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Increasing the effectiveness of 'Power Electronics' classes using a supplementary web-based virtual laboratory setup to impart CDIO skills

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Abstract: **Power electronics is an engineering field dealing with the control and conversion of electrical energy. Many institutions are using CDIO (Conceive/Design/Implement/Operate) framework for their curricular planning and outcome-based assessment which demands huge self-learning. A virtual laboratory is an online platform allowing users to conduct simulations in a digital environment to improve self-learning. In this work, a virtual laboratory which provides an interactive platform for students to learn and experiment with power electronics circuits and devices, without the need for physical equipment is developed. The laboratory consists of a web-based interface that simulates the behaviour of different power electronics circuits. Learners can select different components and parameters to build and test circuits, and observe the results in real-time. The virtual laboratory also provides access to various measurement tools to analyse the behaviour of the circuits. The virtual laboratory has been designed to provide a user-friendly and intuitive interface, with detailed instructions and feedback to support students' learning. The laboratory has been integrated into a power electronics course. Feedback is collected through surveys from a total of 75 students including open ended questions and Likert responses. The learning of two set of students with and without using virtual lab before doing physical experimentation are assessed using a descriptive test. CDIO components analysis is done with the results of Mini projects developed by the students. The results indicate that the virtual laboratory provides a valuable and engaging learning experience and improves learning.**

Keywords: **Virtual laboratory, Online, Simulation, Experimentation, Power Electronics, Analysis, Education**

***JEET Category*—Research**

I. INTRODUCTION

The laboratory features a user-friendly interface that allows users to select and configure different components and parameters, run simulations, and analyse results. Users can also access pre-designed experiments and tutorials or customise their own experiments and projects. In recent years, virtual laboratories have gained popularity in various fields of science and engineering, including power electronics(Rihar et al,2022). They provide several benefits over traditional laboratory setups, such as cost-effectiveness, safety, scalability, and convenience.

Virtual laboratories also allow for real-time visualisation and analysis of complex phenomena, enhancing understanding and conceptualization of theory and practice.

Power electronics is a critical field of electrical engineering that deals with the control and conversion of electrical energy. As the demand for efficient, reliable, and sustainable power systems increases, the need for skilled professionals in power electronics also grows. To meet this demand, education and research in power electronics have become essential for engineering students and researchers. (Cheng, Ka Wai Eric, and Chung Lun Chan 2019)

The CDIO framework offers the learners with an education accenting engineering essential knowledge/skill in the context of Conceiving — Designing — Implementing — Operating (CDIO) real-world structures and products with a positive behaviour. (Berggren, K. F et al, 2003).

Throughout the world, CDIO Initiative collaborators have adopted CDIO as the framework of their curricular planning and outcome-based assessment. Hence, each and every course is required to be delivered with the connection to real world [Crawley, E. F et al, 2011]. It is reported that CDIO skills may be improved by adopting suitable active strategies (Kavitha D, 2023, Anitha D, 2018).

A traditional laboratory setup for power electronics experiments and demonstrations can be expensive, space-consuming, and pose safety risks (Jeyamala, C, 2018). To address these challenges, virtual laboratories have emerged as a promising solution, providing a flexible, accessible, and interactive platform for learning and experimentation [Cheng et al,2017]. A power electronics virtual laboratory designed to enhance the learning experience of students and researchers in power electronics has been discussed using various development applications [H. N. Nhung,2020]. The power electronics virtual laboratory should offer a range of experiments and simulations covering various topics in power electronics, such as AC-DC converters, DC-DC converters, AC-AC converters, etc (P. Ortega,2011).

The virtual laboratory offers several advantages over traditional laboratory setups, including cost-effectiveness, safety, scalability, and convenience. Users can access the laboratory from anywhere with an internet connection, eliminating the need for physical lab equipment and space. The virtual laboratory also enables real-time visualisation and analysis of complex power electronics phenomena, enhancing the understanding and conceptualization of theory and practice. We will discuss the design and implementation of the virtual laboratory, as well as present the results of the laboratory's usage.

Overall, the power electronics virtual laboratory provides a valuable resource for students and researchers in power electronics, enabling them to develop their skills and knowledge through experimentation and simulation in a digital environment.

In this paper, the development of virtual laboratory for power electronics is dealt step by step. The implementation and the usefulness of the developed lab is tested with a experimental group. It is also found that these virtual labs improve the attainment of the learning outcome when this experimental group is compared with a controlled group.

