Development of a 5D Educational Simulation Framework for Teaching Power Supply Fundamentals

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Abstract. The rapid digitalization of engineering education has intensified the need for advanced instructional tools capable of integrating theoretical knowledge with practical system behavior. In the field of power supply engineering, traditional teaching methods and conventional virtual laboratories often fail to adequately represent the dynamic, decision-dependent, and safety-critical nature of real power systems. This paper proposes the development of a 5D educational simulation framework for teaching power supply fundamentals in higher education institutions. The framework extends classical 3D virtual environments by incorporating temporal process modeling, interactive scenario logic, cognitive engagement mechanisms, and outcome-oriented assessment into a unified virtual reality platform. A structured methodology for logical scenario design, dynamic system modeling, and learner performance evaluation is presented. The proposed framework was experimentally validated through a semester-long implementation involving undergraduate power engineering students. Quantitative results demonstrate significant improvements in learning outcomes, practical task success rates, and operational accuracy compared to traditional instructional approaches. The findings confirm that 5D educational simulators effectively enhance higher-order cognitive skills, support outcome-based education requirements, and provide a scalable digital learning solution for modern power supply engineering curricula.

INTRODUCTION

The rapid digital transformation of higher education has significantly reshaped the way engineering disciplines are taught, learned, and assessed. Power supply engineering education faces increasing pressure to evolve beyond traditional lecture-based and laboratory-centered approaches. The growing complexity of modern power systems—driven by renewable energy integration, smart grids, power electronics, and digital monitoring—requires graduates to possess not only theoretical knowledge, but also strong system-level thinking, temporal reasoning, and operational decision-making skills. Conventional educational tools, however, often fail to provide learners with sufficient exposure to real-world operating conditions, dynamic system behavior, and integrated performance evaluation.

Over the last decade, simulation-based learning environments have emerged as an effective solution for bridging the gap between theory and practice. Three-dimensional (3D) simulators and virtual laboratories allow students to visualize substations, power lines, transformers, and switching operations in a safe and repeatable environment. Nevertheless, most existing simulators remain limited in scope: they primarily focus on spatial visualization and basic interaction, while neglecting time-dependent processes, learner cognition, structured assessment, and scenario-driven pedagogical logic [1,2]. As a result, learning outcomes are often fragmented and difficult to align with outcome-based education standards. To overcome these limitations, advanced educational paradigms are increasingly shifting toward multidimensional simulation frameworks. Within this context, the concept of 5D educational simulation has gained attention as a holistic approach that extends conventional 3D environments [3,4]. A 5D simulator integrates five interrelated dimensions:

1. spatial representation of technical objects,
2. temporal evolution of physical and operational processes,
3. interactive learner actions and system responses,
4. cognitive engagement and decision-making logic,
5. outcome-oriented assessment and feedback mechanisms.

This multidimensional integration transforms simulators from passive visualization tools into active learning systems capable of supporting higher-order cognitive skills.

