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DYNAMIC VISUALIZATION OF THE KU DISTRIBUTION SYSTEM

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Abstract

The integration of Distributed Energy Resources (DERs) and Electric Vehicles (EVs) into traditional power distribution systems, often accompanied by uncoordinated extra load addition in distribution lines without knowing their hosting capacity, can lead to poor voltage quality, increased line losses, reduced hosting capability, and higher fault probabilities in the grid. These challenges underline the urgent need for real-time monitoring and visualization of the grid to support informed decision making by grid operators. This paper presents a near real-time visualization method developed for the Kathmandu University distribution network, where different electrical parameters are collected from seven smart meters installed at various buildings and the distribution transformer. These real-time data are transferred to Matpower, which contains the model of the studied distribution system. Using Newton-Raphson power flow analysis, the output monitoring parameters such as bus voltages, line losses, and line loadings are calculated and visualized through an interactive Node-RED dashboard. This dashboard offers intuitive schematic views, various graphical visualizations, and the ability to review grid parameters from past data, providing valuable insights into recent operational trends. The proposed system demonstrates an effective and scalable approach for enhancing situational awareness and reliability in modern distribution networks using open source technologies.

Keywords: Distributed energy resources, Smart meter, Matpower, Node-red, Power flow

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1. Introduction

The integration of distributed energy resources (DERs) such as rooftop solar photovoltaics and electric vehicles (EVs) into electrical distribution systems is transforming grid operations worldwide. Although DERs reduce the dependency on fossil fuels and help mitigate peak load outages, their intermittent nature causes challenges such as voltage fluctuations, overvoltage, and frequency instability (Farhoodnea et al., 2013), with their power electronic converters, introduce harmonic currents, leading to increased line losses and reduced efficiency (Liang, 2016; Rahman et al., 2020). These issues complicate the management of distribution networks, which requires advanced monitoring and visualization tools to maintain power quality and reliability. In Nepal, the Nepal Electricity Authority (NEA), the sole distributor of electricity, faces additional challenges due to aging infrastructure and limited real-time monitoring capabilities in its low voltage distribution networks (Nepal Electricity Authority, 2023). According to NEA's annual report 2022/23, efforts are underway to modernize the grid through initiatives such as the Kathmandu Valley Smart Metering Project, but real-time visualization remains a critical gap (Nepal Electricity Authority, 2023).

Significant research has been conducted to address these challenges through real-time visualization and grid analytics. Real-time visualization provides distribution system operators with graphical insights into network parameters such as bus voltages, line loading, and phase angles, aiding in fault detection, load management, and system planning (Capuder et al., 2017). However, traditional distribution systems are often unmonitored at the low voltage level, with measurement devices mainly installed on the primary side, leaving secondary networks unobservable (Lundstrom et al., 2015; Strachan et al., 2018). Past approaches relied on approximate load profile estimations, which are inadequate for real-time applications (Lundstrom et al., 2015). Recent advances in smart meters and advanced measurement infrastructure (AMI) have improved observability by providing accurate high-frequency data on voltage, current, and power (Barai et al., 2015; Ghasempour, 2019). For instance, a study

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utilized smart meter data with statistical algorithms for load forecasting and outage management, demonstrating enhanced grid control (Wang et al., 2018).

Several tools have been employed to model and visualize distribution systems. Commercial software like DIgSILENT PowerFactory has been used for power flow analysis and visualization, with enhanced capabilities through Python integration (DIgSILENT GmbH, n.d.; Haugdal et al., 2021). However, its cost limits accessibility for smaller institutions. Open-source alternatives like Pandapower and PyPSA offer similar functionalities, including power flow and state estimation, and integrate seamlessly with Python's data analysis libraries (Thurner et al., 2018; Brown et al., 2018). Matpower, another open-source tool, is widely used for power flow analysis due to its computational efficiency, and it is easy to model the system digitally in Matpower. Visualization techniques, such as those using Geographical Information Systems (GIS), have also been explored to enhance situational awareness, though many utilities are limited to offline GIS applications (Capuder et al., 2017).

