

# Design and Implementation of an Immersive VR-Based Labs for Power Electronics Education

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**Abstract** - In engineering education, especially in learning Power Electronics, many obstacles are commonly faced by students. Since the concepts taught in the classroom are mostly presented as theoretical explanations, they are found to be somewhat difficult to be understood in practice by students. In addition to this, the lack of equipment in traditional laboratories, high costs, and safety-related issues are considered as factors that hinder the complete development of students' learning experience. Against this backdrop, the facilitation of Power Electronics learning was attempted using Virtual Reality (VR) technology. Through VR, an immersive environment is created in which the working of circuits can be directly experienced by students. For instance, greater clarity is provided through a 3D visualization of the changes that occur during the operation of a converter or inverter, compared to traditional diagrams. As a result, the concepts are understood more quickly by students.

Also, in VR-based learning, the freedom to learn at an individual pace is provided to students. By being given the opportunity to repeat experiments multiple times, mistakes are able to be self-corrected by them. Their confidence is increased, and the quality of learning is improved. Work can be carried out by students without any fear, particularly since a safe environment without electrical hazards is ensured. As part of the study, an experiment involving 32 undergraduate (UG) students was conducted. In this process, a comparison was made between the performance of students taught using the VR-based learning method and those taught through traditional methods. The obtained results indicated that significant improvement in conceptual understanding and practical approach was achieved by the students who used VR. In particular, complex concepts were understood in a shorter time, and problem-solving ability was improved by them.

**Keywords** - Virtual Reality (VR), Virtual Laboratory, Power Electronics Education, Immersive Learning, Simulation-Based Learning, Interactive Learning Environment

## I. INTRODUCTION

Today's world widely uses power electronics in electric vehicles, solar energy systems, battery charging units, industrial motor drives, smart grids, and many modern electronic devices, so it plays an important role. Semiconductor devices such as MOSFETs, IGBTs, and thyristors efficiently convert and control electrical power in power electronics. Its growing industrial importance has made power electronics a core subject for electrical and electronics engineering students.

Many students find power electronics difficult to understand, even though the subject is highly valuable, because several concepts such as circuit operation, switching principles,

waveform generation, control systems, and energy transfer are combined in it. Equations, static diagrams, and theoretical lectures explain these topics in most classrooms. Basic knowledge is built by these methods, but a clear imagination of what happens inside a converter during real operation is often not provided by them. For example, students may study a buck converter in theory, but they may struggle to visualize how the switch turns ON and OFF, how energy is stored by the inductor, or how the output voltage is changed by duty cycle. As a result, a gap between theoretical learning and practical understanding often remains.

### A. Need for Better Laboratory Learning

Power electronics requires laboratory practice because the actual behavior of circuits can be seen and tested best by students. However, many limitations are created by conventional laboratories. Power electronics lab setups require costly equipment such as oscilloscopes, power supplies, semiconductor modules, controllers, sensors, and protection circuits. Only a limited number of kits are provided by many colleges, so enough hands-on experience is not received by every student.

Safety is another major concern. Power electronics experiments involve high voltage, high current, and fast switching operations. Equipment can be damaged or hazards such as electric shock, overheating, and short circuits can be created by wrong connections. Because of this, too much carelessness is often shown by students, and independent exploration or repetition of experiments is avoided by them. Opportunities for deeper learning are also reduced by time limitations during lab sessions.

For these reasons, a safe, accessible, and more engaging alternative learning method is needed by educators for students.

### B. Role of Virtual Reality in Power Electronics Education

A new way to improve engineering education is offered by Virtual Reality (VR) through the creation of an immersive three-dimensional learning environment. A virtual laboratory can be entered by students, and equipment can be interacted with by them as if they were present in a real lab, instead of only reading theory or watching 2D simulations. Circuits can be connected, switches can be operated, waveform changes can be observed, and experiments can be repeated many times by them without fear of damaging hardware.

