Virtual Reality–Augmented RTDS-Based Digital Twin for Power Grid Operator Training

Khoa Nguyen Nguyen, *Graduate Student Member, IEEE*, Milad Beikbabaei, *Graduate Student Member, IEEE*, and Ali Mehrizi-Sani, *Senior Member, IEEE*
The Bradley Department of Electrical and Computer Engineering, Virginia Tech, Blacksburg, VA 24061
e-mails: {nguyen9, miladb, mehrizi}@vt.edu

***Abstract*—To reliably sustain the operation of the power grid, the power industry must maintain a skilled workforce of operators and engineers. However, the high retirement rate and the emergence of new technologies have made it progressively more demanding and challenging to train new power system operators and engineers. Previous work utilizes virtual reality (VR) to enhance multiple aspects of power system education, including high voltage substation operation, live-line work, as well as power transformer assembly and maintenance. This work employs a Virginia Tech Electric Service (VTES) substation replica rendered in Unreal Engine 5 (UE5), a real-time, RTDS-based VTES digital twin developed at Virginia Tech's Power and Energy Center (PEC), and a user datagram protocol (UDP)-based communication channel to enhance existing grid operator training programs by providing a realistic, hands-on experience. However, due to the anonymity of critical infrastructure data, the capabilities of the VR-based training platform are demonstrated using the results from the IEEE 13-bus feeder distribution system. The trainee can interact with and control the electrical components of the distribution grid using a VR headset and embedded interactions within the virtual environment, while observing grid behavior through the metering and live graph system. Furthermore, two training scenarios developed using the proposed method are discussed.**

***Index Terms*—Digital twin, grid operator training, power system education, real-time simulation, virtual reality.**

I. Introduction

With the primary objective of reliably delivering energy to end consumers, utility companies must maintain a skilled personnel task force to operate their power grids. However, the high retirement rate and the emergence of new technologies have made it progressively more demanding and challenging to train new power system operators and engineers [1]. Traditional operator training programs consist of theoretical lectures and hands-on workshops to provide trainees with the foundational knowledge necessary for working with power system facilities [2]. However, these curricula often require participants to travel to predetermined locations for training, which can be costly for the trainees and make it difficult to apply repetitive learning methods. Additionally, practical exposure in traditional training programs is often insufficient to equip learners with expertise in operating power systems, due to the dynamic nature of power grids and the distinct characteristics of each area. Furthermore, it is not feasible for hands-on training to incorporate scenarios such as severe weather or disconnecting active loads in the power grids [3].

To complement the conventional operator training methodology, a virtual reality (VR)-based training approach emerges as an alternative to enhance the expertise of power system workforces. A virtual environment is developed in [4] to assist in training electricians for work with electrical substations and live-line work. The development of a non-immersive VR-based environment for high voltage substation training is presented in [5]. The training objective is focused on the assembly and maintenance of electric transformers in [6]. However, none of the previously mentioned works developed a virtual training environment for the control and operation of the substation level.

Digital twin is a digital representation of a physical system that mirrors its counterpart's behavior and updates itself using a real-time data link with its physical equivalent. It is a promising concept that could significantly improve the quality of hands-on educational programs. Authors in [7] combine digital twin and virtual reality technology to create an immersive virtual world where industrial operators can experience handling an industrial mobile robot. In [8], the authors investigate a digital twin–based training concept for instructing maintenance personnel in the semiconductor industry on operating human-machine interfaces (HMI) without disrupting production. Reference [9] showcases an accessible web-based virtual environment that replicates a communication system of a power system (CSPS) training room, utilizing a combination of virtual reality and digital twin technology.

This manuscript shares the development of an immersive and realistic virtual learning environment for power grid operators in control and operation at the substation level, achieved by combining a virtual replica of a physical substation with an RTDS-based digital twin of the power grid. Virginia Tech Electric Service (VTES) is a university-owned utility launched in 1893 and has an operational history of more than 125 years. The virtual replica substation is modeled after a VTES substation located in Blacksburg. The following summarizes the main contributions of this work:

- Create a replica of a VTES substation in UE5-based virtual environment.
- Establish a user datagram protocol (UDP)-based communication channel between the RTDS-based VTES digital

This work is supported in part by the State of Virginia's Commonwealth Cyber Initiative (www.cyberinitiative.org) and in part by Virginia Tech Institute for Critical Technology and Applied Science (ICTAS) through the Engineering Faculty Organization.