Despite these advancements, integrating these tools into a cohesive framework for real-time visualization in resource-constrained settings like Nepal remains unexplored. This paper proposes a new approach for real-time visualization studied for Kathmandu University (KU) distribution system, utilizing Matpower for accurate power flow analysis, Python for processing smart meter data, and Node-RED for intuitive, web-based visualization. By leveraging open-source tools and smart meter data, this framework aims to enhance grid reliability and provide some support or guide for NEA's modernization efforts in managing the distribution network effectively.

The rest of the paper is organized as follows: Second section details the proposed methodology, including the system overview and tool integration. Third section provides a comprehensive description of the KU distribution system. Fourth Section presents the model results and their discussion, showing the near real-time visualization dashboard overview, and finally, Fifth Section concludes the study with key findings.

2. Methodology

Figure 1 shows the methodology for real-time visualization of the KU distribution system. It begins with a thorough KU distribution survey and data collection, where the process involves mapping out the entire campus grid, identifying feeders, transformers, and loads, and recording details like line lengths, resistance, reactance, and load patterns to create a complete picture of the system layout and characteristics. Following this, smart meters installed at various nodes across the grid collect real-time data on electrical parameters such as voltage, current, active and reactive power, and energy consumption, transmitting this information to a centralized Meter Cloud, ensuring that the most recent data is always available for analysis.

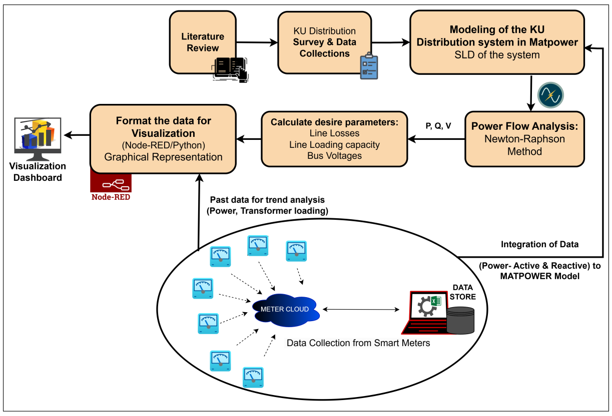


Figure 1. Overview of the overall model of the system

This data then feeds into the modeling of the KU distribution system in Matpower, a simulation tool that builds a digital replica of the grid, capturing all nodes, lines, and connections to enable detailed analysis. Using the Newton–Raphson (NR) method, power flow analysis is performed to compute key system metrics including line losses, voltage profiles at each bus, and line loading levels. The analysis further enables assessment of the available capacity of distribution lines and transformers by comparing calculated electrical quantities with their rated limits, thereby supporting real-time operational monitoring and visualization of the distribution network. These calculations reveal potential weak points in the system, such as overloaded lines or areas with unstable voltage, providing a clear understanding of the grid's health. Finally, Node-Red and Python come together to develop a real-time visualization platform, displaying a graphical representation of the KU distribution system on a dashboard, allowing for continuous monitoring and quick response to any abnormalities in the grid's operation, ensuring reliability and stability for the KU.

Figure 2 illustrates the overall working of the system for real-time visualization of the KU distribution system, structured into three distinct layers: the Data Acquisition Layer, Data Handling Layer, and Data Visualization Layer. The Data Acquisition Layer collects raw data from smart meters installed in the grid, the Data Handling Layer processes and analyzes this data using various tools, and the Data Visualization Layer presents the processed information in a user friendly graphical format for monitoring and decision-making. Each layer plays a critical role in ensuring the system provides accurate and real-time insights into the KU distribution grid's performance.

