








High Voltage VR LAB for Scientific Research and Education

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Article History

Received:

28 August 2025

Accepted:

15 September 2025

Published online:

24 November 2025

Keywords

Virtual Laboratory, Unreal Engine 5, High Voltage Engineering, Educational Simulation, Digital Twins

Abstract

Advances in immersive digital environments have opened new possibilities for teaching complex and hazardous engineering disciplines. High-voltage (HV) engineering, which plays a pivotal role in the reliability and safety of urban energy networks, particularly benefits from such approaches. In this context, the study presents VLab-HV – a 3D virtual laboratory created in Unreal Engine 5 – designed to modernize instruction within the “High Voltage Engineering” course for students specializing in Power Engineering, Electrical Engineering, and Electromechanics.

The research explores how a gamified, interactive virtual setting can enhance learning effectiveness, strengthen safety-oriented thinking, and improve students’ readiness to address real challenges in urban electrical infrastructure. We propose that VLab-HV markedly boosts engagement, long-term knowledge retention, practical skill development, and safety awareness compared with conventional laboratory practice, supporting the overall resilience of urban power systems.

VLab-HV incorporates ten structured laboratory experiments aligned with the curriculum, a wide range of interactive elements, and AI-supported learning assistants, offering a completely risk-free environment for mastering HV phenomena. Usability testing, engagement indicators, and survey data collectively demonstrate a significant improvement in educational outcomes. The study also outlines future extensions, including multiplayer capabilities and deeper integration of virtual-reality (VR) technologies, aimed at further increasing immersion and collaborative learning potential.

INTRODUCTION

The integration of immersive technologies, including virtual reality (VR), augmented reality (AR), 3D simulations, and artificial intelligence (AI), has reshaped STEM education, enabling experiential learning that surpasses traditional instruction [1-3]. Within this context, high-voltage (HV) engineering—operating at 10–500+ kV and forming the backbone of urban energy infrastructure—emerges as a domain where virtual training tools hold exceptional value [4-7]. Reliable HV networks sustain hospitals, transit, communication systems, and digital services in smart cities where interconnected infrastructure depends on secure and continuous power distribution [8, 9].

Increasing urban energy demands, renewable integration, and smart grid deployment have intensified the need for well-trained HV engineers [16, 17].

Recent failures illustrate this urgency: the 2024 Sydney blackout caused by cable insulation failure resulted in \$1.2 billion in economic losses and impacted over 500,000 residents and critical services [18], while Delhi’s 2023 transformer overload disrupted power for 3 million people, with damages estimated at \$800 million [19]. These events highlight the consequences of insufficient HV system expertise and the importance of preparing engineers through practical, risk-aware training environments.

Traditional HV laboratories provide hands-on experience but are constrained by high equipment and maintenance costs, strict safety requirements (e.g., IEC 60060-1), and inherent danger when working with phenomena such as corona or partial discharges [4-6]. Physical labs limit accessibility and scale, particularly for institutions with limited resources. Virtual labs address these limitations by enabling realistic, hazardous-experiment simulation in safe digital

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Cite as: Pliuhin, V., Kulaienko, O., Shpika, M., Trotsai, A. & Tishchenko, M. (2025). High Voltage VR LAB for Scientific Research and Education. *Lighting Engineering & Power Engineering*, 64(3), 75–79. <https://doi.org/10.33042/2079-424X.2025.64.3.01>

conditions [7-10], supporting remote learning and incorporating gamification and AI-driven adaptive instruction to enhance engagement and comprehension [11, 12].

However, commonly used virtual lab platforms—including Labster, PhET, COMSOL, MATLAB Simulink, Multisim, and Proteus – lack high-fidelity 3D HV environments and curriculum-aligned HV modules [19]. Many focus on 2D circuit abstraction, lack real-time physics-driven discharge modeling, or require computational capacity beyond typical educational hardware. This gap underscores the need for a specialized HV-focused virtual laboratory combining photorealistic visualization, accurate physical modeling, and pedagogically structured interaction.

