500 kV SF_6-Insulated Circuit Breaker Maintenance Simulator

Gustavo C. Domingues[1] , **Leticia Z. de Oliveira**[1] , **Thaynara N. de Jesus**[1] , **Jose Lucas H. Macedo**[1] , **Fabiana F. F. Peres**[1] , **Claudio R. M. Mauricio**[1] , **Adriano Peretti**[2] , **Alan de Oliveira Lee**[2]

[1]Centro de Engenharias e Ciências Exatas
Universidade Estadual do Oeste do Paraná – Foz do Iguaçu, PR – Brazil.

[2]CEASB – Itaipu ParqueTec – Foz do Iguaçu, PR – Brazil.

{gustavo.domingues, leticia.oliveira21, thaynara.jesus, jose.macedo1, fabiana.peres, claudio.mauricio}@unioeste.br
adriano.peretti@gmail.com, alan.lee@itaipuparquetec.org.br

Abstract. *The maintenance of 500 kV circuit breakers with SF_6 insulation is a highly complex procedure for which conventional training methods present high risks and costs. This work presents the development of a VR simulator for technical training in this operation. The application guides the user through a modular workflow, covering disassembly, cleaning, component replacement, and reassembly of the equipment. The simulator offers a safe and interactive environment for training critical skills, eliminating the risks of traditional methods and becoming a strategic, high-impact tool for the qualification of professionals in the power sector.*

1. Introduction

The power sector is an essential pillar of the national infrastructure, ensuring well-being and quality of life, rights guaranteed by Brazilian law [1988]. The stability of the power supply, originating from the National Interconnected System, is directly linked to the reliability and safety of its high-voltage substation operations.

Regulation by Agência Nacional de Energia Elétrica [2021] and the technical criteria detailed in the grid procedures of Operador Nacional do Sistema Elétrico [2022] establish rigorous requirements for the maintenance and performance of critical assets. These standards define minimum benchmarks for equipment in transmission facilities, aiming to mitigate operational risks.

Thus, among the most complex and vital equipment in this scenario, the 500 kV circuit breaker with SF_6 insulation stands out, whose hydraulic actuation demands meticulous maintenance procedures, such as disassembly, cleaning, and reassembly of its components. According to [Fuhai et al. 2019], the complexity of this operation is compounded by the nature of the materials involved, and improper handling can trigger a cascade of failures, resulting in unplanned equipment downtime.

Structural defects in its components can have severe consequences, such as sudden gas leaks, and, as reinforced by [Zhang et al. 2021], the criticality of this maintenance requires highly trained professionals to prevent damage to machinery and functional losses.

Currently, the need to enhance the specialized training system for professionals in these operations has become more pressing, given the intrinsic limitations of conventional training methods. These include high operational costs from decommissioning in-service equipment for practical instruction and the impossibility of safely and controllably reproducing risk scenarios, functional conditions, or sporadic failures without exposing personnel or equipment [Ministério do Trabalho e Emprego 2004].

To overcome these challenges, immersive technologies such as Virtual Reality (VR) emerge as a strategic solution for industrial training. VR allows employees to practice tasks and procedures in a photorealistic, interactive, safe, and controlled virtual environment, reducing costs associated with expensive equipment and simulations that demand physical resources and training facilities [Cordeiro et al. 2023].

A concrete example of this application is presented in the case study by Kague [2025], which implemented a VR training prototype focused on Lockout/Tagout safety procedures in the electrical engineering field, allowing the simulation of hazardous situations without exposing personnel to real risks. The results demonstrated high levels of immersion, engagement, and efficiency, with training sessions completed in an average of 10 (ten) minutes. This approach proved its viability for industrial environments, offering practical training without compromising the production routine.

Furthermore, the research by [Holuša et al. 2023] demonstrated that the immersive nature of VR increased participant knowledge by 65%, as well as the acquisition of practical skills without the risk of damaging or destroying objects in the real environment. Therefore, considering the criticality of high-voltage circuit breaker maintenance and the shortcomings of conventional training methods, VR establishes itself as a high-impact solution, combining safety, efficiency, and operational cost reduction.

