Journal of Advanced Technology and Multidiscipline Vol. 04, No. 01, 2025, pp. 22-33

Original article

Estimating Rooftop Photovoltaic Penetration Level on Power Distribution Network Constrained by Power Quality: Case Study in Salodong Feeder

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Received 11 April 2025; Accepted 20 May 2025

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***Abstract*—The growth of rooftop photovoltaic (PV) systems in Indonesia has accelerated significantly as part of the national effort to promote decentralized renewable energy. PT PLN (Persero) North Makassar, serving 409,025 customers with 1,332 MVA total capacity, has integrated seven rooftop PV users totaling 419.5 kWp. A key challenge is maintaining power quality and operational reliability while incorporating solar generation.This study evaluates the impact of rooftop PV penetration on power quality, including voltage fluctuations, harmonics, and system reliability, using the Salodong feeder in North Makassar as a case study. The feeder consists of 137 transformers with a total capacity of 32.9 MVA and serves customers across industrial, commercial, social, and residential sectors, representing the diverse load profile typical of Indonesia's urban distribution systems. Its configuration reflects the unique characteristics of power networks in tropical regions with mixed and variable demands. Using real operational data from PT PLN, this study integrates power quality constraints—voltage, harmonics, and reverse power flow and aligns with national regulations. Different PV penetration levels are analyzed, and strategic recommendations are proposed to optimize integration.**

Findings reveal a critical penetration threshold beyond which power quality is compromised. An optimal rooftop PV penetration level of approximately 30% is recommended to support system planning, minimize adverse impacts, and guide future PV deployment in accordance with regulatory targets.

***Keywords*— Distribution System, Harmonics, Power Quality, Reverse Power, Rooftop Photovoltaic, Salodong Feeder, Voltage Fluctuations.**

I. INTRODUCTION

The global transition to renewable energy has accelerated the adoption of rooftop photovoltaic (PV) systems. The global energy landscape is undergoing a significant transformation, driven by the urgent need to reduce greenhouse gas emissions and mitigate climate change. This shift is characterized by the growing adoption of renewable energy sources, with rooftop photovoltaic systems playing a key role. Specifically, rooftop photovoltaic systems have emerged as a decentralized and scalable solution to harness solar energy, offering numerous environmental and economic benefits [1].

Rooftop photovoltaic systems have been widely adopted around the world, driven by advancements in solar panel technology[2]-[4],reduced installation costs, and supportive government policies. For instance, many countries have implemented feed-in tariffs, tax incentives, and net metering programs to encourage rooftop solar adoption. These incentives, along with growing public awareness, have made rooftop solar an attractive option for residential, commercial, and industrial users [5].

As a developing country with significant energy demand growth, Indonesia is also targeting a renewable energy mix of 23% by 2025 and achieving net-zero emissions by 2060. This goal is further supported by the issuance of the Minister of Energy and Mineral Resources Regulation No. 2 of 2024 regarding rooftop PV [6].

Rooftop photovoltaic systems offer benefits, including carbon emission reduction and increased energy independence [7]. Environmental and economic benefits are among the key motivations for adopting rooftop photovoltaic systems due to their potential to reduce carbon emissions significantly. Unlike fossil fuel-based energy generation, solar power systems produce electricity without emitting greenhouse gases, thereby contributing to a cleaner environment. Additionally, by generating electricity on-site, rooftop solar systems help reduce dependence on centralized power plants, leading to lower transmission losses and improved energy efficiency[8].

Economically, rooftop photovoltaic systems provide substantial cost savings over time. While the initial investment can be significant, the long-term benefits include lower electricity bills and the potential for income from selling excess power back to the grid. Furthermore, declining solar panels and installation costs have made it more accessible to a broader range of consumers, further driving adoption.

PT PLN (Persero) North Makassar Customer Service Unit has become one of the pioneers in integrating rooftop photovoltaic

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DOI: 10.20473/jatm.v4i1.71674

systems into the electricity distribution network in Indonesia. Seven rooftop solar customers have been integrated with a total capacity of 419.5 kWp. This implementation reflects PLN's commitment to promoting renewable energy use while supporting its customers' electricity needs.

Integrating rooftop photovoltaic panels into the existing distribution network (on-grid) presents technical challenges, particularly concerning power quality [9]. The power quality issues include the following:

- Voltage Fluctuations: Voltage fluctuations are among the most common issues associated with high PV penetration. Solar PV systems can cause voltage drops and increases due to rapid changes in generation, especially during events like cloud cover or sudden changes in sunlight intensity. These fluctuations can impact the performance of electrical equipment and the overall reliability of the power supply [10] [11].
- Harmonics: Using inverters to convert the DC output from solar panels into AC power introduces harmonics into the grid. Harmonics are distortions in the waveform of electricity that can lead to reduced efficiency and potential damage to electrical equipment [12][13].
- Reverse Power Flow: At high penetration levels, excess solar power generated during periods of low demand can flow back into the grid, causing reverse power flow. This can lead to other issues, such as voltage rise, overload on distribution transformers, and potential safety concerns [14].
- Frequency Variations: Although rare in distribution systems, frequency variations can occur in isolated or weak grids with high PV penetration. This can affect grid stability and generator synchronization [15].

These issues are exacerbated at higher penetration levels, potentially leading to inefficiencies [16]. This study aims to analyze the impact of rooftop PV penetration on power quality parameters in the Salodong Feeder. The Salodong Feeder case study is a 20 kV distribution feeder that supplies a mix of residential and commercial loads, providing a relevant case for analyzing the impact of rooftop PV penetration on power quality.

The total network load capacity of the Salodong Feeder is 6.5 MW, with the current PV installation contributing 0.25 MW, equivalent to a 3.8% penetration level of the existing load.

The objectives of this research include measuring the degradation of power quality under various PV penetration scenarios, identifying the critical penetration threshold for the Salodong Feeder, and proposing mitigation strategies to address the challenges of power quality. The contribution of this research is that it bridges the gap between renewable energy integration and power quality management by providing actionable guidelines for grid operators.