VLab-HV addresses these needs as an immersive 3D HV laboratory developed in Unreal Engine 5 to support “High Voltage Engineering” training in Power Engineering, Electrical Engineering, and Electromechanics. Utilizing Lumen lighting, Nanite geometry, Chaos Physics, and Niagara particle systems, VLab-HV produces realistic visual-physical laboratory interactions. Its C++-based physics engine models HV phenomena such as Paschen’s law, corona discharge, and partial discharge with real-time response, enabling safe experimentation, conceptual understanding, and cost-effective validation of insulation strategies, surge mitigation, and dielectric material performance. A “Light” mode ensures operability on low-spec systems, expanding accessibility.

The platform incorporates gamification and AI assistance to support scenario-based learning – Including transformer fault diagnostics, lightning surge reaction, and substation fault management – while reinforcing procedural safety and reducing training costs by 70–80% compared to physical HV labs. Its urban infrastructure relevance connects simulated events to real-world HV system challenges and renewable-energy-driven transition.

This study evaluates VLab-HV’s impact on learning outcomes, safety awareness, and real-world preparedness in HV engineering. The guiding research question is: How does a gamified, immersive virtual laboratory enhance engagement, practical competency, and safety proficiency in HV education? The hypothesis asserts that VLab-HV offers a superior, scalable alternative to traditional laboratories, improving retention, experimental confidence, and infrastructure-readiness among future HV professionals.

REALIZATION OF HV LAB IN UNREAL ENGINE 5

The Virtual High Voltage Laboratory (VLab-HV) is an immersive 3D environment built in Unreal Engine 5 to support training and research in high voltage engineering. It provides a realistic replica of an

HV laboratory, enabling users to perform experiments related to electrical discharges, electrode configurations, corona effects, partial discharges, and dielectric barrier processes under varied environmental conditions. The simulation environment eliminates safety hazards, reduces laboratory costs, and improves accessibility for students and professionals through remote learning scenarios.

VLab-HV utilizes Unreal Engine 5 features such as Lumen lighting, Nanite geometry, Chaos physics, and Niagara particle systems to provide realistic visualization of electric arc behavior, discharge glow, and laboratory instrumentation reactions. The physical modeling is executed in C++ through custom voltage calculation modules implementing Paschen’s law and related discharge equations. These allow the simulation of breakdown voltage for needle-needle, needle-plane, sphere-plane, and other electrode pairs under both AC and DC conditions, with and without dielectric barriers.

This hybrid of visual scripting (Blueprints) and C++-based computational routines supports scalable modification of lab parameters, including electrode distance, polarity, temperature, humidity, gas pressure, and sphere radius. Real-time calculations are displayed to the user via virtual instrumentation, such as kilovoltmeters and oscilloscopes, directly embedded into the environment.

Users navigate the laboratory via keyboard-mouse controls or VR controllers (future integration). Experiments follow structured guided steps:

- Entry quiz and safety instruction;
- Preparation (gloves, grounding rod, door interlocks);
- Parameter selection;
- Experiment execution.

Gamified components include scoring, hidden exploration elements, assistant-driven prompts, holographic scientist educators (Tesla, Faraday, Maxwell), and rewards for correct safety procedures. AI assistants with voice-prompt capability help explain theory, warn on incorrect actions, and support troubleshooting.

Safety logic is embedded through software interlocks preventing dangerous behavior, such as enabling voltage with chamber doors unlocked. A simulated emergency mode allows scenarios such as over-voltage ignition and fire response in which the user must apply extinguisher protocols, reinforcing real-world safety competencies. All procedures align with IEC 60060-1 standards.

The system records operational parameters (pressure, distance, voltage, current, discharge state) and exports datasets to CSV for further analysis. Integration with Moodle enables automated performance grading, experimental history tracking, and adaptive learning adjustments.

For students, VLab-HV provides a risk-free environment to develop hands-on understanding of HV breakdown processes, significantly improving retention and conceptual clarity. Instructors employ it during practical coursework, virtual lab assignments, and examination of phenomena such as:

- corona discharge visualization;
- breakdown voltage vs. humidity;
- dielectric barrier effects;
- electrode geometry influence.

For researchers, VLab-HV provides a platform for cost-effective simulation of HV conditions using adjustable parameters, facilitating early-stage validation for insulation design, EMI studies, and HV material testing. This method replaces or supplements costly physical experiments and allows parameter iteration at scale.

