Virtual Reality Framework for Frequency Security and State of Health Monitoring in Microgrids

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***Abstract*—Microgrids deployed in remote regions often operate with narrow stability margins. Grid disturbances and severe weather can cause system failures. This requires a major decision to be made by operators about the system configuration. Therefore, there is a need for tools that can translate complex stability phenomena into clear and intuitive visual representations to support informed decision-making by system operators. This paper presents a Virtual Reality (VR) framework developed in the Unity game engine for interactive frequency security and state-of-health (SoH) monitoring of microgrids. The framework integrates a reduced-order model of microgrid frequency dynamics with live frequency data streaming to compute key reliability indicators, Frequency Security Index (FSI), frequency nadir margin, and rate of Change of Frequency (ROCOF) margin in near real time. These metrics are visualized through immersive 3D dashboards and traffic-light indicators, enabling both technical and non-technical users to interpret system stability and respond to disturbances. The proposed approach presents a visualization tool for operators' training, control room decision making, and bridging the gap between mathematical analytical modeling and visualization.**

***Index Terms*—Frequency Security, Human–Machine Interaction, Microgrid Stability, State-of-Health, Unity Game Engine, Virtual Reality**

I. Introduction

Microgrids operating in remote or weakly interconnected regions often experience narrow stability margins due to limited inertia and reduced grid support. This also results in cascaded blackouts and unreliable electricity [1]. Therefore, monitoring the state of health (SoH) of a microgrid through robust frequency-stability metrics is essential for system operators and planners.

Frequency Security Index (FSI), nadir margin, and Rate-of-Change-of-Frequency (ROCOF) margin have been proposed in [2] and [3] to quantify the SoH of microgrid frequency dynamics. Reduced-order models and analytical formulations to compute these metrics were developed in [2] and [3], providing a computationally efficient alternative to repeated time-domain simulations. Although such formulations enable rapid evaluation of frequency stability, the resulting metrics remain purely numerical and abstract. Control-room operators or emergency personnel, deployed during natural disasters or blackout scenarios and predominantly without a power systems background, have to interpret these metrics in real time. This can be challenging for non-technical personnel, particularly during high-stress or resource-limited situations where monitoring the SoH is of greater significance.

Recent studies in science and human–computer interaction have shown that immersive, visual, and gamified representations of data significantly improve comprehension, retention, and decision accuracy compared to conventional 2D interfaces. For instance, an immersive serious game for aviation safety led to superior knowledge retention one week after training compared to traditional instruction materials, as demonstrated in [4]. Similarly, event segmentation in a Unity-based virtual learning environment—such as passing through distinct spatial or temporal boundaries—improves recall accuracy, and temporal clustering in memory tasks has been reported in [5]. These findings suggest that human memory and decision performance can be optimized when information is presented through structured, interactive, and spatially contextual experiences.

Parallel advancements in Virtual Reality (VR)-based power-system research have demonstrated that VR and Digital Twin (DT) technologies can enhance grid monitoring and situational awareness. An integrated Metaverse–DT power inspection framework was introduced in [6], where the entire power grid was virtualized to enable real-time visualization, intelligent fault detection, and remote inspection for data-driven decision-making. Similarly, a Unity 3D–based VR monitoring and control system for power substations was proposed in [7], offering immersive visualization, operator training, and SCADA integration. These implementations improved spatial awareness, safety, and human–machine interaction, demonstrating how VR and DT can transform traditional grid inspection and control into interactive, human-centric experiences.

Together, these advances in cognitive learning and power-

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system visualization motivate the use of VR not merely as a display interface but as an active, human-centered decision-support platform for power-system operation and analysis. Building upon this concept, the present work explores how VR can serve as an intuitive decision-support tool for microgrid frequency stability assessment. Our earlier studies demonstrated that the Unity game engine, a physics-enabled platform, can successfully perform power-flow calculations and controller integration [8]. This paper extends that foundation by developing a specific use case: a VR framework for near-real-time monitoring of frequency security and SoH of microgrids.