2. Objectives

This work aims to present the development of a VR tutorial that assists in training for maintenance procedures on 500 kV circuit breakers with SF_6 insulation. The simulator was structured to represent, in a virtual environment, the technical steps involved in the process of disassembly, cleaning, component replacement, and reassembly of the equipment.

3. Materials and Methods

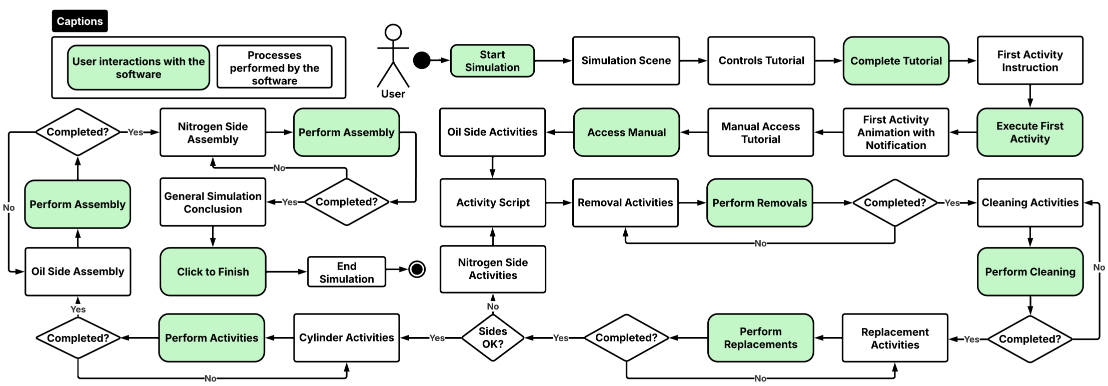

Figura 1. User interaction flow summary

The simulator was developed using the Unity game engine version 6.0, with support for the XR Interaction Toolkit 3.0 to enable VR interactions compatible with various head-mounted displays (HMDs). The system's architecture is based on scripts developed in the C# language.

The virtual scene was modeled based on the real environments where the procedures take place. The modeling included architectural and furniture elements, following photographs obtained during technical visits. The scene was configured in Unity, with the application of textures and lighting elements, aiming to represent the spatial organization of the locations where the maintenance is performed, as illustrated in Figure 2.

Figura 2. A) Overview of the tutorial space; B) Auxiliary Tools selection menu; C) Tool layout on the table

4. Maintenance Simulator

The 500 kV circuit breaker maintenance simulation tutorial is structured as a modular workflow, designed to progressively guide the user through all critical steps of the procedure. The training is divided into four main phases: (1) Familiarization and Preparation; (2) Component Maintenance Cycle; (3) Cylinder Treatment; and (4) Reassembly and Finalization. Each phase has specific learning objectives and requires the correct use of tools and procedures, which are guided by an instruction manual within the virtual environment.

4.1. Phase 1: Familiarization and Preparation

The main objective of the initial training module is the user's familiarization with the VR environment and an introduction to work area preparation procedures. In this phase, the focus is on ensuring the operator masters the movement and interaction controls, as well as correctly performing the initial task of safely handling the equipment to be inspected. The steps performed by the user are:

- **Controls Tutorial:** Initially, the user is guided through an interactive tutorial that demonstrates the mechanics of moving through the scene and interacting with virtual objects.
- **Auxiliary Tool Selection:** Following the tutorial, the operator is instructed to identify and select the necessary equipment for the accumulator's preparation, namely: the pallet jack, the lever hoist, and the ratchet strap.
- **Accumulator Positioning:** The training proceeds with the task of moving the hydraulic accumulator with the pallet jack from its original position to the maintenance table, using the hoist for lifting and the ratchet strap for secure fastening, thus completing the environment preparation.