VR is especially useful for power electronics because many processes are changed dynamically and are not directly visible. Switching states, current flow paths, energy storage in inductors,

capacitor charging behavior, and output waveform variations can be clearly observed by students in a VR environment. For example, the response of output voltage can be immediately seen by students when the duty cycle of a buck converter is changed by them. Similarly, inverter switching sequences and AC waveform generation can be easily and interactively understood by them.

### C. Objectives and Contributions of the Paper

Based on these needs, the development of an immersive VR-based virtual laboratory for power electronics education and experimentation is presented by this paper. The creation of an interactive learning platform that helps students understand difficult concepts in a practical and engaging manner is the main objective.

The key contributions of this work are:

- A realistic VR laboratory for power electronics experiments is developed by this work.
- Real-time visualization of converters, inverters, and switching operations is provided by this system.
- Safe experimentation without electrical hazards or hardware damage can be performed by students.

## II. LITERATURE REVIEW

Virtual Reality (VR) has emerged as a transformative technology in engineering education, enabling immersive and interactive learning experiences. Recent studies highlight that VR-based learning environments significantly enhance student engagement, conceptual understanding, and knowledge retention compared to traditional teaching approaches. A comprehensive review by Radianti et al. [1] analyzed immersive VR applications in higher education and identified key design elements such as interactivity, immersion, and real-time feedback as critical factors influencing learning outcomes. The study emphasized that VR environments bridge the gap between theoretical knowledge and practical implementation by providing realistic simulation-based experiences.

Similarly, Hamilton et al. [2] investigated the role of immersive VR in educational settings and reported that VR-based platforms improve student motivation and participation. Their findings suggest that VR enables active learning by allowing students to explore and manipulate virtual objects, thereby enhancing experiential learning. Recent advancements have focused on integrating VR with laboratory-based education. Jiang et al. [3] developed a mixed reality laboratory framework that enables students to perform experiments in a virtual environment. Their work demonstrated that VR-based labs can effectively replicate real-world laboratory conditions while overcoming limitations such as equipment cost, safety risks, and accessibility constraints.

Furthermore, Stracke et al. [4] conducted a systematic review of immersive VR in higher education and highlighted its potential for remote and collaborative learning. The study emphasized that VR-based platforms support flexible learning environments, enabling students to access laboratory experiences from any location.

In addition, research on VR-based science learning environments shows that immersive simulations significantly improve students' understanding of complex concepts [5]. These

systems provide real-time visualization and interactive feedback, which are particularly beneficial in domains requiring dynamic analysis, such as power electronics. From a technical perspective, VR systems designed for engineering education incorporate interactive interfaces, simulation engines, and real-time data visualization modules. Pirker et al. [6] demonstrated the use of VR for educational applications, highlighting the importance of user interaction and system responsiveness in enhancing learning effectiveness.

Recent developments also explore VR applications specifically for engineering students. Padilla Perez and Keleş [7] showed that immersive VR environments improve learning outcomes and provide a more engaging educational experience compared to traditional methods. Despite significant progress in VR-based educational systems, several limitations remain. Most existing studies focus on general engineering or science education, with limited attention given to specialized domains such as power electronics. Additionally, many VR-based systems lack interactive circuit-level simulation and real-time experimentation capabilities.

To address these gaps, the proposed work focuses on the design and implementation of a VR-based virtual laboratory specifically tailored for power electronics education. The system integrates immersive visualization with interactive simulation of power electronic circuits, enabling safe, cost-effective, and scalable experimentation.

## III. METHODOLOGY

This section explains how the immersive VR based virtual lab was developed for Power Electronics education. The main aim of this system is to give students a practical learning experience in virtual environment, where they can understand converter circuits, switching operation, waveform generation and experiment process in simple way. Instead of only reading theory, students can interact with components and see output instantly.