The proposed system integrates analytical reduced-order models of frequency dynamics and live data streaming, and 3D visualization in Unity. Key reliability metrics: FSI, Frequency Nadir Margin, and ROCOF Margin are computed analytically and visualized as color-coded indicators within an immersive environment. This framework bridges analytical modeling with human interpretability, enabling both technical and non-technical users to assess system stability through intuitive visual cues. Performing this type of stability assessment and accessing SoH metrics in VR provides users with an intuitive and interactive tool for real-time monitoring and control.

The major contributions of this work are summarized as follows:

1) Development of a VR framework in the Unity game engine for near-real-time visualization and computation of microgrid frequency-security metrics.
2) Integration of a reduced-order analytical model and a live SQL-based frequency data stream to support interactive and scalable visualization.
3) Empowering non-specialist operators to help them make informed, technically accurate decisions under critical conditions through immersive visualization.

The remainder of this paper is organized as follows. Section II describes the methodology and the Unity architecture. Section III details the Unity implementation. Section IV presents the results of the case study and discussion. Section V concludes the study and provides directions for future work.

II. Methodology and Unity Architecture

The proposed framework integrates analytical reduced-order models and incorporates a stream of frequency data from the Cordova benchmark [9] with immersive visualization in the Unity game engine to enable near-real-time monitoring of microgrid frequency dynamics. The system combines quantitative modeling with intuitive user interfaces, allowing both technical and non-technical users to interpret frequency stability through visual signals. The framework consists of four primary layers: (i) analytical metric formulation, (ii) data streaming from the Cordova microgrid benchmark, (iii) event-driven computation, and (iv) visualization in a 3D VR environment.

A. Analytical Metric Formulation

The aggregated frequency dynamic of a microgrid system is presented by a second-order model [2]. This model captures the dominant inertial, damping, and droop characteristics that determine the system's transient frequency response.

The details of the second-order model, which resembles the actual Cordova microgrid, and the analytical equations used to calculate frequency security metrics are presented in [2] and [3]. The metrics can be directly calculated from these equations using known microgrid parameters (inertia constant, damping constant, droop coefficient, and turbine-governor time constant) without the need to repeatedly simulate time-domain models. This lightweight formulation makes the method well-suited for online and interactive applications.

B. Cordova Microgrid Benchmark Data

To validate and complement the analytical results, the framework also incorporated frequency data from the Cordova microgrid benchmark. The benchmark is simulated under different load change scenarios, with step load varying from 0.05 pu to 0.5 pu in increments of 0.05 pu, and the resulting frequency trajectories are stored in a SQL database.

Unity connects to this database through a dedicated C# reader script, receiving frequency measurements at high resolution (1 ms sampling). The system then computes the FSI, nadir, and ROCOF metrics based on the streamed data. This setup supports flexible data sources, including simulated results from MATLAB/Simulink or OPAL-RT as well as real-world field measurements, ensuring the framework's adaptability for research, education, and operational use.

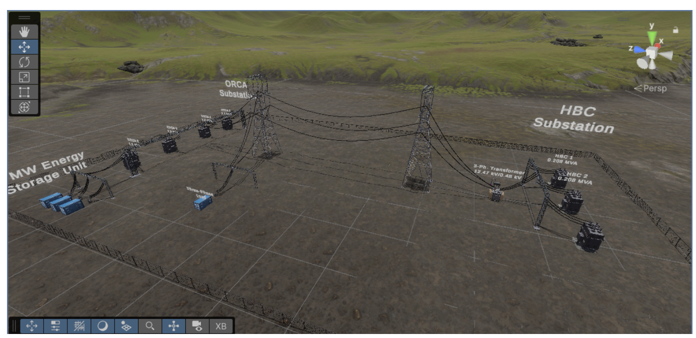

Fig. 1: Unity 3D visualization of the Cordova microgrid benchmark.