4.2. Phase 2: Component Maintenance Cycle

This phase constitutes the core of the practical training, covering the complete maintenance cycle that is applied sequentially to the oil and nitrogen sides of the circuit breaker. The objective is to train the operator to execute the procedural sequence of disassembly, cleaning, and replacement of wear parts, reinforcing the importance of the correct use of each tool and consultation of the virtual technical manual, which is accessible at any time. The cycle consists of the following steps:

1. **Disassembly:** Removal of the larger components (tension thread and lid), using specific tools such as the giant wrench, ratchet wrench, circular bar, and eye bolt.
2. **Detailed Cleaning:** Use of the cleaning kit for the complete removal of oil residue and impurities from the disassembled parts positioned on the workbench.
3. **Wear Part Replacement:** This involves the identification, removal (with the nylon rod), and replacement of the sealing rings, including the application of consumables such as Centroplex grease to the new components.
4. **Pre-assembly:** Reinstallation of the new rings onto their respective parts (thread and lid), leaving them ready for final reassembly.

This cycle is first performed on the oil side, and upon its completion, the user is instructed to repeat the same set of procedures on the nitrogen side, reinforcing learning through repetition. For greater visual clarity, the table below, in Figure 3, specifies the necessary tools for each step of the process.

CYCLE PHASE	TARGET COMPONENT	TOOLS AND CONSUMABLES	MINIATURE
Disassembly	Tension Thread (Oil/Nitrogen)	Ratchet Wrench, Bucket Wrench and Giant Wrench	
Removal	Lid (Oil/Nitrogen)	Circular Bar and Eye Bolt	
Detailed Cleaning	Thread and Lid	Nylon rod	
Replacement	O-rings (Thread and Lid)	Cleaning Kit and Centroplex grease	

Figura 3. Maintenance tools

4.3. Phase 3: Cylinder Treatment

Once the previous cycle is completed, the training advances to the treatment of the accumulator's main body. In this phase, the operator is instructed on the correct procedures for cleaning and applying protective fluids and coatings to the cylinder before final reassembly. The steps include:

- Cleaning the cylinder surface with the tool kit.
- Application of a hydraulic fluid film to its interior.
- Application of Molykote D321R Spray to the external threads.

4.4. Phase 4: Reassembly and Completion

The final stage of the simulator is dedicated to the complete reassembly of the circuit breaker. The objective is to validate the user's ability to reinstall the main components in the correct order, using the appropriate tools to ensure the integrity and functionality of the equipment. The steps are:

- Reinstallation of the lids and tension threads on the oil and nitrogen sides.
- Use of specific tools for assembly, such as the piston installation wrench.
- Conclusion of the training upon the successful assembly of all components.

5. Conclusions

Considering the current challenges related to the maintenance of critical assets in the power sector, such as 500 kV circuit breakers, it is necessary to adopt innovative training strategies that ensure the safety and efficiency of professionals. Aligned with this context, the development of VR simulators emerges as a high-impact training tool, combining immersion and controlled practice, and contributing to the qualification of technicians in highly complex procedures.

The simulator provides a practical and safe maintenance experience, guiding the user interactively and progressively through all stages: disassembly, cleaning, component replacement, and reassembly. The initiative offers a practical solution to what [Fuhai et al. 2019] had already identified as a critical point: the complexity of the operation, where improper handling can trigger a cascade of failures and equipment downtime.

The proposal's relevance and merit were corroborated by preliminary tests conducted with experts from the Centro Avançado em Soluções para Barragens (CEASB). The positive evaluation, including that of an engineer, attested not only to the innovative nature of the VR application but also validated its substantial potential for highly complex technical training.

The next steps of this work consist of validating the usability and effectiveness of the simulator with experts from the power sector and evaluating its impact on the knowledge retention and performance of the target audience. Furthermore, an evolution of the interaction system is proposed, incorporating direct user manipulation with fine motor skill tasks to enhance fidelity to the real procedure. The results will be used to refine the training experience and the technical accuracy of the simulation.

It is concluded, therefore, the proposal demonstrates significant potential as a professional training tool. By combining immersive technology, safety, and a solid technical foundation, its expandable design offers a solution adaptable for new functionalities and systems, directly addressing the demands of a sector vital to the national infrastructure.

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