VIRGINIA TECH

VR-Augmented RTDS-Based Digital Twin for Grid Operator Training

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ATC
RTDS APPLICATIONS & TECHNOLOGY CONFERENCE

APPLICATIONS & TECHNOLOGY CONFERENCE 2025

CHICAGO, ILLINOIS, U.S.A.

RTDS Technologies
AMETEK

Portions of this work are supported in part by State of Virginia's Commonwealth Cyber Initiative (CCI), in part by the National Science Foundation award CPS-1837700, and in part by ICTAS. This talk shares the work of my students in REGAL.

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- Microgrid control
- Inverter-based resources
- Cybersecurity

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AEP Research Professor Emeritus
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- Distribution systems, cyber-power system security
- Industrial software for system restoration

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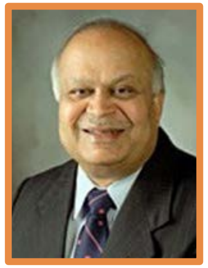

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- Power system protection and control
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- Robust power system parameter and dynamic
- State estimation w/PMUs

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- Utility grounding for lightning protection

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- High-power electronics

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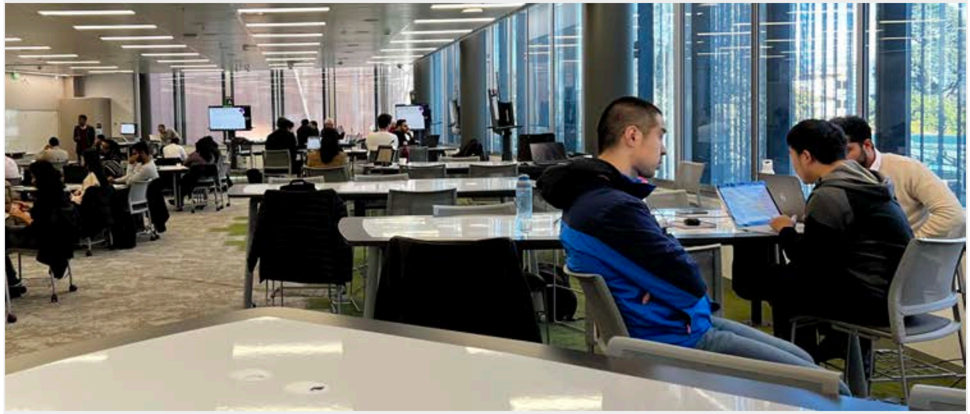
Collegiate Professor

Workforce Needs

- **Who is going to run the power system?**

- **Power system training is in significant demand specially because of the growing workforce needs:**
  - Existing workforce is retiring faster than new workforce is trained, and
  - They need to be trained in new technologies that did not exist a mere few years ago.

RTDS Workshop, August 2023



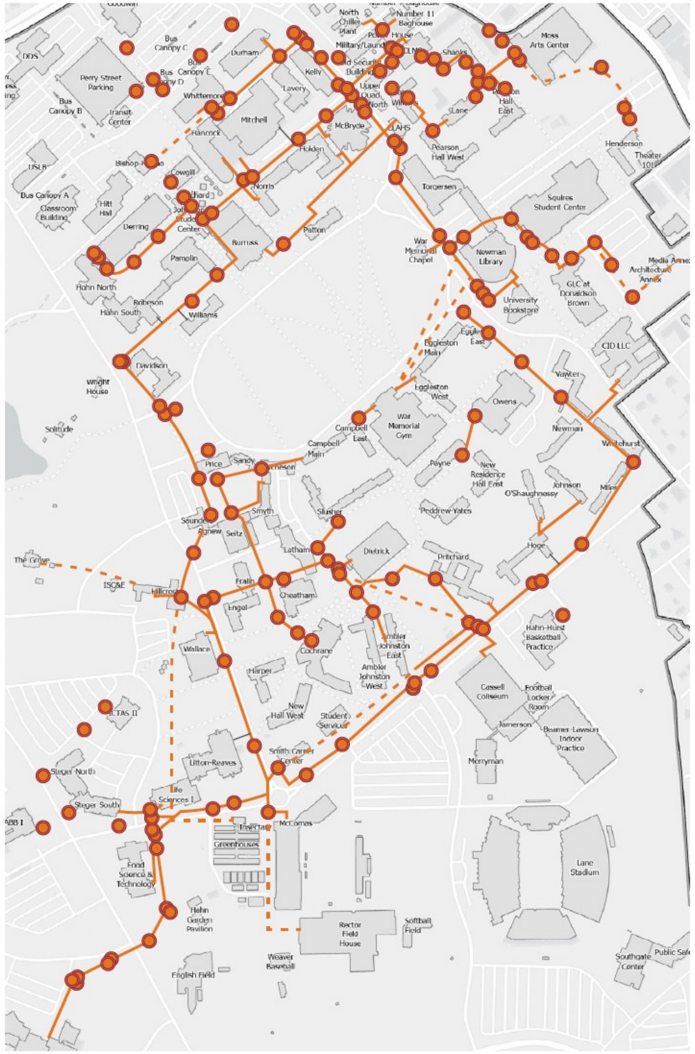
GFM Inverters + PSCAD Training
July 2023 and June 2024

Virginia Tech Electric Service (VTES)

- 69kV delivery from AEP/APCO
- Four 12.5 kV substations
- Eight substation transformers (double redundancy)
- 1,283 distribution transformers
- 138 miles of underground cables
- All time peak - 65MW
- Average daily peak - 45MW

Slide by Nam Nugyen, Executive Director of VT Energy and Utilities, used with permission.

CoGen Power Plant

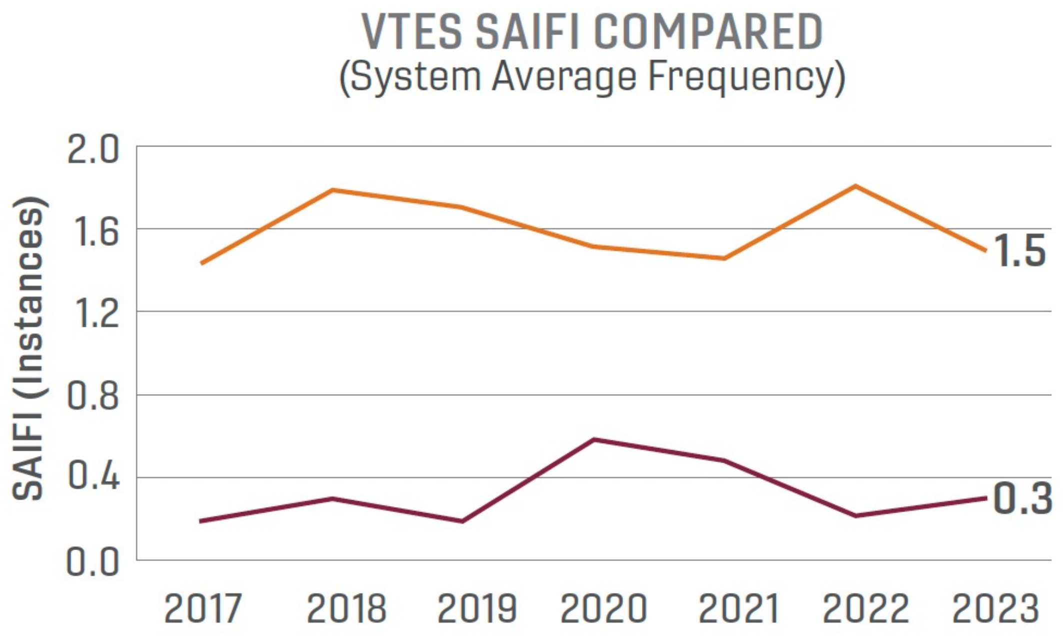


- Total 330,000 lbs/hr capacity
- Four natual gas boilers
- Two coal boilers last operated in 2020 (to be decommissioned)
- 200,000 lbs/hr avg. winter hourly steam load
- 75,000 lbs/hr avg. summer hourly steam load
- 6.25 MW turbine generator

Slide by Nam Nugyen, Executive Director of VT Energy and Utilities, used with permission.

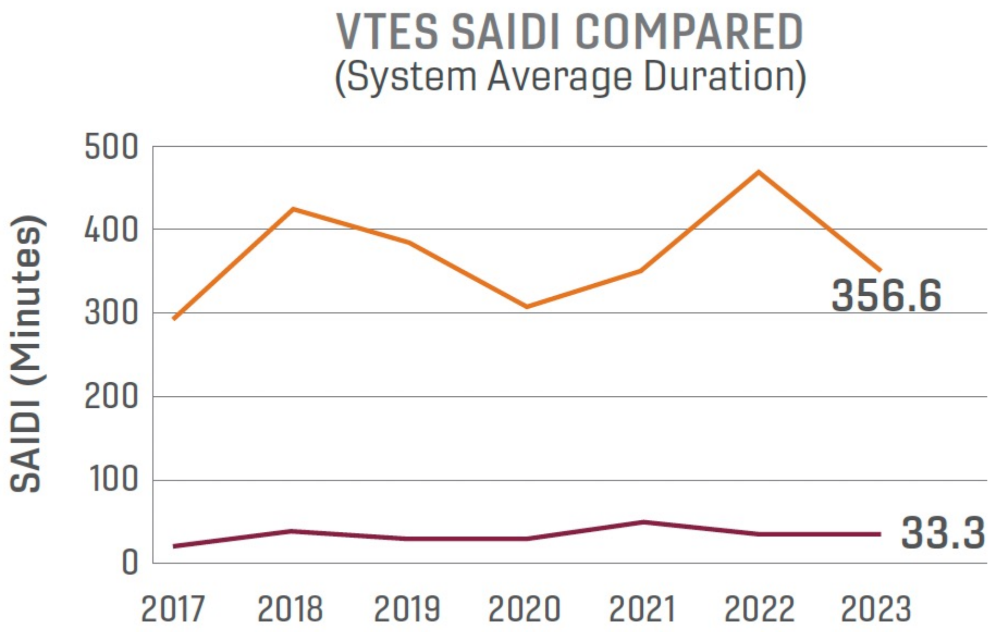
VTES Reliability Metrics

Annual average **number of times** that a VTES customer is out of power



SAIFI - System Average Interruption Frequency Index

Annual average **minutes** that a VTES customer is out of power



SAIDI - System Average Interruption Duration Index

Avg Large Utility — VTES

Slide by Nam Nugyen, Executive Director of VT Energy and Utilities, used with permission.