C. Event-Driven Computation in Unity

The Unity framework follows an event-driven architecture in which any detected load variation or system disturbance triggers a new computation cycle. Once the event occurs, the Unity engine extracts frequency data from the SQL database and calculates metrics. 3D dashboards are used to present the results to maintain near-real-time responsiveness. This modular approach allows easy scaling to multiple microgrids or distributed events without additional reconfiguration.

D. Immersive Visualization in Unity

Display of the frequency trajectories and indices through 3D visualization is done in the Unity 3D environment. Fig.1 represents the 3D model of the Cordova microgrid benchmark implemented in Unity, showing major components including

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the ORCA and HBC substations, transmission lines, distribution transformers, and a 1 MW energy storage unit.

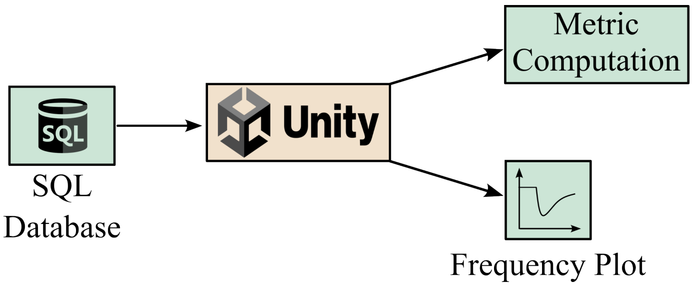

Fig. 2: Unity VR Framework for Microgrid Frequency Monitoring

The visual markers, animated indicators, and color-coded “traffic lights” were used to classify operating states as secure, at-risk, or insecure. Users can adjust load levels and visualize the corresponding impact in the frequency metrics. Such immersive visualization enhances situational awareness and supports rapid interpretation of complex system dynamics.

E. System Architecture

The overall system architecture is shown in Fig. 2. The Unity engine was used as a central processing platform for metric calculations. It communicates with the SQL database, which is used as a data interface between Unity and MATLAB. The integrated setup ensures a seamless transition from numerical modeling to user-centered visualization, providing both speed and interpretability. The resulting framework enables intuitive, near-real-time state-of-health monitoring of microgrid frequency dynamics and lays the foundation for scalable decision-support systems in future smart grids.

III. Unity Implementation

The Unity game engine serves as an integration platform for streaming Cordova microgrid benchmark data, computing frequency security metrics, and visualizing results in an immersive environment. The implementation consisted of four parts: (i) SQL data interface, (ii) User Interaction and Scenario Control, (iii) metric computations, and (iv) User Interface (UI)/VR visualization.

A. SQL Database Interface

Frequency data from the Cordova microgrid benchmark were stored in an SQL database with 1 ms resolution, with time–frequency records for various load disturbance levels. The Unity VR framework uses C# script to communicate with the database and retrieve frequency values at user-defined load selection. This framework enables the use of both simulated benchmark and real-time measurements, which enhances the utility of this framework to visualize the real-time scenarios.

B. User Interaction and Scenario Control

For user interaction, a Unity-based UI was developed. A load-step slider was implemented for the users to vary disturbance across predefined ranges, while other UI elements were added for simulation reset and metric visualization. When a new scenario is selected, the Unity system automatically fetches the corresponding frequency trajectory from the SQL database and initializes the analytical computation sequence. This event-driven approach mirrors real-world operational conditions, where sudden disturbances or parameter changes trigger automatic stability assessment.

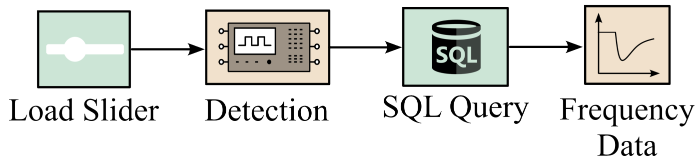

Fig. 3: Load Change Detection and Data Retrieval

The workflow is illustrated in Fig. 3. The slider sets the load increment; Unity maps this selection to the correct SQL dataset, the database streams the frequency trajectory into Unity, and Unity computes and visualizes the stability metrics. This workflow ensures smooth synchronization between user actions, data streaming, and metric updates without manual code intervention.