979-8-3315-8138-1

Fig. 1. (a) VTES substation located in Blacksburg and (b) UE5-based virtual replica of VTES substation

twin distribution system and the virtual environment. Nevertheless, by virtue of the critical infrastructures' data security, the results are presented using the IEEE 13-bus feeder distribution benchmark system.

- Develop a realistic virtual environment where trainees can immersively interact with the RTDS-based digital twin through the substation control room.

Section II detailed the implementation of the UE5-based virtual environment and user interactions. The RTDS-based VTES power grid digital twin implementation is discussed in Section III. Section IV discusses the example training scenarios implemented using the developed virtual substation replica, and Section V concludes the paper.

II. Implementation of the Virtual Environment

This section discusses the concept of virtual reality and the implementation of the VTES substation replica virtual environment.

A. Virtual Reality

Virtual reality is defined as a simulation that utilizes computer graphics to create a realistic-looking world. While this concept is realized for decades, it has only recently become more accessible and realistic with the technological advancements in virtual reality resources, such as VR headsets and glasses. One of the most popular, powerful, and versatile 3D development tools used for simulating a virtual world is Unreal Engine 5, developed by Epic Games. The aforementioned 3D creation software is utilized as the primary program in the development of the VTES substation virtual replica.

B. Implementing VTES Substation Virtual Environment

With the assistance of Applied Research in Immersive Experiences and Simulations (ARIES), a realistic reproduction of a VTES substation is created in Unreal Engine 5.2.1. Figs. 1 (a) and 1 (b) show the real and virtual replica VTES substation, respectively. To construct a faithful and immersive reproduction of a substation with accurate dimensions and distances, several procedures must be applied, including 3D scanning the entire infrastructure, modeling power facilities, rendering the scene, and developing interactions in UE5. Fig. 2 demonstrates the workflow of generating the virtual replica of the VTES substation.

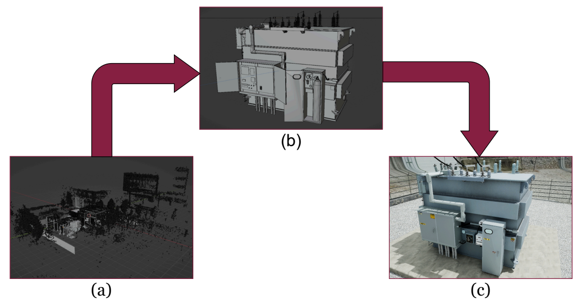

Fig. 2. VTES substation replica creation workflow: (a) 3D and point cloud scan of the VTES substation, (b) 3D modeling of a power transformer, and (c) Rendering of a power transformer

1) 3D Scanning

3D scanning is the process of capturing the three-dimensional data of physical objects. This procedure is crucial for replicating the substation infrastructure in the virtual environment while adhering to the standards, regulations, and clearances of power system facilities. Fig. 2(a) shows the 3D and point cloud scan that has been collected from the physical VTES substation. The aforementioned 3D scanning results are utilized to create the layout of the virtual substation and its equipment.

2) 3D Modeling

As discussed in Subsection 1, for accurate replication of electrical equipment, such as power transformers, data extracted from the VTES substation scanning, along with reference photos, is used to create dimensionally accurate 3D models in Blender 3D creation software. Fig. 2(b) shows a transformer modeled using the discussed method. The generated 3D models are then ready for post-processing to achieve realistic appearances.