II. PROBLEM DEFINITION

The problem that a power electronics virtual laboratory can address is the lack of access to physical laboratory equipment and resources for students, researchers, and engineers. Many educational institutions, particularly in developing countries or remote areas, may not have sufficient laboratory facilities or equipment to support practical experimentation and learning in power electronics. This can hinder students' ability to fully understand and apply theoretical concepts, as well as limit opportunities for research and innovation in the field. (Gourmaj, Mourad, et al 2017) Furthermore, the cost of acquiring and maintaining laboratory equipment can be prohibitive for smaller institutions or individual researchers.

A power electronics virtual laboratory can address these challenges by providing a simulation environment that allows users to conduct experiments, test different circuits and systems, and observe the results without requiring access to physical components or laboratory equipment. This virtual laboratory can also offer a variety of simulations ranging from simple circuits to complex power electronics systems such as converters, inverters, and motor drives. In addition to providing a cost-effective solution, a power electronics virtual laboratory can also offer other benefits, such as:

1. Enhancing student learning by allowing students to experiment with different circuit configurations and parameters, and observe the results in a safe and controlled environment.
2. Enabling researchers to test and validate new power electronics designs and concepts, and conduct experiments without the need for expensive laboratory equipment.
3. Providing a platform for collaboration and knowledge sharing among students, researchers, and engineers in different parts of the world.

Overall, a power electronics virtual laboratory can be an effective solution for addressing the lack of access to physical laboratory equipment and resources in power electronics, and can provide opportunities for learning, research, and innovation in the field. (Evstatiev, Boris, et al 2019)

III. TRADITIONAL LAB VS VIRTUAL LAB

In this section we will discuss both the roles of traditional laboratory and virtual laboratory for learning Power Electronics. A comparative analysis of traditional laboratory and power electronics virtual laboratories can provide insights into the benefits and limitations of both approaches. Here are some points to consider,

A. Benefits of traditional laboratory:

Hands-on experience: Traditional laboratory provides hands-on experience for students to work with real components and equipment, which can enhance their understanding of the subject matter.

Real-time feedback: Traditional laboratories provide real-time feedback to students, allowing them to adjust and modify their experiments based on the results.

Collaboration: Traditional laboratory provides opportunities for students to collaborate with their peers and instructors, fostering teamwork and communication skills. (Guo, Liping, et al.2022)

B. Limitations of traditional laboratory:

Cost: Traditional laboratory equipment can be expensive to purchase, maintain, and repair, making it challenging for some institutions to provide access to adequate laboratory resources.

Safety concerns: Traditional laboratories involve working with high-voltage components and equipment, which can pose safety risks to students and instructors.

Limited availability: Traditional laboratory resources may not be available to all students, particularly those in remote or under-resourced areas.

C. Benefits of virtual laboratory:

Accessibility: Power electronics virtual laboratory provides students with access to laboratory resources regardless of their location, making it accessible to a wider audience.

Cost-effectiveness: Power electronics virtual laboratory is more cost-effective than traditional laboratory, as it eliminates the need for expensive equipment and maintenance costs.

Flexibility: Power electronics virtual laboratory allows students to explore and experiment with different scenarios and parameters, providing greater flexibility in learning and experimentation.

Safety: Power electronics virtual laboratory eliminates the safety concerns associated with traditional laboratory, as it does not involve working with high-voltage equipment.

D. Limitations of virtual laboratory:

Lack of physical feedback: Power electronics virtual laboratory does not provide physical feedback to students, which can limit their understanding of the subject matter.

Dependence on technology: Power electronics virtual laboratory relies on technology, which can be prone to errors, failures, and malfunctions, and can limit the effectiveness of the laboratory experience.

Unrealistic results: Power electronics virtual laboratories may not always produce realistic results, particularly when the simulations do not accurately model the real-world environment.

Both traditional laboratory and power electronics virtual laboratories have their benefits and limitations. A **hybrid approach** that combines both approaches may provide the best of both worlds, offering students a rich and diverse laboratory experience that enhances their understanding of power electronics.

