



# Bozok Journal of Engineering and Architecture

e-ISSN: 3023-4298

Araştırma Makalesi/Research Article

## From Risk to Reality: Paradigm Shift in the Industry with VR Assisted Maneuver Training (ManeVRa)

Orkun TEKE<sup>1, \*</sup>, Fatih ÇAY<sup>2</sup>, Dinçer YARGICI<sup>2</sup>

<sup>1</sup>Manisa Celal Bayar University, Manisa Technical Vocational School, Department of Electric and Energy, 45100, Manisa, Türkiye

<sup>2</sup>Enerjisa Üretim Inc, Enerjisa Üretim Academy, 46100, Kahramanmaraş, Türkiye

### MAKALE BİLGİSİ

Makale Tarihleri:

Geliş tarihi  
03.09.2025  
Kabul tarihi  
01.12.2025  
Yayın tarihi  
31.12.2025

Anahtar Kelimeler:

Sanal gerçeklik  
Manevra eğitimi  
Unity  
Enerji  
Şalt sahası

### ÖZET

Enerji santrallerinde yüksek gerilimli ekipmanların manevrası, enerji sektöründeki en kritik ve riskli operasyonlardan biridir ve hem ileri düzey teknik yeterlilik gerektirmektedir. Geleneksel eğitim yöntemleri, özellikle İSG yönetmeliklerinin kısıtlamalarıyla, bu hayati önem taşıyan prosedürler için güvenli, tekrarlanabilir ve gerçekçi uygulama fırsatları sağlamada yetersiz kalmaktadır. Bu çalışma, Türkiye elektrik sektöründe şalt ekipmanı manevra operasyonları için geliştirilen yenilikçi, modüler ve son derece gerçekçi bir VR eğitim platformu olan "ManeVRa"nın tasarımını, geliştirilmesini ve uygulamasını sunmaktadır. Platform, çevik proje yönetimi, gerçek dünya saha çalışmaları ve sektör uzmanlarıyla yakın iş birliği yoluyla oluşturulmuştur. Unity ile oluşturulan sistem, 225'ten fazla benzersiz operasyonel ve acil durum senaryosunu simüle ederek güvenli bir ortamda hem bireysel hem de çok oyunculu eğitim modlarına olanak tanır. Pilot çalışmalar, ManeVRa'nın geleneksel yöntemlere kıyasla operasyonel hataları en aza indirmeye ve iş güvenliği farkındalığını artırmaya katkıda bulunduğunu göstermektedir. Bu makalede, VR tabanlı endüstriyel eğitimin zorlukları, sistem geliştirme sürecinde dikkate alınan teknik ve pedagojik hususlar ve uygulamanın operasyonel güvenlik ve iş gücü yeterliliği üzerindeki etkisi ele alınmaktadır. Bulgular, ManeVRa'nın literatürde tespit edilen temel boşlukları doldurarak, yüksek riskli sektörlerde yeni nesil VR tabanlı eğitim çözümleri için bir referans modeli sunduğunu göstermektedir.

## From Risk to Reality: Paradigm Shift in the Industry with VR Assisted Maneuver Training (ManeVRa)

### ARTICLE INFO

Article history:

Received  
03.09.2025  
Accepted  
01.12.2025  
Published  
31.12.2025

Keywords:

Virtual Reality  
Maneuver Training  
Unity  
Energy  
Switchyard

### ABSTRACT

The maneuvering of high voltage equipment in power plants represents one of the most critical and risk-laden operations in the energy sector, demanding both advanced technical proficiency. Traditional training methods fall short in providing safe, repeatable, and realistic practice opportunities for these life-critical procedures, especially as OHS regulations. This study presents the design, development, and implementation of "ManeVRa" an innovative, modular, and highly realistic VR training platform developed for switchgear maneuver operations in the Turkish electricity sector. The platform was created through agile project management, real-world field studies, and close collaboration with industry experts. Unity based System simulates over 225 unique operational and emergency scenarios, enabling both individual and multiplayer training modes in a safe environment. Pilot studies suggest that ManeVRa contributes to minimizing operational errors and enhancing occupational safety awareness compared to traditional methods. This paper discusses the challenges of VR-based industrial training, the technical and pedagogical considerations involved in system development, and the impact of the application on operational safety and workforce competence. The findings demonstrate that ManeVRa bridges key gaps identified in the literature, offering a reference model for next-generation VR-based training solutions in high-risk industries.

ORCID ID: Yazar1: 0000-0003-4390-263X; Yazar2: 0009-0002-4572-0522; Yazar3: 0009-0008-6852-3031

\*Sorumlu yazar(lar)/Corresponding author(s): Merkez Kampüs Teknik Bilimler MYO Yunusemre/ Manisa

Tel:+90 326 2344460

Fax: +90 326 2344461

E-mail:orkun.teke@cbu.edu.tr

Bu makaleye atıfta bulunmak için/To cite this article: :Teke, O., Çay, F., Yargıcı, D. (2025). From Risk to Reality: Paradigm Shift in the Industry with VR Assisted Maneuver Training (ManeVRa), Bozok Journal of Engineering and Architecture, 4(2), 13-30

## 1. INTRODUCTION

Maneuvering operations, which are critical in electrical energy generation and transmission processes, constitute one of the riskiest work areas in the sector, as they are complex operations performed under high voltage. It is known that errors made during switching and power transfer can jeopardize not only the health and safety of employees but also the continuity of the nationwide electrical infrastructure [1]. However, traditional training methods often make it impossible for employees to learn these high-risk operations safely and effectively. Therefore, the need for innovative training solutions that enhance occupational safety and operational competence across the sector is increasing [2].

Switching and maneuvering operations carried out in power generation plants inherently carry both technical and human-related risks. Even the smallest error during these operations can lead to serious consequences, such as loss of life and significant material damage. Training in a real-world environment, particularly in high voltage systems, is nearly impossible, as it poses both occupational health and safety (OHS) risks and carries operational risks such as energy supply disruptions [3], [4]. Furthermore, the sector's need for experienced technical personnel has become even more evident during extraordinary circumstances such as the pandemic, highlighting the need for a sustainable and standardized training infrastructure.

In recent years, virtual reality (VR) technologies have offered revolutionary innovations in industrial training, emerging as a significant alternative where traditional methods fall short [5]. VR-based training applications allow participants to repeatedly experience complex and dangerous operations in a safe virtual environment without assuming real-world risks. This approach, particularly in the electric power sector, increases the opportunity for technical personnel to practice, accelerates error-making and learning processes, and ultimately contributes to the strengthening of an occupational safety culture.

To meet these critical needs in the sector, “Enerjisa Üretim Akademi” has developed a realistic and modular VR-based maneuver training product. Designed with an exact digital replica of a real hydroelectric power plant and a comprehensive variety of scenarios, this application aims to enhance the operational competencies of employees, both individually and as a team, and maximize occupational safety. Furthermore, thanks to the application's modular structure, new power plant types and scenarios can be easily added, ensuring system flexibility and sustainability [6]. Since its implementation, there have been no reports of incidents related to maneuvering errors. This has enabled systematic training, particularly for employees who are inexperienced in medium and high voltage maneuvers and who lack the opportunity to practice due to the system being constantly energized.

This article will comprehensively address the challenges encountered in training critical maneuvering operations in power plants and the advantages offered by VR-based solutions. Additionally, the design, development, and implementation processes of the “ManeVRa” which is VR Maneuver application developed by Enerjisa Üretim Akademi will be examined in detail, and the product's contribution to the industry and literature will be discussed.

### 1.1 Literature Review

#### 1.1.1 The Importance and Risks of Maneuvering Training in Power Plants

Maneuvering operations in electrical power generation and transmission systems are among the most complex and risky steps in industrial operations [7], [8]. Errors that may occur during switching, commissioning, or decommissioning operations, particularly on medium and high voltage power lines, can have cascading consequences such as fatal accidents for personnel, serious material damage to equipment, and nationwide power outages [9], [10], [11].