3) Scene Rendering

To create an immersive, realistic virtual world, the training equipment and environment must not only be accurate in dimensions but also visually realistic. The desired goals are achieved through the post-processing of the 3D models and the creation of a high dynamic range image (HDRI)-

979-8-3315-8138-1

based background. For the post-processing of the 3D models, customized materials and textures are created in Adobe 3D Substance Painter from reference images to add to the realistic aspects of the substation facilities. HDRI-based background is created using the aforementioned 3D scan results to create an immersive and lifelike environment. The finished 3D models and HDRI-based background are then imported into UE5 for the creation of the training scene. Fig. 2(c) presents the rendered transformer in the virtual training environment.

4) Implementing Interactions

For the trainees to be able to interface with the virtual substation, such as navigating the environment or controlling a breaker on an HMI panel, user interactions are embedded inside the virtual reality character and the rendered 3D objects in the scene. The Virginia Tech News article [10] highlights a former version of the developed environment, showcasing the digital twin's capabilities. Recent versions of the virtual substation support hand tracking technology, gesture interactions, and real-time graphs for an intuitive and immersive experience for the trainees.

III. Implementation of the RTDS-Based Digital Twin

This section explains the definition of digital twin, the basics of real-time simulation, and the implementation of RTDS-based digital twin in the context of virtual reality-augmented grid operator training.

A. Concept of Digital Twin

Based on [11], a digital twin is defined as a virtual representation that simulates a physical object or entity. Digital twin implementation comprises a physical layer, a virtual layer, and a two-way communication framework that enables data to flow between the physical and virtual layers, as well as the services provided by the system [12]. In the power and energy systems domain, real-time simulation technology enables cost-effective, reliable approaches to developing dynamic digital twins of complex power grids [13]. This work facilitates a previously developed digital twin of the VTES distribution system at the Power and Energy Center [14].

B. Real-time Simulation

Power system digital real-time simulation (DRTS) utilizes computer models to accurately replicate the behavior of physical power grids within a specified time step, thereby achieving real-time processing speed [15]. DRTS finds extensive applications across power system research areas such as cybersecurity [16], control hardware-in-the-loop (CHIL) [17], and protection [18]. Several commercial platforms offer reliable and accurate power grid DRTS, including RTDS, OPAL-RT, and Typhoon HIL. In this work, the RTDS framework is utilized to develop the digital twin.

C. RTDS-Based VTES Digital Twin Implementation

The VTES digital twin implementation comprises the VTES distribution system as the physical layer and the RTDS-based VTES power grid model, as well as the UDP-based communication channel as the virtual layer. A secure data link with access to real-time sensor and measurement data is installed at PEC to regularly update the accuracy of the virtual layer model. The UDP-based communication channel is a two-way data path among the trainee, VR headset, the substation virtual replica, a UDP-based middleware, and the real-time simulated VTES digital twin. The UDP-based middleware is implemented in Python using the socket library to facilitate the data exchange. Fig. 3 portrays the UDP-based communication path between the RTDS-based digital twin and the trainee. The UDP communication scheme is measured with a Round-Trip Time latency of 125 us and 0.06% package loss The trainee can interact with the virtual substation's HMI panels to control the electrical components of the power grid, such as breakers, while observing real-time measurements from the power grid through the VR headset. However, due to the nondisclosure nature of critical infrastructure data, the demonstration results for the developed training environment are based on the IEEE 13-bus feeder distribution system.

D. IEEE 13-bus Feeder Distribution System

The IEEE 13-bus feeder distribution system is used as the demonstration case for this work's realistic VR-based training framework for grid operators, serving both practical and security purposes in lieu of the VTES digital twin. Fig. 4 illustrates the single-line diagram of the power grid with breakers added between bus 671 and 692, for the single-phase delta-connected load at bus 691, as well as for the capacitor bank at bus 675. The power grid is implemented in RSCAD FX using a combination of RTDS NovaCor and PB5 hardware.

IV. Performance Evaluation

By utilizing the developed virtual reality-augmented RTDS-based training architecture, multiple training scenarios that are traditionally costly or impossible to implement can be readily and cost-effectively created. The platform also features a feedback system which can be tailored for different scenarios, notifying the trainee after a certain duration whether they successfully resolved the scenario in time. In this section, two training scenarios using the developed methods are discussed.