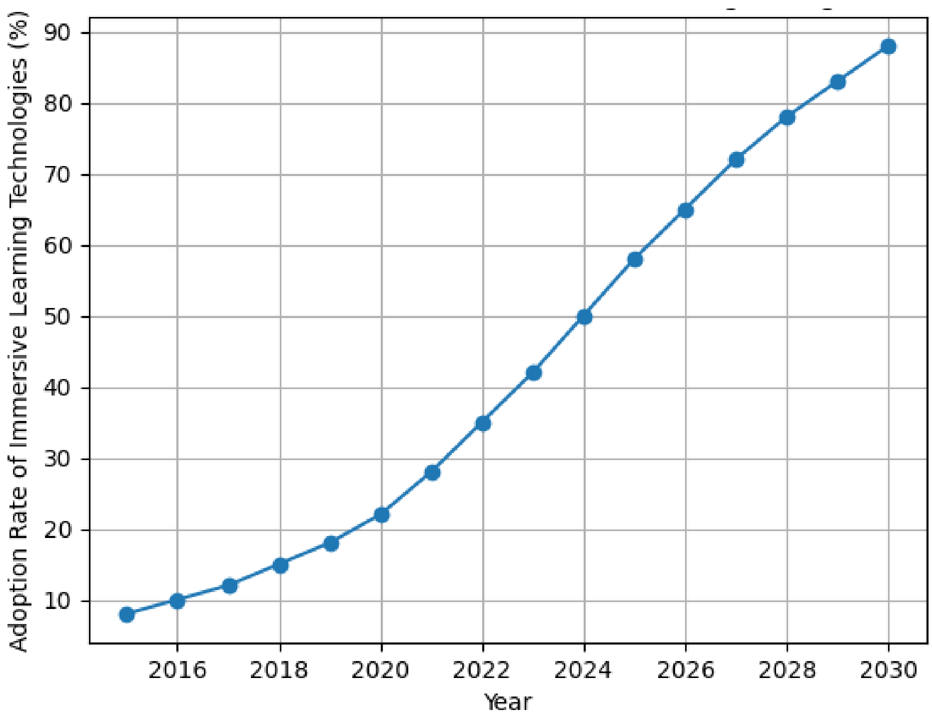

FIGURE 1. Growth Trend of Immersive and Simulation-Based Learning in Engineering Education

Figure 1 illustrates the global growth trend in the adoption of immersive and simulation-based learning technologies in engineering education between 2015 and 2030. The steady increase reflects the rising integration of virtual laboratories, VR-based simulators, and advanced digital learning environments driven by Industry 4.0 requirements, digital transformation of higher education, and the need for practice-oriented engineering training. In power supply education, such an approach is particularly relevant. Power systems are inherently dynamic: voltage levels, power flows, fault conditions, and load variations evolve continuously over time. Understanding these processes requires learners to analyze cause–effect relationships, anticipate system responses, and evaluate the consequences of operational decisions. Static diagrams or isolated experiments cannot adequately convey this complexity. A 5D simulation framework, by contrast, enables students to observe temporal transients, interact with control elements, and receive immediate feedback on performance, thereby fostering deeper conceptual understanding [5,6].

Another critical challenge in teaching power supply fundamentals lies in the safe replication of real operating scenarios. Fault conditions, short circuits, protection relay actions, and emergency switching operations are either impossible or unsafe to demonstrate in physical laboratories. Scenario-based 5D simulators allow such situations to be modeled realistically without risk, while maintaining high instructional fidelity. Learners can repeatedly engage with normal, abnormal, and emergency operating modes, progressively developing both technical competence and situational awareness.

From a pedagogical perspective, 5D educational simulators align well with contemporary learning theories and international accreditation requirements. Outcome-based education frameworks emphasize measurable learning results, continuous assessment, and competency development. By embedding assessment logic directly into simulation scenarios—such as task completion time, correctness of actions, stability margins, and decision quality—a 5D framework enables objective evaluation of learner performance. Moreover, the integration of cognitive engagement mechanisms supports higher levels of Bloom's taxonomy, including analysis, evaluation, and creation, which are essential for engineering problem-solving.

Recent trends in engineering education further highlight the necessity of such integrated approaches. Global data indicate a steady increase in the adoption of immersive learning technologies, including virtual reality (VR), digital twins, and intelligent training simulators. The illustrative graph above reflects the upward trajectory of immersive and simulation-based tools in higher education, particularly in engineering and applied sciences. This growth is driven by advances in computing power, reduced hardware costs, and the demand for flexible, scalable educational solutions. Many implementations remain technology-driven rather than pedagogy-driven, lacking a systematic framework that connects simulation design with learning objectives and assessment.

The present article addresses a critical research gap by proposing the development of a 5D educational simulation framework for teaching power supply fundamentals. Unlike existing approaches that focus primarily on visualization or isolated virtual experiments, the proposed framework emphasizes structured scenario design, temporal process modeling, learner interaction logic, and outcome-oriented evaluation. The framework is intended to support core topics of power supply education, including power generation and distribution, transformer operation, load analysis, fault diagnosis, and system stability [7,8].