C. Metric Computation

Within Unity, frequency data are continuously processed to compute the FSI, Nadir Margin, and ROCOF Margin using analytical formulations derived from the reduced-order model. These computations occur asynchronously with data retrieval to preserve near-real-time performance.

- **FSI:** evaluates how safely the system recovers after a disturbance.
- **Nadir Margin:** measures how close the frequency dips to the critical threshold.
- **ROCOF Margin:** measures how close the maximum rate of frequency change during a disturbance comes to the safe operating limit.

Once calculated, these metrics are instantly transmitted to the visualization dashboard and converted into color-coded indicators reflecting the system’s operational state. This setup enables continuous tracking of stability trends as users modify load conditions.

D. VR-Based Visualization

Unity’s 3D rendering engine provides a spatially immersive interface for visualizing both raw frequency trajectories and computed stability indices. The computed FSI, nadir margin, and ROCOF margin are displayed in a UI text and traffic lights to indicate the region (green for secure, yellow for at-risk, and red for insecure). The user can use VR controls to switch between load steps interactively, which automatically trigger new scenarios and metric calculations. Fig. 4 illustrates the Unity 3D implementation of the proposed framework. The left panel displays stability metrics (FSI, nadir margin, and ROCOF margin) calculated from both reduced-order analytical equations and Cordova benchmark frequency data retrieved via SQL. A load slider allows interactive adjustment of the

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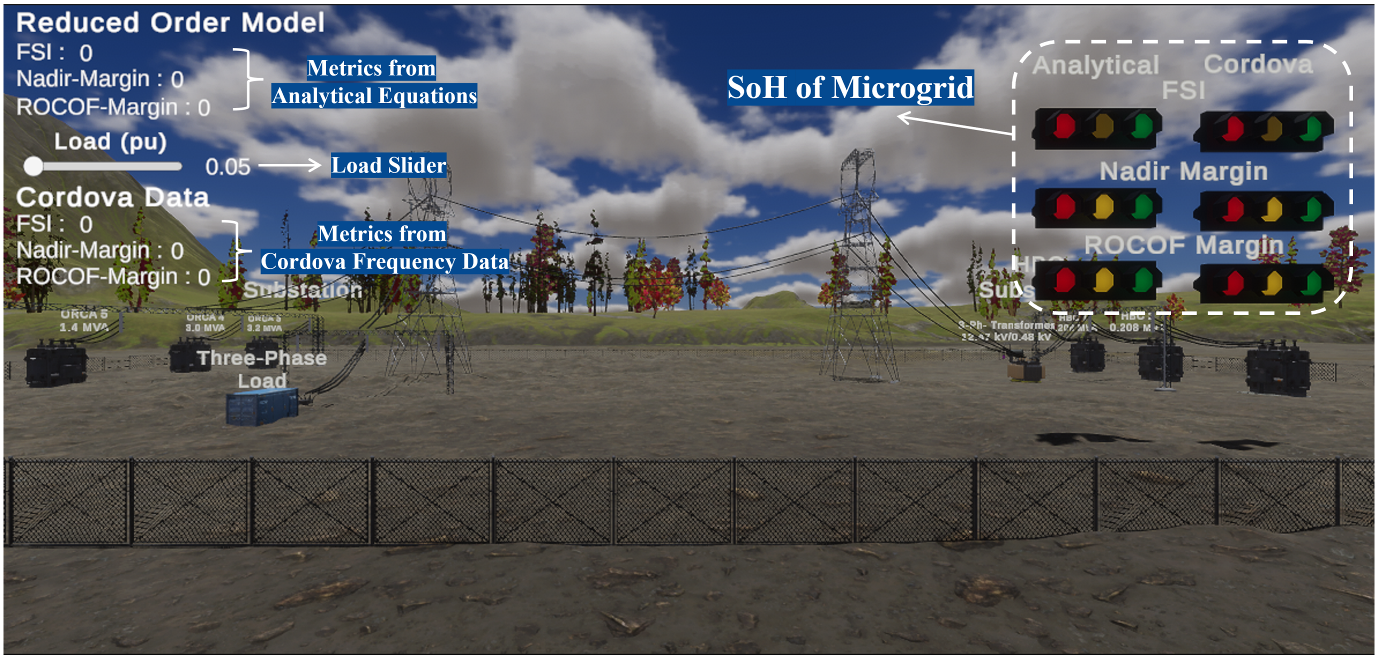