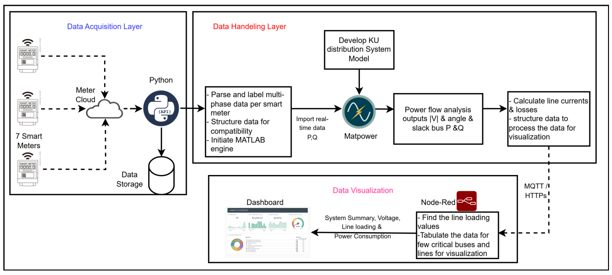


Figure 2. Block diagram of the system

2.1. Data Acquisition Layer

The Data Acquisition Layer serves as the starting point of the system, focusing on gathering real-time data from the KU distribution grid using seven smart meters installed at different buildings and distribution points, which constantly measure parameters such as voltage, current, and power usage. Each smart meter is uniquely identified by its own serial number so the system can accurately identify which meter is sending specific data. This layer uses the Iammeter smart meter API, implemented through Python, to collect data from these meters. Python sends a request to the smart meter cloud, where all meter data is stored, allowing it to fetch the latest readings from each of the seven meters by referencing their serial numbers. The meter cloud responds with the requested data, which includes various parameters in a JSON format that Python can process, with updates occurring every five minutes. As an alternative to cloud-based API calls, data can also be obtained through a local server or directly from IP configured Wi-Fi modules on the meters, offering enhanced security compared to the manufacturer hosted cloud, which may pose data privacy risks. This setup ensures that fresh and accurate data from all seven meters is consistently collected and passed to the next layer for processing, enabling real-time monitoring of the KU grid. Additionally, the cloud stores historical data, allowing the system to analyze yearly and monthly consumption trends.

2.2. Data Handling Layer and Network Modeling

The Data Handling Layer processes the raw data collected from the smart meters and transforms it into meaningful information about the KU distribution system, including voltage levels, line loading, line losses, and current, which are essential for understanding grid performance. The process begins with creating the Single Line Diagram (SLD) as shown in Figure 3 of the KU distribution system to make labeling of lines and buses easier for modeling. The system is then modeled in Matpower with 57 buses, acting as a digital map of the KU grid, showing all line branches, transformers, load buses, and connection points.

The model is built using key Matpower functions such as bus data, branch data, and generator data, where all buses except Bus 1 are PQ buses with specified active and reactive power demands, and Bus 1 serves as the slack bus. The line branches extend over 2.38 km of underground cables and overhead conductors, incorporating both resistance and reactance, with a base MVA set to 0.2. Since the smart meter data format is not directly compatible with Matpower, Python reformats it into a matrix before feeding it into the KU distribution model.

The program ensures that data from all seven meters is collected before proceeding, preventing any missing information.Matpower performs power flow analysis using the NR method, a mathematical approach that solves equations to determine how electricity flows through the grid. This method uses power mismatch vectors (ΔP and ΔQ) and a Jacobian matrix to compute the system state vectors, θ for voltage angles and V for voltage magnitudes. The analysis is carried out using Matpower default balanced, positive sequence equivalent network model, which represents the three phase distribution system as an equivalent single phase system. Accordingly, the three phase measurements obtained from the smart meters are processed into equivalent balanced load quantities by averaging phase voltages and aggregating phase powers and power factors for each building, which are then modeled as constant PQ loads at the corresponding buses. This modeling approach enables seamless integration of real-time smart meter data into the load flow framework for system-level analysis and visualization; however, it does not explicitly capture phase unbalance, neutral currents, or harmonic effects that may be present in low-voltage distribution networks and are the limitations of this approach.

$$\begin{bmatrix} \Delta P_2 \\ \vdots \\ \Delta P_n \\ \Delta Q_2 \\ \vdots \\ \Delta Q_n \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2}{\partial \theta_2} & \cdots & \frac{\partial P_2}{\partial \theta_n} & \frac{\partial P_2}{\partial |V_2|} & \cdots & \frac{\partial P_2}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n}{\partial \theta_2} & \cdots & \frac{\partial P_n}{\partial \theta_n} & \frac{\partial P_n}{\partial |V_2|} & \cdots & \frac{\partial P_n}{\partial |V_n|} \\ \frac{\partial Q_2}{\partial \theta_2} & \cdots & \frac{\partial Q_2}{\partial \theta_n} & \frac{\partial Q_2}{\partial |V_2|} & \cdots & \frac{\partial Q_2}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_n}{\partial \theta_2} & \cdots & \frac{\partial Q_n}{\partial \theta_n} & \frac{\partial Q_n}{\partial |V_2|} & \cdots & \frac{\partial Q_n}{\partial |V_n|} \end{bmatrix} \begin{bmatrix} \Delta \theta_2 \\ \vdots \\ \Delta \theta_n \\ \Delta |V_2| \\ \vdots \\ \Delta |V_n| \end{bmatrix} \tag{1}$$

Solving Equation (1) helps calculate power flow, line losses, and voltage profiles for all the load buses in the KU grid. The NR method is chosen over others because it's faster and better at handling complex equations, making it ideal for real-time analysis.

