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Real-Time Learning to run Power Distribution Networks

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***Abstract*– This study presents the development of a platform for real-time simulation and optimization of power distribution networks. The proposed system integrates OPAL-RT hardware and the ePHASORSIM module as the core real-time simulation tool, enabling dynamic modelling of network behaviour, while a phasor-based framework facilitates real-time phase analysis under variable loading conditions. A high-speed fibre optic communication infrastructure operating under the DNP3 protocol ensures reliable synchronization and data transmission from two substations to the simulation environment. In addition, artificial intelligence techniques are incorporated through large language models (LLMs) and reinforcement learning algorithms to generate automated operational recommendations aimed at optimizing power flow and improving decision-making processes. Software-based analysis is employed for voltage profile assessment, contingency scenario simulation, and operational stability evaluation in low-inertia distribution networks. By simulating multiple operating conditions, the platform enhances early fault detection and improves overall system reliability, reducing the impact of external disturbances on network performance. The proposed methodology is validated through technical studies conducted using the CYMDIST power distribution simulation software and automated diagnostics performed through specialized Python scripts for signal processing and data evaluation. The obtained results accurately reproduce network dynamics and optimal operational strategies, demonstrating the feasibility and robustness of the proposed approach. Furthermore, an interactive dashboard and a geographic information system (GIS) interface implemented in ArcGIS are integrated to centralize real-time data visualization, providing operators with geospatial insight required for comprehensive network supervision, preventive maintenance planning, and rapid emergency response. The developed platform establishes a scalable framework for future integration of advanced control strategies, intelligent monitoring systems, and large-scale distribution network applications.**

Keywords-- Real-time simulation, Power distribution networks, Reinforcement learning, phasor analysis, Large Language Modelling.

I. Introduction

The operation of electrical distribution networks has become increasingly complex in recent years due to the growing penetration of distributed energy resources (DERs), the intermittency of renewable generation, and the increasing need for flexible and resilient grid infrastructure.

In this context, real-time simulation has emerged as a valuable tool for analyzing the dynamic behavior of power systems and validating operational strategies before deployment. Platforms capable of emulating realistic operating scenarios contribute to a deeper understanding of system behavior during load changes, switching events, and fault conditions.

The literature demonstrates the potential of simulation environments under realistic conditions; for example, the "Learning to Run a Power Network" (L2RPN) challenge series [1] has provided a framework for comparing decision-making strategies in complex network scenarios, highlighting the value of coupling simulation with network events. Similarly, the L2RPN Delft 2023 competition [2] introduced further scenarios, including topological changes, switching limitations, and contingency management under time constraints, reflecting real-world operating conditions. While early approaches focused on static optimization, recent literature [3] highlights the shift towards AI-driven operations to manage the increasing complexity of carbon neutral grids. However, bridging the gap between theoretical AI agents and practical utility grade communication remains a challenge, particularly regarding the synchronization of real-time data streams with cognitive models in hardware in the loop (HIL) environments.

Building upon these efforts, our work presents a platform that integrates real-time simulation via OPAL-RT using the EPhasorsim solver with technical evaluation tools and configurable analysis scenarios. This integration specifically addresses the need for low latency feedback loops in distribution networks, utilizing DNP3 over fiber optics to ensure data integrity for automated decision making.

The proposed platform includes: a real-time simulation environment based on real-time simulation hardware, capable of replicating the behavior of power feeders using operational data; technical analysis, including voltage profile assessments and contingency simulations; phasor domain modeling to monitor voltage magnitude and angular dynamics; and a configuration interface designed to streamline the setup of operating scenarios and facilitate the interpretation of results.

The proposed research demonstrates a scalable architecture for the simulation and monitoring of distribution networks. It allows for the evaluation of system performance under various dynamic conditions, while also laying the foundation for future integrations with Large Language Models (LLMs) and advanced Reinforcement Learning agents [4], which have shown results in processing complex grid data for real-time decision support. By incorporating modern automated and configuration tools [5,6], this framework moves beyond traditional monitoring, enabling a digital twin environment where AI can interpret phasor domain dynamics in sub second intervals to enhance system responsiveness.

Consequently, this work explores how real-time simulation, coupled with industrial grade communication protocols, can enhance the operation of electrical distribution networks, with a particular focus on improving decision-making and system responsiveness under dynamic conditions.