IV. DEVELOPMENT OF VIRTUAL LAB – TOOLS

*A. Objectives***:** Provide a simulated environment for students to conduct experiments and simulations. To enhance students' understanding of power electronics concepts and principles, including circuit analysis, power electronics devices, and control methods. The experiments developed are,

1. Single Phase Semi Converter
2. Single Phase Full Converter
3. DC Chopper
4. AC Voltage Controller
5. Commutation of SCR

*B. Necessary software/tech stack***:** To develop the virtual laboratory, various tech stacks are used such as HTML, CSS, Javascript, Git and Javascript libraries such as ChartJS. Now let us discuss each tech stack briefly.

1. **HTML** (Hypertext Markup Language) provides the structure and content of web pages.
2. CSS (Cascading Style Sheets) is a styling language which allows us to customise the appearance and layout of the user interface.
3. JavaScript is a programming language used to add interactivity and dynamic behaviour to web pages. It is an essential tool for developing a virtual laboratory as it allows you to create simulations, interactive exercises, and other dynamic content.
4. Git is a version control system that is used to manage and track changes in code and other files. It is an essential tool for developing a virtual laboratory as it allows us to keep track of changes, collaborate with teammates, and revert to previous versions if necessary.
5. ChartJS is a JavaScript library that is used to create interactive and customizable charts and graphs in a virtual laboratory. It is an essential tool for displaying data and simulation results in a visual and intuitive way.
6. GitHub is a web-based platform that provides hosting for Git repositories and offers various collaboration features for software development projects. It is an essential tool for developing a virtual laboratory as it provides a centralised location to store the project code and manage the development process.
7. A web browser with internet connection is required to access and interact with the virtual lab, as it provides the interface for displaying the lab components and interacting with them.

C. Design of user interface and user experience:

Before designing the user experience, it is crucial to understand the users' needs. The virtual laboratory can be used by students, researchers, and industry professionals. The laboratory is designed to cater to their varying levels of expertise. The user interface (UI) of the virtual laboratory is designed to be intuitive and easy to use. It allows users to navigate through the different components and functionalities of the laboratory without much difficulty. The UI should be aesthetically pleasing and visually engaging. The virtual laboratory should be **optimised for different devices**, including desktops, laptops, tablets, and smartphones.

This will ensure that users can access the laboratory from different devices, making it more accessible. Simulations are a critical component of the virtual laboratory. They enable users to conduct experiments virtually, which provides a safe environment without the risks associated with real-life experiments. The simulations should be realistic and accurate. The virtual laboratory should provide users with real-time feedback on their experiments. This feedback will help users adjust the values and interpret results more effectively. It is important to design the feedback system to be clear and easy to understand.

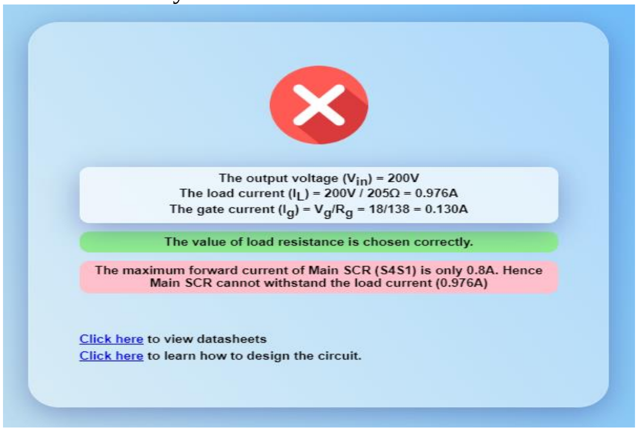

Fig 1: Intuitive hints and feedback for the users for designing the circuit for the required specifications

The user experience of a power electronics virtual laboratory can greatly impact its effectiveness as a learning and experimentation tool. A positive user experience can lead to greater engagement, increased learning, and improved performance, while a negative user experience can lead to frustration, confusion, and disengagement. The virtual laboratory has a graph plotter tool that allows users to analyse and interpret the output waveforms of their experiments. The tool is easy to use and provides the necessary functionalities for data analysis.