II. Rooftop PV Penetration Level Estimation

This scenario is developed to evaluate the impact of integrating rooftop photovoltaic (PV) systems on the performance of the internal electrical network in industrial facilities. In the existing condition, simulations are conducted based on the actual system configuration, which includes two installed rooftop PV systems located in the Untia Section and Gudang 88 Section.

For the low penetration scenario (<30%), each section is assigned an additional rooftop photovoltaic capacity equal to 30% of the total transformer capacity in that section. The medium penetration scenario (30–50%) and high penetration scenario (>50%) model a gradual increase in the contribution of rooftop PV systems [17]. These scenarios are designed to analyze the electrical system's response to higher levels of renewable energy integration, particularly regarding potential impacts on the power quality of the distribution network.

This study explores the allocation of rooftop PV systems in various sections of distribution networks. The deployed PV units in each area are chosen according to the real conditions and load profiles. All technical parameters and system characteristics are obtained directly from field measurements for the modeling process, guaranteeing that the simulations correspond closely to a real operational context and infrastructure constraints.

Simulations of interactions with the grid were run for up to 100% of the installed capacity of each distribution substation to gain a deeper insight into how increased PV penetration affects the network. The simulation loads are modeled without considering noise or environmental factors, such as changes in solar irradiation, to isolate the electrical effects. This enables the study to specifically examine the impacts of PV integration on system parameters, such as those related to voltage regulation, harmonic distortion, and load flow analysis.

To evaluate the impact of rooftop PV integration, this study first analyzes the voltage profile along the feeder. Stable voltage is essential for reliable system operation and equipment protection. Monitoring voltage at multiple nodes can identify potential overvoltage or undervoltage issues due to PV fluctuations.

The study also examines Total Harmonic Distortion (THD) since inverter-based PV systems may introduce harmonics that reduce power quality. Tracking THD helps assess whether PV integration leads to disturbances that affect system performance or exceed standard limits.

Power flow analysis observes how electricity moves through the network under different PV scenarios. It highlights line loading, transformer stress, and possible reverse power flow, which are key factors in ensuring the grid can handle higher renewable penetration.

To better understand the research methodology, the flowchart below outlines the key stages in evaluating rooftop PV penetration. It visually represents the sequence of activities, from initial data collection to final analysis and conclusion.

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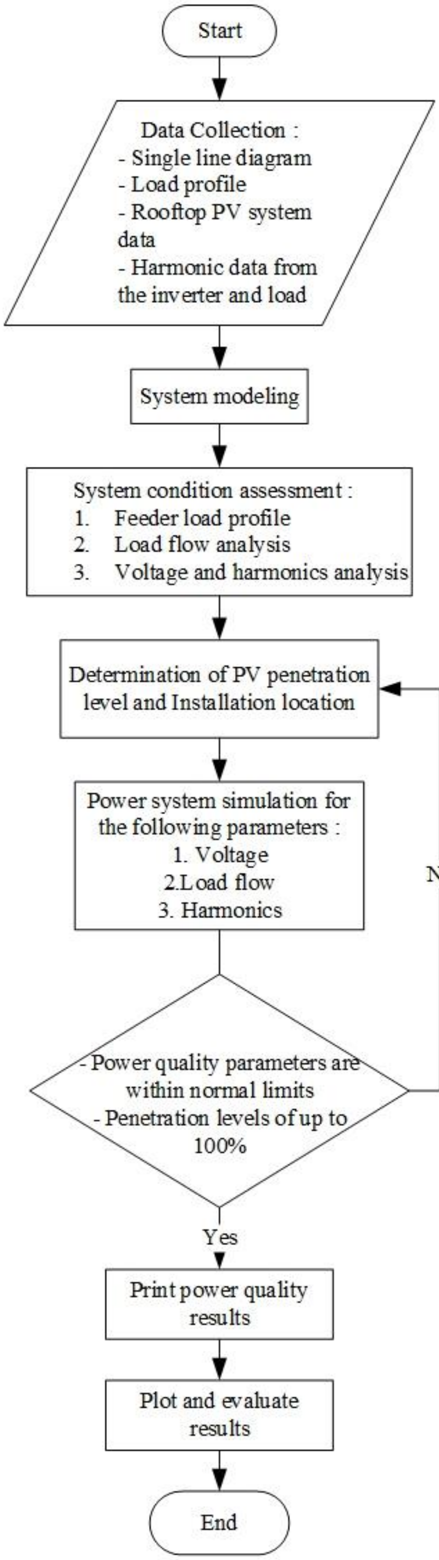

Figure 1. Flowchart of rooftop PV penetration estimation method

This research begins with collecting technical data, including a single-line diagram, load profile, rooftop photovoltaic technical data, and the harmonic characteristics of the inverter and load. This data is the basis for modeling the electrical system using analytical software. Once the system model is developed, an initial calculation of the system's condition is performed to obtain each feeder's active (P) and reactive (Q) power values and conduct load flow, voltage, and harmonic content analyses.

The next step is to determine the rooftop photovoltaic system's penetration level and installation locations. Subsequently, a power flow simulation is carried out, considering parameters such as voltage, power flow, and harmonics. The simulation results are then analyzed to evaluate whether the power quality parameters remain within acceptable limits and whether the PV penetration can be increased up to a maximum of 100%. If the criteria are unmet, the penetration level will be adjusted, and the simulation will be repeated. If the criteria are met, the simulation results will be documented in a power quality report, and the results will be plotted and conducted in a comprehensive system evaluation to conclude the study.

The simulations in this study were carried out using DIgSILENT PowerFactory, a well-established tool for analyzing power systems. To closely represent real-world conditions, the model includes several essential elements, such as the system's load profile, which captures typical daily demand patterns, and a detailed layout of the distribution network, reflecting its actual structure and connections.

Key electrical components, including the impedance and capacity of lines and transformers, are also factored into the simulation to represent system behavior accurately. In addition, the rooftop PV systems are modeled based on their installed capacities and technical characteristics. This setup allows the study to explore how different levels of PV penetration affect the overall performance and dynamics of the distribution network.

III. Modelling & Simulation

A. *System Description*

The South Sulawesi system is an interconnected power system that supplies electricity to the city of Makassar. The system is characterized as provided in Table 1.