The system updates every five minutes, meaning after getting the latest data from the meters, it continuously runs the load flow calculations again to show the current state of the KU grid in near real-time. Additionally, the model stores the past hour's power flow data so users can look

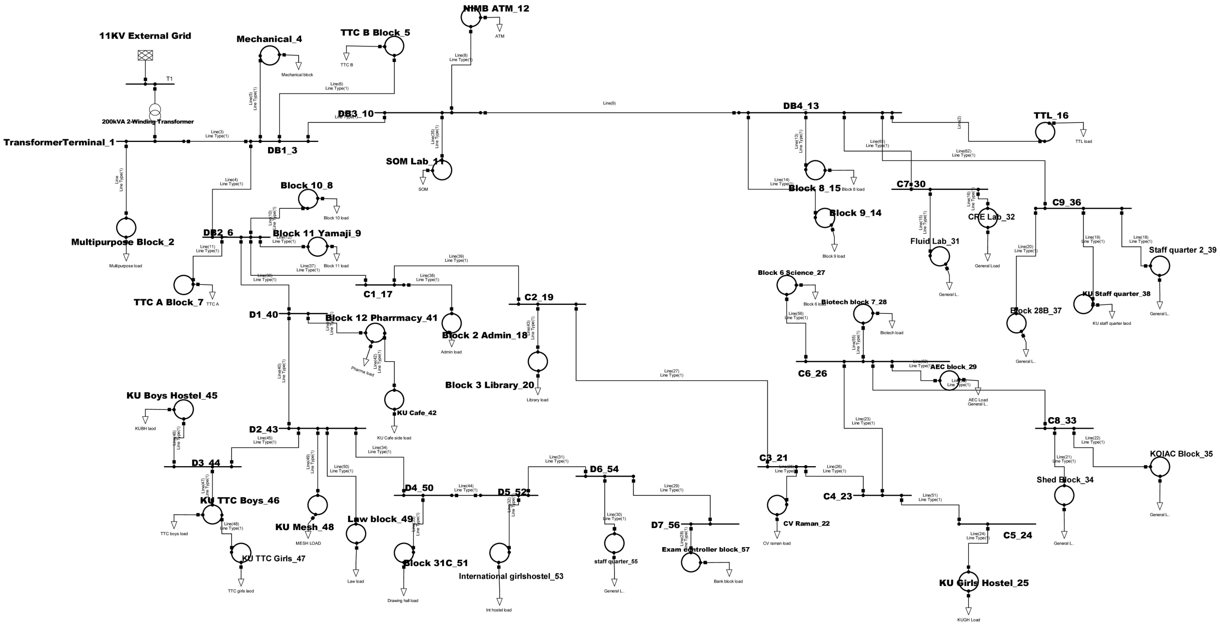


Figure 3. Single Line Diagram of the KU distribution system

back and see the system's parameters, which is helpful for spotting trends or issues over time. Once Matpower finishes its calculations, the results, such as voltage profiles and line losses, are packed into a Python dictionary, a kind of organized list in Python, and sent back to Python for the next step, which is visualization.

2.3. Data Visualization Layer

The Data Visualization Layer transforms calculated parameters from the Data Handling Layer, such as bus voltages, line losses, and line loadings into a clear, graphical format using Node-RED. In this approach, line loading is calculated by comparing the branch currents with the corresponding rated current limits of the distribution lines, thereby providing a practical indication of available operating margin. No dedicated hosting capacity algorithm or DER integration assessment method is applied instead, the analysis focuses on operational line utilization derived directly from measured load data and power flow results. Once processed by Matpower in Python, the output parameters are transmitted to Node-RED via the MQTT (Message Queuing Telemetry Transport) protocol, a fast and reliable communication method that ensures swift and dependable data delivery, keeping the visualization up-to-date. The system updates every five minutes, allowing Node-RED to refresh its visualizations accordingly, providing a near real-time view of the KU grid's status. For clarity, Node-RED's dashboard focuses on key parameters, displaying graphs for five bus voltages, five line losses, and five line loading parameters to avoid overcrowding and help users quickly identify the system's weakest points. Additionally, Node-RED offers a comprehensive view of the network's performance, allowing users to monitor all buses and the entire system when needed.