D. Development of simulation modules

The first step is to identify the simulation needs of the virtual laboratory. This includes identifying the different types of experiments that users will conduct and the parameters and variables that need to be considered. We have chosen the experiments by referring to the course outcomes of the course 18EE670 Power Electronics and Drives Laboratory offered to the sixth semester UG EEE students of Thiagarajar College of Engineering. There are many tech stacks and software tools available to build a virtual laboratory. Since we were skilled in Javascript and related languages, we chose HTML, CSS, Javascript to develop this virtual laboratory. This involves creating a circuit model that represents the real-life circuit and includes all the necessary components, such as diodes, transistors, capacitors, and inductors. Then the simulation models should be verified by comparing the simulated results with real-life experimental results. This ensures that the simulation models are accurate and reliable. The simulation modules must be tested with real users to identify areas for improvement. Based on the feedback received, the simulation modules should be iterated to improve the user experience and the accuracy of the simulations.

E. Testing and refining the virtual laboratory:

Testing and refining a power electronics virtual laboratory is a crucial step in ensuring that the laboratory provides an optimal learning experience to its users.

Testing: Users were invited to test the virtual laboratory and provide feedback on its usability and effectiveness. The testing included users with varying levels of expertise to identify any potential issues and areas for improvement.

Functionality testing was also done which involves testing the laboratory's functionality to ensure that all components and features are working correctly. This includes testing simulations, data analysis tools, and real-time feedback mechanisms.

Refining: Based on the user feedback received during sting, we have iteratively made changes in the virtual laboratory to address identified issues. This includes changes to the user interface, simulations, output waveforms. We have optimised the virtual laboratory to improve its performance, reduce loading times, and user experience. We have addressed the bugs and technical issues identified during testing.

Testing and refining a power electronics virtual laboratory is a continuous process that requires careful consideration of user feedback and optimization of the laboratory's functionality and performance. By following the steps outlined in this report, we can ensure that the virtual laboratory provides an optimal learning experience to its users and remains a valuable resource for power electronics education and research.

F. Deploying the virtual laboratory:

Deploying and maintaining a power electronics virtual laboratory on Github requires specific steps to ensure its proper setup and maintenance. We need to install the necessary dependencies, such as Python libraries and Javascript frameworks, using a package manager. Then the virtual laboratory is deployed to Github, ensuring that all components and features are functional. Regularly updating the virtual laboratory with the latest software updates is necessary to ensure optimal performance and better user experience. User support and assistance must be provided to ensure that users have a seamless and positive experience using the virtual laboratory. Github's version control system is used to track changes to the virtual laboratory's codebase and collaborate with other developers.

V. FUNCTIONALITIES OF VIRTUAL LAB:

The power electronics virtual laboratory offers a variety of functionalities, which are showcased in the following screenshots.

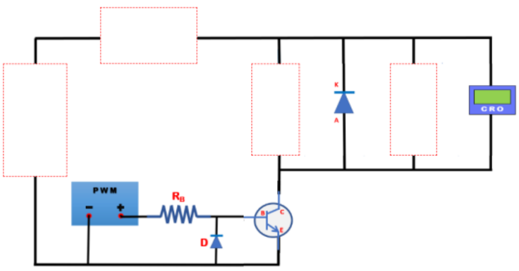

Fig-2: Drag and Drop Workspace

Figure-2 displays the laboratory's simulation capabilities, with a user-friendly interface that allows users to drag and drop the complex power electronics components and make a complete circuit. The laboratory offers a range of components and devices, such as power diodes, transistors, and SCRs, which can be easily **dragged and dropped onto the canvas** for circuit creation.

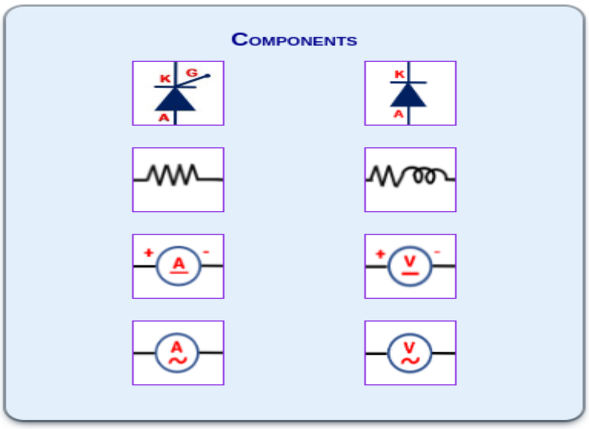

Fig-3: Components that are draggable and droppable into the workspace

Figure-3 displays the components that are available to the user to build the circuit. These components are easily draggable and can be dropped anywhere in the workspace. Later, in the workspace, the circuit will be verified, if not correct, the user will be indicated with error messages and hints.