II. Methodology

The communication system is a fiber optic communication infrastructure that interconnects selected substations in Lagos del Batán and the Tennis Club in Samborondón county with the data center; from there, the data is transferred to the Escuela Superior Politécnica del Litoral (ESPOL), where the real-time simulator is hosted. Fig. 1 illustrates the development of the project methodology.

A. *Communication infrastructure*

The project's development is based on a robust framework, as shown in Fig. 2. This communication system enables the real-time transfer of critical data, such as voltage and current measurements, from the substations to the simulator. The fiber optic infrastructure not only guarantees data integrity but also data synchronization, which is essential for the simulation of dynamic electrical systems [6,7].

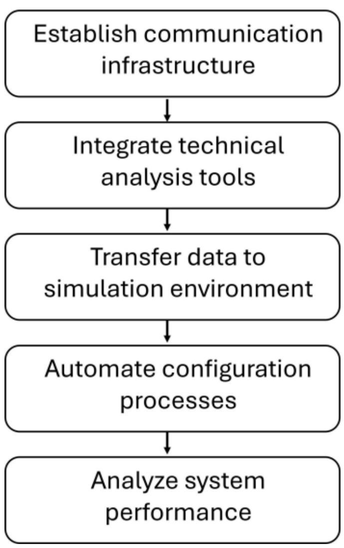

Fig. 1 Methodological workflow for real-time distribution network simulation and analysis

B. *Real-time simulation with OPAL-RT*

The OPAL-RT simulator, located at ESPOL, serves as the central computational tool responsible for simulating the real-time behavior of electrical feeders. Using actual operational data from substations, OPAL-RT is able to model various operating conditions, thus enabling in-depth analysis of the system's stability, reliability, and efficiency [6,8].

Fig. 2 Framework architecture

Communication between the simulator and the substations is carried out using the DNP3 protocol in a master-slave configuration, where the simulator acts as the master and the substations as slaves, providing operational data. This data includes voltage measurements and current magnitude and angle, which are essential for validating the simulated models.

C. *Technical analysis with CymDist*

For preliminary studies and data preparation, CymDist was used due to its recognized capabilities for modeling and performing technical analyses of electrical distribution networks [9]. The software facilitated comprehensive studies of two electrical feeders, including voltage profile assessments, contingency scenario simulations, and operational stability evaluations. For preliminary studies and data preparation, CymDist analyzed two specific electrical feeders with the following objectives:

1) Voltage Profile Analysis: Evaluating voltage variations at selected nodes under different operating conditions,

2) Contingency Scenarios: Simulating faults and load changes to analyze system behavior,

3) Operational Stability: Assessing the system's ability to maintain normal conditions in the face of disturbances [10]. The results obtained from CymDist are exported to a compatible file that is then used by the OPAL-RT simulator to perform advanced real-time simulations.

D. *Integration with EPhasorSim*

The integration of EPhasorSim within OPAL-RT enabled dynamic simulations in the phasor domain [11, 12]. A structured communication process was established using an Excel based data interface, facilitating the smooth exchange of information between CymDist and EPhasorSim and allowing for real-time system evaluation. The OPAL-RT simulator utilized the EphasorSim module, a block specialized in phase simulations. This module is responsible for performing dynamic calculations of the magnitude and angle of voltage and current variables. An Excel file, acting as the data interface, is used to establish communication between CymDist and EphasorSim. The integration workflow includes:

1) Excel file preparation: The file contains a list of nodes and variables to be analyzed (voltage and current, both in magnitude and angle). This data is predefined in CymDist.

2) Communication between systems: The Excel file is processed by EphasorSim, which uses the information to configure the real-time simulation. The simulated results are returned to the file for analysis.

3) Visualization of results: An LLM manages the communication between the Excel file and an interactive dashboard, where the data is presented in real time, allowing operators to analyze the system's behavior.

E. Artificial intelligence and spatial visualization

As part of the system development, a set of reinforcement learning algorithms [13] was implemented to support the analysis performed with CymDist. These algorithms were trained using the results obtained from technical studies of two distribution feeders, particularly those related to voltage profiles, contingency scenarios, and system behavior under different operating conditions. The objective was to evaluate patterns in the data and provide recommendations that could be compared with the simulation results.