Numerous studies in recent years have shown that a significant portion of occupational accidents in the energy sector are caused by human factors [12], [13]. Electrical accidents remain a significant concern in the workplace, with fatal injury rates in the electric power industry reported at 3.29 per 100,000 employee-years. Line workers face the highest risk of fatal injuries, often due to vehicle collisions and contact with electric current [14]. In Japan, 81% of fatal electrical accidents occur in companies with fewer than 50 workers, where safety supervision is not mandatory. Hand contact with live wires is a leading cause of fatalities, accounting for 58% of cases [15]. A comprehensive review of human factors in electrical safety incidents highlights the complexity of injury prevention, emphasizing the need for interventions at individual, team, organizational, and regulatory levels [16]. Continued research and tailored interventions for high-risk occupations are crucial to enhance electrical safety in the workplace. Similarly in Turkey, Studies indicate underreporting of accidents and insufficient data on their root causes across sectors [17], [18]. Analysis of

accidents in the electricity sector from 2003-2011 revealed numerous incidents in production, transmission, and distribution facilities. While there has been a decrease in accident rates due to increased occupational health and safety efforts, Turkey still lags developed countries in this area. Key factors contributing to workplace accidents include inadequate training and lack of experience among workers. To address these issues, researchers recommend regular training for employers on accident reporting, active involvement of safety experts in the reporting process, and improved data collection on accident causes and injury types across different sectors [18], [19].

The high risk of maneuvering operations requires not only technical proficiency but also advanced competence in areas such as operational awareness, timely decision-making, crisis management, and team communication [20], [21], [22]. Training in real-world settings, however, has serious limitations for such complex and hazardous operations. Practicing on energized systems is often impossible due to occupational health and safety regulations, the facility's need for continuous production, and potential financial losses [21]. These findings underscore the importance of developing both technical proficiency and advanced competencies in operational awareness, timely decision-making, crisis management, and team communication for high-risk maneuvering operations.

In this context, it is vital that technical personnel working in the sector are equipped not only with theoretical knowledge but also with practical and systematic experience. However, traditional training methods, such as classroom training, written documentation, or simple simulations fail to adequately convey the realistic dynamics and rapidly evolving risk factors of maneuvering operations [23], [24]. In summary, the challenges encountered in training for maneuvering operations in power plants are directly proportional to the magnitude of both technical and human-related risks. Therefore, the need for innovative and practice-based training solutions for sustainable occupational safety, operational efficiency, and energy supply security in the sector is becoming increasingly evident [25].

### **1.1.2. VR-Based Applications in the Energy Sector**

Studies have explored the use of VR to create realistic simulations of power substations, wind farms, and photovoltaic (PV) power plants. These virtual environments allow students and new hires to interact with complex equipment, understand its function, and practice operational procedures without any risk. For instance, Erten et al. (2022) demonstrated the application of VR in occupational health and safety training for photovoltaic power systems has also been explored, with gamification scenarios developed to enhance learning experiences [26]. Similarly, Abichandani et al. created a cloud-based VR system for solar energy education, which provided students with foundational knowledge of photovoltaic systems and safe installation procedures. This work effectively promoted early-stage training in solar energy [27]. Perez-Ramirez et al. (2019) created VR training system typically include components such as virtual equipment warehouses, interactive 3D environments, and course management systems [28]. Also, Satu et al. (2024) reviewed all nuclear power plant training applications with VR and mentioned that it can provide benefits over conventional training, but challenges remain for its widespread adoption [29]. Andrii et al. investigated how virtual and augmented reality can be used in nuclear power plants. Their research showed that these technologies are useful for training operators in both emergency situations and regular maintenance tasks. The simulated environment they created accurately reflects real-world conditions, allowing for effective and safe practice [30]. Li et al. (2022) developed a virtual reality (VR) system to simulate the wind turbine construction process. The system was designed to provide immersive training for workers on critical stages, including assembly, maintenance, and disassembly. This training methodology was found to improve workers' understanding of the process and heighten their awareness of associated risks, thereby contributing to enhanced safety and operational efficiency [31]. Mantelli et al. (2023), presented the use of VR to create a realistic simulation of a steam generator for training operators, allowing them to interact with the system and practice procedures without risk. These systems allow operators to visualize information captured by supervision systems and simulate operation procedures, thereby avoiding risk and potential injuries [32].

### **1.1.3. Literature Gaps and Needs**

While VR-based training applications have become widespread in the electric power sector in recent years, significant gaps and unmet needs remain in literature. While much of the existing research focuses on pilot-scale applications or specific equipment/scenarios, there are limited examples of modular and sustainable digitalization of real industrial environments, with all their complexity [33], [34], [35]. Many VR training platforms either focus solely on a specific technical procedure or are limited to general safety awareness. In contrast, the industry's true need is for holistic and flexible solutions that integrate all voltage levels, different power plant types, dozens of different operational scenarios, and human-machine interactions, including real-time risk

simulations [33], [34]. Furthermore, these applications must be easily updated according to current legislation, technical developments, and operational needs, meaning they must be modular and sustainable [36].

Another fundamental gap is the lack of standardized and objective measurement of VR-based training effectiveness, as well as the widespread availability of internationally recognized certification systems. This hinders inter-institutional comparisons of VR-based training and its industry-wide standardization. Initial investment costs, lack of technical infrastructure, and the need for industry-specific expertise in content creation are among the other primary obstacles to its widespread adoption [37], [38], [39].

Within all these considerations, the ManeVRa application, developed by Enerjisa Üretim Akademi, provides a holistic solution to many existing gaps in the literature and makes a significant contribution to the literature with its innovative approach that addresses industry-specific requirements. ManeVRa is one of the first examples of a hydroelectric power plant that fully digitalizes all its equipment and processes, encompasses over 225 real-world operational and failure scenarios, and allows for the easy addition of new plants and procedures thanks to its modular structure. Furthermore, real-time user performance monitoring, automatic feedback on error-related actions, and the inclusion of real-time risk scenarios in the training elevate the product beyond traditional and most existing VR applications.

Furthermore, Enerjisa Üretim Akademi's prioritization of occupational safety, operational competence, and sustainable training approaches throughout the development of ManeVRa positions the product not only as a technical solution but also as a model that paves the way for standardization and innovation within the industry. Thus, this study has the potential to establish a new benchmark for VR-based industrial training both in Turkey and internationally.

## 2. MATERIAL AND METHODS

This study covers the technical analysis and development details of a professionally developed virtual reality platform. All technical details and processes of the application, from the project management phase to the validation and testing processes, are explained. This aims to provide an in-depth understanding of the software product, contribute significantly to literature, and inspire new research. Graphical abstract of ManeVRa product shown in Figure 1.

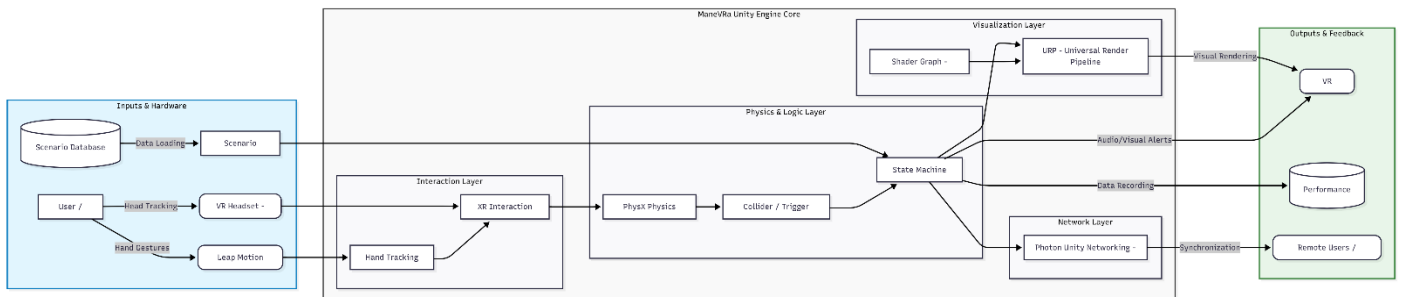


Figure 1. Graphical abstract of this study

### 2.1. Project Management Approaches

The project management for the ManeVRa application, developed by Enerjisa Üretim Akademi, was based on the agile approach, a key component of contemporary software development methodologies. This method was designed to adapt to the dynamic and multi-stakeholder nature of the project process (Figure 2). Rather than a rigid, pre-determined roadmap, agile project management facilitates flexible and iterative development cycles, continuous feedback, and adaptation mechanisms [40]. Throughout the project, this approach enabled the continuous integration of actual educational needs, technical challenges, and stakeholder feedback into the product's design and development processes.