Games, 3D Games

Wolfenstein 3D (1992)

Doom (1993)

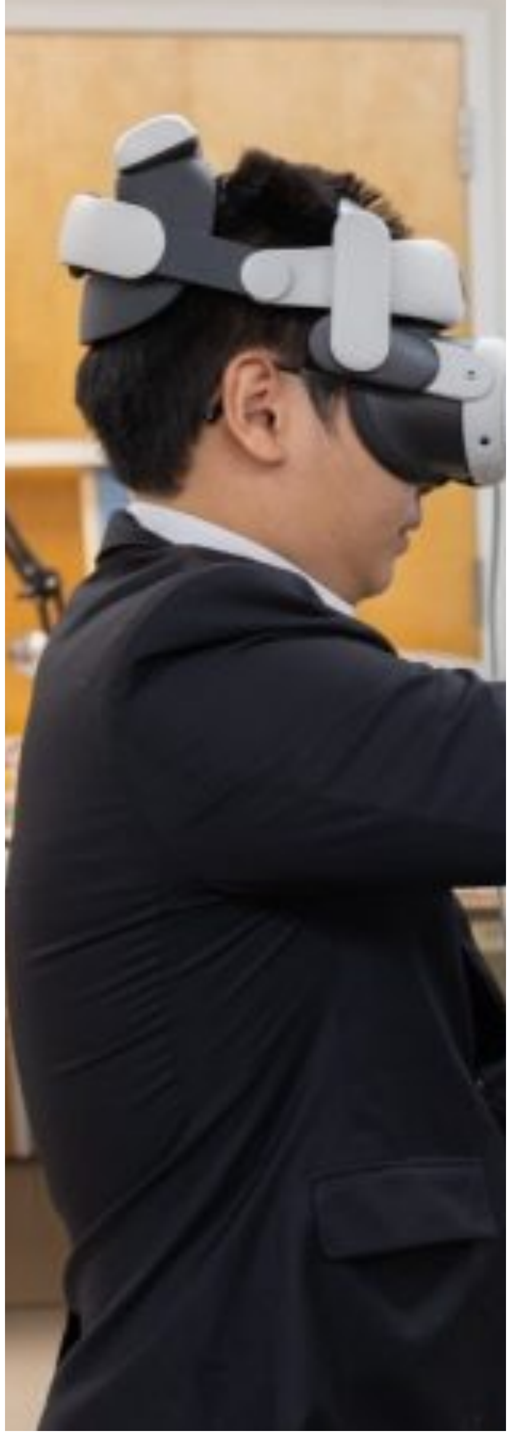
Duke Nukem 3D (1996)

Three Ingredients

Need: Workforce Development

Enabler: University-Owned Utility

Idea: Games 3D/VR



VR-Based Grid Operator Training

- **Traditional training programs are often based on conventional methods, such as studying documentation or practical training with equipment level operation.**

- **Our goal is to provide experience hands-on experience in working with human-machine interface (HMI) panels of the grid- level control.**
  - Monitor grid conditions
  - Control assets
  - Coordinate local resources
  - Restore service after unplanned outages

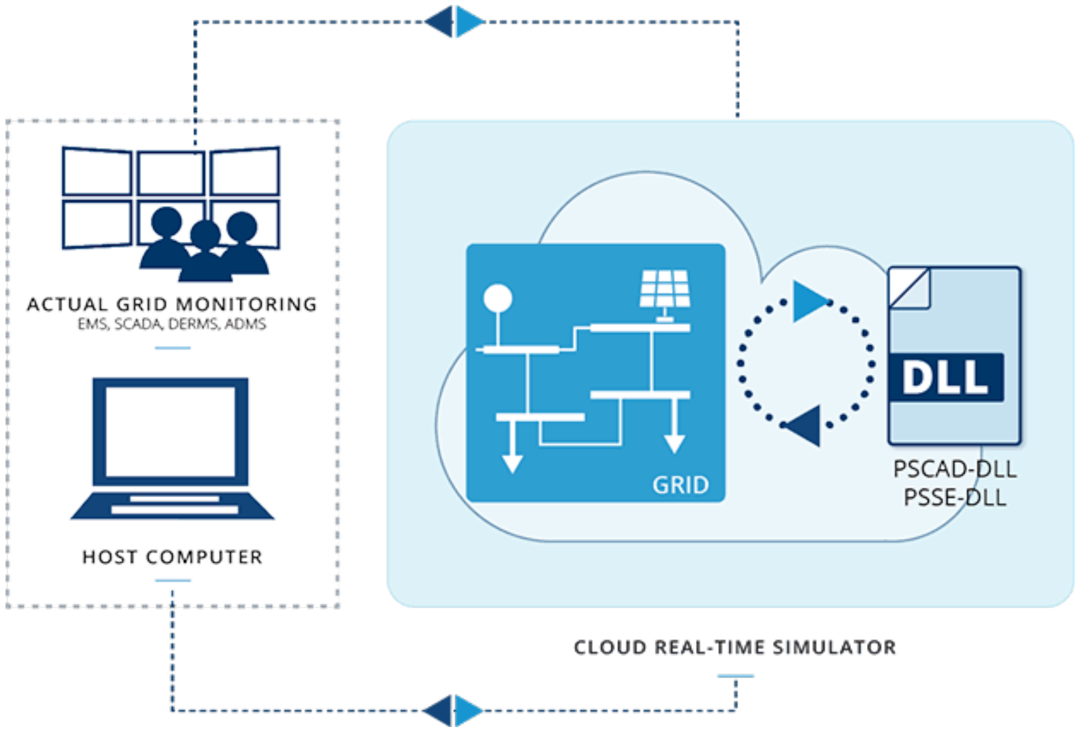
https://www.bpa.gov/about/careers/explore-a-career-at-bpa/bpa-apprenticeship-program/substation-operators

But First, the Digital Twin

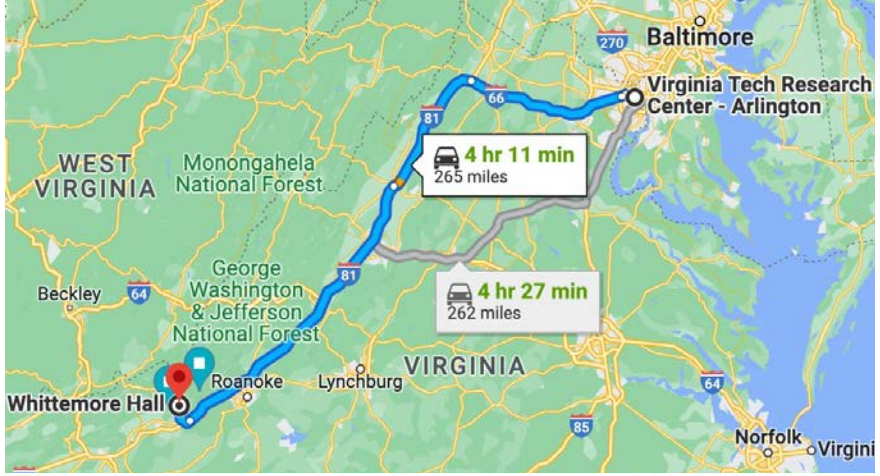
- A digital twin is a virtual replica of a physical system with live data link.

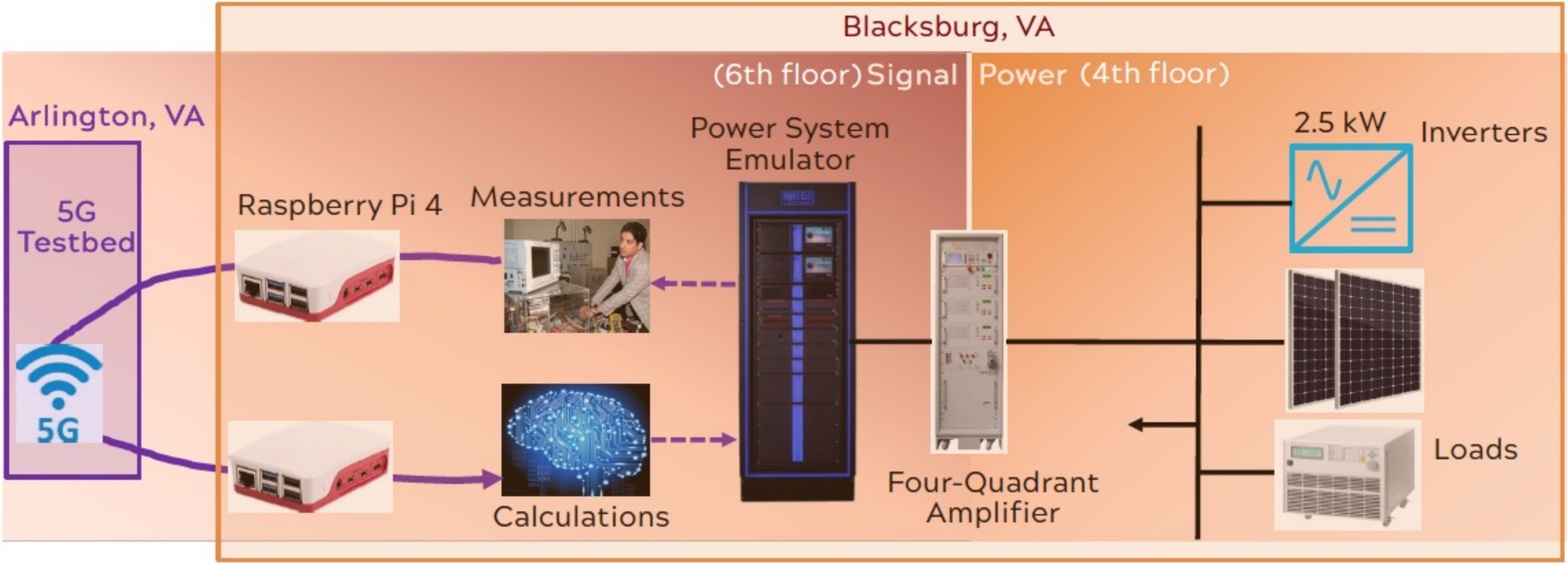
- A digital twin is based on the digital simulation of the system, but instead of using arbitrary data and inputs, it uses actual data from sensors connected to the physical system. That is, it has two major components:
  - A simulator
  - Real-time data input

- In power system, a digital twin is typically (but not always) built using a real-time simulator.



VT PEC Digital Twin

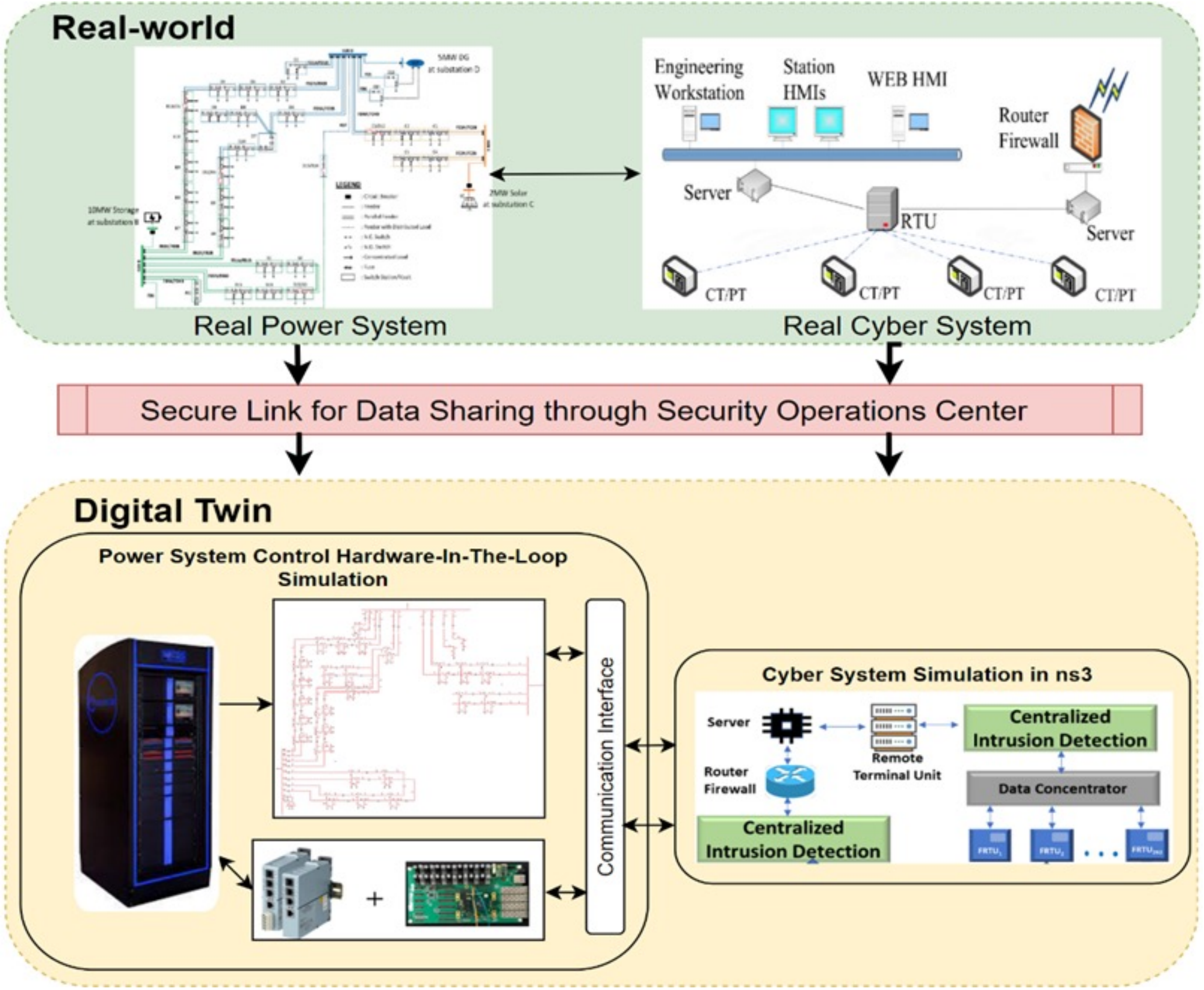




Equipment acquired through a grant from Virginia's Commonwealth Cyber Initiative (CCI). PB5 is donated by Dominion Energy.