Fig. 4: Unity 3D implementation of the proposed framework showing stability metrics from analytical equations and Cordova benchmark data, an interactive load slider, and traffic-light indicators classifying the state of health of the microgrid

disturbance magnitude. On the right, traffic-light-type indicators classify each metric into insecure, secure, or absolutely secure regions, with results from both methods shown side by side. This setup integrates metric computation and intuitive VR visualization within a single immersive environment, enabling real-time state-of-health monitoring of microgrid frequency dynamics. Such a design enhances situational awareness, allowing operators without deep electrical engineering expertise to quickly interpret stability status and take appropriate action.

IV. Results and Discussion

The proposed Unity-based VR framework enables an interactive, near-real-time visualization of microgrid frequency stability. Instead of focusing on quantitative validation, which has already been established in earlier work [3], this section illustrates how immersive visualization and intuitive interaction can improve the interpretability and situational awareness of operators during dynamic events.

Fig. 5a shows the Unity VR scene for a load disturbance of 0.05 pu. The dashboard displays real-time frequency trajectories alongside the computed metrics. Both analytical and benchmark (Cordova) results are represented by traffic-light indicators. At this small disturbance, all three indicators remain green, confirming that the microgrid maintains adequate inertial and damping support. The operator can directly observe the system's stable behavior without analyzing numerical plots—stability is conveyed through color and animation.

As the magnitude of the disturbance increases, the visual indicators gradually shift from green to yellow and then to red, signaling reduced frequency stability. Fig. 5b and Fig. 5c demonstrate this progressive transition for higher load changes. At 0.15 pu, the nadir margin and the rocof margin start to decrease, producing yellow warnings in the indicator, while at 0.50 pu the system enters the insecure region, indicated by red lights. Such color-coded indicators grab the immediate attention of the user, providing a better tool for decision makers.

Beyond numerical accuracy, the major advantage of this framework lies in its human-centered design. Traditional analysis platforms such as MATLAB or PowerFactory present detailed data but require expert knowledge to interpret. In contrast, the Unity environment transforms frequency-security metrics into immediate, visually perceptible feedback. Regardless of technical background, operators can intuitively recognize emerging risks and take corrective action. Dynamic color transitions, motion cues, and animated assets (such as transformers, houses, and loads) create a realistic context that strengthens spatial awareness and reaction speed during abnormal events.

Furthermore, the Unity architecture is modular and extensible. The metric computation functions can be reused with any grid dataset simply by updating the SQL input table. Multiple microgrids can be represented as animated clusters within the same scene. Also, allow the user to zoom in for local inspection or zoom out to view network-wide reliability.

In summary, these results demonstrate that the Unity VR framework not only computes frequency-security metrics in near real time but also converts them into actionable visual information. By bridging analytical rigor with immersive visualization, the framework empowers both technical and non-technical operators to assess microgrid stability quickly and confidently, contributing to more resilient and accessible control-room environments.