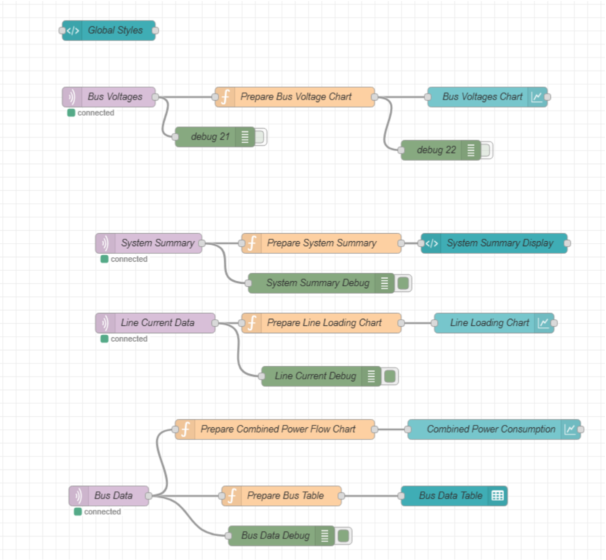


Figure 4. Organized nodes in Node Red for data visualization

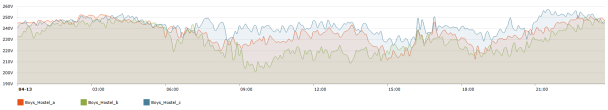


Figure 5. Voltage profile of KU Boys Hostel from smart meter data

3. System Description

The study focuses on the distribution system of Kathmandu University, which serves as the case study for this research. This system operates as a radial network, supplied by a 200 kVA step-down distribution transformer, 11kV to 0.4kV that reduces the voltage for safe use across the campus. The KU distribution network comprises 57 buses, which are connection points where power is distributed to various loads, such as buildings and facilities. A detailed breakdown of the system's components, including conductor lengths, cable types, and other specifications, is provided in Table 1 for a clearer understanding of the network's structure. Additionally, Figure 6 shows a survey image of the KU distribution system is included to visually represent the layout and connections of the grid, helping to illustrate how the buses, conductors, and cables are arranged.

Table 1. System Description

System	Description
Voltage Level	0.4 kV
Total Line Length	2.847 km
Underground Cable(XLPE Cables)	1.466 km
Overhead Conductors(Dog Conductor)	1.187 km
Conductor Resistance	0.082 Ω/km
Transformer Capacity	200 kVA
Number of Buses	57
Peak Load	140 kW

Table 2. Smart Meter Details

Description	Value
Name	WEM3080T
Type	3 phase
Rating	230V, 150A, 50Hz
Communication Medium	2.4G WIFI, Modbus
Measurement Accuracy	1. Voltage: ±1.0% 2. Current: ±1.0% 3. Active Power: ±1.0%
Reporting Interval	1–5 minutes interval
Report Contents	Active Energy (Forward and Reverse),Active Power, Voltage, Current, Frequency

4. Results and Discussions

4.1. Survey Results

The survey outcomes provided critical insights into the electrical distribution system, enabling a comprehensive tabulation of the system description (refer to Table 1). The survey captured key parameters such as line lengths, conductor types, and load profiles, which are essential for system analysis. Additionally, the survey included a detailed mapping of the network, showcasing the placement of meters and distribution boxes across the system. The voltage profile from a smart meter installed at the Boys Hostel (Figure 7) is shown in Figure 5, this data reflects the voltage stability and variations during peak and off-peak periods, aiding in the assessment of system performance.