VTES Digital Twin Architecture

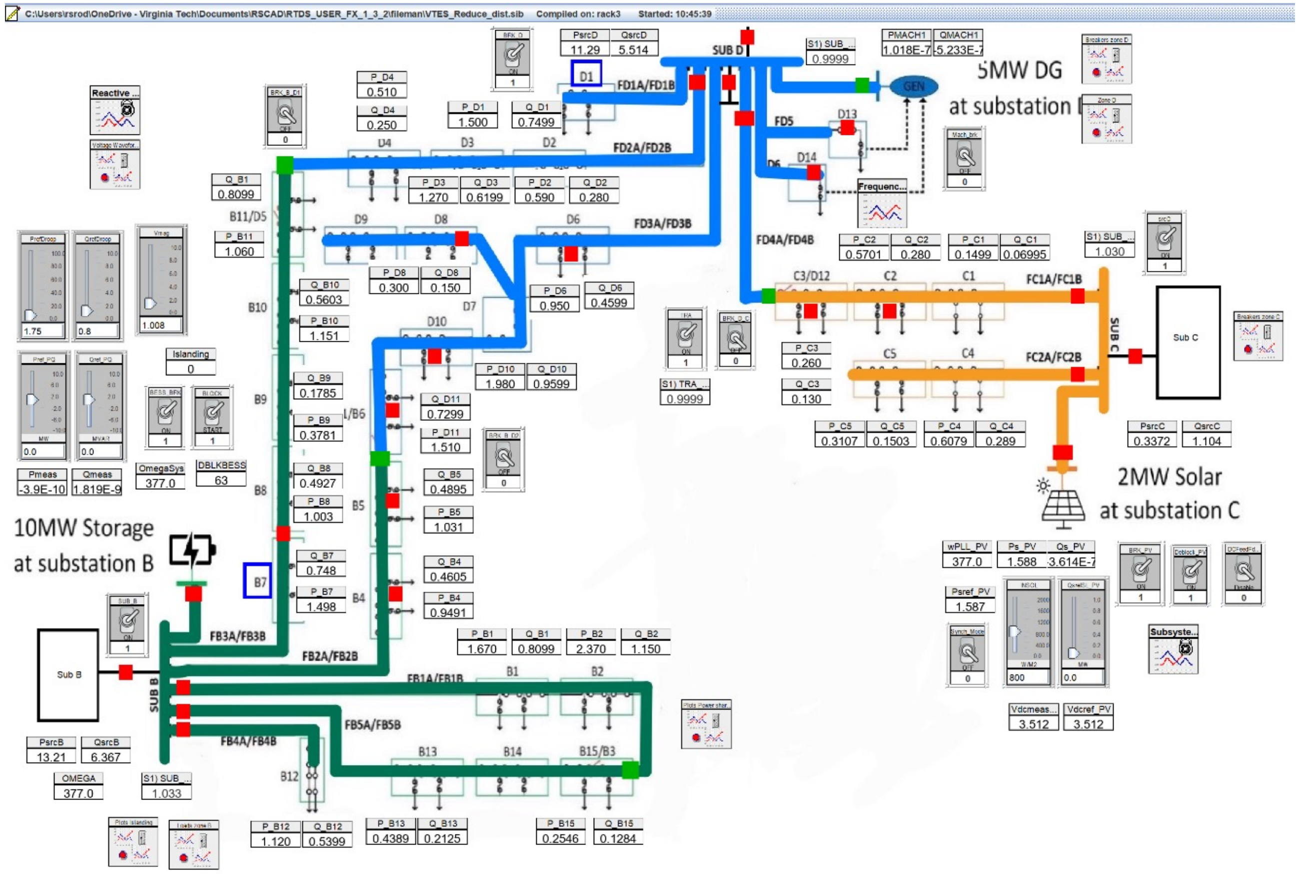
- **Components**
  - Physical system
    - VTES system
  - Virtual system
    - Cyber-power simulation testbed
  - Connection
    - Secure data link with VTES control center
    - Real-time data

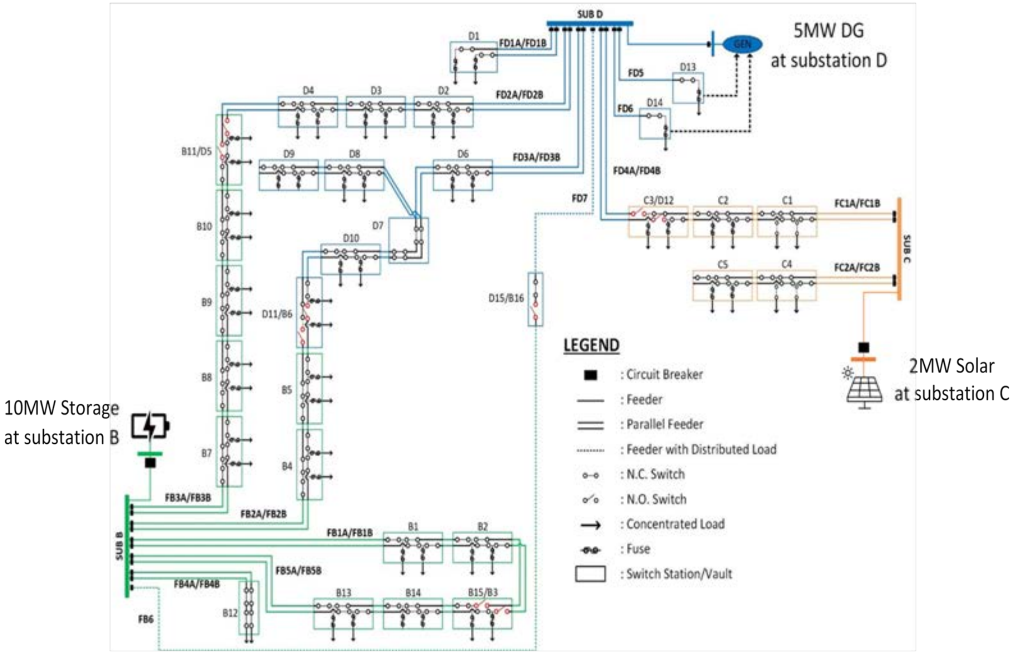


- **Services**
  - Resilience planning
  - Cybersecurity testing
  - Decision support
  - Workforce training

Courtesy of Prof. Chen-Ching Liu, Virginia Tech, 2024.

VTES Simulation in RTDS





B. Somda and C. -C. Liu, "Digital Twin for Resilient Power Distribution Systems," *2024 22nd International Conference on Intelligent Systems Applications to Power Systems (ISAP)*, Budapest, Hungary, 2024, pp. 1-6, doi: 10.1109/ISAP63260.2024.10744374.

Second, the Virtual Reality Environment

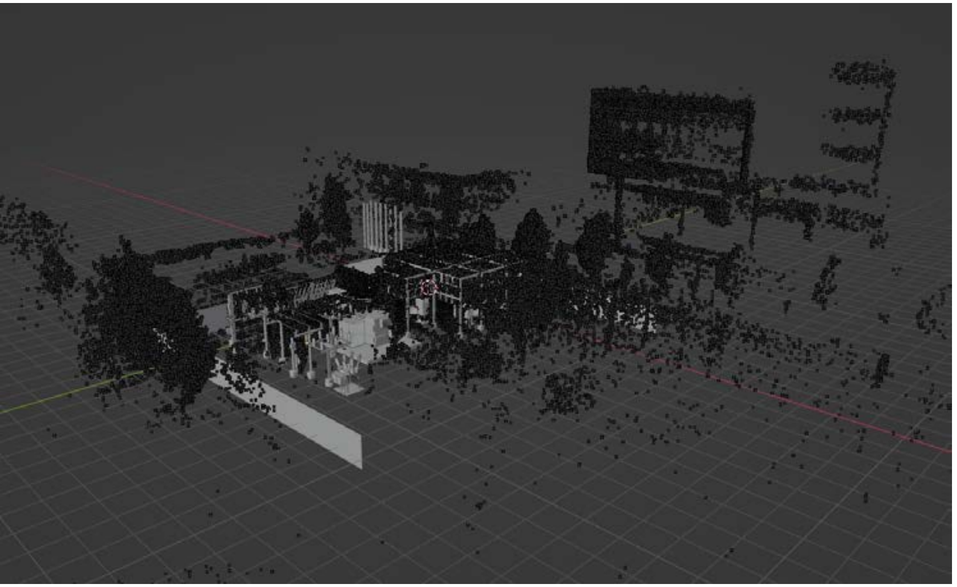
- The virtual reality environment is developed using Unreal Engine 5.

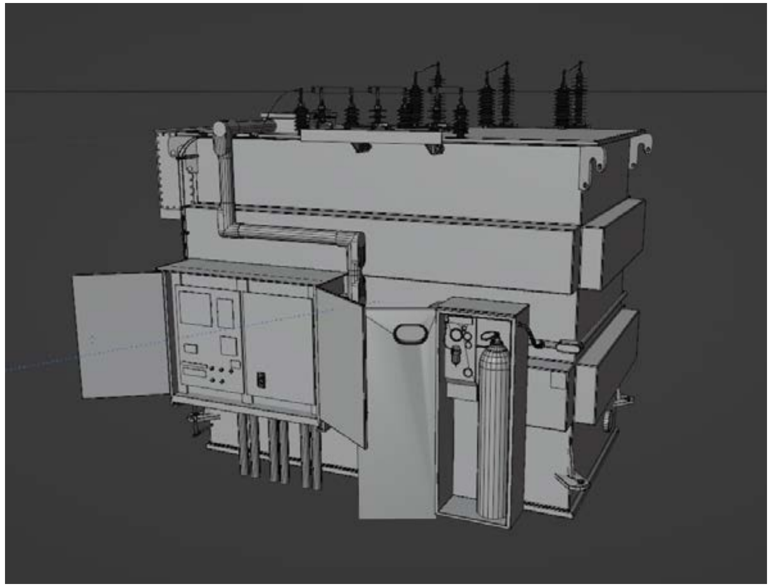
- This environment offers a setting where trainees can interact and operate with substation equipment and observe the effects of their actions on the digital twin of the grid.

- A Virginia Tech Electric Service (VTES) substation is modeled as the basis for the virtual reality environment.