Table 1. South Sulawesi power system data

Asset Data	Value	Unit
Peak Load of South Sulawesi System	1,902.43	MW
Installed Capacity	3,256.529	MW
Net Capacity	2,790.24	MW
Total Number of Power Plants	33	Units
Hydropower Plants	4	Units
Coal-Fired Power Plants	10	Units
Thermal Power Plants	16	Units
Variable Renewable Energy Plants	3	Units
Transmission Voltage Levels	150/70	kV
Transmission Length (ACSR)	6,118.08	km

Salodong Feeder is a 20 kV distribution feeder that supplies electricity to household and commercial consumers. The total load capacity of the feeder is 6.5 MW, with the current PV installation contributing around 0.25 MW (3.8% penetration). The Single Line Diagram of the Salodong feeder is presented in Fig. 2, and the Salodong system data is provided in Table 2.

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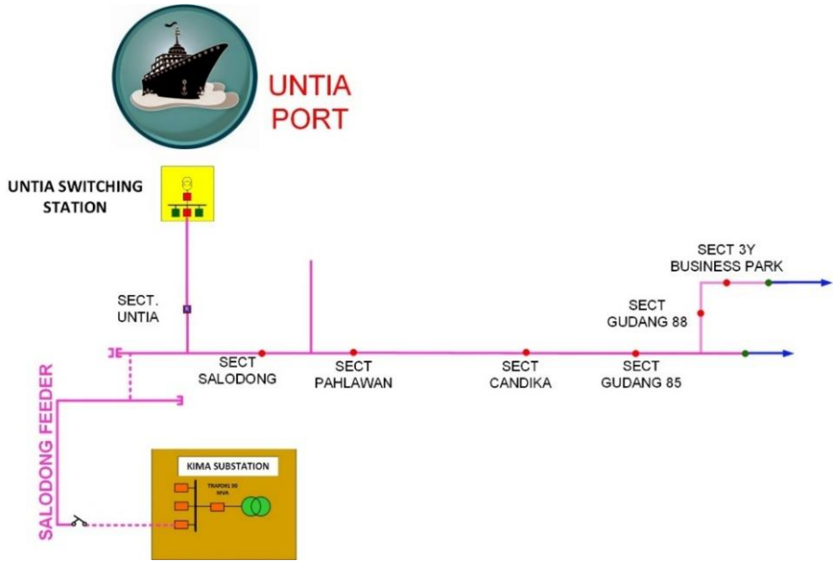

Figure 2. Salodong feeder

Table 2. Salodong feeder system data

Asset Data	Value	Unit
Feeder Length	29.367	km
Number of Keypoints	7	units
No. of Distribution Transformers	137	units
Number of Customers	8,506	customers
Number of Rooftop PV Systems	2	units
Rooftop PV Capacity in North Makassar	419.5	kWp
Rooftop PV Capacity in Salodong Feeder	250	kWp
Total Feeder Load	6.5	Mw
Load Power Factor	0,85	-
Conductor Type	A3C 150, XLPE 240	mm

B. System Modeling

System modeling was performed using DIgSILENT PowerFactory, as shown in Fig. 3, and the inverter specification is provided in Table 3. It shows the simulation circuit diagram for penetration, where each section is given a rooftop photovoltaic penetration value ranging from 10% to 100%, assigned to each feeder section.

Table 3. Inverter specifications

Parameter	Specification
Inverter Model	SUN2000-60KTL-M0
Rated Output Voltage	220/380 V, 230/400 V, 277/480 V
Total Harmonic Distortion	< 3%
Rated AC Output Power	60 kW

The modeling approach incorporates the following considerations:

1. The PV population was allocated for each feeder section based on actual distribution potential.
2. Technical parameters were based on real field data provided by PLN.
3. PV penetration was simulated up to 100% of the transformer capacity in each distribution substation.
4. Solar irradiance variability was excluded from the model (steady-state analysis).
5. The evaluation parameters include voltage profile along the feeder, Total Harmonic Distortion (THD), and load flow analysis.
6. The load condition used in the simulation corresponds to the system's peak load.
7. All acceptance thresholds for power quality parameters are based on the Indonesian Ministerial Regulation [6] and national grid code standards [18].

To calculate the hosting capacity, it is necessary to determine the maximum rooftop solar power system capacity at each customer that can be injected without causing violations to system quality, such as customer voltage, thermal overload, and reverse power. One of the considerations is reverse power flow, as it can result in overloads and power losses [19]. The maximum injection at the Point of Common Coupling (PCC) can be calculated using Kirchhoff's Voltage Law (KVL) [20].

The network characteristics are formulated using impedance (1) based on the circuit. To determine the voltage at the Point of Common Coupling (Vpcc), the sending end voltage is added to the calculated voltage drop across the distribution network (2). Therefore, to obtain the maximum power transfer function available at the Point of Common Coupling (P_{pcc}^{max}) the following equation is used [21]:

$$P_{pcc}^{max} = \frac{V_{pcc}^{max}(V_{pcc}^{max} - V_1)}{Z_{th}\,(\cos\theta + \tan\emptyset . \sin\theta)} + P_L \qquad (1)$$

Equation (1) determines the maximum allowable power injection at the Point of Common Coupling (PCC), referred to as the hosting capacity. This equation takes into account the maximum permissible voltage at the PCC (V_{pcc}^{max}), the sending

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end voltage (V_1) and the Thevenin equivalent impedance Z_{th} of the network t also includes the impact of the load angle θ, the power factor angle ∅ , and the existing load power at the PCC (P_L).

It is then simplified by calculating the voltage rise from the measured load current at the sending end and the current at the receiving end, using the line equation theory to obtain the voltage difference (ΔV) at the node.

$$P_{DG}^{max} = \frac{V_{Grid}^{max}(\Delta V)}{Z_{th}} \quad (2)$$

Equation (2) presents a simplified approach to estimating the maximum distributed generation capacity (P_{DG}^{max}) that can be connected to the grid. It is derived by analyzing the voltage rise (ΔV) due to power injection in association with the Thevenin impedance.