The results generated by the learning models were spatially represented using a GIS interface developed in ArcGIS. This interface was not directly connected to the simulation platform but served to visualize key indicators, such as voltage deviations and areas most sensitive to load changes, based on the AI outputs. The spatial layer included feeders, substations, and measurement points from the original network model.

This visualization allowed for a better understanding of the areas where operational problems were likely to occur and served as a basis for comparing different strategies. Although still in a preliminary phase, the integration between technical analysis, learning algorithms, and geographical representation showed potential for future use in operational planning.

F. Limitations in the integration of CymDist and ePHASORsim

During development, attempts were made to export network models from CymDist version 7.0 to the OPAL-RT environment using XML files. However, these files exhibited convergence problems when executed within EPhasorSim, preventing their functional use. Manual edits were made to the XML structure, modifying internal variables and node parameters, but the root cause of the errors remains unresolved.

Nevertheless, the document includes illustrative representations of the expected voltage and current magnitude/angle results, based on the IEEE 34-node system. These serve to demonstrate the intended workflow and simulation output, assuming the integration problem is resolved.

G. Proposed future integration: Automating Excel configuration using LLMs

Although the current system architecture references the use of a large language model (LLM) to automate simulation setup via Excel, this functionality was not implemented in the pilot phase. A proposed methodology for future integrations is described below:

1) Natural language input: The operator issues commands such as simulate a 15% voltage drop at node 810 under a 20% load increase.

2) LLM processing: This involves interpreting the user's instructions using a language model (such as GPT or LLaMA) and translating them into a simulation-ready configuration.

This process includes identifying the target nodes for automatic Excel generation: a properly structured Excel file is produced, compatible with phasor simulation requirements or parameter validation. The model verifies historical data and operational thresholds to recommend optimal simulation settings or flag anomalies. A feedback loop is also included, where post-simulation results are interpreted by the LLM to suggest further adjustments or optimizations. The expected benefits are streamlined automation of simulation setup, a significant reduction in manual errors, scalability for large or complex distribution systems, and improved interoperability with visualization and analysis platforms. This integration is expected to enhance system adaptability, reduce operational burden, and improve its ability to scale across multiple feeders or contingency scenarios.

III. RESULTS

DNP3 Communication Verification Master-Slave Configuration: The first set of tests focused on verifying communication between the OPAL-RT simulator and the slave system using the DNP3 protocol. This protocol is widely used in power systems due to its robustness and ability to ensure reliable transmission of operational data. In the tests, the OPAL-RT was configured as the master, and a server deployed in LabVIEW was configured as the slave. Validation of this communication included transmitting analog values from the slave to the master and verifying their integrity and accuracy. To ensure system reliability, the LabVIEW platform was used to monitor the transmitted and received values. The results showed that the master (OPAL-RT) could read analog values from the slave without any problems. The master-slave configuration worked as expected, establishing a solid foundation for integrating real-time measurements from substations into the simulator. Fig. 3 illustrates how this communication was established and how the analog values were correctly reflected in the system.

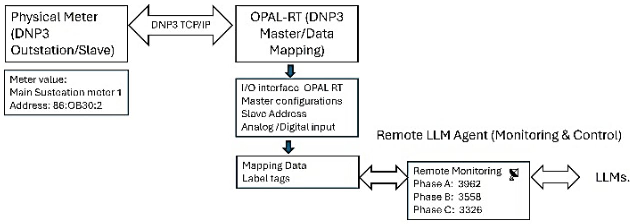

Fig. 3 Slave structure of the DNP3 communication master.

The integration of EPhasorSim within OPAL-RT enabled dynamic simulations in the phasor domain. A structured communication process was established using an Excel based data interface, which facilitated the seamless exchange of information between CymDist and EPhasorSim, allowing for real-time system evaluation. One of the main challenges of the project was establishing an effective link between the models generated in CymDist and the EPhasorSim module of OPAL-RT. CymDist was used to perform preliminary analyses of two electrical feeders, generating models that were subsequently exported for real-time simulation. It is important to note that the version of CymDist used during the project (version 7.0) is outdated, which partially limited the scalability of the system for use with additional feeders. Although this software may still be useful in distribution companies that use older versions, it is recommended to migrate to more modern versions to improve functionality and compatibility with modern tools. Despite this limitation, the tests performed successfully linked the models obtained from CymDist with EPhasorSim. Communication between the two systems allowed for querying voltage and current values in terms of both magnitude and angle. The results and expected values, validating the accuracy of the link. Fig. 4 shows the voltage diagrams of the three phases at a selected node, where the stability of the measurements can be observed.