Modeled VTES substation

Creating a Virtual Substation 101


3D Scanning

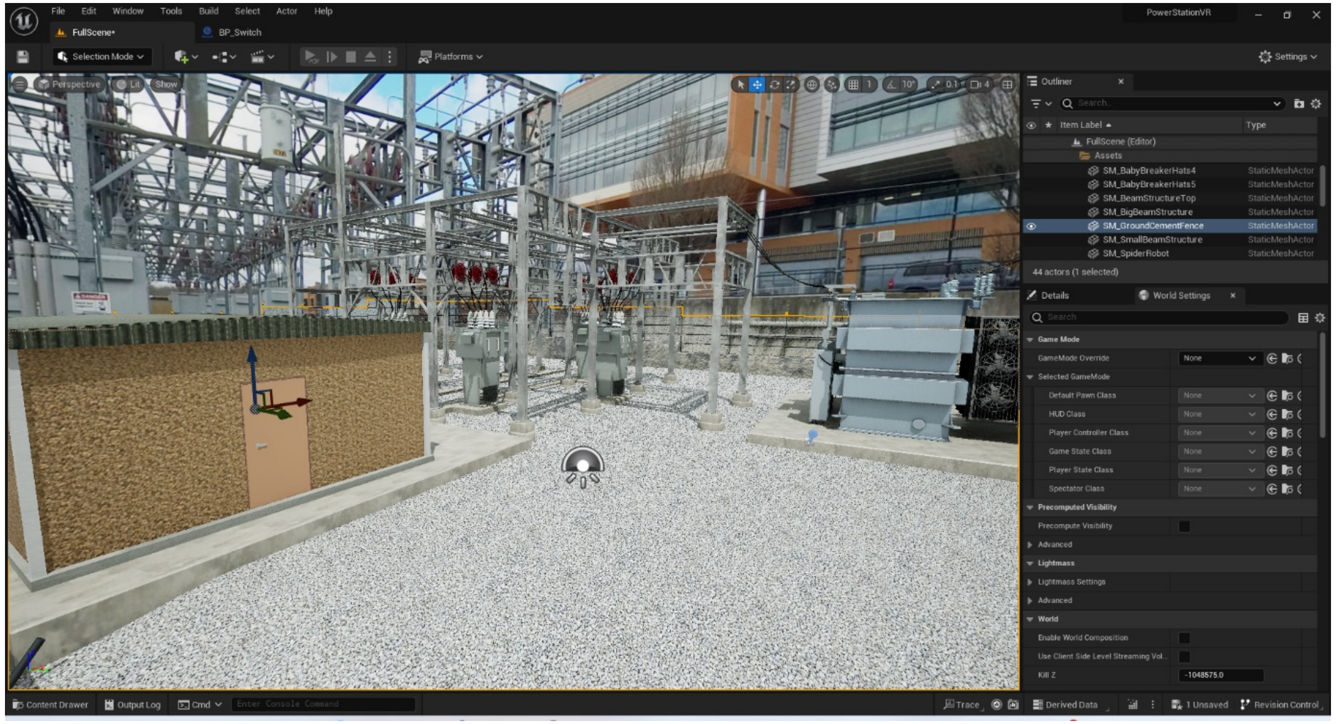

3D Modeling and Texturing


Game-Like Environment

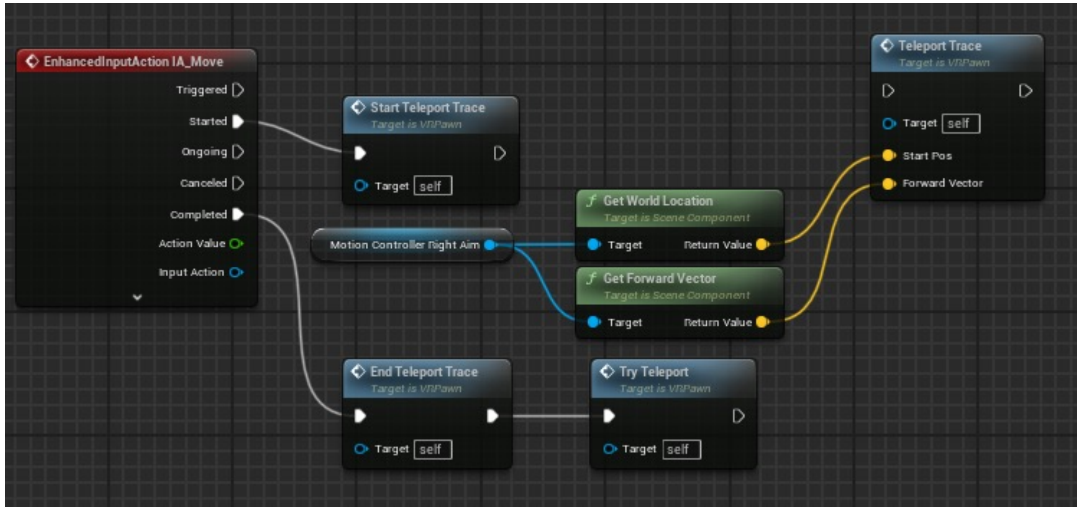

Control Room

Control Room Interactions

Unreal Engine 5 Workspace

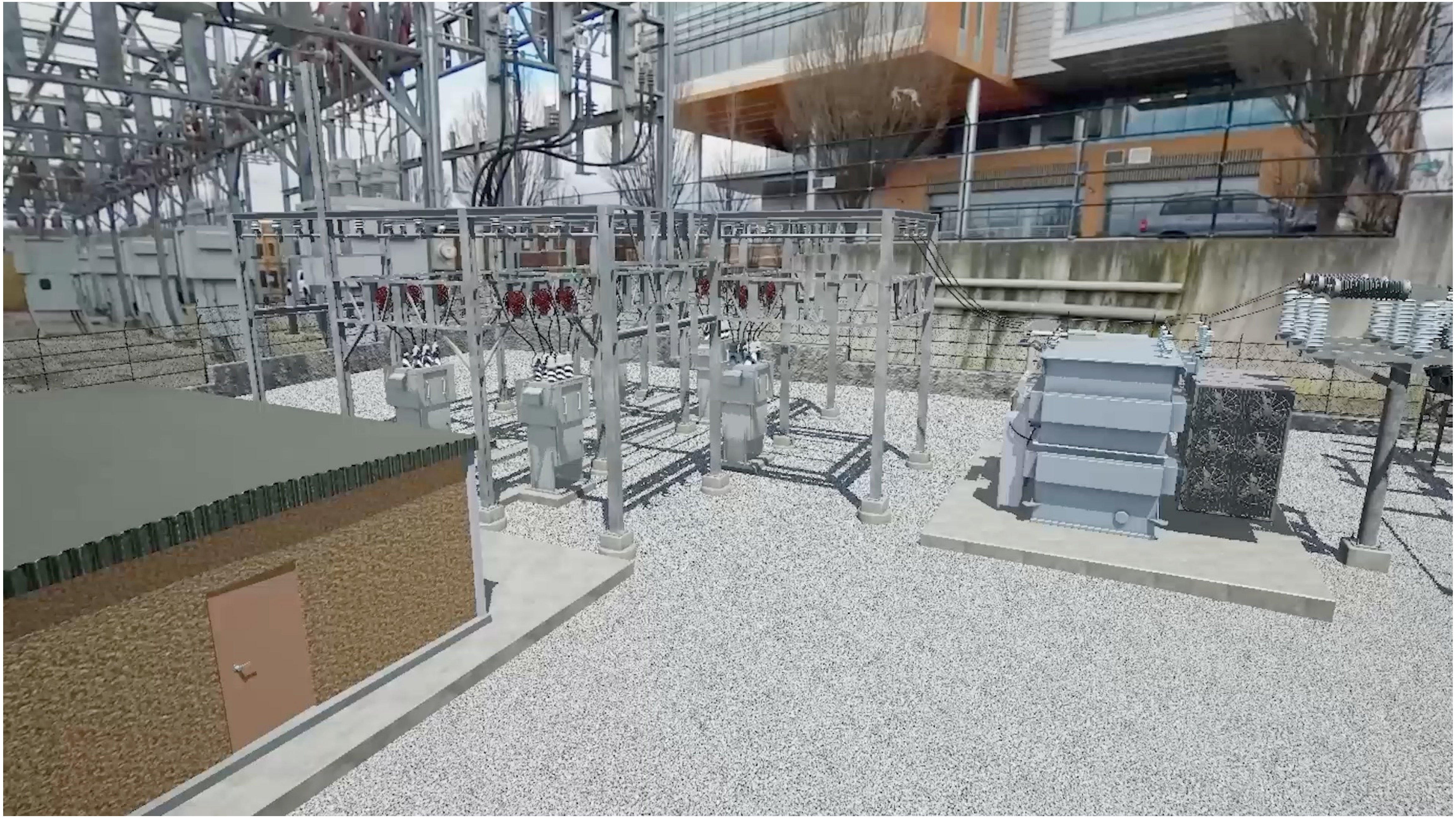


Unreal Engine 5 Level Editor



An example of Blueprint Visual Scripting

Video



Virtual vs Actual Reality

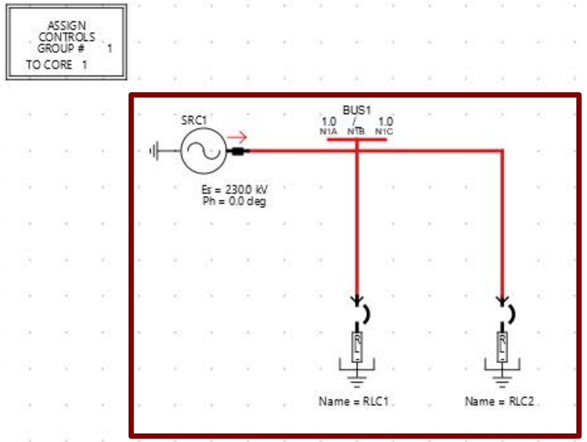
- Video (20 seconds) by Niki Hazuda
- https://news.vt.edu/articles/2025/04/eng-ece-digital-twins-virtual-reality-workforce-training.html

"With virtual training, we exponentially reduce restrictions and increase flexibility," said Nam Nguyen '88, executive director of Energy and Utilities at Virginia Tech. "There are more opportunities to virtually walk around the substation. Trainees can make mistakes, and we can even create outage issues. It allows our new linemen to go through the process of identifying and problem solving, all without affecting the real system or people."

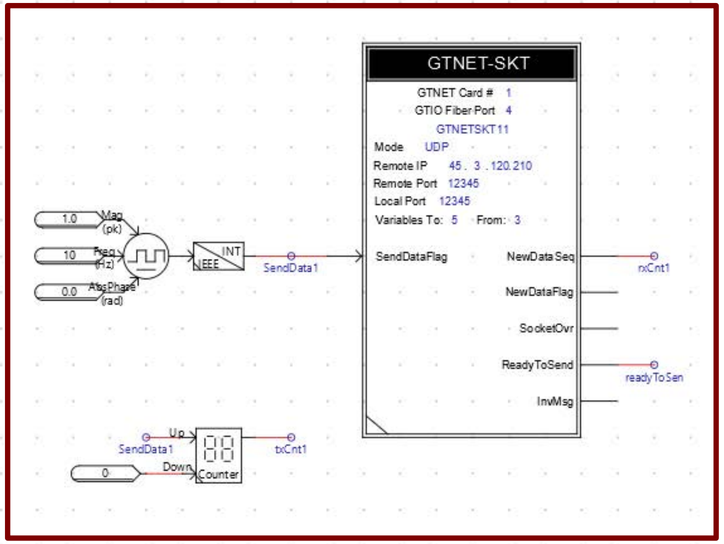
Case for Real-Time Simulation

- Grid-level control training requires trainees to interact with and operate on a functioning electricity grid.
- Inducing catastrophic unplanned outages or similar events in the power system for training purposes is unfeasible.
- Traditional simulation software do not provide practical, timely feedback to trainee actions due to the mismatch in timescales between simulated environments and the real power grid.
- To address this, we utilize the capability of RTDS real-time simulation platform to provide a cost-effective and accurate digital twin of the grid.