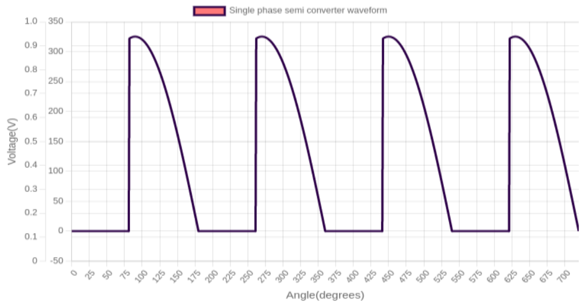

Fig-4: Output voltage waveform plotted dynamically based on the user's circuit design

Figure-4 shows the output waveform of a single phase semi converter plotted on the screen. The output waveform will only be displayed if the user's circuit design is correct and the components are connected correctly. The output waveform dynamically varies when the firing angle is adjusted using a range slider.

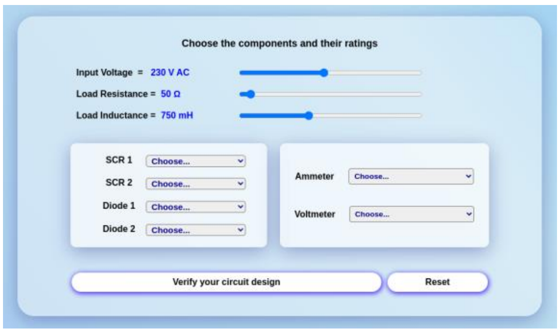

Fig-5: Circuit design page

Figure-5 shows the circuit design page. Here, the user can choose their components based on their design requirements. The user will be provided a step-by-step guidance till he/she designs the entire circuit correctly. The user will be shown alerts, warnings and hints.

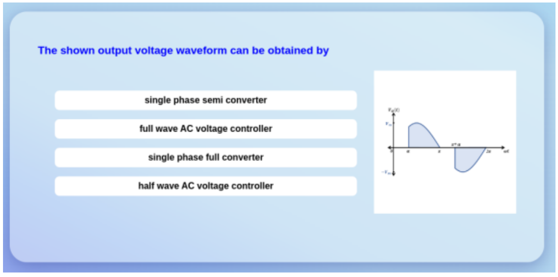

Fig-6: Post Quiz Question in virtual lab

Figure-6 shows the post quiz question containing images and four choices. Once the user has answered all the quiz questions, his/her total score will be revealed.

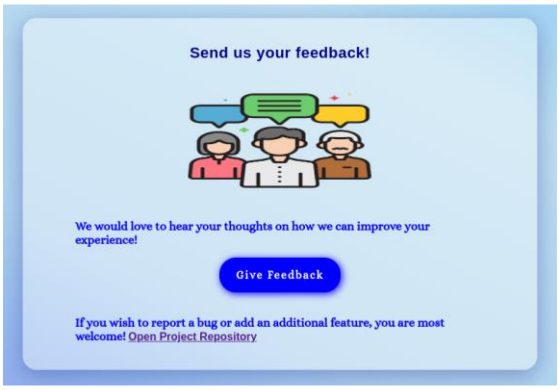

Fig-7: Collecting User Feedback

Figure-7 shows the link for submitting user feedback. We collect feedback using google forms, where the user can share their experience, suggestions, etc. Based on the responses collected, we will reiterate the simulation modules and perform bug fixes, if any.

VI. RESULTS AND DISCUSSIONS

The power electronics virtual laboratory was evaluated for its performance in terms of accuracy and reliability. The laboratory performed well in most aspects, with high clarity that was found to be reliable. Feedback is collected through surveys from a total of 75 students from sixth semester UG EEE, Thiagarajar College of Engineering. The collected feedback is analysed to understand the usefulness of our virtual laboratory for better understanding of practical laboratory experiments. The responses of open-ended questions and Likert scale to justify the results of the research [Kavitha et al, 2021].

A. Open Ended Questions:

Open-ended questions in a survey questionnaire are important when analysing the effectiveness of a power electronics virtual lab because they provide respondents with an opportunity to share their thoughts and opinions in their own words. Open-ended questions are not constrained by predefined response options, which allows for a more free-form response that can capture unique perspectives and insights that may not have been anticipated by the survey creator. The questions and their top responses are tabulated in table I.