A. Scenario 1: De-Energizing a Line due to Scheduled Maintenance

For this scenario, the power grid is operating in its normal condition, and all breakers are in a closed state. Due to scheduled maintenance on the line between buses 671 and 692, the trainee must operate the R1 breaker control to disconnect and de-energize the specified line. Fig. 5 shows part of the HMI panels of the substation replica after the action has been taken to trip breaker R1.

Fig. 5 includes the R1 breaker control switch as well as the voltage and power meters of bus 650. Fig. 5(b) shows the three-phase voltage meter for bus 650. Due to the voltage regulator located at bus 650, all three-phase voltages stay at 1 p.u. after the breaker R1 has been tripped. Fig. 5(c),(d), and (e) show the power meters of phases A, B, and C at bus

Fig. 3. RTDS-based digital twin data path: (a) trainee, (b) VR headset, (c) virtual substation, (d) UDP-based communication channel, and (e) VTES model simulated in RTDS NovaCor and PB5 racks.

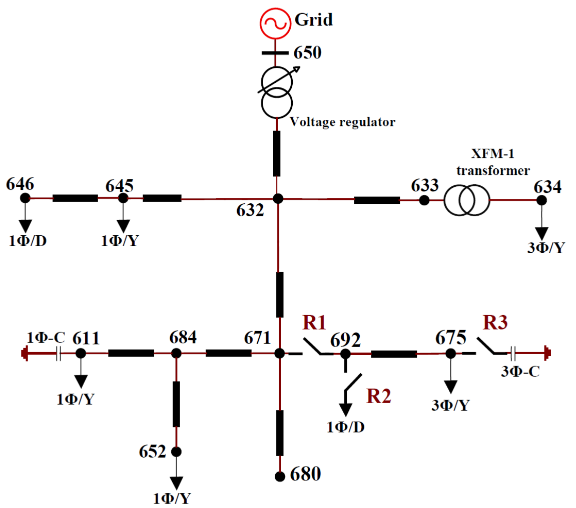

Fig. 4. One-line diagram of the IEEE 13-bus feeder.

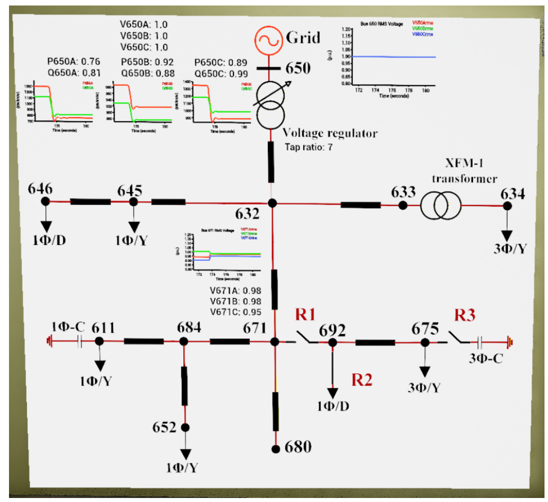

Fig. 6. Virtual substation SCADA panel after breaker R1 has been tripped.

Fig. 5. Virtual substation HMI panels after breaker R1 has been tripped: (a) R1 breaker control switch, (b) Bus 650 voltage meter, (c) Bus 650 phase A power meter, (d) Bus 650 phase B power meter, and (e) Bus 650 phase C power meter.

650, respectively. To enhance the learning experience, where trainees can observe the transient behavior of the power grid, a SCADA panel is developed to visualize the grid as well as its responses in real-time voltage and power waveforms. Fig. 6 demonstrates the SCADA panel visualization capability for scenario 1. The live graph feature of the SCADA panel also captures the nonlinear dynamics of the power grid after breaker R1 state has been changed. Fig. 6 shows that bus 650's phase A real power drops from 1.3 MW to 0.76 MW, and reactive power drops from 1.12 MVAr to 0.81 MVAr. Similarly, bus 650 phase B real power decreases from 0.99 MW to 0.92 MW, and reactive power drops from 0.93 MVAr to 0.88 MVAr. Bus 650 phase C is recorded to drop from 1.35 MW to 0.89 MW, and reactive power falls from 1.18 MVAr to 0.99 MVAr.

