann-Whitney U	113,500	111,500	89,000	94,000	115,000
Wilcoxon W	204,500	202,500	180,000	185,000	206,000
Z	-,395	-,477	-1,363	-1,196	-,343
Asymp. Sig. (2-tailed)	,693	,633	,173	,232	,731
Exact Sig. [2*(1-tailed Sig.)]	,705[b]	,650[b]	,195[b]	,270[b]	,762[b]
[a] Grouping Variable: Classes					
[b] Not corrected for ties.					

4.2. Results of Both Classes Post-Test

Following the learning treatment, a post-test was administered to both classes. The results of the Mann-Whitney post-test for both classes are presented in Table 6. According to Table 6, the significance value exceeds 0.05. Therefore, it can be concluded that the learning outcomes of both classes are similar.

Table 6. The results of the Mann-Whitney post-test for both classes

Test Statistics[a]					
	Pre-test of separately	Pre-test of Shunt	Pre-test of Series	Pre-test of short compound	Pret-est of long compound
Mann-Whitney U	123,500	110,500	117,500	118,500	117,500
Wilcoxon W	313,500	300,500	307,500	308,500	307,500
Z	,000	-,610	-,304	-,227	-,273
Asymp. Sig. (2-tailed)	1,000	,542	,761	,820	,785
Exact Sig. [2*(1-tailed Sig.)]	1,000[b]	,623[b]	,821[b]	,850[b]	,821[b]
a. Grouping Variable: Class					
b. Not corrected for ties.					

4.3. Results of Both Classes' Pretests and Posttests

The knowledge levels before and after the learning treatment in both classes were analyzed by comparing the pre-test and post-test results. Table 7 presents the findings of the Wilcoxon test for the experimental class, while Table 8 displays the results for the control class. According to the Wilcoxon test results, the significance value is below 0.05 for both the control and experimental classes. This indicates that there are significant differences in knowledge levels before and after the learning treatment in both classes. Consequently, it can be concluded that both classes demonstrated an improvement in knowledge following the learning treatment.

Table 7. Wilcoxon test results pretest-posttest experimental class

Test Statistics[a]					
	Pre–Post. of separately	Pre–Pos. of Shunt	Pre–Post of Series	Pre–Post of short compound	Pre–Post of long compoun d
Z	-3,201[b]	-3,220[b]	-3,205[b]	-3,204[b]	-3,210[b]
Asymp . Sig. (2-tailed)	,001	,001	,001	,001	,001
a. Wilcoxon Signed Ranks Test					
b. Based on negative ranks.					

Table 8. Wilcoxon test results pretest-posttest control class

Test Statistics[a]					
	Pre–Post of separately	Pre–Post of Shunt	Pre–Post of Series	Pre–Post of short compound	Pre–Post of long compound
Z	-3,844[b]	-3,865[b]	-3,926[b]	-3,838[b]	-3,841[b]
Asymp. Sig. (2-tailed)	,000	,000	,000	,000	,000
a. Wilcoxon Signed Ranks Test					
b. Based on negative ranks.					

4.4. Effective Use of Multimedia

The gain value is used to determine how well the virtual DC motor laboratory is implemented in the learning process. Table 9 displays the distribution of gain values received by category. According to Table 9, most students achieved gain scores falling within the high criteria category, with only a few cases attaining scores meeting the moderate criteria, and there were no instances of gain scores falling into the low criteria category. The learning treatment in the experimental class using a virtual DC motor laboratory was proven to be effective in the experimental class.

Table 9. Summary of class experiment gain score distribution

Criteria	Motor Connection Type				
	Separately	Shunt	Series	Short compound	Long compound
High	69,23%	76,92%	84,62%	76,92%	76,92%
Medium	30,77%	23,08%	15,38%	23,08%	23,08%
Low	0%	0%	0%	0%	0%

5. Discussion

This study focuses on the development and implementation of a virtual laboratory for DC motors, designed to replicate testing procedures typically conducted in a physical lab. These virtual laboratories offer an interactive and realistic environment, enabling students to practice dc motor assembly, testing, and data interpretation without the risks associated with physical equipment. The effectiveness of this virtual lab is evidenced by significant improvements in student learning outcomes, underscoring its potential as a valuable educational tool.