### A. Overall System Design

The proposed system was designed with different parts such as VR hardware, software platform, simulation model and student interaction system. First, the student wears VR headset and enters into virtual laboratory. Then user can choose experiments like Buck Converter, Boost Converter, Inverter or Rectifier.

After selecting the experiment, the circuit setup will open inside VR lab. Student can change values like input voltage, duty cycle, frequency and load resistance. Based on that, the system calculates output and shows waveform results directly.

This method helps students to connect theory and practical knowledge in better way.



Fig. 1. Block diagram of system design

### B. Hardware Requirements (VR Headset, Controllers)

For smooth working of VR lab, some hardware devices are needed. Main device is VR headset which gives 3D view to the

student. Hand controllers are used for selecting buttons, moving objects and changing values.

TABLE I. HARDWARE REQUIREMENTS

Component	Minimum	Recommended
VR Headset	Meta Quest 2	Meta Quest 3
Controllers	2 Hand Controllers	Motion Controllers
Processor	Intel i5	Intel i7
RAM	8 GB	16 GB
Graphics Card	GTX 1660	RTX 3060
Storage	256 GB	512 GB SSD

The headset gives immersive feeling like real lab. Controllers help student to touch, grab and operate virtual instruments.

#### C. Software Framework (Unity 3D Engine)

Unity 3D software was used for creating the virtual lab. It is easy and powerful tool for making VR applications. Using Unity, 3D models of converters, switches, meters and lab environment were created.

C# programming language was used for controlling the functions inside VR. For example:

- Opening experiment menu
- Make the circuit connections
- Starting converter operation
- Showing voltage/current graph
- Resetting experiment

#### D. Integration with Simulation Tools

Only 3D model is not enough for engineering learning, so simulation logic was also connected with VR system. Converter formulas or tools like MATLAB / Simulink can be linked with Unity.

When student changes input values, the simulation calculates output result and sends back to VR screen.

Example:

- Increase duty cycle → Output voltage increases
- Increase load → Current changes
- Change frequency → Ripple changes

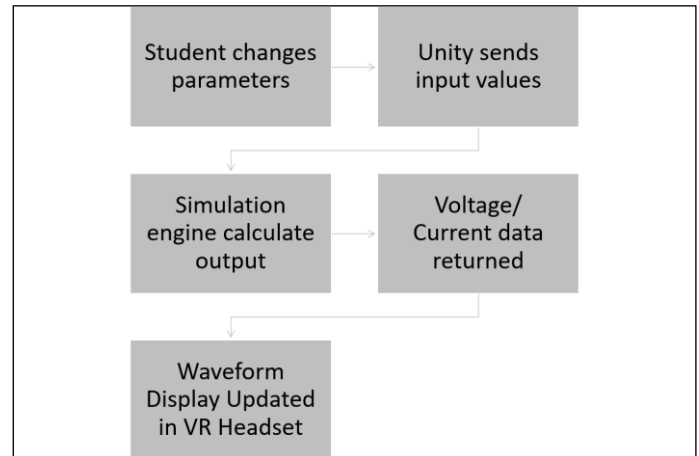


Fig. 2. Flow of data process

This gives real learning feel to students. The proposed methodology combines VR headset, Unity 3D software, simulation model and user interaction system to create a virtual Power Electronics laboratory. It helps students to learn safely, repeat experiments many times and understand difficult concepts in easy visual method. This system can improve learning quality compared to only normal classroom teaching.

### IV. DESIGN OF VIRTUAL POWER ELECTRONICS EXPERIMENTS

#### A. Selection of Experiments

This section explains how the virtual power electronics experiments were designed inside the VR laboratory. The main aim of this work was not only to create a 3D virtual environment, but also to give students a feeling similar to performing real laboratory experiments. In many cases, students understand formulas and theoretical concepts in the classroom, but they face difficulty when they enter the actual laboratory and work with practical circuits. To reduce this gap between theory and practice, the VR system was developed as an interactive learning platform where students can observe circuit behavior, change parameters, and understand outputs in real time.