B. Scenario 2: Reconnecting a Critical Load

In this scenario, due to a change in the grid's load profile, bus 671 experiences undervoltage on phase C. The trainee is tasked with restoring the bus voltage to its nominal operating range. The operation consists of changing the voltage regulator tap position from 7 to 11, connecting the capacitor bank at bus 675, and disconnecting the non-critical load from bus 692.

Fig. 7 includes the related control as well as the voltage and power meters of bus 650. After the grid undergoes a load profile change, the voltages at bus 671 are 0.94 p.u., 1.0 p.u., and 0.85 p.u. for phase A, B, and C, respectively. From Fig. 8, the voltages at bus 671 are increased to 0.99 p.u. for phase A, 1.04 p.u. for phase B, and 0.9 p.u. for phase C after the trainee performed the required sequence of actions.

V. Conclusions

This work summarizes the implementation of a digital twin to enhance power grid operators' hands-on training in

979-8-3315-8138-1

Fig. 7. Virtual substation HMI panels after phase C voltage at bus 671 has been restored to nominal range: (a) R2 breaker control switch, (b) Voltage regulator control, (c) R3 breaker control switch,(d) Bus 650 voltage meter, (e) Bus 650 phase A power meter, (f) Bus 650 phase B power meter, and (g) Bus 650 phase C power meter.

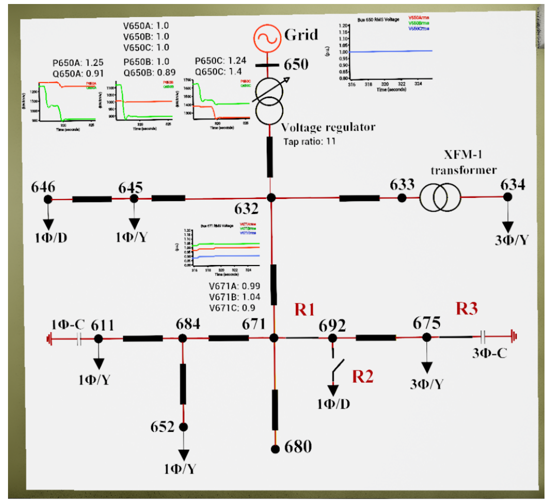

Fig. 8. Virtual substation SCADA panel after phase C voltage at bus 671 has been restored to nominal range.

power grid control and operation. The developed digital twin utilizes virtual reality and real-time simulation for improved immersion and realism. The physical layer of the digital twin is an authentic UE5-based VTES substation replica using 3D scanning and modeling techniques. The virtual layer is the VTES distribution grid digital twin implemented using RTDS-based real-time simulation platform. To facilitate the data exchange between the training framework and the digital twin's virtual layer, a UDP-based communication scheme is realized using socket programming. The trainee can interact with the power grid's electrical components through the embedded interactions, while observing the power grid's real-time behavior using the metering and live graphs system. Two training scenarios developed using the IEEE-13 bus distribution system are implemented and discussed. Using the proposed methodology, different realistic training scenarios can be realized straightforwardly and cost-effectively. Future work would include different environments, larger systems, more complex training scenarios, and the ability to accommodate multiple operators.

References

[1] A. Bose, R. Podmore, and U. Spanel, "Challenges in operator training: Avoiding blackouts in the evolving power grid," *IEEE Power and Energy Magazine*, vol. 21, no. 3, pp. 61–69, Apr. 2023.

[2] I. F. Mondragón Bernal, N. E. Lozano-Ramírez, J. M. Puerto Cortés, S. Valdivia, R. Muñoz, J. Aragón, R. García, and G. Hernández, "An immersive virtual reality training game for power substations evaluated in terms of usability and engagement," *Applied Sciences*, vol. 12, no. 2, Jan. 2022.

[3] W. Drożdż, "Virtual reality training system as a comprehensive and effective method for delivering technical hands-on training in the field of distribution system operators," *Procedia Computer Science*, vol. 192, Sep. 2021.