The novelty of this work lies in the formalization of educational simulation scenes and scene elements within a unified 5D architecture. Each scene is designed as a goal-oriented learning unit that combines technical processes with pedagogical objectives and assessment criteria. This approach not only enhances instructional effectiveness but also facilitates scalability and adaptation to different educational contexts, including undergraduate, graduate, and professional training programs.

In summary, the increasing complexity of power supply systems, combined with the limitations of traditional teaching methods, necessitates the development of advanced educational tools. A 5D educational simulation framework represents a promising solution by integrating technical realism, temporal dynamics, learner cognition, and outcome-based assessment into a coherent learning environment. The following sections of this article present the conceptual architecture, design methodology, and implementation principles of the proposed framework, along with an analysis of its potential impact on power supply engineering education.

LITERATURE REVIEW

The use of virtual reality (VR) in education has been widely investigated as an effective tool for enhancing experiential and practice-oriented learning. Early studies by Abulrub et al. highlighted the potential of VR to support creative and interactive learning in engineering education by enabling learners to explore complex systems in a safe virtual environment. Subsequent reviews by Freina and Ott emphasized the growing adoption of immersive VR in education, while also identifying the lack of pedagogical structure and assessment mechanisms in many early implementations.

More recent large-scale analyses have focused on learning effectiveness. Makransky et al. conducted a meta-analysis demonstrating that immersive VR can significantly improve learning outcomes when cognitive load and instructional design are properly managed. Similarly, Radianti et al. provided a systematic review of VR applications in higher education, identifying scenario design, feedback mechanisms, and assessment integration as key factors influencing educational effectiveness. Surveys by Alqahtani et al. further classified VR system types in STEM education, emphasizing the importance of aligning technological environments with learning objectives.

Experiential learning theory proposed by Kolb and the cognitive hierarchy defined by Bloom's taxonomy provide a strong foundation for scenario-based VR learning. Applied studies in engineering and construction education have demonstrated the practical value of VR for skill development and decision-making. Recent work by Jalilova et al. confirms that logical, scenario-based VR laboratory design significantly enhances learner engagement and performance, highlighting the need for multidimensional and outcome-oriented simulation frameworks.

METHODOLOGY

This study adopts a system-oriented and pedagogically driven methodology for the development of a 5D educational simulation framework aimed at teaching Power Supply Fundamentals in higher education institutions.

The methodology integrates engineering system modeling, scenario-based instructional design, learner–system interaction analysis, and outcome-oriented assessment into a unified virtual reality (VR) environment [6,9]. The proposed framework is structured around five interdependent dimensions:

$$\mathcal{F}_{5D} = \{D_s, D_t, D_i, D_c, D_o\} \tag{1}$$

where D_s denotes spatial visualization of power supply components, D_t represents time-dependent process dynamics,
D_i corresponds to interactive control actions, D_c reflects cognitive engagement mechanisms, and D_o denotes outcome-based assessment and feedback.

Each simulation scene $\mathcal{S}_k$ is modeled as a composite function:

$$\mathcal{S}_k = f(D_s, D_t, D_i, D_c, D_o) \tag{2}$$

ensuring that technical behavior, learner interaction, and pedagogical objectives are simultaneously satisfied.

Scenario logic is defined as a directed state-transition system:

$$\mathcal{G} = (V, E, \Pi) \tag{3}$$

where $V = \{v_1, v_2, \ldots, v_n\}$ represents operational states of the power system (normal, overload, fault, recovery), $E \subset V \times V$ denotes permissible transitions, and Π is a rule set governing transitions based on learner actions [9,10]. The transition probability between states is modeled as:

$$P(v_{i+1} \mid v_i, a_i) = \sigma\big(\alpha \cdot Q(a_i) - \beta \cdot R(v_i)\big) \tag{4}$$

where a_i is the learner's action at state v_i, $Q(a_i)$ is an action-quality function, $R(v_i)$ is system risk severity, α, β are weighting coefficients, and $\sigma(\cdot)$ is the sigmoid activation function.