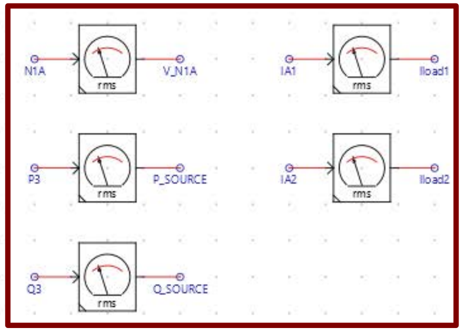
Digital Twin of the Grid (Simple Version Due to NDA)



Proof of concept digital twin grid



GTNET-SKT Communication Channel



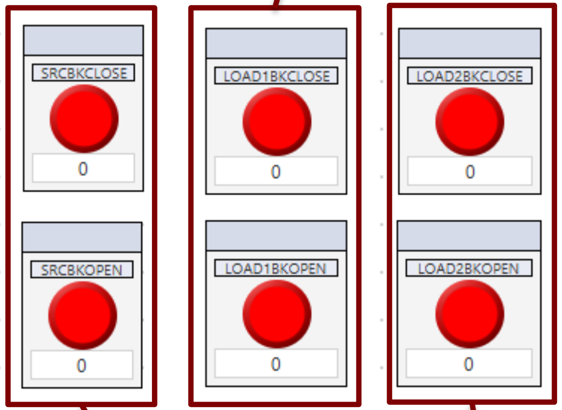
Measurements

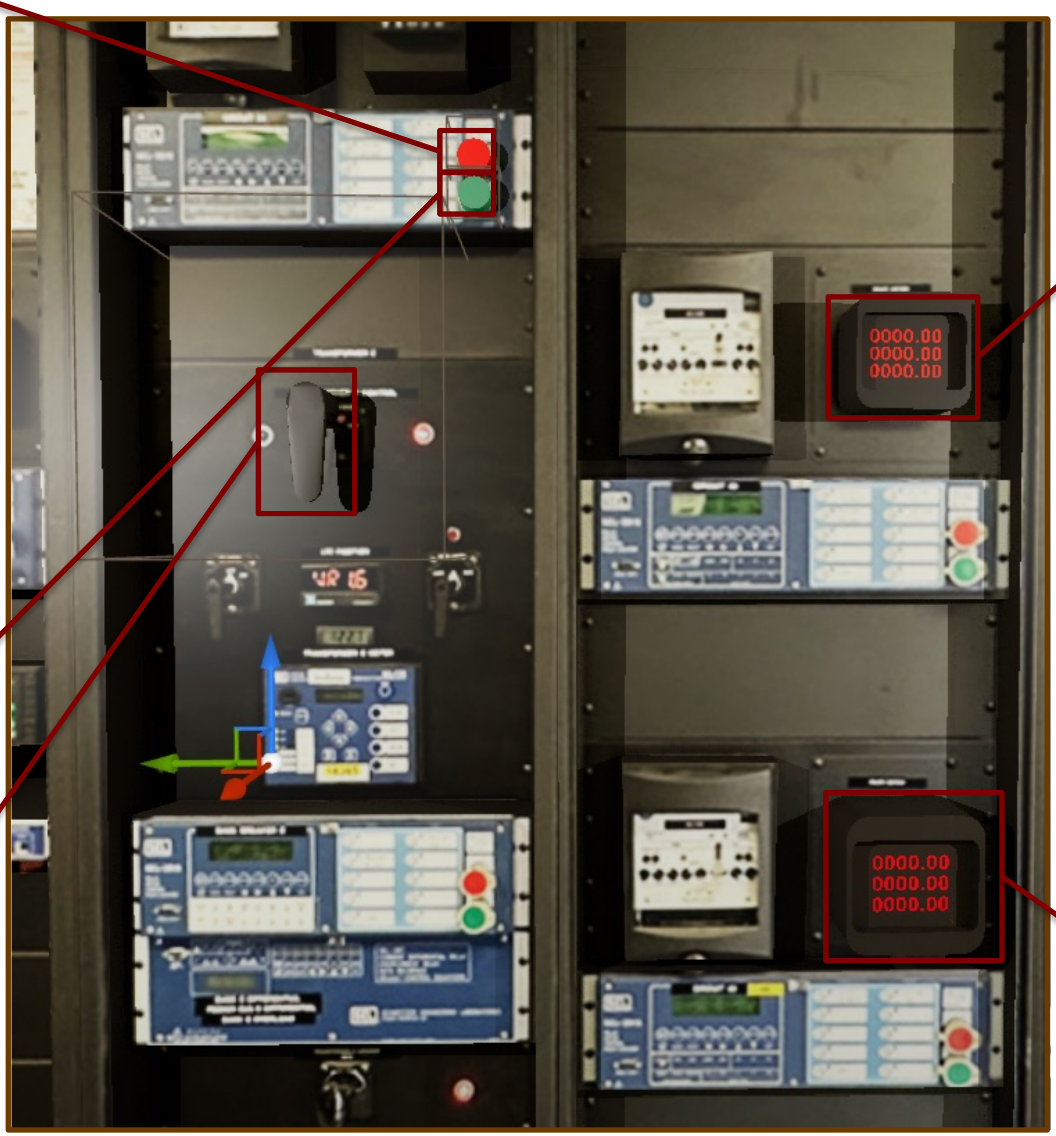
Source Parameters	
Parameter	Value
Source Voltage	230 kV
Frequency	60 Hz

Load Parameters	
Parameter	Value
First Load Resistance	1.5 Ω
First Load Inductance	0.1 H
Second Load Resistance	10 Ω
Second Load Inductance	0.05 H

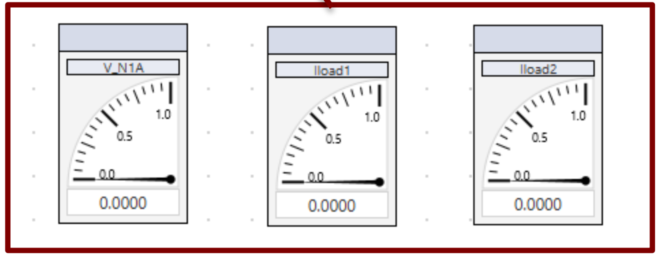
RSCAD Runtime vs VR Interface

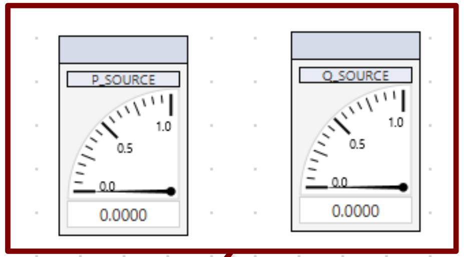
Load 1 breaker control





Meters





Load 2 breaker control

Source breaker control

Meters

UDP Communication Code

Inititalize measurements and control data

```python
# Initialize measrements send from RTDS
shared_data_measurements = {"Iload1": 0, "Iload2": 0, "Vbus_1": 0, "P_SOURCE": 0, "Q_SOURCE": 0,}
# Initialize control data send from UE5
shared_data_control = {"SWD1": 0, "SWD2": 0, "SBRKSOURCE": 0}
data_lock = threading.Lock()

if __name__ == "__main__":
    # Initialize PC IP and RTDS IP
    local_ip = local_pc_ip
    local_port = 12345
    remote_ip = rtds_send_ip
    remote_port = 12345

    # Start the receiver thread for UE5
    receiver_thread_UE5 = ServerThread(ip=local_ip, port=PC_SERVER_PORT)
    receiver_thread_UE5.start()

    # Start the sender thread for UE5
    sender_thread_UE5 = ClientThread(
        ip=local_ip, port=SIM_SERVER_PORT, sim_server_ip=local_ip, sim_server_port=SIM_SERVER_PORT
    )
    sender_thread_UE5.start()

    # Initialize UDP communication with RTDS
    udp_comm = UDPCommunication(local_ip, local_port, remote_ip, remote_port)

    # Start the receiver thread for RTDS
    receiver_thread_RTDS = threading.Thread(target=udp_comm.start_server)
    receiver_thread_RTDS.daemon = True
    receiver_thread_RTDS.start()

    # Start the sender thread for RTDS
    sender_thread_RTDS = threading.Thread(target=udp_comm.send_data_repeatedly, args=(SEND_INTERVAL,))
    sender_thread_RTDS.daemon = True
    sender_thread_RTDS.start()
```

Store local PC and RTDS IP address and port

Initialize and start UDP connection with the VR environment

Initialize and start UDP connection with RTDS GTNETx2 Card

Setup

- The setup can provide trainees with a realistic training environment for real-time station and bay level control related tasks.
- The setup consists of a Meta Quest 3 VR headset, a VR environment in Unreal Engine 5, and a digital twin running on RTDS
- The communication between the VR environment and the simulated grid is handled by an UDP-based communication channel.

Data flow diagram of the Substation VR project setup

Demo

- Video (1 min and 46 sec)

Next Steps

- Create training scenarios, lesson plans.
- Bring more of the control room equipment to "life."
- Expand to substation yard.
- Other niche applications, e.g., training for hard-to-reach places.

https://www.southcoasttoday.com/picture-gallery/special/2025/02/07/national-offshore-wind-institute-photo-gallery/78298160007/

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RTDS Applications & Technology Conference
Chicago, IL | May 7, 2025

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Resilient Renewable Energy Grid Adaptation Laboratory (REGAL)

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Virtual Reality-Augmented RTDS-Based Digital Twin for Substation Operator Training

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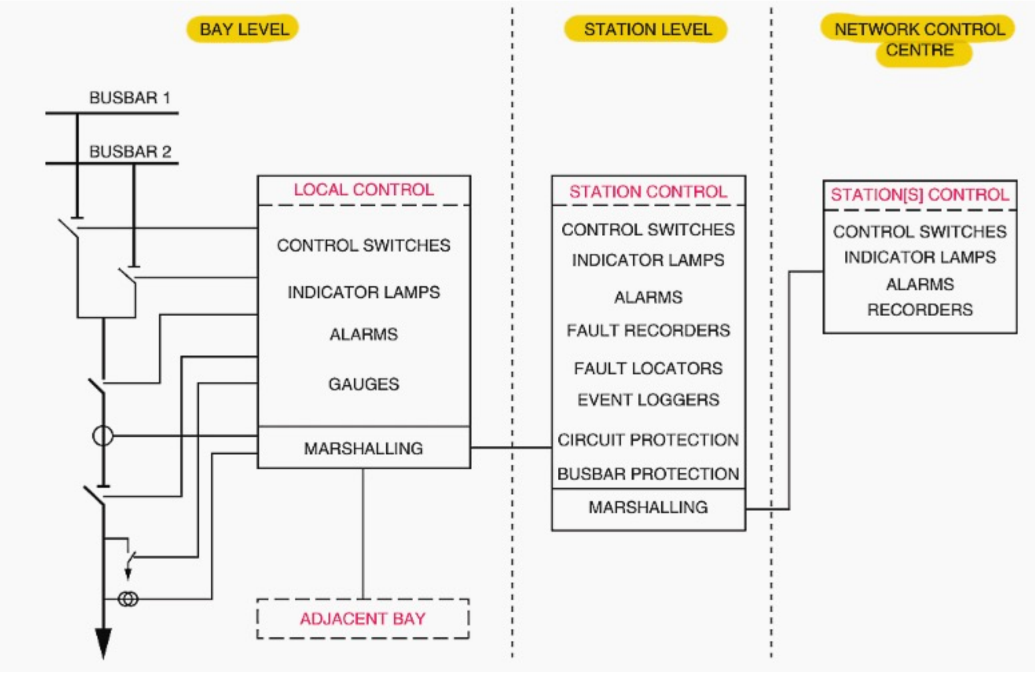
Grid Operator Training

- Grid operator training has a broad range of topics.

- This project is currently focused on the supervisory control and data acquisition (SCADA) aspects of the training.