**Figure 2.** Agile Project Cycle [41]

After the process designs and preliminary analyses were completed, the project team—a multidisciplinary team comprised of field experts, software developers, and trainers—participated in a week-long switchgear maintenance program at the Arkun Hydroelectric Power Plant (HEPP) to gain real-world field experience. During this critical phase, all switching and maneuvering operations at the plant were observed in detail, workflows were recorded, and any challenges encountered were noted. Exceptional circumstances, unexpected risks, and practical occupational safety measures emerged during operation, formed the foundational dataset for designing realistic and comprehensive virtual scenarios during the software development phase.

The scenario development phase was conducted with a unique and systematic approach to project management. Through regular meetings and workshops with the Arkun HEPP operation team, a total of 225 unique maneuver scenarios encountered in the real operating environment were individually identified and documented. These scenarios encompassed commissioning, decommissioning, various fault and hazard situations, emergency response procedures, and routine maintenance processes. Thanks to the project's agile structure, these scenarios were both updated and enriched with new scenarios throughout the development cycle. Meeting notes and developed documentation established a transparent standard of information sharing and internal communication within the project.

As part of the project, a one-to-one, three-dimensional digital modeling of the entire switchgear system, that is the circuit breakers, disconnectors, and grounding elements of a real power generation plant was achieved. The primary goal here was to simulate high voltage switching operations up to 380,000 volts in a virtual environment, with realistic equipment and process dynamics. This modeling process incorporated not only visualization of the equipment but also the physical consequences of the operations, system dynamics, and equipment status changes. This enabled participants to fully and safely observe the real-world effects of every maneuver performed during the training process (e.g., energy flow, equipment location changes, safety warnings).

The rapid prototyping and continuous testing opportunities provided by the agile approach throughout the project management ensured that both the software and training scenarios were fully aligned with real-world field needs. User feedback obtained throughout the process was immediately incorporated into the software during iterative cycles, and any software bugs and scenario deficiencies that arose were quickly addressed. Furthermore, by keeping the project documentation up-to-date, different stakeholders and technical teams maintained the same level of knowledge, ensuring the sustainability of the development process.

As a result, the agile project management approach adopted in the development of the ManeVRa application resulted in a flexible, continuously improved training solution based on real-world needs in a field requiring high security and technical complexity. This methodological choice enabled both rapid project completion and full compliance with industry requirements.

## 2.2. Needs Analysis and Scoping

One of the first and most critical stages of the ManeVRa application development process was the systematic analysis of the training environment's requirements and user needs. A multifaceted needs analysis encompassing both technical and pedagogical dimensions was conducted.

First, the challenges experienced by technical personnel and trainers working in power plants with traditional training methods were detailed. Preliminary interviews conducted at Enerjisa Üretim Akademi determined that employees had limited opportunities to

experience high voltage maneuvering operations in a real-world environment, and that training sessions lacked opportunities for practical repetition and use of real equipment. Operations posing risks in terms of occupational health and safety (OHS) are often not simulated in practical training, significantly limiting the development of employees' decision-making and implementation competencies in critical scenarios.

Following the clarification of these needs, a series of workshops and focus group meetings were held with a stakeholder group consisting of plant members, engineers, and trainers to define the project scope. In these meetings, the plant's operating processes and the operational problems encountered were analyzed in detail. Common real-world fault types, critical error scenarios, emergency response situations, and routine maintenance procedures were individually documented. Furthermore, rare and complex situations encountered by technical personnel during daily operations were specifically evaluated to increase the comprehensiveness of the simulation scenarios.

Based on findings from field studies and meetings, the scenario pool and training modules to be covered by the application were determined. Both the technical steps and expected learning outcomes were defined for each scenario. Furthermore, the training environment was designed to foster not only individual experience but also team collaboration and communication. To this end, the application was designed to be suitable for both individual and multiplayer modes.

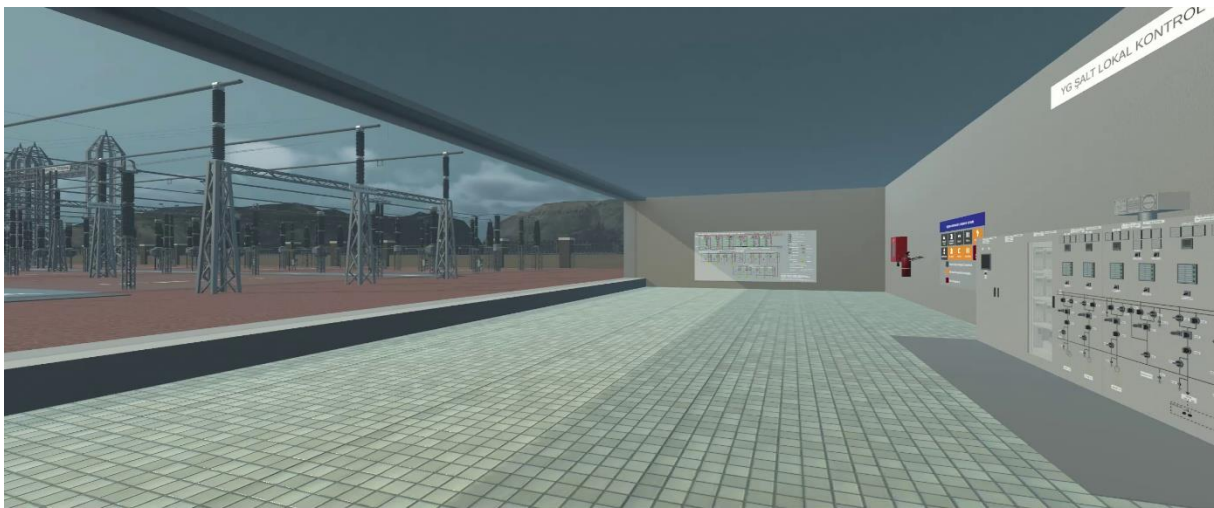
The findings obtained during the needs analysis process guided the software development and design phases; the included scenarios were continuously updated with real-world data and instructor suggestions. Thus, the application aimed to provide a technically and pedagogically comprehensive, safe, and functional training solution.