The experiments included in the virtual laboratory were selected based on common engineering syllabus, practical importance, and difficulty level faced by students. The selected experiments mainly cover AC to DC conversion, DC to DC conversion, and DC to AC conversion. Therefore, rectifier circuits, DC-DC converters, and inverter systems were chosen. These experiments are basic and important because they form the foundation for advanced applications such as motor drives, renewable energy systems, UPS systems, electric vehicle charging units, and industrial automation.

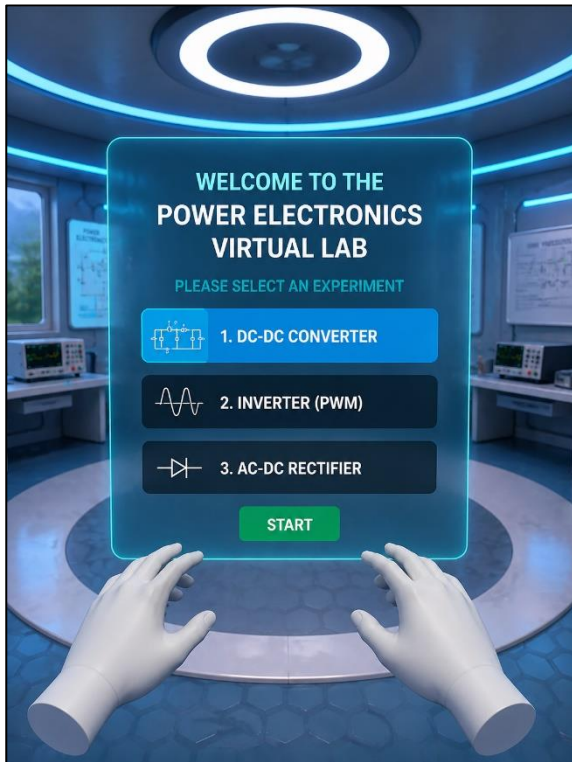


Fig. 3. VR - Welcome screen

### Rectifier (Half-wave / Full-wave)

Rectifier experiments included both half-wave and full-wave rectifiers. In the half-wave rectifier model, students can observe how a single diode conducts during the positive half cycle and blocks during the negative half cycle, producing pulsating DC output. In the full-wave rectifier model, both half cycles are converted into DC output, resulting in better average voltage and lower ripple. In the VR environment, students can clearly observe current flow direction, diode ON/OFF condition, and compare the output waveforms of half-wave and full-wave rectifiers. This gives better understanding than only watching CRO output in conventional labs.

### DC-DC Converter (Buck / Boost)

The DC-DC converter section included buck and boost converters. These converters are widely used in chargers, battery systems, laptops, solar applications, and electric vehicles. The buck converter was designed to reduce input DC voltage into lower output voltage, while the boost converter increases input DC voltage into higher output voltage. Inside the VR lab, students can vary duty cycle using sliders and immediately observe changes in output voltage. They can also study switch ON/OFF operation, inductor charging and discharging process, capacitor smoothing effect, and PWM-based control. This helps students understand switching states and energy transfer process in an easier way.

### Inverter

The inverter experiment was also included because it is one of the important circuits in power electronics. Inverters convert DC power into AC output and are used in UPS systems, solar power conversion, and motor drives. In the VR model, a single-phase H-bridge inverter was created where students can observe switching sequence, positive and negative half-cycle generation,

and square wave AC output. Students can compare DC input and AC output visually and understand how switching devices generate alternating waveform from DC supply.

### B. Circuit Modeling and Simulation

All the experiments were designed with proper circuit logic and mathematical modeling, not only as visual objects. When the student changes input voltage, load resistance, frequency, or duty cycle, the system recalculates the output instantly and updates the waveform display. This real-time simulation helps students connect theoretical equations with practical behavior. For more advanced implementation, external tools such as MATLAB/Simulink can also be connected to improve simulation accuracy.