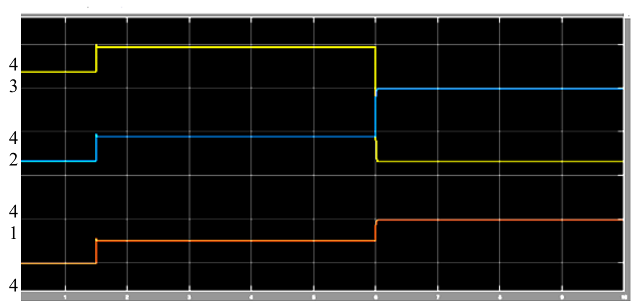

Fig. 4 OPAL interface.

A. Analysis of load changes at specific nodes

The OPAL-RT simulator allowed load changes to be made at specific feeder nodes and enabled real-time analysis of the system's behavior. This functionality is crucial for evaluating the system's response to operational modifications or contingency events. Figure 5 illustrates how load changes affect the voltage profile at a feeder node, showing a controlled decrease in voltage magnitude because of the increased load. This type of analysis provides critical information for grid operators, helping them anticipate and mitigate potential problems before they occur.

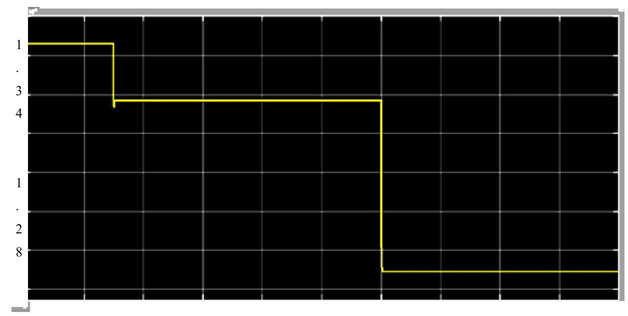

Fig. 5 Changes in load with OPAL

B. File configuration in Excel and integration with artificial intelligence

To make changes and perform simulations, an Excel file was used as a configuration interface between CymDist and EphasorSim. This file defined the nodes to be analyzed, the specific variables (voltage, current, magnitudes, and angles), and operational changes, such as load adjustments. Excel also included labels for inputs (incoming queries) and outputs (modified values), which allowed for structuring the data inputs and outputs in the simulator.

The configuration performed in Excel is translated, and the resulting block is then formed in the simulator's solver, as shown in Fig. 6.

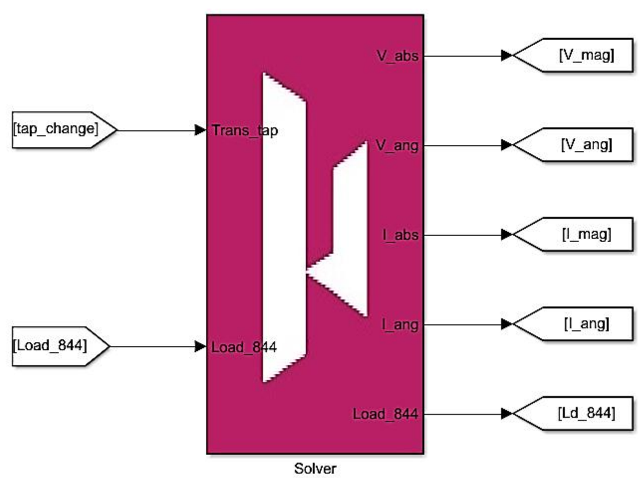

Fig. 6 Solver in OPAL

To improve the adaptability and scalability of this process, a large language model (LLM) was integrated to support the configuration of the Excel file. This approach automated and optimized data preparation, minimizing manual errors and facilitating dynamic configurations. The workflow includes:

interpretation but also allows for quick adjustments to configurations to address specific problems.