### 2.3. Design and Modelling

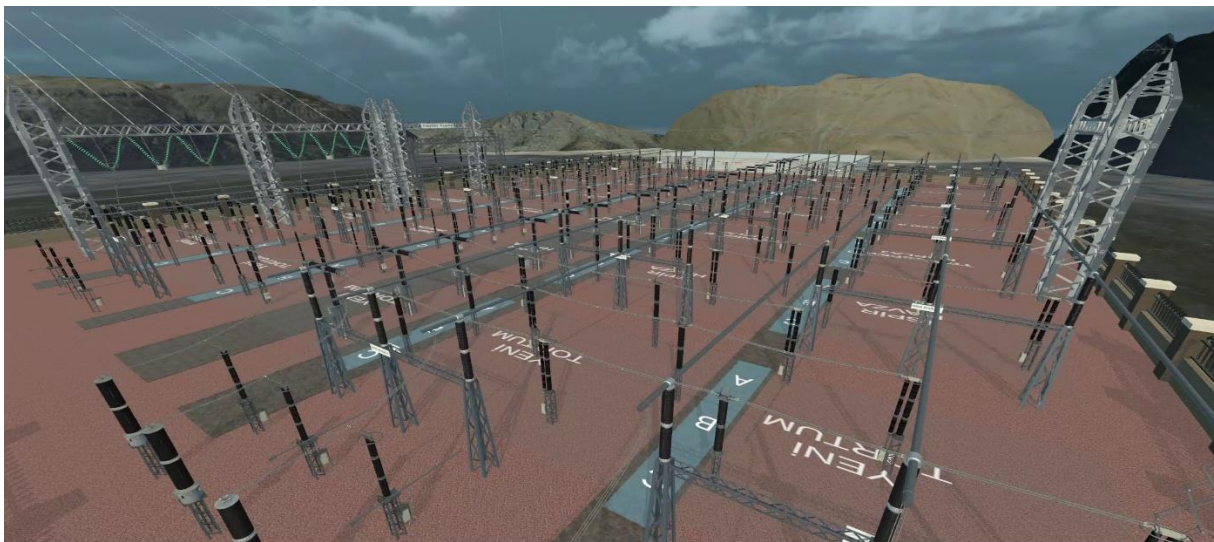
The design and modeling phases of the ManeVRa application were driven by the principles of high realism and user-centricity. In the first stage of development, the Enerjisa Üretim Akademi Arkun Hydroelectric Power Plant's switchyard and equipment were precisely transferred to the digital environment using technical drawings and site photographs. Each critical piece of equipment (breakers, disconnectors, grounding blades, protection panels, etc.) was created using advanced modeling tools such as 3ds Max and Blender, aiming for both visual fidelity and functional integrity. During modeling, Unity's Universal Render Pipeline (URP) infrastructure and PBR (Physically Based Rendering) material techniques were utilized to accurately reflect the physical properties of real-life material textures (metal, porcelain, plastic surfaces) in the virtual environment. High-resolution textures, along with realistic light and shadow effects, ensured that the equipment achieved detailed visual quality (Figure 3- 4- 5- 6- 7- 8).



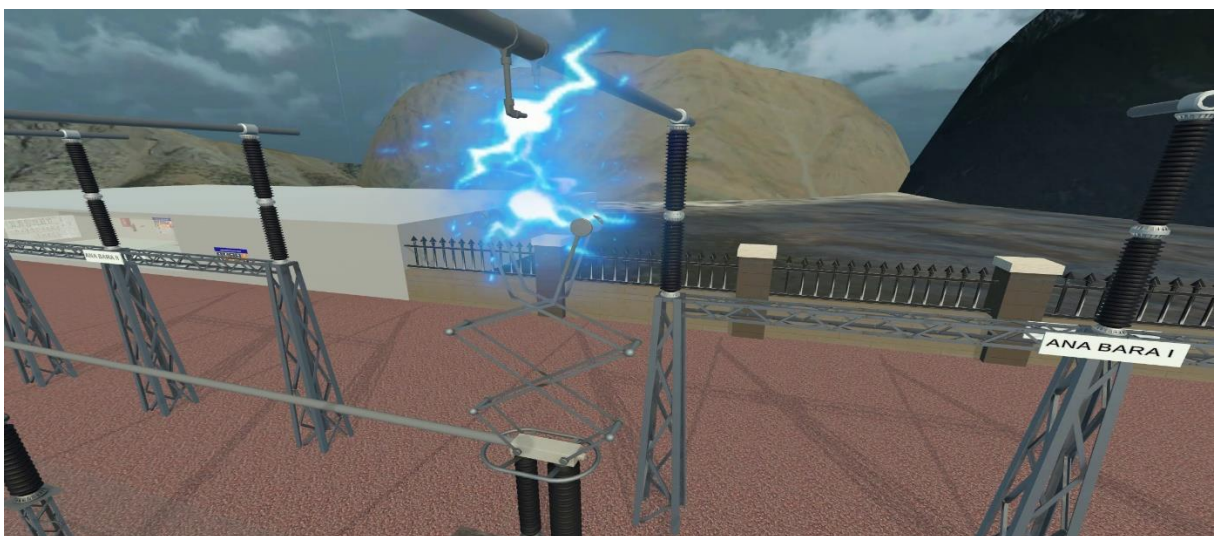
**Figure 3.** Outside Area of Environment with User



**Figure 4.** Inner Environment



**Figure 5.** Switchyard



**Figure 6.** Reality of Electric Arc



**Figure 7.** Explosion Scenario of Switchyard



**Figure 8.** Real and VR Environment Applications

The software development and integration phase was carried out entirely in Unity. The software's architecture is built on a modular and extensible structure. Each major component, equipment control scripts, scenario management, user interface, and data logging system, is designed with independently developed C# script files that can be easily updated as needed. This architecture allows the integration of new scenarios, different plant types, or additional training modules into the application. Unity's XR Interaction Toolkit was used for direct access and interaction support with VR devices. Various plugins (ProBuilder, Post-Processing Stack, Curved UI, VRTK, TextMeshPro) available from the Unity Asset Store ensured both the environment layout and the user interfaces were modern and user-friendly. Performance improvements were made, particularly through LOD (Level of Detail), occlusion culling, and light baking techniques for scene optimization, ensuring a smooth VR experience even on low-end systems.

- **Physics engine and interaction:** The mechanical movements of all power plant equipment (e.g., opening switch levers, activating disconnect switches) are realistically programmed with Unity's PhysX-based physics engine. Furthermore, using Trigger and Collider components, users are guaranteed that every action performed on the equipment in the VR environment is performed safely and in a controlled manner.
- **Using Shaders and Effects:** Customized material and particle systems have been developed with the Shader Graph, particularly for special effects such as electrical arcs, short circuits, and fault simulations (Figure 5- 6). This provides users with realistic visual and auditory feedback in the event of a potential error.

- **User interaction and hand tracking:** Thanks to Leap Motion SDK integration, users can project their hand and finger movements into the VR environment in real time, allowing them to directly perform actions such as switching, pressing buttons, and opening lids by naturally extending their hands onto virtual equipment (Figure 2- 5- 7). The natural interaction flow both accelerates technical learning and increases the immersion of the simulation.
- **Scenario management and modularity:** More than 225 scenarios are stored in the system with a JSON-based structure dynamically loaded by the software. Each scenario includes the initial state, actions to be taken, potential errors, and visual/audio feedback on success and failure. Instructors can monitor user progress through a custom interface and add new scenarios as needed.
- **Multiplayer support and network infrastructure:** Developed using Unity's Photon Networking package, the multiplayer module allows multiple technical personnel to receive collaborative training simultaneously within the same centralized environment. Team members can communicate with each other in real time in a virtual environment and share tasks (Figure 9).



Figure 9. Multiplayer Using of VR Environment

- **Data security and logging system:** All user actions, errors and corrections, and the time spent during training are stored in a system-defined database and analyzed to track individual progress. All data transfers are encrypted over a local network or secure connection, with special emphasis placed on the protection and integrity of personal data.
- **Sample scenario flow:** For example, when the user initiates the "commissioning a high voltage power line" scenario, they proceed step-by-step with the system's instructions. The correct sequence of operations for each piece of equipment is communicated to the user visually (step indicator on the UI panel) and audibly (informative voice announcement). If an error is made, the equipment displays a visual alert (red flashing light or alarm) (Figure 6) and a descriptive error message. Successfully completed scenarios are recorded in the instructor panel, and the user is notified

In conclusion, ManeVRa's design and modeling phase offers a realistic, safe, and effective training environment for power plant personnel, featuring high-quality 3D modeling, optimized VR software architecture, advanced interaction techniques, and a data-safe infrastructure. Specialties of application is presented in Figure 10- 19



Figure 10. Application with Technical Staff

As seen in Figure 10, the integration of Leap Motion technology allows users to interact with the control panels bare-handed, eliminating the need for handheld controllers and increasing immersion by mimicking natural manual operations



Figure 11. Teamwork on VR Environment

Collaborative learning is a key feature of ManeVRa; Figure 11 demonstrates the multiplayer environment where avatars of team members can communicate and coordinate complex maneuvers using hand gestures in real-time.