TABLE-I
FEEDBACK PARAMETERS

Q1	**Are you able to understand/revise the theory content using our virtual lab facility?** 1. Yes, I found the power electronics virtual lab facility to be an excellent resource for understanding and revising the theory content. 2. The simulations were engaging and interactive, which made it easier for me to grasp the concepts. 3. The lab simulations were easy to use and provided a clear visualisation of the concepts
Q2	**Briefly comment about the UI/UX of the virtual laboratory** 1. The UI/UX of the laboratory was well-designed and effective. 2. I appreciate the attention to detail in the design, which made it easier for me to focus on the concepts being presented. 3. The interface was clean and easy to understand.
Q3	**If you have found any flaw in the theory content, please explain about it** 1. No flaw identified in theory 2. Nil
Q4	**Is there any enhancement required in the simulation workspace of our virtual lab? If yes, please specify** 1. The values I have set in the circuit design page are not reflecting in the output waveform. 2. It would be great if the values of load resistance, load current, etc are marked in the circuit diagram also. 3. A zoom in and zoom out feature, if possible, will be helpful for bigger circuits.
Q5	**Please give your overall feedback** 1. The explanation was so appropriate and to the point. 2. The animations were smooth and all the blocks were clearly visible. The theory is also explained neatly. 3. More questions can be added in the quiz section. 4. The option for addition of 'RLE' load will be good. 5. We are expecting even more circuits and experiments in this Virtual laboratory as it will be more helpful for circuit branch students.

We have made changes in the virtual lab based on the responses for the Question-4. Some of the significant changes we have made are discussed below.

Some users have mentioned some sort of data storage should be present so we have made use of the **localStorage** feature available in web browsers to save and retrieve data across different web pages. When the user correctly designs the circuit, the values (load resistance, SCRs chosen, ammeter & voltmeter readings, etc) are stored in the localStorage. Later this data is used in the output waveforms and in the circuit diagram for better user experience.

Few users have asked for zoom-in and zoom-out features. Currently we don’t have any requirements for those features in our virtual lab as the circuit diagrams are not very big in size and they fit the screens just fine. But in future, if simulations with very large and complex circuits were added, zoom-in and zoom-out features will be included in the virtual lab.

B. Likert Scale:

Likert scales are a type of rating scale used to assess the perceived importance or effectiveness of various features of this project. Participants of the survey are asked to rate each feature on a **scale of 1 to 5**, where 1 represents "not useful/effective" and **5 represents "very useful/effective."** The Likert scale can provide valuable insights into the perceived strengths and weaknesses of the project and can help identify areas for improvement and shown in table II.

TABLE-II
LIKERT SCALE FOR FEATURES OF VIRTUAL LAB

Feature	1	2	3	4	5
Drag and Drop Feature	0	0	0	7	68
UI / UX (Look and feel)	-	-	8	12	55
Verification of user's circuit design	-	-	-	4	71
Dynamic Waveforms	-	-	-	9	66
Relevance to the subject	-	-	-	13	62
Circuit Simulation	-	-	-	2	73
Explanations given if circuit is wrong	-	-	5	11	59

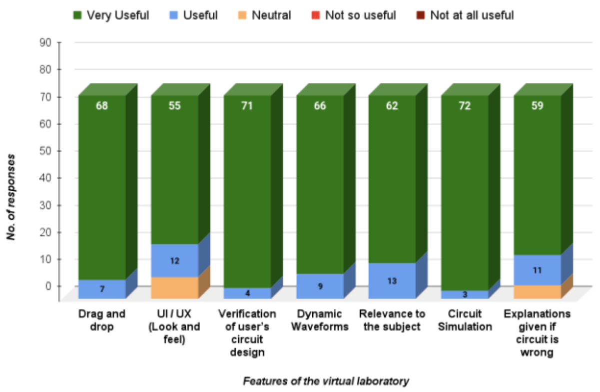

Fig-8: Likert Scale Responses

C. Descriptive test and Mini project for the students:

Two groups of students were considered. Group A with 50 students who have directly conducted experiments in the physical laboratory and Group B with 50 students who have used virtual lab setup before conducting experiments in the physical laboratory. These students are given a written test (duration 1 hour) and their performance was analysed. Their average mark is tabulated in table III.