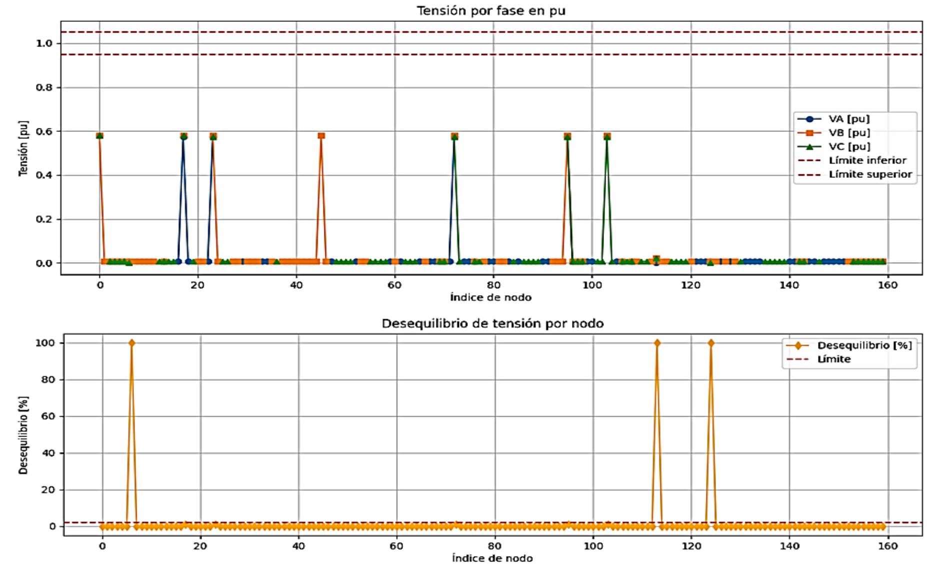

Fig. 7 Top: Phase voltage magnitude per node (VA, VB, VC in pu).
Bottom: Percentage of voltage unbalance per node. The dashed red lines indicate the operating limits.

1)Automatic Excel file generation: Using the LLM, operators can specify the necessary queries or changes in natural language. The model translates these instructions into specific configurations within the Excel file.

2) Parameter validation: The LLM analyzes historical node data and suggests optimal configurations for simulations, including relevant parameters for complex scenarios.

3) Adaptability: The Excel file generated can be automatically adjusted to include new nodes, feeders, or variables, significantly reducing the time required to configure larger-scale simulations.

This integration resulted in not only more efficient configuration but also improved system interoperability.

C. System Validation and Reliability Analysis

The results obtained in the segmented tests confirmed that the OPAL-RT simulator, in combination with CymDist, EphasorSim, and the Excel file configured with artificial intelligence support, can provide reliable analyses of the electrical distribution system [14]. This type of architecture, based on continuous data acquisition, digital communication, and automated processing, aligns with the current trend toward integrating IoT technologies into modern electrical systems, enabling more granular monitoring, interoperability between platforms, and greater operational responsiveness [15]. The values obtained from the substations via DNP3 communication were consistent and accurate, validating the system's functionality.

The interactive panel, driven by the Excel file, allowed for the centralization of information and facilitated the real-time visualization of results. This approach not only improves data

future work: Outdated CymDist version: The 7.0 version used during the project restricts the system's ability to manage additional feeders. Upgrading to more recent versions of the software is recommended. Excel Optimization: Despite the integration with the LLM, the Excel file remains an intermediate tool that could be replaced by a more advanced interface or a fully automated system. Computational Requirements: Real-time simulations, especially in larger systems, may require more advanced computational resources.

D. Node voltage analysis and automated evaluation

As part of the technical evaluation, an additional diagnostic step was implemented to assess phase voltages and voltages imbalance at the network nodes. This process was based on post-simulation analysis of the voltage magnitude per phase (VA, VB, VC) and the percentage of voltage imbalance for each node, as shown in Fig. 7.

Fig. 8 presents the results of the per-phase voltage magnitude per unit (pu), along with the upper and lower limits. The bottom of the figure shows the voltage imbalance calculated for each node. It reveals that several nodes exhibit voltage values close to zero or significantly below the expected threshold, as well as high levels of imbalance in isolated cases. Following an inspection of the data, a summary of the findings was compiled in text format. This report includes detected patterns, anomalous values, and operational recommendations for specific nodes. An example of this evaluation is shown in Fig. 9.