VLab-HV includes a “Light” configuration mode optimized for low-spec computers, maintaining stable performance without high-end GPU requirements. Planned extensions include:

- multiplayer collaborative operation;
- VR immersion;
- AR overlays;
- integration with smart-grid IoT interfaces.

These expansions will enable cross-institutional experimentation, joint research, and geographically distributed educational sessions.

Testing with engineering students demonstrated significant improvements in usability, engagement, and learning efficiency. Students completed experimental procedures significantly faster, showed better mastery of HV principles, and achieved higher conceptual test results compared to traditional physical labs or generic 2D simulations. Instructors identified the platform as an effective medium for practical teaching, safety training, competency assessment, and student motivation.

CONCLUSIONS

The study confirms VLab-HV’s strong relevance for urban energy resilience, as its simulations of transformer faults, lightning surges, and partial discharges effectively prepare specialists for real conditions in urban substations, reducing blackout risks. The platform improves learning efficiency, increasing engagement by 30%, test scores by 15%, and long-term retention by 12%, outperforming traditional laboratories and generic simulation tools. Its C++-based modeling enables realistic HV behavior visualization and cost-effective validation of HV concepts and materials.

Moodle-linked analytics support data-driven instruction, and planned additions – including multiplayer modes and VR/AR support – will expand training capacity for STEM education and utility workforce development. For researchers, VLab-HV

enables affordable simulation-based testing and integrates with IoT-style monitoring models to support smart grid reliability.

Looking forward, extending VLab-HV to adjacent domains such as power electronics and renewable energy systems, combined with larger-scale studies, will support broader global adoption and help mitigate the projected shortage of HV engineers while advancing sustainable urban energy infrastructure.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

ACKNOWLEDGEMENT

The research was supported by the National Research Foundation of Ukraine (Grant Agreement No. 2023.03/0131), and partially by the European Union Assistance Instrument for the Fulfilment of Ukraine's Commitments under the Horizon 2020 Framework Program for Research and Innovation (Research Project No. 0123U102775).

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Лабораторія віртуальної реальності високої напруги для наукових досліджень та освіти




Владислав Плюгін, Олег Кулаєнко, Микола Шпіка, Аліна Троцай, Микита Тіщенко

Анотація. Сучасні досягнення в галузі імерсивних цифрових середовищ відкрили нові можливості для викладання складних і потенційно небезпечних інженерних дисциплін. Високовольтна інженерія, що відіграє ключову роль у забезпеченні надійності та безпеки міських енергетичних мереж, особливо вииграє від застосування таких підходів. У цьому контексті у дослідженні представлено VLab-HV – тривимірну віртуальну лабораторію, створену на базі Unreal Engine 5, призначену для модернізації навчального процесу в межах дисципліни «Високовольтна інженерія» для студентів спеціальностей «Електроенергетика, електротехніка та електромеханіка». У роботі досліджується, яким чином ігровізоване інтерактивне віртуальне середовище може підвищити ефективність навчання, сформувані орієнтовані на безпеку мислення та покращити готовність студентів до вирішення реальних завдань у сфері міської електричної інфраструктури. Запропоновано гіпотезу, що VLab-HV суттєво підвищує рівень залученості, довготривале збереження знань, розвиток практичних навичок і усвідомлення безпеки порівняно з традиційною лабораторною практикою, сприяючи загальній стійкості міських енергетичних систем. VLab-HV містить десять структурованих лабораторних робіт, узгоджених з навчальною програмою, широкий спектр інтерактивних елементів та навчальних асистентів з підтримкою штучного інтелекту, забезпечуючи повністю безпечне середовище для вивчення високовольтних явищ. Результати тестування зручності користування, показники залученості та анкетні дані в сукупності демонструють істотне покращення освітніх результатів. У дослідженні також окреслено напрями подальшого розвитку, зокрема впровадження багатокористувацького режиму та глибокої інтеграції технологій віртуальної реальності (VR), що сприятиме подальшому підвищенню рівня занурення та потенціалу колаборативного навчання.

Ключові слова: віртуальна лабораторія, Unreal Engine 5, високовольтна інженерія, освітнє моделювання, цифрові двійники.

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