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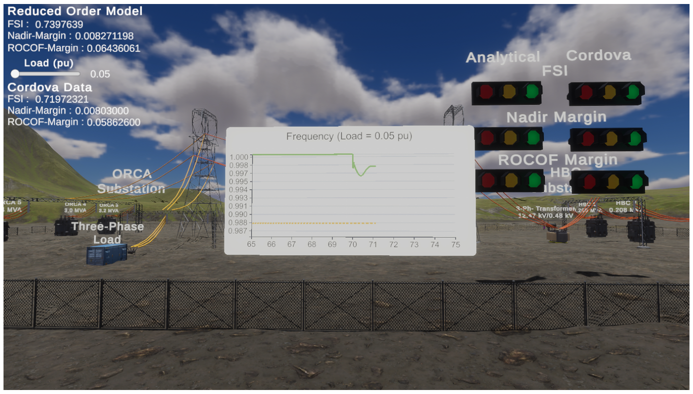
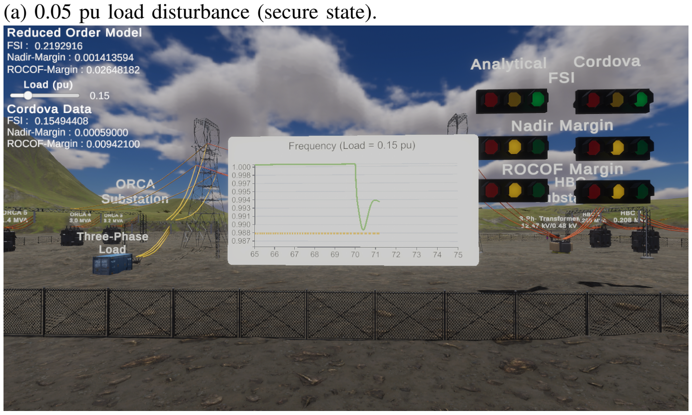
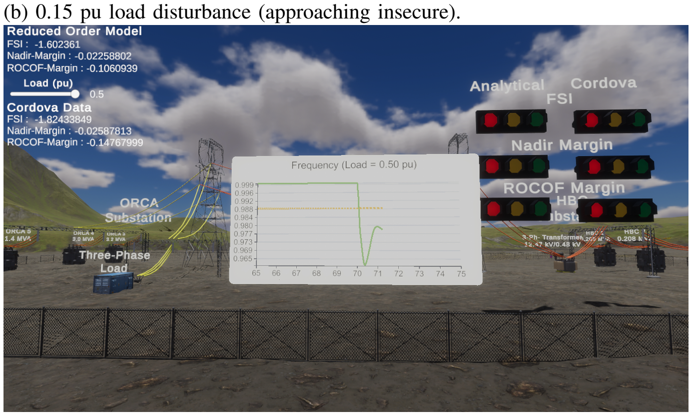


(a) 0.05 pu load disturbance (secure state).



(b) 0.15 pu load disturbance (approaching insecure).



(c) 0.5 pu load disturbance (insecure state).

Fig. 5: Unity VR environment showing microgrid security levels under increasing load disturbances. (a) 0.05 pu, (b) 0.15 pu, and (c) 0.5 pu.

V. Conclusion and Future Work

Overall, the paper proposed a VR framework developed in the Unity game engine for frequency-security and state-of-health monitoring of microgrids. Unlike conventional analytical or simulation-only environments, the proposed system combines reduced-order modeling, near-real-time data streaming, and immersive visualization within a single interactive platform. The results presented in this paper demonstrated how the mathematical frequency stability metrics can be visualized in a 3D environment using color-coded indicators understandable to non-specialist users. By embedding established frequency-stability formulations into a VR environment, the framework enables both technical and non-technical operators to perceive system health through color rather than complex plots or tables. This approach not only enhances operator situational awareness but also supports faster and more confident decision-making during disturbances, especially in emergency or low-staffing conditions.

Future development of this framework will focus on expanding interoperability with real-time hardware platforms such as OPAL-RT and integrating SCADA feeds. Overall, the proposed framework takes advantage of both analytical frequency security assessment and immersive visualization.

VI. Acknowledgmnet

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