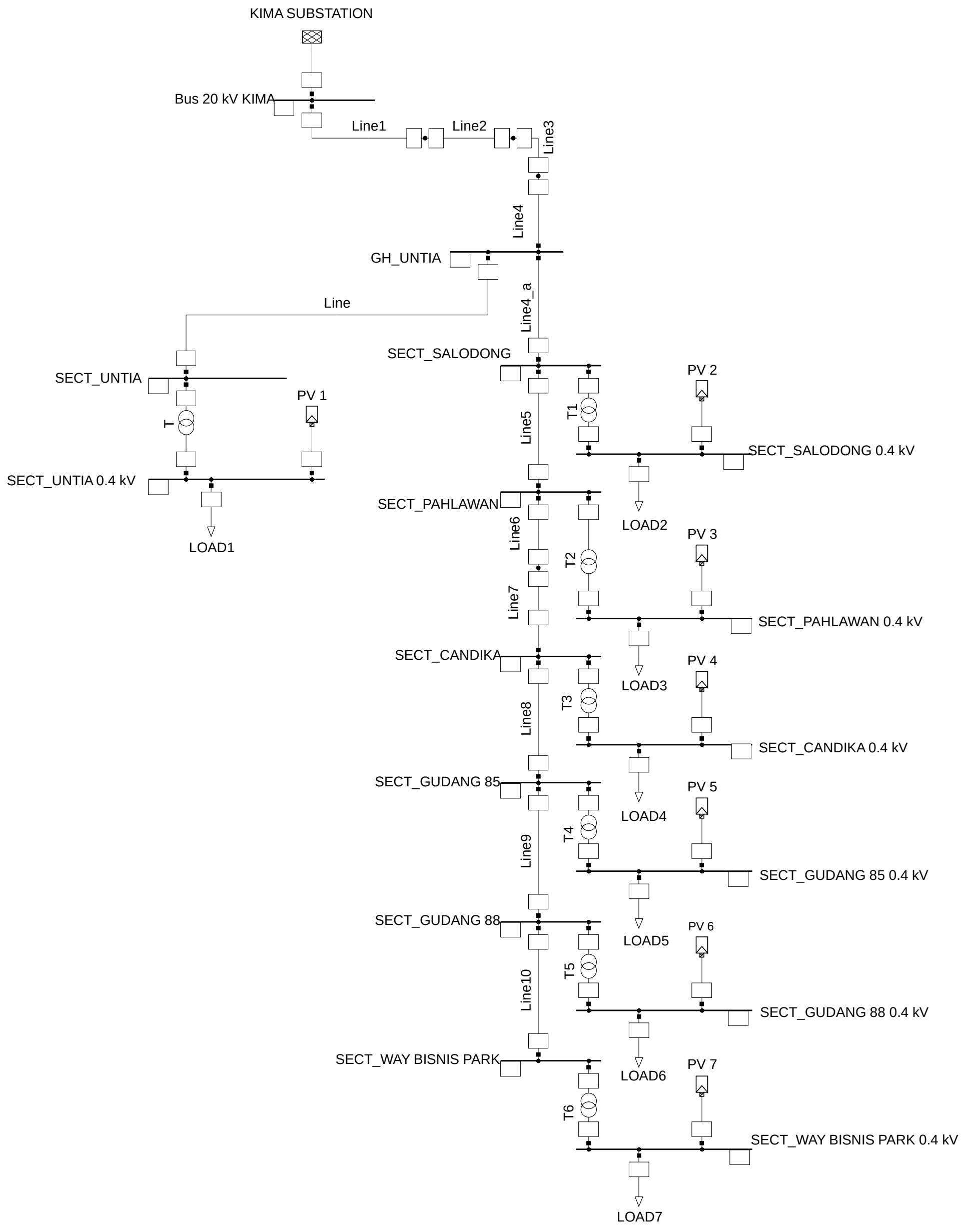

Figure 3. rooftop PV penetration modeling in DIgSILENT

Hosting capacity, in this case, can be formulated as P_{pcc}^{max} based on the following relationship:

1. Hosting capacity is directly proportional to the loading.
2. The greater the voltage difference in the network, the smaller the hosting capacity becomes, following a quadratic relationship.

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3. The longer the network, the greater the voltage drop, which causes the hosting capacity at the end of the network to decrease.

IV. RESULTS & DISCUSSION

A. *Voltage Profile*

Based on the Grid Code issued by the Ministry of Energy and Mineral Resources Regulation No. 20 of 2020 [7] and SPLN standards, the voltage reference is expressed in per-unit (p.u). The base voltage is 400 V, representing the substation's line-to-line voltage. Therefore, the upper limit (+5%) is 420 V, and the lower limit (-10%) is 360 V. The simulation was conducted with rooftop PV penetration levels ranging from 10% to 100%

A.1. Condition Without Rooftop PV

Table 4 presents the simulation results of the voltage profile at each section of the Salodong feeder under the condition of rooftop PV systems. It can be seen that the voltage varies across different sections, with the lowest voltage recorded at Sect Untia and the highest at Sect Candika.

Table 4. The voltage of the Salodong feeder at each *section*

Bus 0.4 kV	Existing voltage (p.u.)
1 SECT_UNTIA	0.9456301
2 SECT_SALODONG	0.9700649
3 SECT_PAHLAWAN	0.9729661
4 SECT_CANDIKA	0.9902705
5 SECT_GUDANG 85	0.9784885
6 SECT_GUDANG 88	0.9751989
7 SECT_WAY BISNIS PARK	0.971282

Based on the data above, it can be concluded that the existing system without rooftop PV meets the applicable voltage standards, as the voltage remains within the acceptable range of 0.9 p.u < V < 1.05 p.u.

A.2. Existing condition with Rooftop PV at Sections 1 and 6

Figure 4 presents the simulation results of 0.4 kV bus voltage under various rooftop PV penetration levels at sections 1 and 6. It can be seen that the voltage at all sections generally increases as the PV penetration level rises; however, all values remain within the accepted standard voltage limit, below 1.05 p.u.