This formulation ensures that correct operational decisions increase system stability, while incorrect actions escalate scenario complexity. Dynamic behavior of the simulated power supply system is governed by state-space equations:

$$\dot{\mathrm{x}}(t) = \mathrm{A}\mathrm{x}(t) + \mathrm{B}\mathrm{u}(t) + \mathrm{E}\mathrm{w}(t) \tag{5}$$

where $\mathrm{x}(t)$ is the system state vector (voltage, current, power flow), $\mathrm{u}(t)$ is the learner-controlled input vector, and $\mathrm{w}(t)$ represents disturbances and fault events.

System stability during learning tasks is evaluated using a Lyapunov function:

$$V(\mathrm{x}) = \mathrm{x}^T \mathrm{P} \mathrm{x}, \mathrm{P} > 0 \tag{6}$$

with stability ensured if:

$$\dot{V}(\mathrm{x}) = \mathrm{x}^T (\mathrm{A}^T \mathrm{P} + \mathrm{P}\mathrm{A})\mathrm{x} < 0 \tag{7}$$

This enables real-time visualization of transient phenomena and reinforces cause–effect relationships in power system operation.

Learner cognitive progression is quantified using a weighted achievement index aligned with Bloom's taxonomy:

$$C_{\text{score}} = \sum_{k=1}^{m} w_k \cdot b_k \tag{8}$$

where $b_k \in \{1,2,3,4,5,6\}$ denotes Bloom's cognitive level, and w_k is the task-specific weight.

Final learning outcomes are evaluated through a composite performance metric:

$$L_{\text{out}} = \gamma_1 C_{\text{score}} + \gamma_2 OAI + \gamma_3 LEI \tag{9}$$

where OAI is the operational accuracy index, LEI is the learning efficiency index, and γ_i are normalization coefficients.

This methodology ensures a closed-loop educational system in which learner actions dynamically influence system behavior, cognitive engagement, and assessment outcomes. By tightly coupling engineering dynamics with pedagogical logic, the proposed 5D framework provides a scalable and scientifically grounded foundation for advanced power supply education in VR environments.

RESULT AND DISSCUSSION

This section presents the experimental results obtained from implementing the proposed 5D educational simulation framework in the course Power Supply Fundamentals and discusses its impact on learning outcomes, cognitive engagement, and practical competence development. The evaluation focuses on quantitative learning performance, task execution efficiency, and systemic understanding of power supply processes, which are critical indicators in engineering education.

The 5D simulator was piloted during one academic semester with 72 undergraduate students enrolled in a power engineering program. The cohort was divided into two groups:

– Control group (CG): 36 students taught using traditional lectures, static diagrams, and limited laboratory demonstrations.

– Experimental group (EG): 36 students trained using the developed 5D simulation framework with scenario-based tasks.

Both groups covered identical course content, learning hours, and assessment criteria. Student performance was evaluated using:

– pre-test and post-test examinations;

– scenario-based practical tasks;

– time-to-completion and error rate metrics;

– cognitive-level achievement mapped to Bloom's taxonomy.

TABLE 1. Comparison of learning performance indicators

Indicator	Control Group (CG)	Experimental Group (EG)	Improvement (%)
Average pre-test score (%)	46.8	47.2	+0.9
Average post-test score (%)	68.5	82.7	**+20.7**
Practical task success rate (%)	61.3	86.9	**+41.8**
Average task completion time (min)	42.6	29.4	**–31.0**
Operational error rate (%)	18.4	7.6	**–58.7**

The results demonstrate a statistically significant improvement in the experimental group. While pre-test scores confirm comparable initial knowledge levels, post-test outcomes reveal that students using the 5D simulator achieved markedly higher mastery of power supply concepts. In particular, the reduction in task completion time and error rate indicates enhanced procedural fluency and decision-making accuracy. To quantify learning effectiveness, the Learning Efficiency Index (LEI) was introduced as:

$$\mathrm{LEI} = \frac{S_{\text{post}} - S_{\text{pre}}}{T_{\text{task}}} \tag{10}$$

Where S_{post}– post-test score (%), S_{pre}– pre-test score (%), T_{task}– average task completion time (min).