To facilitate this evaluation, a custom Python script was developed to extract and format the voltage data from the nodes

```
Ingrese la tensión base del nodo principal en volts (ej. 7976):  13800
Ingrese el limite inferior de tensión en pu (ej. 0.95):  0.95
Ingrese el limite superior de tensión en pu (ej. 1.05):  1.05
Ingrese el máximo desequilibrio permitido (ej. 0.02):  0.02

Resumen de nodos con problemas:
```

	Nombre nodo	VA_pu	VB_pu	VC_pu	Desequilibrio_%
0	NODOFUENTE-09TC030T12	0.579710	0.579710	0.579710	0.0
1	IMTS_L_161186	NaN	0.007246	NaN	0.0
2	IMTS_L_106998	0.007246	0.007246	0.007246	0.0
3	IMTS_L_177667	0.007246	0.007246	0.007246	0.0
4	IMTS_L_197402	0.007246	0.007246	0.007246	0.0
...	...	...	...	...	...
155	IMTS_L_8056	0.007246	0.007246	0.007246	0.0
156	IMTS_L_115010	0.007246	0.007246	0.007246	0.0
157	IMTS_L_16651	0.007246	0.007246	0.007246	0.0
158	IMTS_L_16655	0.007246	0.007246	0.007246	0.0
159	IMTS_L_62742	0.007246	0.007246	0.007246	0.0

Fig. 8 Text-based evaluation of the voltage behavior of the nodes

in the dataset. The script filtered the key variables and performed a text-based assessment of the voltage conditions at each node. The following code snippet shows a portion of the Python script used to read node data from a CSV file, extract relevant variables, and prepare a text-based diagnostic summary of the voltage behavior of each node.

The combination of numerical graphs, structured textual output, and automated data processing improves the identification of critical nodes.

To facilitate this evaluation, a custom Python script was developed to extract and format the voltage data from the nodes in the dataset. The script filtered the key variables and performed a text-based assessment of the voltage conditions at each node. The following code snippet shows a portion of the Python script used to read node data from a CSV file, extract relevant variables, and prepare a text-based diagnostic summary of the voltage behavior of each node. Using this diagnostic approach to provide a more robust statistical assessment, the voltage stability was quantified. During steady-state operation, the automated report demonstrated a highly stable profile: Phase A maintained a mean voltage of 0.9850 p.u. with a standard deviation σ of 0.0050; Phase B averaged 0.9920 p.u. (σ = 0.0030); and Phase C averaged 0.9880 p.u. (σ = 0.0040). The average baseline voltage imbalance was recorded at a low 0.71%. These metrics confirm that the platform effectively monitors both normal operational boundaries and critical anomalies (such as the sudden drops to near-zero values) with high statistical precision.

E. Geospatial representation of critical nodes

This representation allows for the identification of voltage behavior patterns based on node location and the spatial correlation of critical events. Fig. 9 shows a dashboard where the nodes are represented on a map with color-coded categories based on their evaluation results. The bar chart indicates the distribution of voltage conditions, and the counter summarizes the number of critical nodes detected.

Fig. 10 provides a broader geographical view of the analyzed feeders, showing the location and status of each node. The markers represent nodes evaluated under different conditions derived from the technical analysis. A closer view of the area with the highest concentration of problems is provided on Fig. 11, where the individual node conditions are easier to analyze. This type of spatial visualization supports both the validation of the analysis and the planning of field interventions.

Fig. 9 Visualization of the control panel: Critical node count, categorized bar chart, and spatial distribution of nodes.

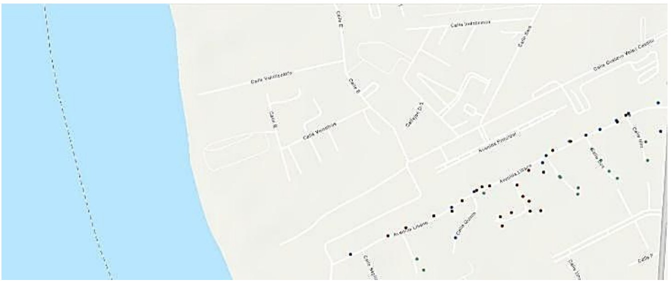

Fig. 10 Geographic distribution of the status of the evaluated network nodes.