- Grid control is typically structured into three hierarchical levels:
  - Central Network Control Center
  - Station Control
  - Bay Control



Three levels of grid control HMI

https://electrical-engineering-portal.com/substation-control-monitoring-systems

Significance of Grid Operator Training

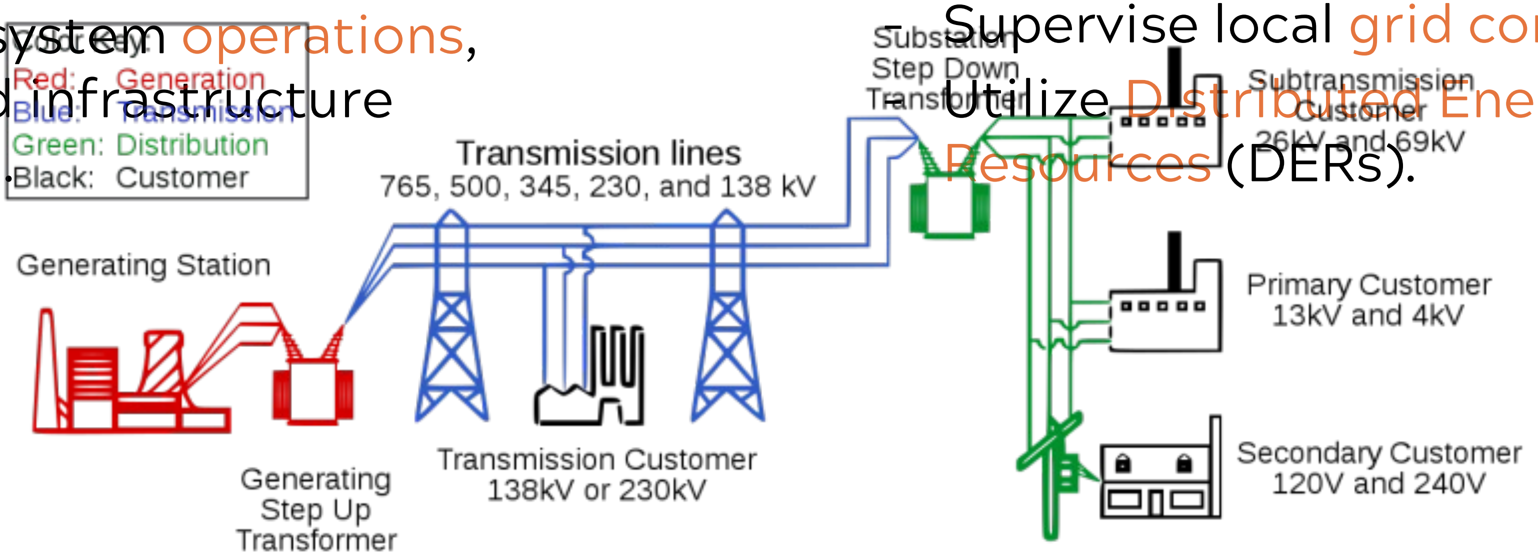
- Providing continuous and reliable power to the end consumers is a key aspect of the power system.
- Grid operators are responsible for monitoring grid performance, balancing supply and demand, and guaranteeing system security.
- Grid operator training is critical for ensuring competent personnel in the management of electric substations.

https://www.incsys.com/power4vets/what-is-a-system-operator/

Types of Grid Operator

- **Transmission system operator (TSO)**
  - Ensure safe, reliable, and efficient power transport to distribution networks.
  - Connect networks with the neighboring utilities.
  - Provide balancing services.
  - Supervise system operations, upkeep and infrastructure expansions.

- **Distribution system operator (DSO)**
  - Assist in real-time tasks: track grid conditions and deploy local assets in real-time.
  - Coordinate local resources: load forecasting, scheduling, and compensation.
  - Supervise local grid conditions.
  - Utilize Distributed Energy Resources (DERs).



https://en.wikipedia.org/wiki/Electrical_grid

Other Grid Operator Training Tools

GE Vernova HV Asset Operations and Maintenance Training

https://www.gevernova.com/grid-solutions/press/gepress/vr_for_hv_equipment_technical_training.htm

- **Advantages:**
  - Cover HV equipment technical detail and performance extensively.
  - Simulate real onsite experience.
- **Disadvantages:**
  - Focused solely on operation and maintenance of Power Transformers.

Digital Engineering and Magic Electrical Substation Training Platform

https://www.digitalengineeringmagic.com/vr-training/vr-training-hv-electrical-substation/

- **Advantages:**
  - Polished user interface.
  - Great visualizations.
- **Disadvantages:**
  - Cover only simple training, such as substation layout and basic equipment information.

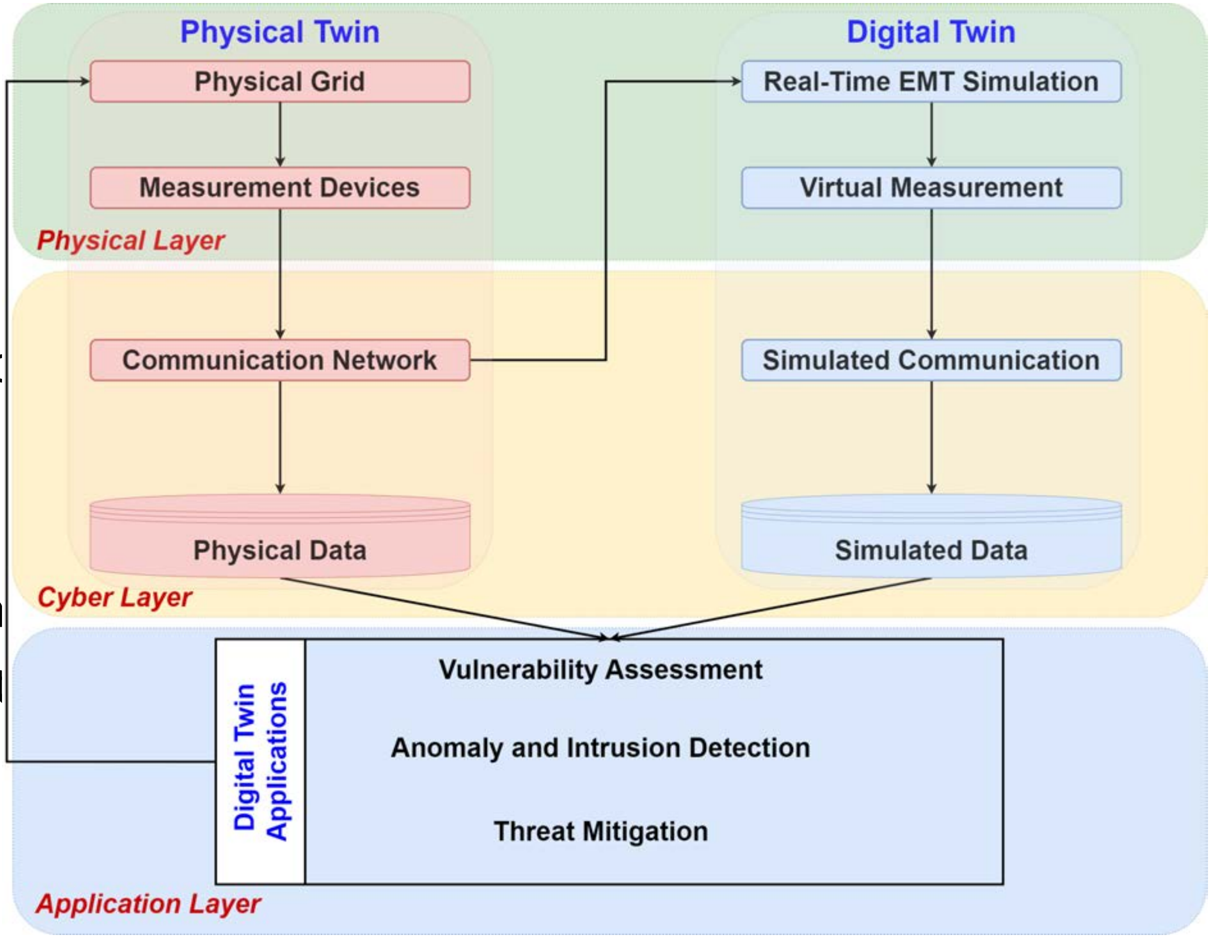
E-Spaces VR Substation

https://e-spaces.com/electrical-substation-vr-simulator/

- **Advantages:**
  - Utilize digital twins for equipment simulation.
  - Include electric field visualization.
- **Disadvantages:**
  - Visualization is not realistic.
  - Controls and interactions are not intuitive.
  - Small grid size.

Cyber Resilience Applications of Digital Twins

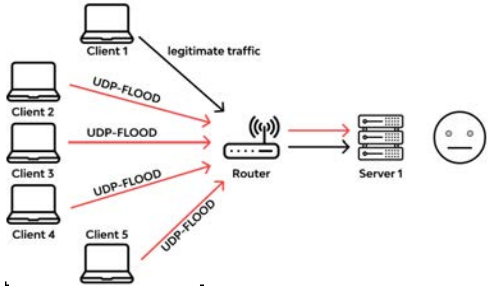
- **Cyber vulnerability assessment**
  - Penetration testing.
  - Identification of potential attack vectors.
  - Analysis of the potential impact of coordina
- **Anomaly/intrusion detection (IDS)**
  - Dataset generation for training of ML-basec
  - Online testing of IDS.
- **Threat mitigation**
  - Resilience planning for impact minimization
  - Development and testing of mitigation strat

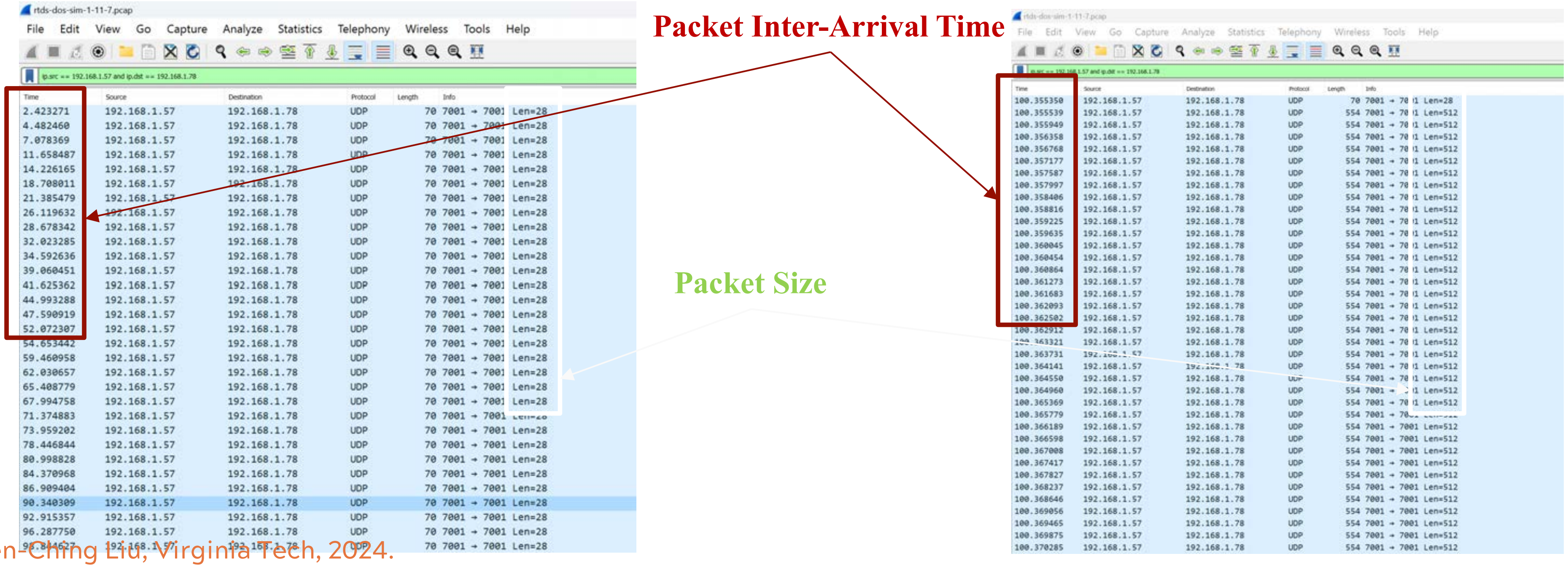


Courtesy of Prof. Chen-Ching Liu, Virginia Tech, 2024.

Coordinated Cyberattack Scenario

- **All attacks are conducted within ns-3, and results are observed in RTDS.**
- **Phase 1: Direct Switching Attack against substation breakers.**
- **Phase 2: Denial-of-Service Attack using UDP flooding:**
- **Results:**
  - All substations are disconnected.
  - The packet size and inter-arrival rate increase, causing legitimate packets to be discarded.