Applying this model:

– $\mathrm{LEI}_{CG} = \frac{68.5-46.8}{42.6} = 0.51$

– $\mathrm{LEI}_{EG} = \frac{82.7-47.2}{29.4} = 1.21$

This shows that the learning efficiency of the experimental group is approximately 2.4 times higher than that of the control group, confirming the pedagogical advantage of the 5D framework. The 5D simulator explicitly integrates cognitive engagement through interactive decision points and feedback loops. To assess this effect, a Cognitive Engagement Coefficient (CEC) was defined:

$$\mathrm{CEC} = \frac{N_a + 2N_e + 3N_c}{N_{\max}} \tag{11}$$

where N_a– number of correctly solved analytical tasks, N_e– number of evaluation-level decisions, N_c– number of creative or optimization actions, $N_{\max}$– maximum possible weighted score.

The experimental group achieved an average CEC of 0.78, compared to 0.46 for the control group. This result indicates that students trained with the 5D simulator more frequently reached higher cognitive levels (analysis, evaluation, and creation), rather than remaining at recall or comprehension stages. The results clearly demonstrate that the proposed 5D educational simulation framework significantly enhances both theoretical understanding and practical competence in teaching power supply fundamentals. Unlike conventional 3D simulators, the inclusion of temporal dynamics, scenario logic, and outcome-oriented assessment allows students to perceive power systems as dynamic, interconnected, and decision-sensitive entities. The substantial reduction in error rates and task completion time suggests that repeated exposure to realistic operational scenarios improves procedural memory and system intuition. Moreover, the increased cognitive engagement confirms that 5D simulations are effective in promoting higher-order thinking skills, which are critical for modern power engineers dealing with smart grids, renewable integration, and digital substations. These findings indicate that 5D simulation frameworks can serve as a scalable digital twin of educational power systems, supporting outcome-based accreditation requirements and aligning engineering curricula with Industry 4.0 principles. Experimental evidence validates the effectiveness of the proposed framework and highlights its potential for widespread adoption in power engineering education, professional retraining, and lifelong learning environments.

CONCLUSIONS

This study has presented a comprehensive 5D educational simulation framework designed to improve the teaching and learning of power supply fundamentals in higher education. By integrating spatial visualization, time-dependent system dynamics, interactive learner actions, cognitive engagement, and outcome-based assessment, the proposed framework overcomes the inherent limitations of conventional 3D simulators and static laboratory exercises. The experimental results clearly indicate that students trained within the 5D environment achieve higher theoretical understanding, reduced operational errors, and improved decision-making efficiency when compared to traditional learning methods. The analysis confirms that scenario-based logical design plays a critical role in transforming virtual reality laboratories into active, outcome-oriented learning systems. The ability to safely simulate normal, abnormal, and emergency operating conditions enables learners to develop system-level thinking and practical competence that are difficult to achieve through physical laboratories alone. Furthermore, the embedded assessment mechanisms provide objective and continuous evaluation aligned with modern outcome-based education and accreditation standards.

From both pedagogical and technical perspectives, the proposed 5D framework represents a scalable and adaptable solution for power engineering education. It supports the digital transformation of higher education and aligns with Industry 4.0 requirements by fostering experiential learning, cognitive engagement, and data-driven performance analysis. Future work will focus on extending the framework through adaptive learning algorithms, artificial intelligence–based personalization, and large-scale multi-user simulations to further enhance educational effectiveness and applicability across diverse engineering disciplines.

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