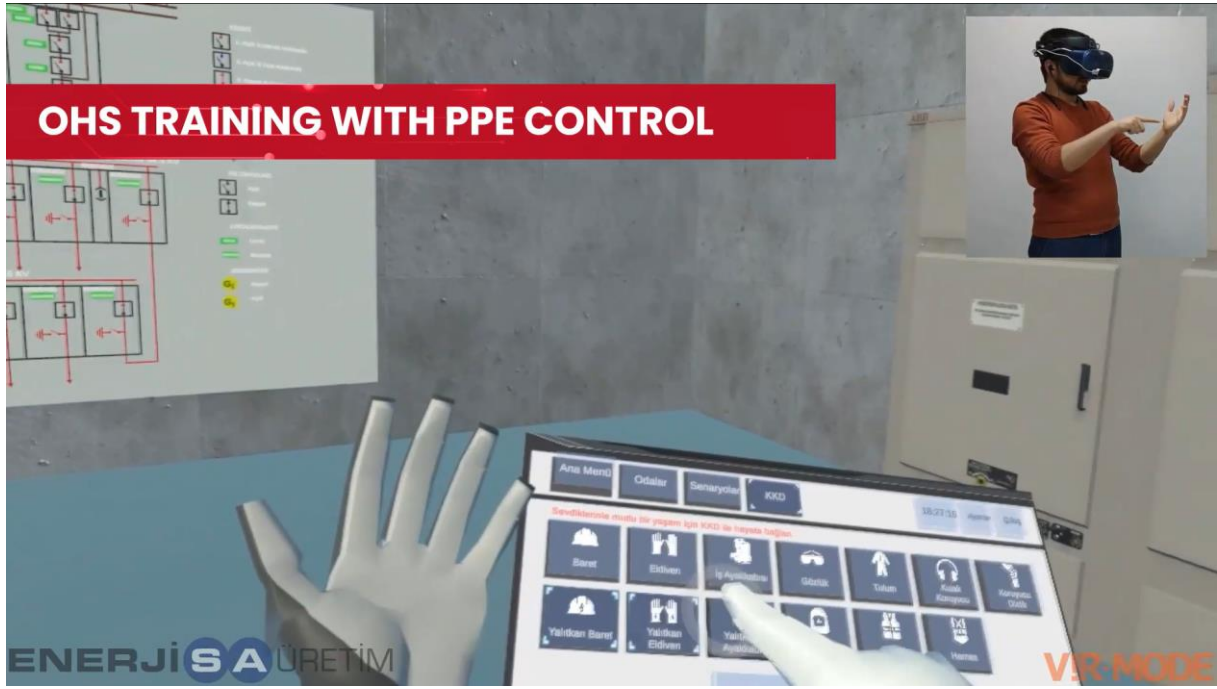


Figure 12. OHS Training Pipe Control

Safety starts before the operation; Figure 12 shows the interactive PPE (Personal Protective Equipment) selection module, where users must equip the correct gear (e.g., insulating gloves, helmets) suitable for the specific voltage level before entering the field.



Figure 13. Task Based Scenario Selection

The training curriculum is managed through a task-based interface shown in Figure 13, allowing users to select specific operational scenarios ranging from routine maintenance to emergency fault responses



**Figure 14.** Realistic Interactions with 3D Model of Electrical Rooms

Figure 14 highlights the high-fidelity 3D modeling of the electrical rooms, where users can read digital displays and interact with control buttons that function exactly like their physical counterparts.



**Figure 15.** Taking Switchgear to Test Position with Maneuver Lever

Detailed mechanical procedures are also simulated; Figure 15 depicts a user manually operating the maneuver lever to rack a circuit breaker into the 'test' position, requiring precise physical movement

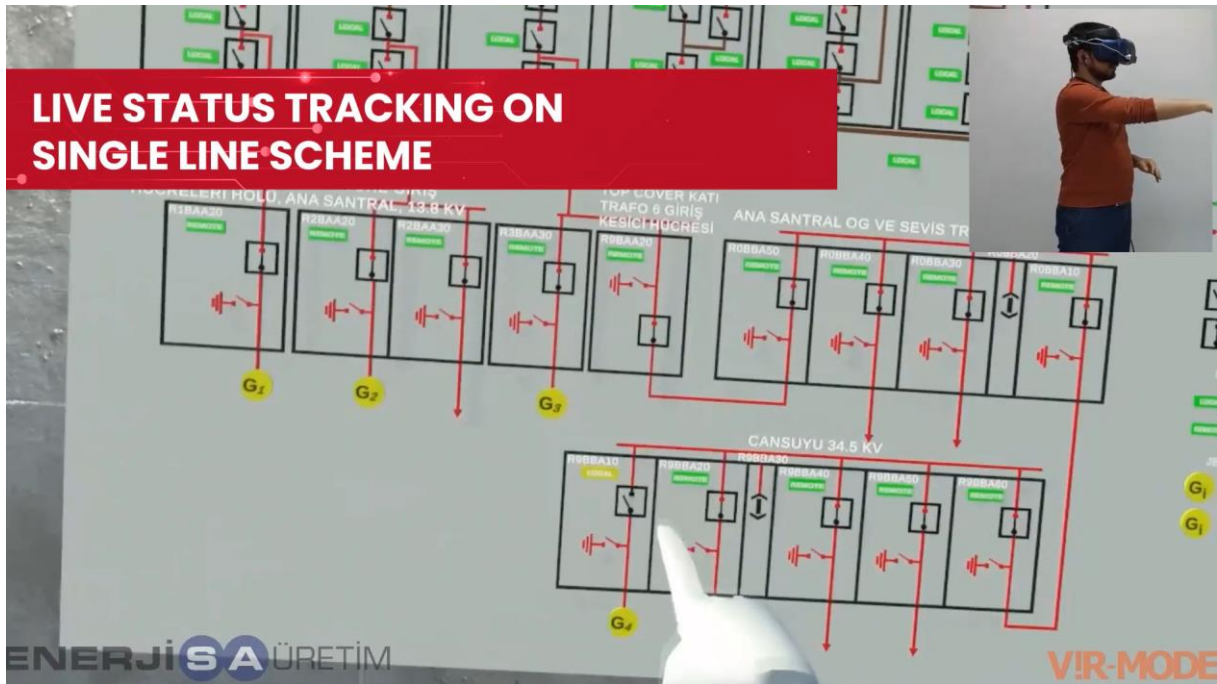


Figure 16. Live Status Tracking On Single Scheme

Operational awareness is supported by dynamic diagrams. Figure 16 displays the live single-line diagram in the virtual control room, which updates instantaneously to reflect the energized or de-energized status of the lines based on user actions