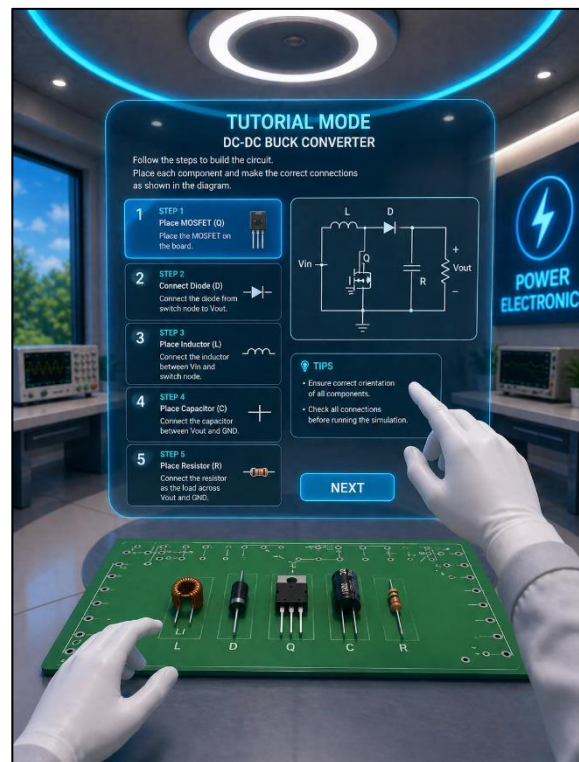


Fig. 4. Tutorial screen

### C. User Interaction Design in VR

The user interaction design was kept simple so that even first-time users can easily operate the system. Students can walk inside the virtual laboratory, choose experiments from menu boards, grab wires or components, press start and stop buttons, rotate knobs, and move sliders to control duty cycle or other parameters. They can also observe digital meters and waveform graphs directly inside the VR environment. The overall interaction was designed to make students feel like attending a real practical class.

### D. Safety and Real-Time Feedback Mechanism

Safety was considered as one of the major advantages of the proposed VR laboratory. In real power electronics labs, wrong connections may damage components or create electric shock risk. In the virtual lab, students can freely perform experiments without any danger. If the student makes wrong connection, the system provides warning sound, red light indication, or error

messages such as “Wrong Polarity” or “Check Connection.” If the connection is correct, green light indication appears, the experiment starts, and output graphs are displayed. This type of feedback improves student confidence and supports self-learning.

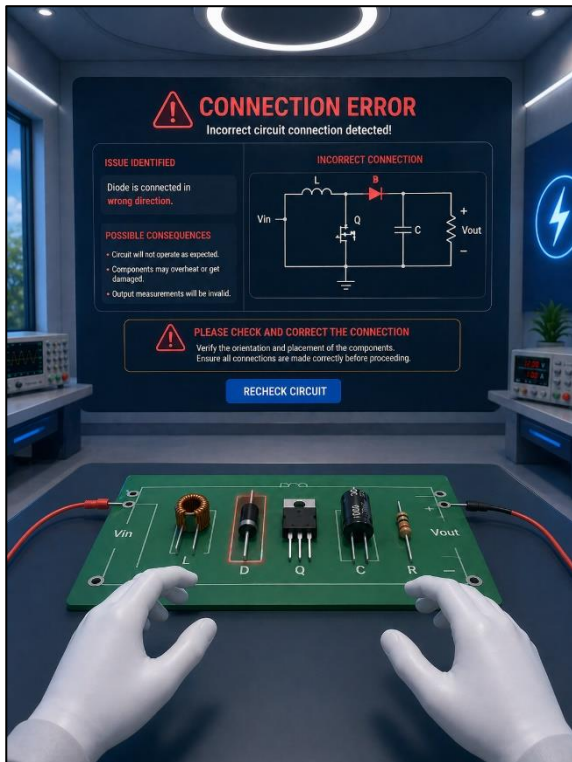


Fig. 5. Display warning errors

values, changing graphs, resetting circuits, and displaying warning messages. Separate scripts were created for each module for easy maintenance.