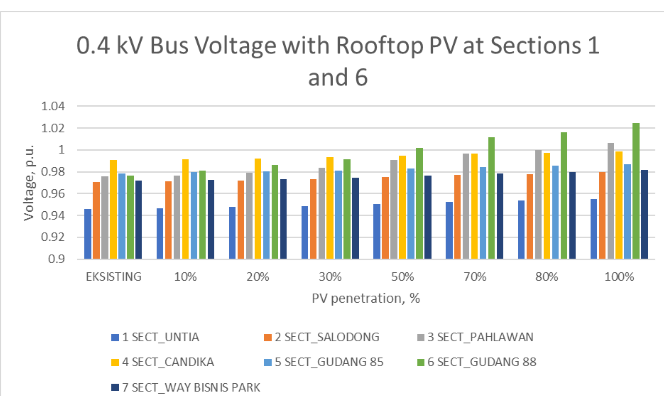

Figure 4. 0.4 kV bus voltage with rooftop PV at sections 1 and 6

A.3. Condition with Rooftop PV at Sections 1, 2, and 6

Figure 5 presents the simulation results of 0.4 kV bus voltage under various rooftop PV penetration levels at sections 1, 2, and 6. It can be seen that the voltage at all sections generally increases as the PV penetration level rises; however, all values remain within the accepted standard voltage limit, below 1.05 p.u.

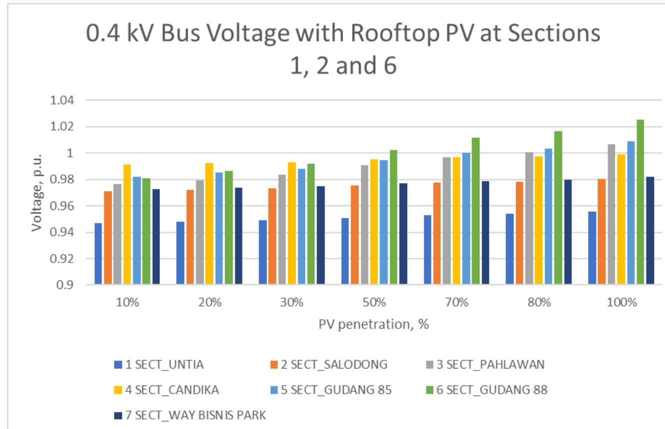

Figure 5. 0.4 kV bus voltage with rooftop PV at sections 1, 2 and 6

A.4. Condition with Rooftop PV at Sections 1, 2, 3, and 6

Figure 6 presents the simulation results of 0.4 kV bus voltage under various rooftop PV penetration levels at sections 1, 2, 3, and 6. It can be seen that the voltage at all sections generally increases as the PV penetration level rises; however, all values remain within the accepted standard voltage limit, below 1.05 p.u.

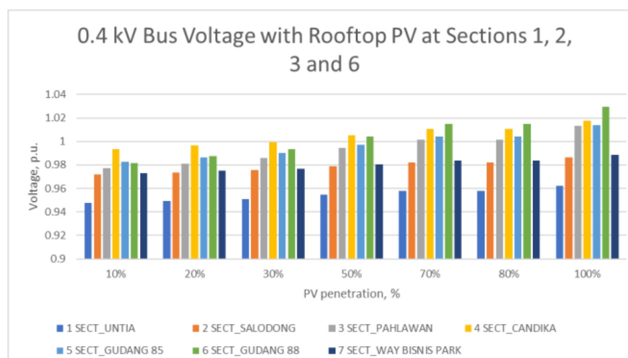

Figure 6. 0.4 kV bus voltage with rooftop PV at sections 1, 2, 3, and 6

A.5. Condition with Rooftop PV at Sections 1, 2, 3, 4 and 6

Figure 7 presents the simulation results of 0.4 kV bus voltage under various rooftop PV penetration levels at sections 1, 2, 3, 4, and 6. It can be seen that the voltage at all sections generally increases as the PV penetration level rises; however, all values remain within the accepted standard voltage limit, below 1.05 p.u.

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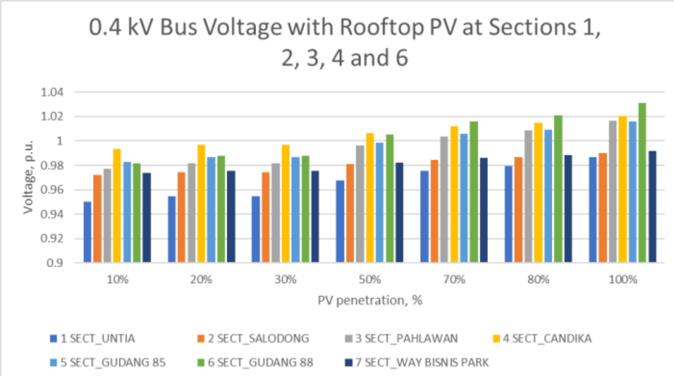

Figure 7. 0.4 kV bus voltage with rooftop PV at sections 1, 2, 3, 4, and 6

A.5. Condition with Rooftop PV at Sections 1 - 6

Figure 8 presents the simulation results of 0.4 kV bus voltage under various rooftop PV penetration levels at sections 1, 2, 3, 4, 5, and 6. It can be seen that the voltage at all sections generally increases as the PV penetration level rises; however, all values remain within the accepted standard voltage limit, below 1.05 p.u.

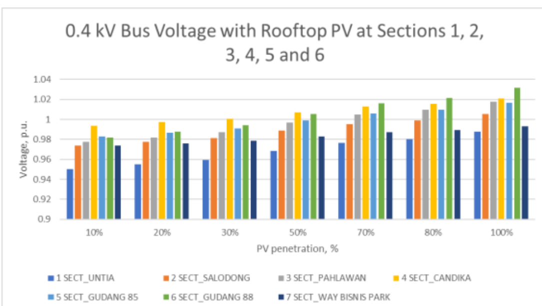

Figure 8. 0.4 kV bus voltage with rooftop PV at sections 1 – 6

A.6. Condition with Rooftop PV at Sections 1 - 7

Figure 8 presents the simulation results of 0.4 kV bus voltage under various rooftop PV penetration levels at sections 1, 2, 3, 4, 5, 6, and 7. It can be seen that the voltage at all sections generally increases as the PV penetration level rises; however, all values remain within the accepted standard voltage limit, below 1.05 p.u.