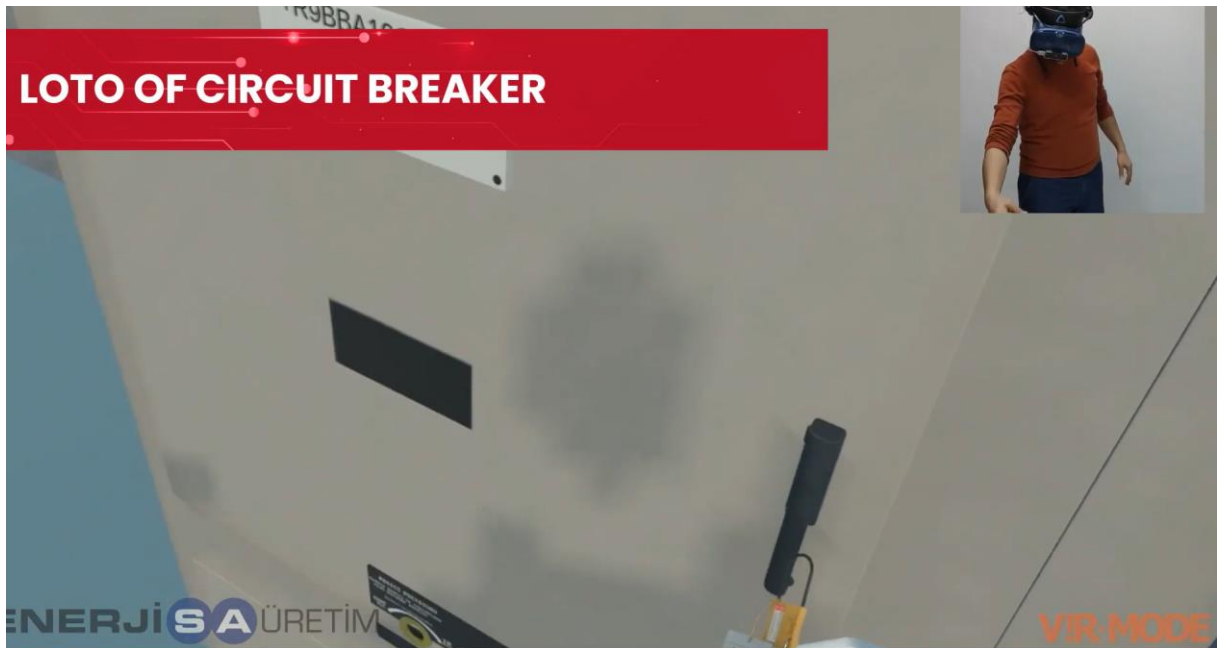
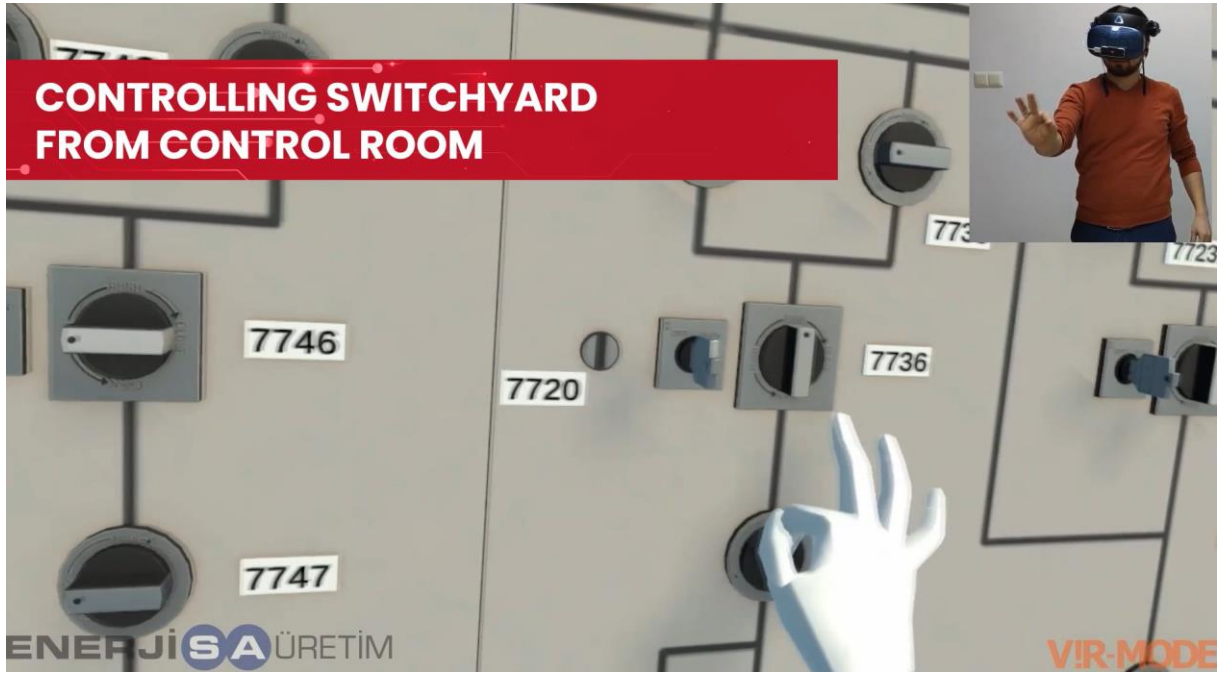


Figure 17. LOTO of Circuit Braker

Procedural compliance is enforced strictly. Figure 17 illustrates the application of Lock-Out/Tag-Out (LOTO) protocols, where a user physically hangs a warning tag on a breaker to prevent accidental re-energization during maintenance.



**Figure 18.** Controlling Switchyard from Controlling Room

Figure 18 showcases the remote-control interface, allowing operators to perform switching maneuvers from the safety of the control room, a critical procedure for minimizing exposure to arc flash hazards.



**Figure 19.** Realistic Use of Ground Lever

Figure 19 demonstrates the use of a grounding stick in the switchyard. The physics engine ensures the stick behaves realistically, requiring the user to make proper contact with the line to ensure the system is safely discharged.

#### 2.4. Hardware Selection

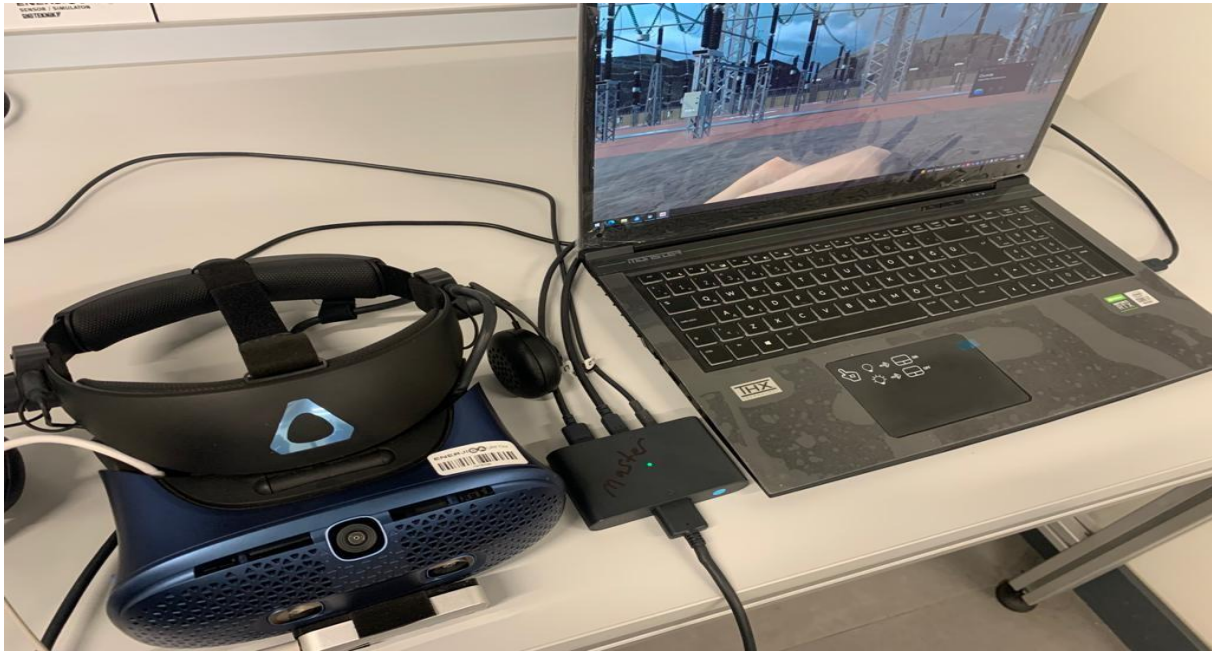
Hardware selection and integration, as well as the software infrastructure, played a critical role in the effectiveness of the ManeVRa application. In virtual reality-based training applications, realism, ease of use, and system performance are largely dependent on the

hardware used. Therefore, the hardware selection was made to both support the desired level of realism for the application and to be accessible and sustainable for the power plant's technical staff.