#### Integration with MATLAB/Simulink

For higher accuracy, Unity can also be linked with MATLAB/Simulink to generate converter responses such as PWM-based buck converter output, inverter harmonic analysis, and transient load response. This gives both practical visualization and engineering accuracy. VR enhances understanding of complex engineering concepts through real-time visualization of dynamic processes [5].

#### Testing and Debugging

After development, the system was tested carefully to ensure smooth performance. Functional testing was done for buttons and controls, graph testing was done for waveform correctness, VR motion testing was done for user movement, and debugging was performed to remove issues such as controller misalignment, graph delay, slow loading, and menu errors.

Overall, the virtual experiments were designed based on student needs and academic syllabus. By combining real-time simulation, interactive controls, safety feedback, and immersive 3D learning, the proposed VR laboratory provides students with a better practical understanding of power electronics in a modern and safe way.

#### E. Implementation

The complete system was implemented using Unity 3D software because it supports VR development, real-time graphics rendering, and scripting functions. Unity XR Toolkit was used for VR controls and motion tracking. Visual Studio was used for C# programming, and Blender software was used to create 3D models of components such as diodes, MOSFETs, IGBTs, resistors, capacitors, inductors, batteries, oscilloscopes, and converter boards. Realistic component models increase immersion feeling and make the learning environment more attractive.

#### Development Environment (Unity Setup)

Unity 3D was used as the main platform for creating the virtual laboratory. Different scenes such as lab room, experiment table, control panels, menus, and display boards were developed inside Unity. XR Toolkit helped in headset movement and controller interactions.

#### 3D Modeling of Components

Realistic 3D models were designed for all important power electronics components including diode, MOSFET, IGBT, resistor, capacitor, inductor, battery, CRO, and converter boards. These models improved the visual quality and user immersion.

#### Scripting and Control Logic (C#)

C# scripting was used to control all system functions such as starting experiments, detecting controller touch, updating output

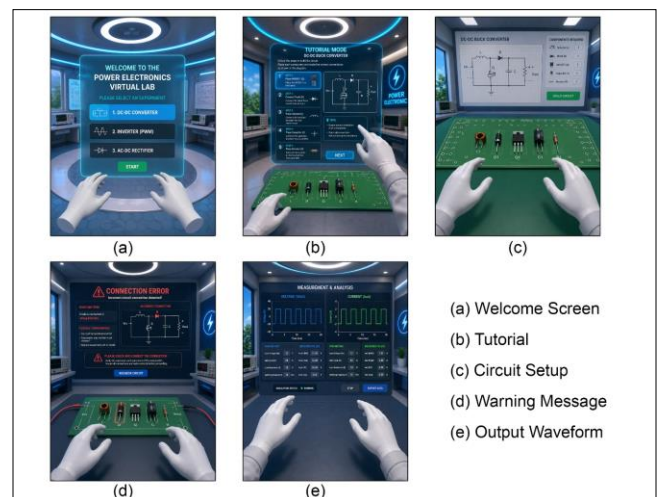


Fig. 6. Overall model of VR Power Electronics Laboratory

### V. RESULTS AND ANALYSIS

The developed VR-based virtual laboratory was tested with a group of 32 UG Engineering students to evaluate its learning effectiveness and system performance. The students performed experiments such as rectifier, buck converter, and inverter inside the virtual environment. After completing the sessions, their understanding, response time, and engagement level were analyzed. Most students were able to complete the experiments correctly and showed better understanding of circuit operation compared to only classroom learning.

The main performance metrics considered were accuracy, response time, and user engagement. Accuracy refers to correct circuit connections, correct parameter selection, and proper

understanding of output waveform. Response time means how quickly the system reacts when the student changes values such as duty cycle or load. The VR system showed smooth response with instant graph updates. User engagement was higher because students actively interacted with the system instead of only watching demonstrations.