[4] F. Górski, D. Grajewski, P. Buń, and P. Zawadzki, "Study of interaction methods in virtual electrician training," *IEEE Access*, vol. 9, 2021.

[5] X. Liao, J. Niu, H. Wang, and B. Du, "Research on virtual reality simulation training system of substation," in *2017 International Conference on Virtual Reality and Visualization (ICVRV)*, 2017, pp. 413–414.

[6] Z. Jiang, Y. Yang, Q. Yuan, P. Leng, Y. Liu, and Z. Pan, "Virtual reality training environment for electric systems," in *IEEE 7th International Conference on Virtual Reality (ICVR)*, Foshan, China, May 2021.

[7] A. Martínez-Gutiérrez, J. Díez-González, P. Verde, and H. Perez, "Convergence of virtual reality and digital twin technologies to enhance digital operators' training in industry 4.0," *International Journal of Human-Computer Studies*, vol. 180, Aug. 2023.

[8] G. Schneider, M. Wendl, S. Kucek, and M. Leitner, "A training concept based on a digital twin for a wafer transportation system," in *IEEE 23rd Conference on Business Informatics (CBI)*, vol. 02, Bolzano, Italy, Nov. 2021.

[9] Z. Lei, H. Zhou, W. Hu, G.-P. Liu, and S. Guan, "Web-based digital twin communication system of power systems for training and education," *IEEE Transactions on Power Systems*, vol. 39, no. 2, pp. 3592–3602, Aug. 2023.

[10] Virginia Tech News by Niki Hazuda, "Digital twins and virtual reality transform utility workforce training," 2025, accessed: 2025-06-17. [Online]. Available: https://news.vt.edu/articles/2025/04/eng-ece-digital-twins-virtual-reality-workforce-training.html

[11] B. R. Barricelli, E. Casiraghi, and D. Fogli, "A survey on digital twin: Definitions, characteristics, applications, and design implications," *IEEE Access*, vol. 7, pp. 167 653–167 671, Nov. 2019.

[12] F. Tao and M. Zhang, "Digital twin shop-floor: A new shop-floor paradigm towards smart manufacturing," *IEEE Access*, vol. 5, pp. 20 418–20 427, Sep. 2017.

[13] F. Arraño-Vargas and G. Konstantinou, "Modular design and real-time simulators toward power system digital twins implementation," *IEEE Transactions on Industrial Informatics*, vol. 19, no. 1, pp. 52–61, May 2023.

[14] B. Somda and C.-C. Liu, "Digital twin for resilient power distribution systems," in *2024 22nd International Conference on Intelligent Systems Applications to Power Systems (ISAP)*. Budapest, Hungary: IEEE, Sep. 2024, pp. 1–6.

[15] M. D. Omar Faruque, T. Strasser, G. Lauss, V. Jalili-Marandi, P. Forsyth, C. Dufour, V. Dinavahi, A. Monti, P. Kotsampopoulos, J. A. Martinez, K. Strunz, M. Saeedifard, X. Wang, D. Shearer, and M. Paolone, "Real-time simulation technologies for power systems design, testing, and analysis," *IEEE Power and Energy Technology Systems Journal*, vol. 2, no. 2, pp. 63–73, Jun. 2015.

[16] M. Beikbabaei, N. K. Nguyen, and A. Mehrizi-Sani, "Cyber-resilient control for a 100% inverter-based microgrid: Analysis and real-time simulation," in *22nd International Conference on Intelligent Systems Applications to Power Systems (ISAP)*, Budapest, Hungary, Sep. 2024.

[17] G. Lauss and K. Strunz, "Accurate and stable hardware-in-the-loop (HIL) real-time simulation of integrated power electronics and power systems," *IEEE Transactions on Power Electronics*, vol. 36, no. 9, pp. 10 920–10 932, Sep. 2020.

[18] P. Kundu and A. K. Pradhan, "Real-time analysis of power system protection schemes using synchronized data," *IEEE Transactions on Industrial Informatics*, vol. 14, no. 9, pp. 3831–3839, Jan. 2018.

979-8-3315-8138-1