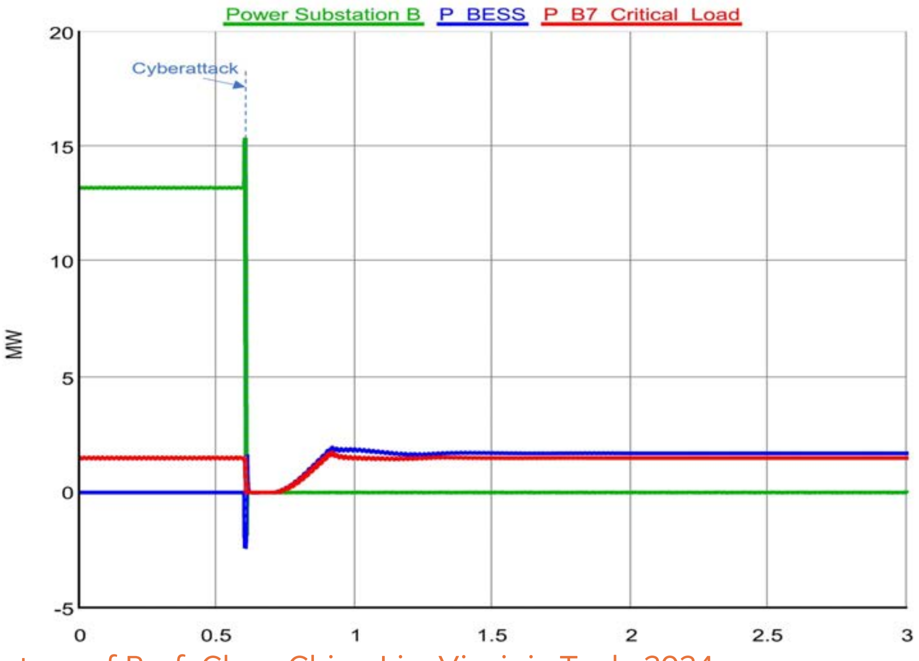


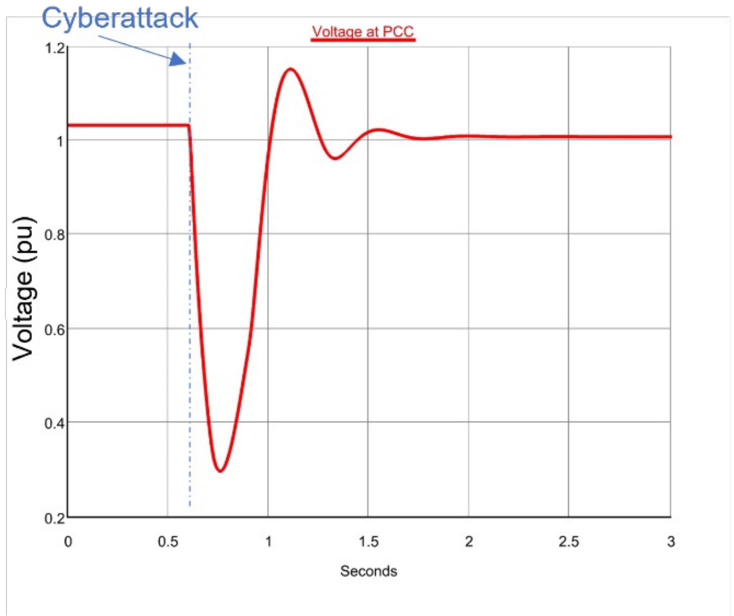


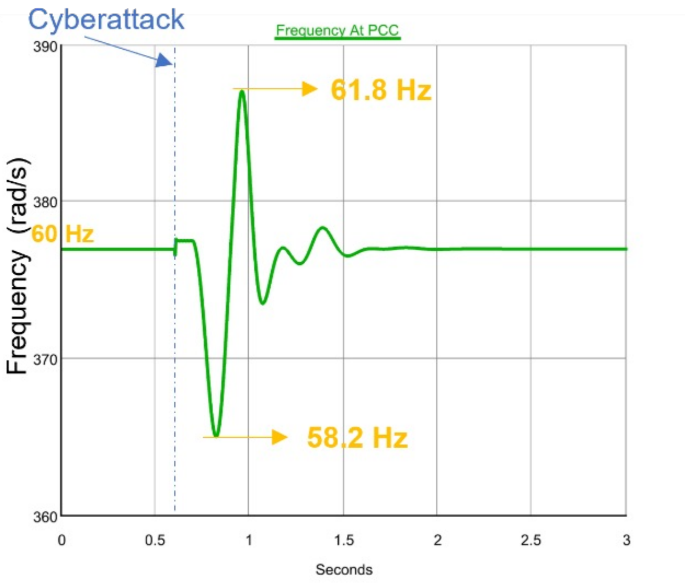
Courtesy of Prof. Chen-Ching Liu, Virginia Tech, 2024.

Sequence of Actions after Cyberattack

- **Sequence of actions in Zone B:**
  - Non-critical loads are disconnected.
  - The BESS inverter switches to grid-forming mode (islanded operation).
  - The BESS picks up Critical Load B7.
- **Similar actions are taken in zones D and C to pick up all critical loads while avoiding large transients.**



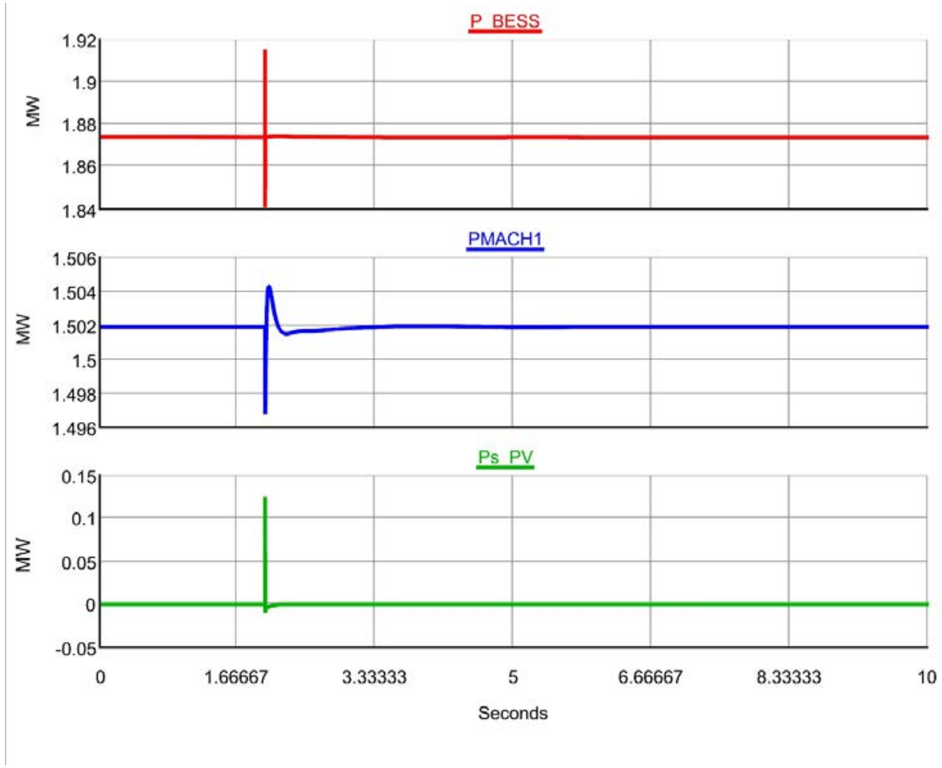


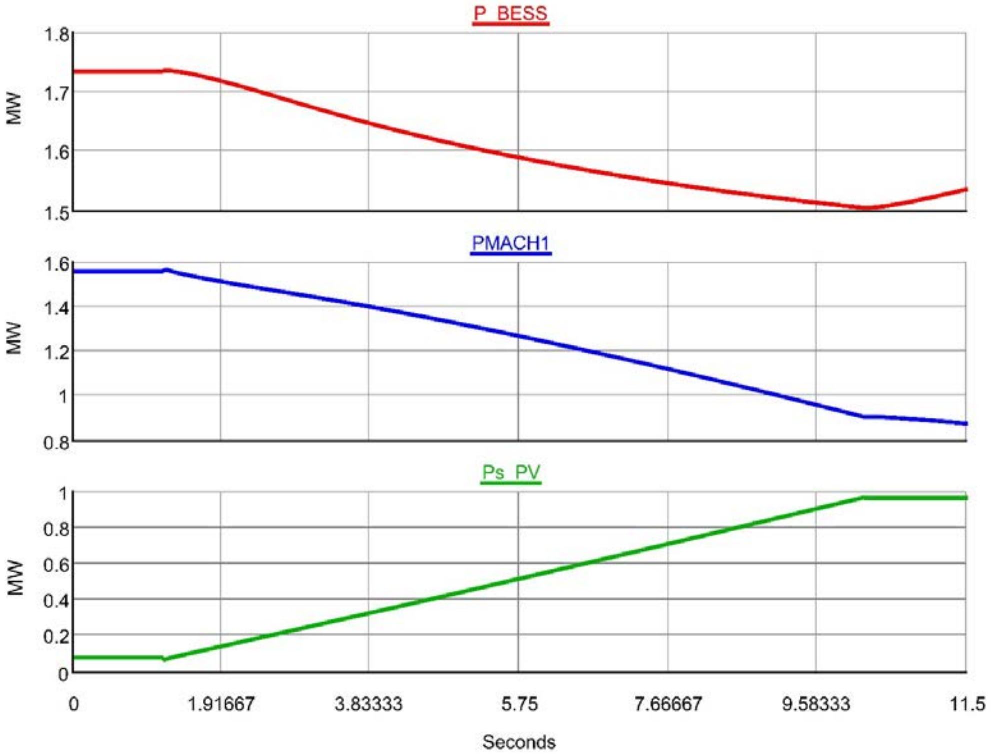


Courtesy of Prof. Chen-Ching Liu, Virginia Tech, 2024.

Resilient Operation

- The three electrical islands are interconnected with minimal transients.
- The PV plant uses Maximum Power Point Tracking to generate as much power as possible given weather conditions.
- The remaining load is shared between the BESS and the synchronous machine according to their droop setting.

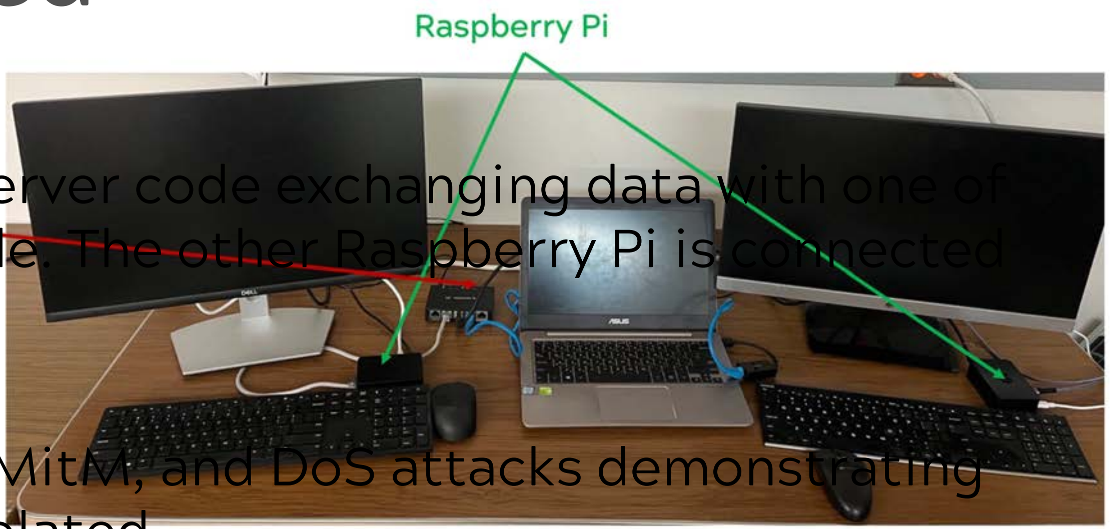


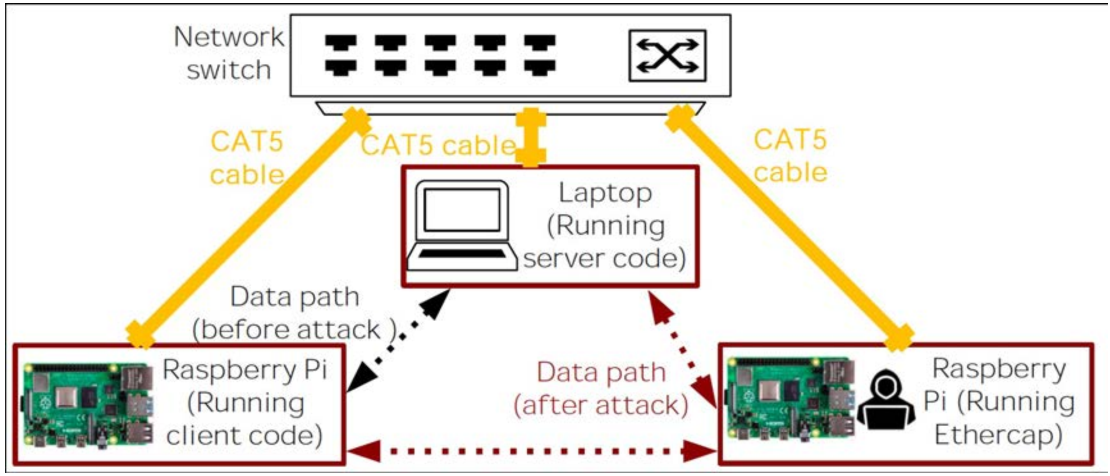


Courtesy of Prof. Chen-Ching Liu, Virginia Tech, 2024.