When compared with traditional laboratory learning, the VR system provided better visualization and repeat learning opportunities. In normal labs, students get limited time and may hesitate due to fear of damaging components. In VR, they freely repeated experiments many times. Feedback collected from users indicated that most students felt the system was easy to use, interesting, and helpful for understanding difficult concepts.

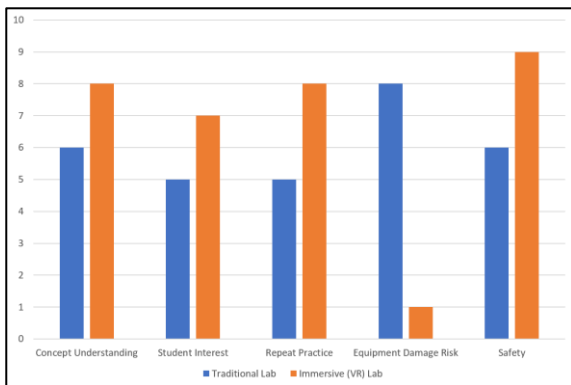


Fig. 7. Student Feedback Summary

The feedback scores presented in Fig. 7 are expressed on a normalized 0–10 scale, representing the average response of all 32 undergraduate engineering students who participated in the study. Each rating corresponds to the mean value obtained by aggregating individual student scores and dividing by the total number of participants. For clearer interpretation, these averages can also be viewed in terms of cumulative scores. For example, a rating of 8 in concept understanding under immersive VR corresponds to a total of 256 points ( $8 \times 32$ ), whereas a rating of 6 in the traditional method corresponds to 192 points. Similarly, student interest improved from a total of 160 (average 5) in traditional learning to 224 (average 7) in VR-based learning. Ease of practice increased from 160 (average 5) to 256 (average 8), while safety showed a notable rise from 192 (average 6) to 288 (average 9). In contrast, equipment damage risk, which is an undesirable factor, reduced significantly from a higher total of 256 (average 8) in traditional labs to just 64 (average 2) in the VR environment.

Students demonstrate higher satisfaction and preference for VR-based laboratory experiences [7]. This analysis clearly indicates both the improvement in average scores and the overall positive shift in cumulative student perception. The results confirm that immersive VR learning creates a more engaging, safer, and more effective educational platform, while also reducing experimental risks compared to conventional laboratory methods.

## VI. CONCLUSION

This paper presented the development of an immersive VR-based virtual laboratory for Power Electronics education and experimentation. The proposed system was designed to help students understand important concepts such as rectifiers, DC-

DC converters, and inverters through interactive 3D learning environment. Unlike conventional teaching methods, the VR platform allows students to observe circuit behavior, change parameters, and study output waveforms in real time. The system also provides a safe and cost-effective alternative to physical laboratories where equipment cost and electrical risk are major concerns.

From the results and user feedback, it was observed that the VR-based learning method improved student engagement, conceptual understanding, and practical confidence. Students were able to repeat experiments many times without fear of component damage or connection mistakes. The immersive nature of VR made learning more interesting and helped bridge the gap between theoretical classroom knowledge and practical laboratory experience. Therefore, the proposed virtual laboratory can be considered as a useful supplementary tool for modern engineering education, especially in institutions with limited laboratory resources.

Future research can further enhance the proposed system in several directions. Integration with Augmented Reality (AR) can combine virtual circuit models with real laboratory equipment for mixed learning experience. AI-Based Adaptive Learning can be introduced to track student performance and provide personalized guidance, quizzes, and difficulty levels based on learning progress. Multi-User Collaborative VR Labs can allow multiple students and instructors to join the same virtual lab simultaneously for teamwork, remote practical sessions, and interactive teaching. These improvements can make future Power Electronics education more intelligent, accessible, and collaborative.

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