5.1. The Virtual Laboratory of DC Motor

This research project culminates in a virtual simulator program designed for DC motors. The virtual laboratory of DC motor was developed to mimic the DC motor testing procedures in a physical laboratory.

The virtual DC motor laboratory is presented on a computer screen, mimicking the two-dimensional format of the electrical machine trainers found in traditional physical laboratories. Features for connecting machine components, measuring instruments, measurement results, and the interpretation of test data make this application very interactive and representative. Students are asked to determine what type of motor will be tested, then determine the connection between components through the banana plug terminal and test the correctness of the circuit, which will be immediately corrected by the application if there is a connection error. After the connection is declared correct and appropriate, the next step is the simulation testing process. Students are asked to run the DC motor with the correct procedure; if the procedure carried out is not appropriate, there will be overspeed or overcurrent on the DC motor being tested. Experiencing overspeed and overcurrent during electrical machine testing in a physical laboratory can pose high risks. The testing procedure involves applying a load to the DC motor through a DC generator, where an increase in DC generator load leads to a corresponding rise in motor load due to their shared axis. Armature current, motor torque, and motor speed data are among the parameters that are recorded during loading. These data points are utilized to make a graph that illustrates a DC motor's characteristics.

Similar research has also been developed regarding virtual laboratory electric machines, including asynchronous motor testing [24], [34], [35], synchronous machine testing [23], [25], [15], [9], [16], DC motor testing [17], and testing of other conventional electrical machines [27], [18], [10]. One notable benefit of the virtual laboratory of DC motors is their enjoyable user interface (UI), which simulates the skills needed to assemble, start, test (loading process), and stop DC motors. This ensures that students gain a consistent experience when using the virtual laboratory of DC motor compared to utilizing electric machine props in a traditional physical laboratory.

Limitations in developing virtual laboratory of DC motor applications include: 1) simulation limited to separately excited, shunt, series, and cumulative compound; 2) absence of a wiring diagram for compound differential motor connection; 3) ideal conditions during testing without accounting for losses due to armature reactions or eddy currents' heat losses; and 4) lack of online accessibility, requiring installation on a computer. The digital electric machine laboratory has previously been developed based on AR and VR; the VR environment resembles an electric machine in a physical laboratory [22].

The forthcoming research will concentrate on creating a virtual environment-based laboratory for practical testing of DC machines, AC machines, and transformers.

5.2. Learning Effectiveness

Student learning outcomes increase after using the DC motor virtual laboratory. Table 7 and Table 8 display the results of the Wilcoxon test for each respective class. The significance level of both tables is below 0.05. Thus, it is concluded that students in each class experienced increased learning outcomes. Increasing learning outcomes is consistent with earlier research [15]. The experimental class demonstrated a notable enhancement in learning outcomes. Utilizing virtual laboratories as part of the learning treatment scenarios can effectively enhance learning outcomes.

The learning outcomes following the learning treatment in each class were assessed using the Mann-Whitney test. As shown in Table 6, the significance level exceeds 0.05. This indicates that there is no significant difference in learning outcomes between the experimental class and the control class. Consequently, it can be concluded that the utilization of virtual DC motor laboratory applications for learning yields outcomes comparable to the use of electrical machine teaching aids in physical laboratories.

6. Conclusion

The digital era promotes digital multimedia-based learning that is flexible and representative of technological advances. A virtual laboratory of DC motor application has been developed on a computer-based system for practical learning of electric machines. Students can install the virtual laboratory of DC motor applications on their computers running the Windows operating system. The application's user interface is designed as a two-dimensional display corresponding to the actual teaching aids in a physical laboratory, making it possible to use it as a substitute or learning aid for a physical laboratory. This virtual lab not only enhances accessibility for students who may not have direct access to physical labs but also reduces the risks and costs associated with physical equipment handling. However, limitations such as the need for a Windows operating system and the lack of accounting for certain real-world variables, like losses due to armature reactions or eddy currents, suggest areas for improvement. Future research could focus on developing cross-platform compatibility, incorporating more realistic simulation parameters, and exploring the use of augmented and virtual reality to create even more immersive learning experiences.

These advancements could further bridge the gap between theoretical learning and practical application in the field of electrical engineering.

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