Fig. 11 Enlarged view of the distribution network segment with the most critical nodes, highlighting their respective status.

The combination of technical simulations and geographical visualization allows for a clearer understanding of system performance under real world spatial constraints. This integration contributes to improved planning, asset management, and field diagnostics.

IV. Discussion

The implementation of a pilot platform for real-time simulation and analysis of distribution networks yielded promising results in terms of responsiveness, technical consistency, and data integration. The combination of dynamic simulation using OPAL-RT, phasor analysis via EPhasorSim, and data-driven evaluation provided a detailed view of feeder behavior under varying conditions.

The technical analysis performed in this work is based on classical power flow formulations, nodal modeling, and mathematical representation of electrical power systems, widely documented in the specialized literature [16]. Additionally, several studies have shown that real-time simulation applied specifically to distribution networks allows for the evaluation of control and protection strategies under realistic operating conditions, improving algorithm validation and system reliability before field deployment [8].

However, some limitations were encountered during the development process. The use of CymDist version 7.0 imposed certain restrictions, particularly regarding system scalability and compatibility with more recent modeling tools. While suitable for preliminary analysis of two feeders, future applications should consider updating software versions to improve functionality, user experience, and model interoperability.

The current configuration workflow, based on Excel as an intermediate interface, allowed for flexible definition of simulation parameters and node queries. However, as system complexity grows, this approach may become less practical. Migrating to a dedicated configuration interface or an integrated control panel could streamline operations and reduce reliance on manual editing.

Another relevant aspect is the computational load associated with real-time simulations. As the number of substations and monitored elements increases, so does the demand for processing capacity. The use of modular simulation architectures or distributed processing environments may be necessary to ensure consistent performance in larger scale implementations.

To support the diagnostic phase of the project, an automated post-simulation evaluation routine was implemented, focusing on node voltage levels, phase balance, and overall behavior underload variation. The results of this analysis were organized and visualized using a geographic dashboard created in ArcGIS. This tool allowed for the spatial representation of node conditions, highlighting areas with concentrated deviations or operational vulnerabilities.

Geospatial visualization played a key role in contextualizing the technical results and facilitating planning decisions. By overlaying network data onto real-world geographic layouts, it was possible to identify clusters of concern and prioritize field inspections or corrective actions. Although the dashboard operated independently of the simulation environment, its contribution to operational clarity was significant.

Overall, the project demonstrated the feasibility of integrating real-time simulation tools, structured technical analysis, and spatial representation to support the operation and evaluation of distribution networks. Future developments should aim to improve interoperability, user interaction, and system scalability to meet the demands of more complex network environments.

V. Conclusions

In response to the first research question on how the integration of real-time simulations can improve the management of electrical distribution networks, the developed platform demonstrated its ability to replicate the dynamic behavior of the system under various operating conditions. By combining OPAL-RT with phase analysis using EPhasorSim and technical evaluations using CymDist, the system enabled early fault detection, contingency scenario assessment, and a better understanding of voltage and current behavior. These capabilities proved essential for supporting informed decision-making and validating operational strategies before their implementation.

Regarding the second research question, the study explored the role of artificial intelligence in interpreting and analyzing the results obtained from technical simulations. A large language model (LLM) was integrated to process data related to phase voltages, voltage imbalance, and node-level behavior. Based on this analysis, the model was able to identify patterns, detect anomalies, and generate textual summaries with operational recommendations. This approach complemented traditional engineering evaluation, providing a secondary diagnostic layer that enhanced the interpretation of results and supported more agile and informed operational decisions.

Concerning the third question about potential future improvements, the study identified key areas where technological upgrades could enhance the platform's efficiency and scalability. These include migrating from outdated software versions such as CymDist 7.0, replacing the Excel based configuration with a more integrated control interface, and considering distributed computing frameworks to support larger systems. Furthermore, combining simulation results with geospatial analysis using ArcGIS allowed better visualization of critical areas and improved the contextual interpretation of technical data, which could inform future advancements in planning and operational tools.

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