All technical materials and their properties used within the scope of the project are presented in Table 1. Also, Figure 20 shows the technical equipment on operation.

**Table 1.** Technical Equipment and Specifications

Equipment	Technical Specifications
HTC Vive Cosmos	<ul style="list-style-type: none"> <li>➤ Six Cameras</li> <li>➤ Field of View Support</li> <li>➤ 2880x1700 Resolution</li> </ul>
Laptop	<ul style="list-style-type: none"> <li>➤ Intel i7-9750H Processor</li> <li>➤ Nvidia GTX1660Ti Graphic Card</li> <li>➤ 512 GB SSD</li> <li>➤ 16 GB Ram</li> </ul>
Leap Motion	<ul style="list-style-type: none"> <li>➤ 850 nm Operating Wavelength</li> <li>➤ 120 FPS Camera Framerate</li> <li>➤ Depth between 10 cm- 110 cm</li> </ul>



**Figure 20.** Using Technical Materials

## 2.5. Field Applications

In the early stages of development, alpha tests were conducted to validate core functionality and key scenarios. During these tests, project team members and a limited number of technical experts examined each component of the application functionally and holistically, identifying fundamental system errors, software conflicts, and hardware incompatibilities. In the next phase, real-world user groups, Enerjisa Üretim Akademi technical staff, and trainers actively used the application as part of the beta tests. Beta tests were conducted on various power plant scenarios, error simulations, and training modules, analyzing user interaction with the system, scenario flow, feedback mechanisms, and performance metrics.

After alpha and beta tests, field testing processes were then initiated. A crucial part of the testing process is testing the application in real-world conditions. During field tests conducted at the AHPP, technical personnel repeatedly experienced real-world operational scenarios in a virtual environment, gathering comprehensive data on process accuracy, error detection, and user safety. During this process, tests were conducted in both individual and multi-user modes, and team communication, coordination, and collaboration competencies were also observed.

User feedback collected during testing was regularly communicated to the software development team; any deficiencies and suggested improvements were quickly evaluated and integrated into the product. Erroneous operations, system performance disruptions, and inadequate visual/auditory feedback were corrected with each iteration, increasing user satisfaction with the application. Compatibility and stress testing were conducted to ensure the app would work seamlessly with various VR hardware, analyzing network latencies and data integrity in multi-user mode. Furthermore, data logging and personal information security mechanisms were audited for compliance with national and international standards. At the end of the testing period, the ManeVRa application was observed to operate stably and reliably in all main scenarios, successfully simulating user behavior in real-world operations. Users reported a decrease in error rates, increased occupational safety awareness, and high overall training effectiveness. Furthermore, since the application's launch, no incidents related to maneuvering errors have been reported.

Consequently, comprehensive validation and testing processes have ensured the effectiveness and reliability of the ManeVRa application, both technically and educationally, and have laid a solid foundation for its widespread adoption.

### **3. RESULTS AND DISCUSSION**

The ManeVRa application is the first and pioneering example of a comprehensive virtual reality-based maneuvering training program in the Turkish electricity sector. The developed system, with its innovative approach, eliminates the practical deficiencies and occupational safety risks that traditional training methods cannot overcome. The ability of technical personnel to repeat high voltage switching operations in a safe and controlled environment has contributed to both individual competency development and the reduction of organizational risks.

The application's modular and sustainable structure allows for the easy integration of different power plant types and new training modules into the system in the future, thus establishing a foundation for standardization and continuous improvement in the sector. User feedback and training performance analyses demonstrate that the application provides a high level of effectiveness from both technical and pedagogical perspectives.

Going beyond existing gaps and requirements identified in the literature, the ManeVRa application digitizes all the equipment and scenarios of a real production plant, providing a model that can serve as a benchmark across industry. This success serves as a guide for the widespread adoption of VR-based training in industrial applications and the transition to next-generation training systems supported by artificial intelligence.

#### **3.1 Limitations**

While the application provides a universally applicable work environment for switchyards and the energy sector, its effectiveness depends heavily on users' VR experience and hardware compatibility; similar results may not be achieved across different hardware configurations. Finally, follow-up studies on the long-term learning retention and occupational safety impact of the application have not yet been completed.

#### **3.2 Future Works**

Future work plans to implement the ManeVRa application in different power plant types and with a broader user group and conduct a comparative analysis of the results. Longitudinal studies can also be conducted to assess the long-term impact of the application. Furthermore, the aim is to further enhance the application both pedagogically and technically by integrating AI with personalized training paths, automated performance analytics, and remote access features. Adaptation capabilities to different sectors and next generation hardware will also be explored in the future.

While the current version of ManeVRa runs on a predefined offline scenario database, the system's modular architecture can be designed to support future integration with Supervisory Control and Data Acquisition (SCADA) systems. By establishing a secure API bridge between the plant's SCADA servers and the VR platform, ManeVRa can become a 'Digital Twin.' This integration allows real-time plant data (e.g., voltage levels, breaker status) to be visualized in a VR environment, allowing operators to remotely monitor the actual plant or rehearse interventions on live data before physically implementing them. Such connectivity will also facilitate 'predictive maintenance' training by simulating potential future failures based on real-time sensor trends.

## ACKNOWLEDGMENT

This study prepared with Enerjisa Üretim Inc data and support.

## AUTHOR'S CONTRIBUTIONS

Author 1: Supervised the experiment's progress, result interpretation and helped in manuscript preparation. Author 2: Drafted and wrote the manuscript and data collection. Author 3: Drafted and wrote the manuscript and data collection.

## CONFLICTS OF INTEREST

The authors declare no conflict of interest.