TABLE-III
DESCRIPTIVE TEST QUESTIONS AND THE AVERAGE MARKS OBTAINED BY THE TWO GROUPS

Q. No	Question (10 Marks Each)	Average Mark	
		Group A	Group B
1	Explain the differences between semi-converter and full converter operation with RL Load	6.75	8.15
2	Explain the working of Step-down DC Chopper with neat diagrams.	7.5	8.5
3	Briefly discuss the specifications to be considered while choosing an SCR for a circuit.	6.25	7.85
4	Explain how resonant pulse commutation is achieved with neat diagrams.	7.0	8.5

Based on the results of the descriptive test given to two groups of students in power electronics, it appears that the use of the power electronics virtual laboratory has a positive impact on the performance of the students who used it. Group-B, who had used the virtual lab before conducting experiments in the physical lab, performed well on the test compared to Group-A, who conducted experiments directly in the physical lab without the use of the virtual lab. This suggests that the power electronics virtual lab has provided Group-B with a **deeper understanding of the concepts and principles** of power electronics, which translated to better performance on the test. Similar analysis is done with the results of Mini projects developed by the students. The rubrics used and the average marks obtained by both groups are provided in the table 4. In this assessment, students required to identify a real time application of power electronics in an industry and conceive a problem. Then they design the electronics circuit with alternate designs and evaluate the best one. Then they will implement the circuit using suitable software and perform the design for failure modes and effects analysis (DFMEA). The mini project components are mapped with CDIO skills in the table IV.

TABLE-IV
MINI PROJECT COMPONENTS ANALYSING THE CDIO SKILLS

Q. No	Parameter	CDIO Component	Average Mark	
			Group A	Group B
1	Identifying practical PE application to be developed	Conceive	9.5/10	9.5/10
2	Feasible design with alternatives	Design	35/40	32/40
3	Software implementation	Implement	22.5/25	20/25
4	Checking operation with DFMEA	Operate	20/25	19/25

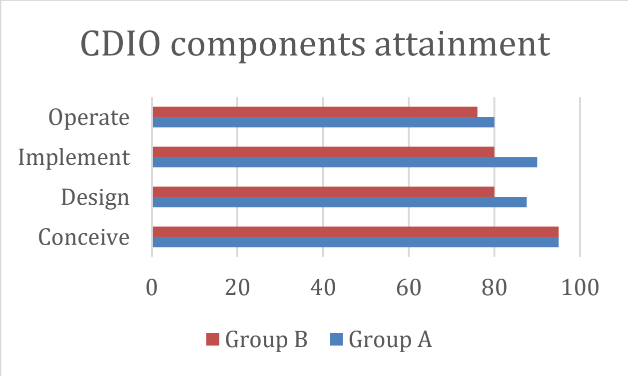

Fig 9: Percentage attainment of CDIO components

It is found that the usage of PE virtual lab improves the CDIO skill, in particular for the design and implement phase. Overall, the evaluation revealed that the power electronics virtual laboratory was a highly effective tool for learning power electronics, with excellent performance metrics, positive user feedback, and superior features and functionality compared to other similar tools. The laboratory's ease of use and comprehensive features make it an ideal tool for both students and researchers interested in power electronics.

VII. CONCLUSION

For those interested in accessing the power electronics virtual laboratory developed, it can be accessed through a web browser using the following URL **https://suriyamu1.github.io/PowerElectronicsLab/**

The power electronics virtual laboratory presented in this study has several advantages over traditional physical laboratories. Firstly, it provides a safe and controlled environment for students to experiment with power electronic circuits, reducing the risk of injury or equipment damage. Additionally, it allows students to repeat experiments multiple times, providing a deeper understanding of the concepts being taught. Furthermore, the virtual laboratory is cost-effective, as it eliminates the need for expensive equipment and reduces the costs associated with maintenance and repair. This makes it an ideal solution for institutions with limited budgets or those located in areas where physical laboratory space is at a premium. The evaluation of the virtual laboratory was carried out using both quantitative and qualitative methods. Student feedback was collected through questionnaires, with results indicating a high level of satisfaction with the virtual laboratory. Additionally, assessment scores for students who used the virtual laboratory were compared with those who used a traditional physical laboratory, with results showing significant difference in performance. Overall, the power electronics virtual laboratory presented in this study has the potential to enhance engineering education by providing a safe and cost-effective means of providing practical experience in power electronics.

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