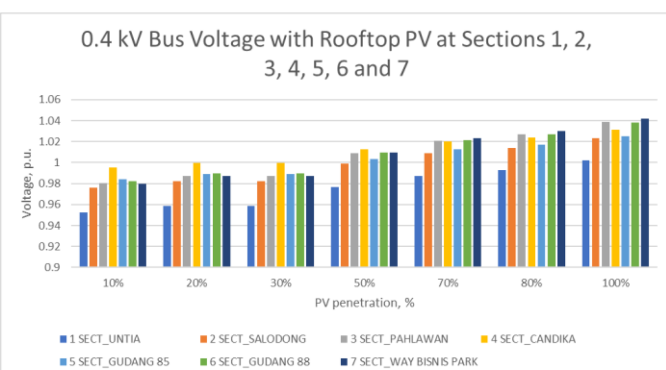

Figure 9. 0.4 kV bus voltage with rooftop PV at sections 1 – 7

Based on the power flow analysis results, the lowest voltage in the Salodong system occurs under the condition without rooftop PV, where the voltage is 0.9456301 p.u. This value is still within the limits permitted by the applicable standards of the State Electricity Company (PLN) and, therefore, does not cause any operational disturbances in the distribution system. In contrast, under the scenario where rooftop PV is distributed across seven locations with a penetration level of 100%, the highest recorded voltage in the system is 1.04218 p.u., which also remains within the acceptable standard range. This indicates that integrating rooftop PV into the distribution system does not result in overvoltage conditions that exceed regulatory thresholds. Thus, although there are changes in the voltage profile due to renewable energy penetration, either with or without rooftop PV, the voltage remains within the permissible tolerance limits. This suggests that the distribution system can accommodate high levels of rooftop PV penetration without posing significant voltage stability concerns.

B. Harmonics

Total Harmonic Distortion (THD) is the ratio of the total harmonic components to the fundamental component. Due to the nature of harmonics, which can interfere with electrical equipment, there are specific limitations on harmonic levels in power systems [22], including both voltage and current harmonics. According to the SPLN D5.004-1:2012 standard [23], the allowable limits for voltage harmonics are as follows:

Table 5. SPLN voltage harmonic limits

Voltage at Connection Point (Vn)	**Individual Voltage Harmonic Distortion(%)**	**Total Voltage Harmonic Distortion– THDvn (%)**
Vn ≤ 66 kV	3	5
66 kV < Vn ≤ 150 kV	1.5	2.5
Vn > 150 kV	1	1.5

B.1. Existing Condition with Rooftop PV at Sections 1 and 6

Figure 10 presents the simulation results of voltage THD under various rooftop PV penetration levels at sections 1 and 6. It can be seen that voltage THD values across all sections tend to decrease as the PV penetration level increases. This indicates that integrating rooftop PV systems can reduce harmonic distortion within the distribution network. Moreover, all THD values remain below the 5% threshold, in accordance with standard power quality limits, ensuring that no significant harmonic issues are introduced.

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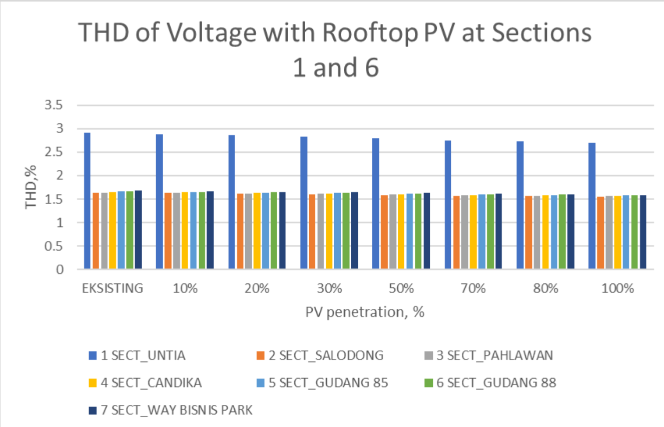

Figure 10. THD of voltage with rooftop PV at sections 1 and 6

B.2. Condition with Rooftop PV at Sections 1, 2, and 6

Figure 11 presents the simulation results of voltage THD under various rooftop PV penetration levels at sections 1, 2, and 6. It can be seen that voltage THD values across all sections tend to decrease as the PV penetration level increases. This indicates that integrating rooftop PV systems can reduce harmonic distortion within the distribution network. Moreover, all THD values remain below the 5% threshold, in accordance with standard power quality limits, ensuring that no significant harmonic issues are introduced.

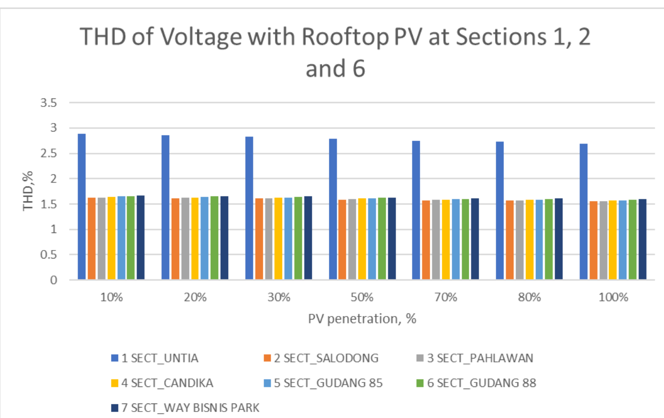

Figure 11. THD of voltage with rooftop PV at sections 1, 2, and 6

B.3. Condition with Rooftop PV at Sections 1, 2, 3, and 6

Figure 12 presents the simulation results of voltage THD under various rooftop PV penetration levels at sections 1, 2, 3, and 6. It can be seen that voltage THD values across all sections tend to decrease as the PV penetration level increases. This indicates that integrating rooftop PV systems can reduce harmonic distortion within the distribution network. Moreover, all THD values remain below the 5% threshold, in accordance with standard power quality limits, ensuring that no significant harmonic issues are introduced.