## REFERENCES

- [1] A. D. Baka and N. K. Uzunoglu, "Prevention of injuries among electricians due to unexpected re-energization of power lines," *IEEE Potentials*, vol. 35, no. 2, pp. 34–39, 2016.
- [2] D. J. Hill and K. A. L'Esperance, "Avoid miscues during electrical switching: Create and follow clear, preplanned, written procedures," *IEEE Ind. Appl. Mag.*, vol. 21, no. 3, pp. 27–39, 2015.
- [3] A. Kaljević, G. Nikčević, and D. Gardašević, "Training for safe work in high voltage plants," in *International Conference "Occupational Safety and Health"*, 2024, pp. 95–101.
- [4] V. Saxena and R. K. Sharma, "High voltage in nuclear applications: Occupational safety aspects and standards," *Radiat. Prot. Environ.*, vol. 47, no. 1, 2024.
- [5] A. Geris, B. Cukurbasi, M. Kilinc, and O. Teke, "Balancing performance and comfort in virtual reality: A study of FPS, latency, and batch values," *Softw., Pract. Exper.*, vol. 54, no. 12, pp. 2336–2348, 2024.
- [6] Z. Jiang, Y. Yang, Q. Yuan, P. Leng, Y. Liu, and Z. Pan, "Virtual reality training environment for electric systems," in *2021 IEEE 7th Int. Conf. Virtual Reality (ICVR)*, 2021, pp. 314–318.
- [7] B. Li, "Safety risk assessment and control to operation control system of the virtual power plant based on COBIT 5 for risk," in *Proc. Int. Conf. Netw. Commun. Inf. Secur. (ICNCIS 2021)*, vol. 12175, 2022, p. 121750S.
- [8] S. Xu, M. S. Mastoi, and D. Wang, "Operation risk assessment of power system with high proportion of new energy integration," in *2024 IEEE 10th Int. Power Electron. Motion Control Conf. (IPEMC2024-ECCE Asia)*, 2024, pp. 3980–3985.
- [9] H. Haes Alhelou, M. E. Hamedani-Golshan, T. C. Njenda, and P. Siano, "A survey on power system blackout and cascading events: Research motivations and challenges," *Energies*, vol. 12, no. 4, 2019.
- [10] S. Imai, D. Novosel, D. Karlsson, and A. Apostolov, "Unexpected consequences: Global blackout experiences and preventive solutions," *IEEE Power Energy Mag.*, vol. 21, no. 3, pp. 16–29, 2023.
- [11] B. Schäfer, D. Witthaut, M. Timme, and V. Latora, "Dynamically induced cascading failures in power grids," *Nature Commun.*, vol. 9, no. 1, p. 1975, 2018.
- [12] C. D. Nwankwo, A. O. Arewa, S. C. Theophilus, and V. N. Esenowo, "Analysis of accidents caused by human factors in the oil and gas industry using the HFACS-OGI framework," *Int. J. Occup. Safety Ergonomics*, vol. 28, no. 3, pp. 1642–1654, 2022.
- [13] C. Yılmaz and A. H. Turan, "The causes of occupational accidents in human resources: the human factors theory and the accident theory perspective," *Int. J. Occup. Safety Ergonomics*, vol. 29, no. 2, pp. 796–805, 2023.
- [14] T. A. Fordyce et al., "An analysis of fatal and non-fatal injuries and injury severity factors among electric power industry workers," *Amer. J. Ind. Med.*, vol. 59, no. 11, pp. 948–958, 2016.
- [15] N. Ichikawa, "Electrical fatality rates in Japan, 2002-2011: New preventive measures for fatal electrical accidents," *IEEE Ind. Appl. Mag.*, vol. 22, no. 3, pp. 21–26, 2016.
- [16] T. W. Casey, H. M. Mason, J. Huang, and R. C. Franklin, "Shaping frontline practices: A scoping review of human factors implicated in electrical safety incidents," *Safety*, vol. 7, no. 4, 2021.
- [17] B. Bertan, "Türkiye'de iş kazası istatistiklerine yönelik sorunlar ve çözüm önerileri," *Bandırma Onyedli Eylül Üniversitesi Sosyal Bilimler Araştırmaları Dergisi*, vol. 8, no. 1, pp. 149–171, 2025.
- [18] O. Dalyan, E. Canpolat, H. Dalyan, Ö. F. Öztürk, and M. Pişkin, "Türkiye'de iş kazası eksik bildirimlerinin incelenmesi," *Karaelmas J. Occup. Health Safety*, vol. 5, no. 2, pp. 121–132, 2021.
- [19] H. Ceylan, "Türkiye'deki elektrik üretim, iletim ve dağıtım tesislerinde meydana gelen iş kazalarının analizi," *Int. J. Eng. Res. Dev.*, vol. 4, no. 2, pp. 30–42, 2012.

- [20] P. A. Brennan, J. Hardie, and R. S. Oeppen, "Applying human factors to improve patient safety, morale and team working for oral pathology and medicine specialists," *J. Oral Pathol. Med.*, vol. 52, no. 4, pp. 283–287, 2023.
- [21] G. Casali, W. Cullen, and G. Lock, "The rise of human factors: optimising performance of individuals and teams to improve patients' outcomes," *J. Thoracic Disease*, vol. 11, suppl. 7, pp. S998–S1008, 2019.
- [22] R. Wynn, H. Durrah, and D. B. Wesley, "Chapter 126 - Using human factors to achieve patient and family-centered care," in *Clinical Engineering Handbook*, 2nd ed., E. Iadanza, Ed. Academic Press, 2020, pp. 881–886.
- [23] F. Bracco, M. Masini, D. Glowinski, T. Piccinno, and S. Schaerlaeken, "Simulation as a training method for electricity workers' safety," *Int. J. Environ. Res. Public Health*, vol. 18, no. 4, 2021.
- [24] R. Eiris, A. Jain, M. Gheisari, and A. Wehle, "Safety immersive storytelling using narrated 360-degree panoramas: A fall hazard training within the electrical trade context," *Safety Sci.*, vol. 127, Art. no. 104703, 2020.
- [25] H. Stefan, M. Mortimer, B. Horan, and S. McMillan, "How effective is virtual reality for electrical safety training? Evaluating trainees' reactions, learning, and training duration," *J. Safety Res.*, vol. 90, pp. 48–61, 2024.
- [26] B. Erten, B. Oral, and M. Z. Yakut, "The role of virtual and augmented reality in occupational health and safety training of employees in PV power systems and evaluation with a sustainability perspective," *J. Cleaner Prod.*, vol. 379, Art. no. 134499, 2022.
- [27] P. Abichandani, W. McIntyre, W. Fligor, and D. Lobo, "Solar energy education through a cloud-based desktop virtual reality system," *IEEE Access*, vol. PP, p. 1, 2019.
- [28] M. Perez-Ramirez, G. Arroyo-Figueroa, and A. Ayala, "The use of a virtual reality training system to improve technical skill in the maintenance of live-line power distribution networks," *Interact. Learn. Environ.*, vol. 29, no. 4, pp. 527–544, 2021.
- [29] P. Satu et al., "Virtual-reality training solutions for nuclear power plant field operators: A scoping review," *Prog. Nucl. Energy*, vol. 169, Art. no. 105104, 2024.
- [30] I. Andrii et al., "Immersive technology for training and professional development of nuclear power plants personnel," in *4th Int. Workshop on Augmented Reality in Education (AREdu 2021)*, 2021, pp. 3980–3985.
- [31] W. Li, B. Esmaeili, and L.-F. Yu, "Simulating wind tower construction process for virtual construction safety training and active learning," in *2022 IEEE Conf. Virtual Reality and 3D User Interfaces Abstr. Workshops (VRW)*, 2022, pp. 369–372.
- [32] L. Mantelli et al., "Integration of dynamic models and virtual reality for the training of steam generator operators," *ASME J. Energy Resour. Technol.*, vol. 145, no. 6, Art. no. 061701, Jun. 2023, doi: 10.1115/1.4056561.
- [33] C. Menezes, B. França, and Y. Lopes, "A survey on extended reality, digital twins, and metaverse applications in power systems," *IEEE Internet Things J.*, vol. 11, no. 21, pp. 34953–34977, 2024.
- [34] A. Sudiarno, R. S. Dewi, R. Widyaningrum, A. M. D. Ma'arij, and A. Y. Supriatna, "Investigating the future study area on VR technology implementation in safety training: A systematic literature review," *J. Safety Sci. Resilience*, vol. 5, no. 2, pp. 235–248, 2024.
- [35] R. Toyoda, F. Russo Abegão, and J. Glassey, "VR-based health and safety training in various high-risk engineering industries: a literature review," *Int. J. Educ. Technol. High. Educ.*, vol. 19, 2022.
- [36] D. F. R. Parracho et al., "Modular construction in the digital age: A systematic review on smart and sustainable innovations," *Buildings*, vol. 15, no. 5, 2025.
- [37] S. G. Kanade and V. G. Duffy, "Exploring the effectiveness of virtual reality as a learning tool in the context of task interruption: A systematic review," *Int. J. Ind. Ergonomics*, vol. 99, Art. no. 103548, 2024.
- [38] S. S. Man, H. Wen, and B. C. L. So, "Are virtual reality applications effective for construction safety training and education? A systematic review and meta-analysis," *J. Safety Res.*, vol. 88, pp. 230–243, 2024.
- [39] S. K. Renganayagalu, S. C. Mallam, and S. Nazir, "Effectiveness of VR head mounted displays in professional training: A systematic review," *Technol., Knowl. Learn.*, vol. 26, no. 4, pp. 999–1041, 2021.
- [40] R. Hoda, J. Noble, and S. Marshall, "Agile project management," in *Proc. New Zealand Comput. Sci. Res. Student Conf. (NZCSRSC 2008)*, 2008.
- [41] Slite. "Agile Project Cycle." Accessed: Aug. 2, 2025. [Online]. Available: <https://slite.com/en/learn/agile>