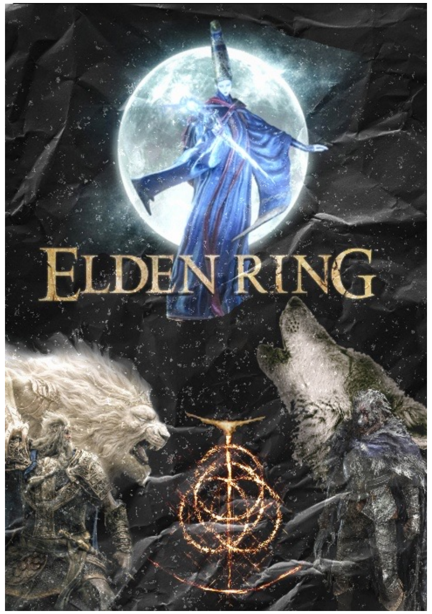
Other Components Being Added

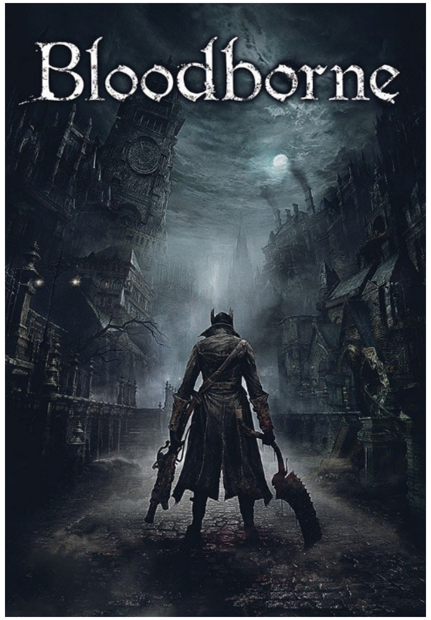
- **Red teaming**
  - Hardware implementation: The PC runs a UDP server code exchanging data with one of the Raspberry Pi units and runs a UDP client code. The other Raspberry Pi is connected to the network switch launching cyberattacks.
  - We have preliminary results for *successful* FDI, MitM, and DoS attacks demonstrating the vulnerability of local networks even when isolated.





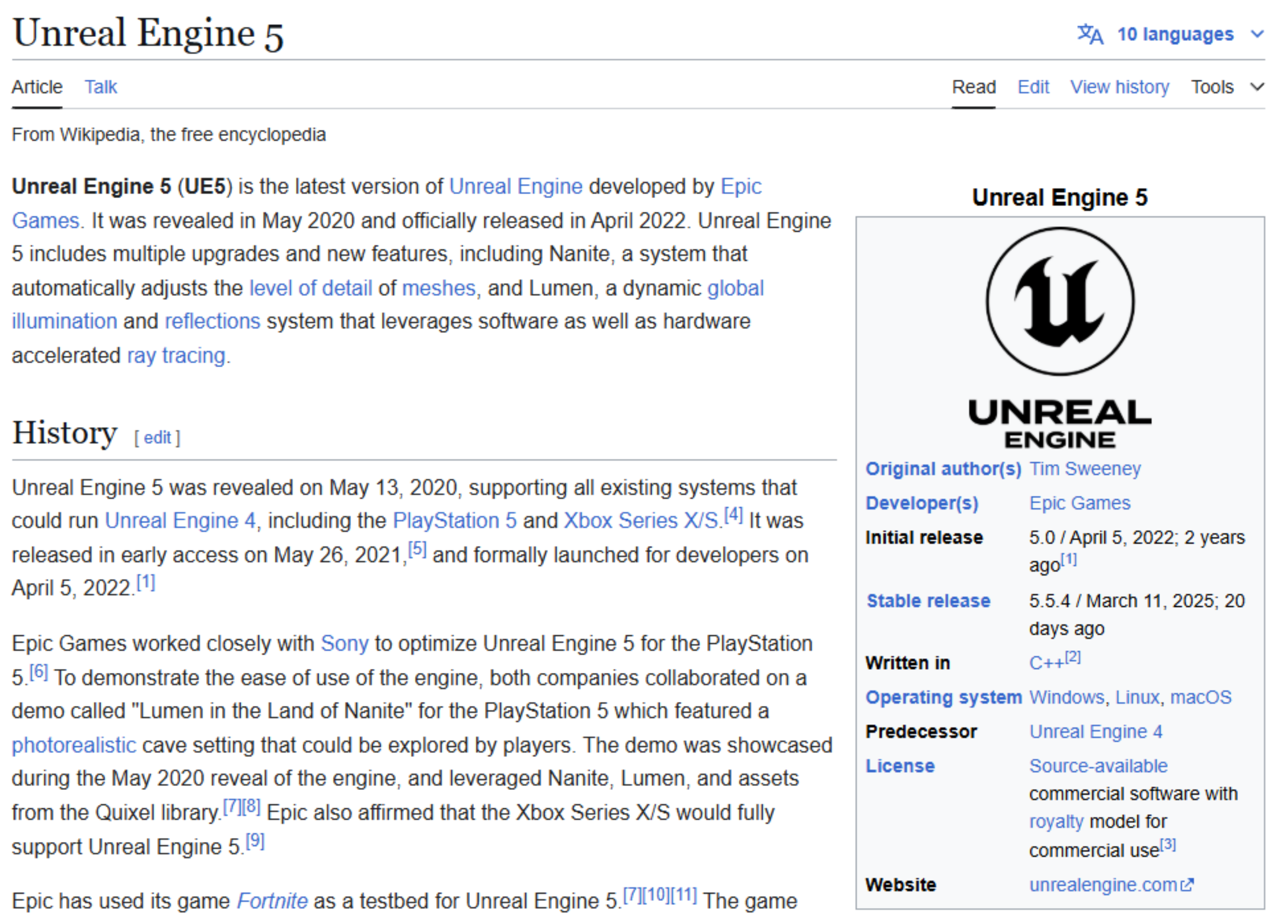
(My Student's) Favorite 3D Games





Unreal Engine 5

- Unreal Engine 5 is a real-time 3D creation tool developed by Epic Games.
- UE is widely used in simulation ... g photorealistic visualizations.
- It also features a Blueprint Visu



Unreal Engine 5

10 languages

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From Wikipedia, the free encyclopedia

Unreal Engine 5 (**UE5**) is the latest version of Unreal Engine developed by Epic Games. It was revealed in May 2020 and officially released in April 2022. Unreal Engine 5 includes multiple upgrades and new features, including Nanite, a system that automatically adjusts the level of detail of meshes, and Lumen, a dynamic global illumination and reflections system that leverages software as well as hardware accelerated ray tracing.

History [edit]

Unreal Engine 5 was revealed on May 13, 2020, supporting all existing systems that could run Unreal Engine 4, including the PlayStation 5 and Xbox Series X/S.[4] It was released in early access on May 26, 2021,[5] and formally launched for developers on April 5, 2022.[1]

Epic Games worked closely with Sony to optimize Unreal Engine 5 for the PlayStation 5.[6] To demonstrate the ease of use of the engine, both companies collaborated on a demo called "Lumen in the Land of Nanite" for the PlayStation 5 which featured a photorealistic cave setting that could be explored by players. The demo was showcased during the May 2020 reveal of the engine, and leveraged Nanite, Lumen, and assets from the Quixel library.[7][8] Epic also affirmed that the Xbox Series X/S would fully support Unreal Engine 5.[9]

Epic has used its game *Fortnite* as a testbed for Unreal Engine 5.[7][10][11] The game

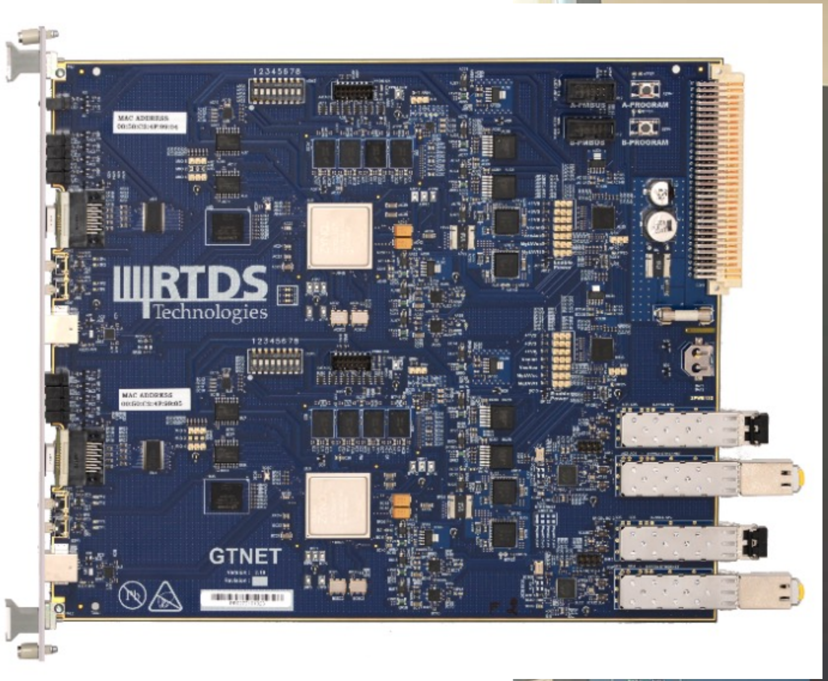
Unreal Engine 5

UNREAL ENGINE

Original author(s)	Tim Sweeney
Developer(s)	Epic Games
Initial release	5.0 / April 5, 2022; 2 years ago[1]
Stable release	5.5.4 / March 11, 2025; 20 days ago
Written in	C++[2]
Operating system	Windows, Linux, macOS
Predecessor	Unreal Engine 4
License	Source-available commercial software with royalty model for commercial use[3]
Website	unrealengine.com

https://en.wikipedia.org/wiki/Unreal_Engine_5

RTDS Hardware



GTNETx2 Communication Card

RTDS RB5 (left) and NovaCor (right) racks

Station-Level Control

- Local substation control room located physically at the substation.

- **Typical equipment found in a station-level control room:**
  - Control Switches
  - Metering and Data Loggers
  - Indicator Lamps and Alarms
  - Fault and Circuit Protection Equipment

Station-level Control HMI panels

https://electrical-engineering-portal.com/substation-control-monitoring-systems

Bay-Level Control

- **Low level control as a fallback when station and central control center is not in service.**
- **Typical equipment found in bay-level control:**
  - Control Switches
  - Indicator Lamps and Alarms
  - Gauges

Bay-level Control HMI panels

https://selinc.com/solutions/transmission/bay-control-substations/