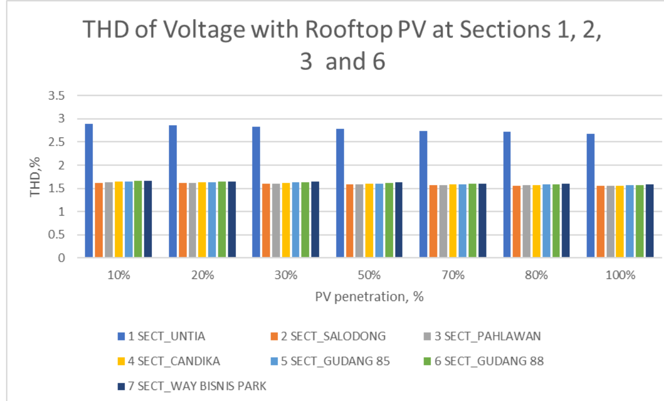

Figure 12. THD of voltage with rooftop PV at sections 1, 2, 3, and 6

B.4. Condition with Rooftop PV at Sections 1, 2, 3, 4 and 6

Figure 13 presents the simulation results of voltage THD under various rooftop PV penetration levels at sections 1, 2, 3, 4, and 6. It can be seen that voltage THD values across all sections tend to decrease as the PV penetration level increases. This indicates that integrating rooftop PV systems can reduce harmonic distortion within the distribution network. Moreover, all THD values remain below the 5% threshold, in accordance with standard power quality limits, ensuring that no significant harmonic issues are introduced.

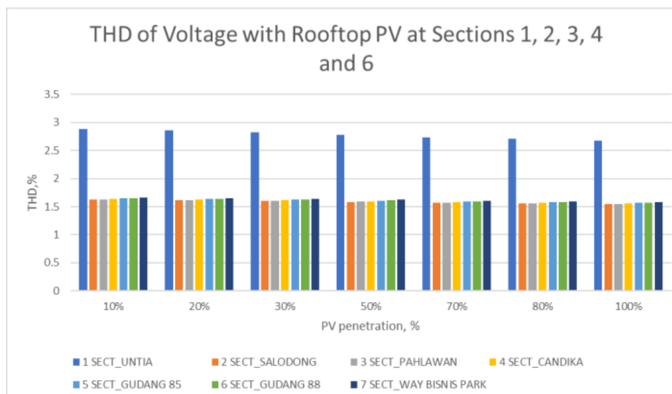

Figure 13. THD of voltage with rooftop PV at sections 1, 2, 3, 4, and 6

B.5. Condition with Rooftop PV at Sections 1 - 6

Figure 14 presents the simulation results of voltage THD under various rooftop PV penetration levels at sections 1, 2, 3, 4, 5, and 6. It can be seen that voltage THD values across all sections tend to decrease as the PV penetration level increases. This indicates that integrating rooftop PV systems can reduce harmonic distortion within the distribution network. Moreover, all THD values remain below the 5% threshold, in accordance with standard power quality limits, ensuring that no significant harmonic issues are introduced.

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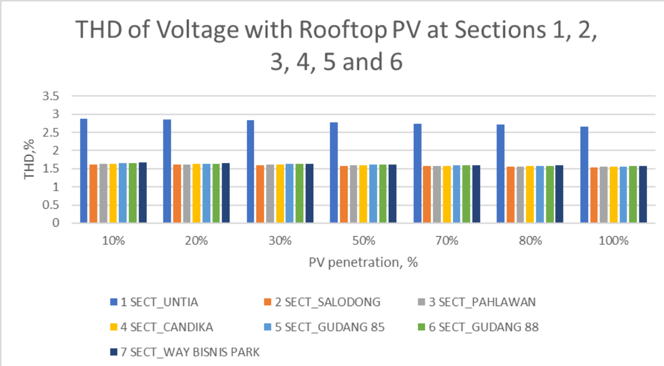

Figure 14. THD of voltage with rooftop PV at sections 1 - 6

B.6. Condition with Rooftop PV at Sections 1 - 7

Figure 15 presents the simulation results of voltage THD under various rooftop PV penetration levels at sections 1, 2, 3, 4, 5, 6, and 7. It can be seen that voltage THD values across all sections tend to decrease as the PV penetration level increases. This indicates that integrating rooftop PV systems can reduce harmonic distortion within the distribution network. Moreover, all THD values remain below the 5% threshold, in accordance with standard power quality limits, ensuring that no significant harmonic issues are introduced.

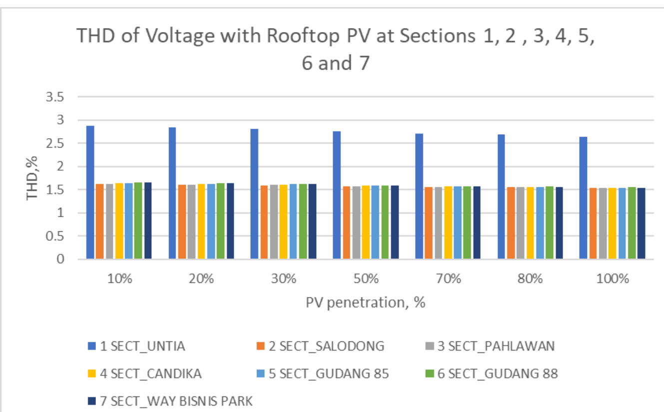

Figure 15. THD of voltage with rooftop PV at sections 1 - 7

The results show that under the existing condition, where rooftop PV is installed only at Sections 1 and 6, the highest voltage harmonic value is 2.909468%, and the lowest is 1.53952% at 100% penetration across all sections.

The increasing distribution and penetration of rooftop PV systems can reduce total harmonic distortion due to harmonic cancellation, impedance changes, and improved inverter technology. Distributed inverters operating at slightly different frequencies or phases can offset each other's harmonics, while higher PV levels modify system impedance and attenuate harmonic propagation. Modern inverters also feature advanced controls and built-in filters that further suppress harmonics.