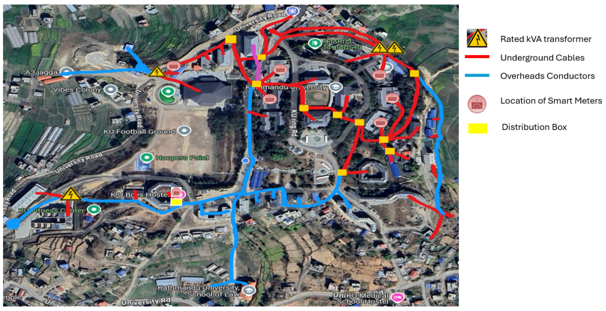


Figure 6. Survey results of KU distribution system

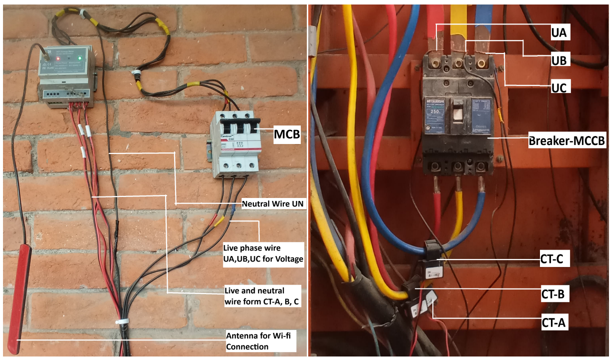


Figure 7. Smart Meter Installed at KU Boys Hostel

4.2. Load Flow Results

The model incorporates dynamic updates for seven specific loads, refreshed every five minutes, while the remaining loads rely on static survey data due to the limited deployment of smart meters currently only seven are operational. The analysis revealed grid losses of 1.056 kW. The voltage profiles and line loading outcomes are presented in Tables 3 and Table 4 respectively. Line 1-3 means line form bus 1 to bus 3 and so on. Here five data are taken based on most frequent fault occurrence lines-as seen mostly in monsoon days and the blocks which are near and far to main transformer

4.3. Data Visualization

The data visualization for the distribution system is facilitated through Node-RED, a flow-based programming tool, as depicted in the Node-RED flow diagram (Figure 4), which processes and displays system metrics in near

Table 3. Voltage Profile

Bus Name	**Voltage (pu)**
KU Boys Hostel	0.983
Block 8	0.989
Multipurpose Hall	0.999
Library	0.989
Block 10	0.990

Table 4. Line Loading

Line Name	**Line Loading (%)**
Line 1-3	59
Line 3-6	32.21
Line 10-13	12.29
Line 6-17	14.69
Line 17-19	12.66

real-time, updating every 5 minutes to reflect the latest load flow results. The voltage profile graph (Figure 8) in the visualization window shows per unit value of bus voltage, when on hovering over the graph reveals the bus name and its per unit (pu) voltage.

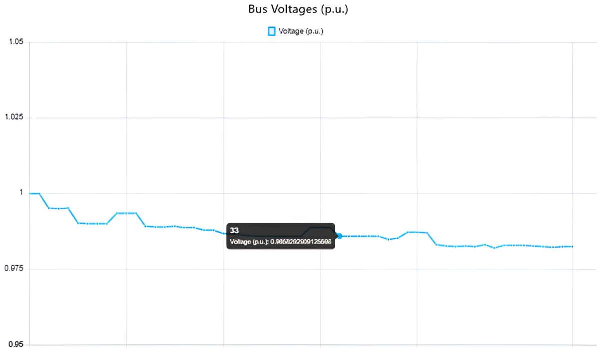


Figure 8. Bus Voltage pu value with respect to bus number

Line Loading Chart node, produce a graph as in Figure 9 that shows the loading levels of five selected lines as a percentage of total rated capacity in the visualization window. Additionally, real power consumption (in watts) are displayed for five buses in Figure 10. So, the overall dashboard provide a near real-time insights during peak and off-peak scenarios, enabling continuous system monitoring and analysis.

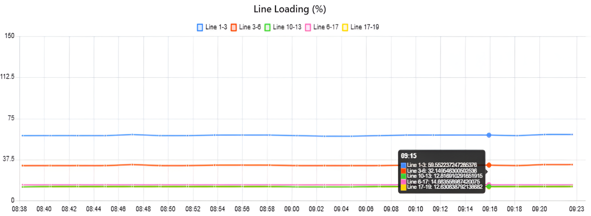


Figure 9. line loading of the system for different time period

In Figure 11 the system summary is shown, where if the power flow converges successfully or not is also shown through success status. On hovering over graph the details like name, and values will pop up giving more clear information. The overall dashboard in organized form will show system summary, bus voltages, power consumption and line loadings with respect to rated capacity. The developed system not only provides real-time visualization but also enables analysis of historical data, revealing important load trends. In Figure 12, from August 2024 to January 2025, data showed that during winter months particularly in December, the transformer operated well above its rated 200 KVA capacity, with loading percentages exceeding 100% and peaking at over 137%. Such

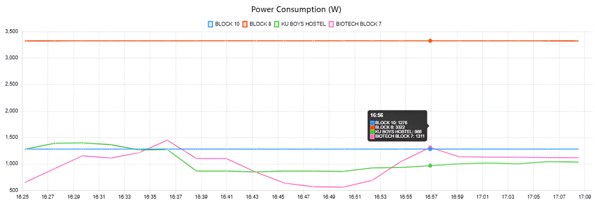
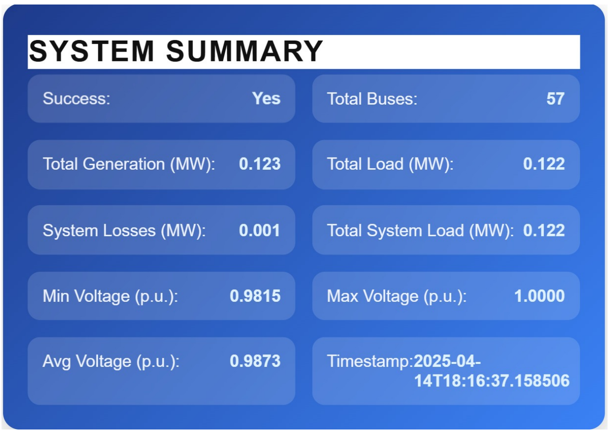


Figure 10. Power Consumption pattern of different buses



SYSTEM SUMMARY

Success: **Yes**	Total Buses: **57**
Total Generation (MW): **0.123**	Total Load (MW): **0.122**
System Losses (MW): **0.001**	Total System Load (MW): **0.122**
Min Voltage (p.u.): **0.9815**	Max Voltage (p.u.): **1.0000**
Avg Voltage (p.u.): **0.9873**	Timestamp:**2025-04-14T18:16:37.158506**

Figure 11. Dashboard showing overall system summary

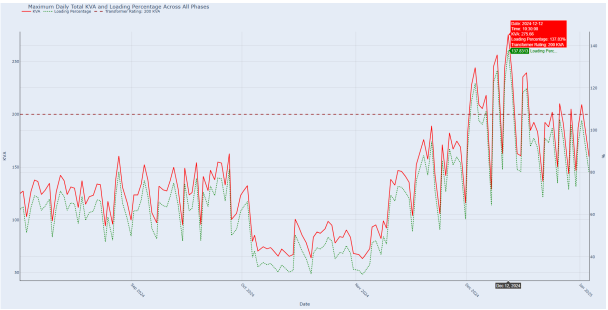


Figure 12. Historical data of main transformer from smart meter

overloading poses a significant risk of failure during peak demand periods. By leveraging these historical insights and by scaling up the model and system will help in future trend predictions, can help in informed decisions making such as timely infrastructure upgrades to enhance system reliability.

5. Conclusion

The rapid change in the distribution system of Nepal due to the addition of new technologies such as roof-top photovoltaics, electric vehicles, and induction stoves has led to various challenges like poor power quality. This study addresses these threats by developing a dynamic visualization tool for electric distribution systems using Node-RED and Matpower environments, utilizing data from smart meters. Using a balanced single-phase equivalent method for Newton Raphson power flow for an unbalanced three phase system enables system level visualization and loading assessment, but does not address phase unbalance, neutral currents, harmonics, or three phase load diversity which are the limitations of this approach. To overcome these limitations, future work should adopt unbalanced three-phase distribution models using tools such as OpenDSS through Python-based interfaces like PyDSS or OpenDSS, which are more suitable for detailed distribution analysis. While the current model does not directly interface with protection equipment, it provides valuable insights that can indirectly inform operational strategies. Further integration with SCADA could enable real-time control actions, enhancing operational efficiency. By incorporating a greater number of sensors or advanced devices like phasor measurement units, the system's accuracy and reliability can be improved, allowing for testing in higher voltage grids. Additionally, integrating GIS mapping would enable spatial visualization of grid assets, improving situational awareness for geographically dispersed networks. Testing the tool on a larger feeder will validate its scalability and guide further refinements for broader applications in modern grid management.

6. Acknowledgments

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