C. Reverse Power Flow Analysis

Load flow analysis is used to analyze the distribution of voltage, current, active power, and reactive power in an electrical power system. As Distributed Generation (DG) penetration increases, particularly from Solar Power Plants, the distribution system faces a new challenge in reverse power flow. Reverse power occurs when the power generated by the DG exceeds local consumption, causing the power to flow back into the distribution network. This results in voltage fluctuations, increased power losses, and operational disturbances in protection equipment [12].

C.1. Existing Condition with Rooftop PV at Sections 1 and 6

Figure 16 presents the results of load flow analysis under various rooftop PV penetration levels at Sections 1 and 6. It can be seen that reverse power flow begins at 30% penetration, as shown by the appearance of negative active power values, and becomes more significant as the penetration level increases.

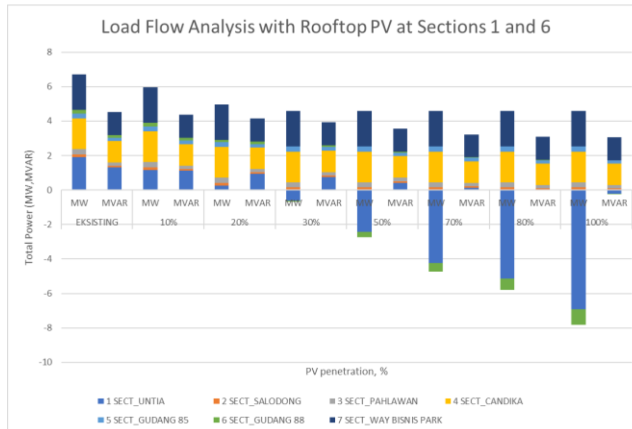

Figure 16. Load flow analysis with Rooftop PV at sections 1 and 6

C.2. Condition with Rooftop PV at Sections 1, 2, and 6

Figure 17 presents the results of load flow analysis under various rooftop PV penetration levels at sections 1, 2, and 6. It can be seen that reverse power flow begins at 30% penetration, as shown by the appearance of negative active power values, and becomes more significant as the penetration level increases.

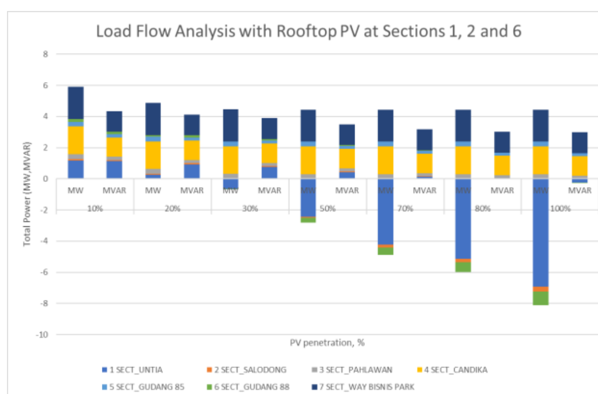

Figure 17. Load flow analysis with rooftop PV at sections 1, 2, and 6

C.3. Condition with Rooftop PV at Sections 1, 2, 3, and 6

Figure 18 presents the results of load flow analysis under various rooftop PV penetration levels at sections 1, 2, 3, and 6. It can be seen that reverse power flow begins at 20%

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penetration, as shown by the appearance of negative active power values, and becomes more significant as the penetration level increases.

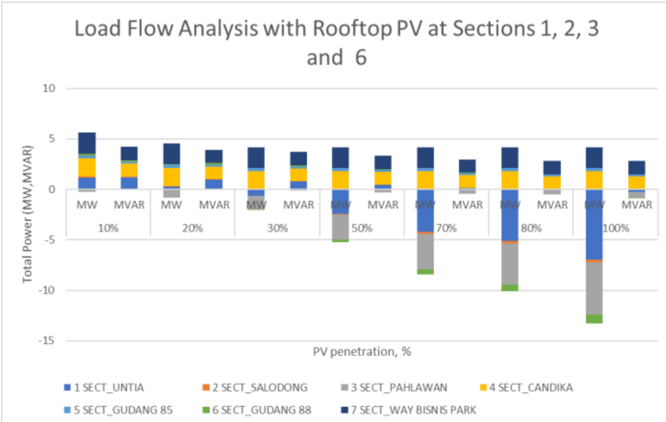

Figure 18. Load flow analysis with rooftop PV at Sections 1,2,3 and 6

C.4. Condition with Rooftop PV at Sections 1, 2, 3, 4 and 6

Figure 19 presents the results of load flow analysis under various rooftop PV penetration levels at Sections 1, 2, 3, 4, and 6. It can be seen that reverse power flow begins at 10% penetration, as shown by the appearance of negative active power values, and becomes more significant as the penetration level increases.

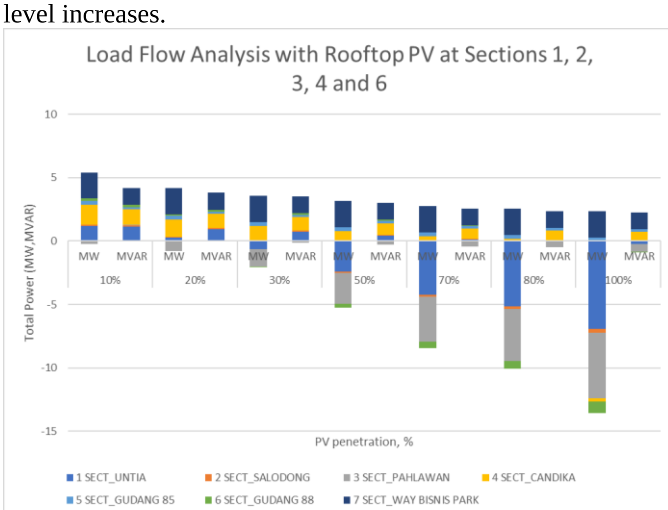

Figure 19. Load flow analysis with rooftop PV at sections 1, 2, 3, 4 and 6

C.5. Condition with Rooftop PV at Sections 1 - 6

Figure 20 presents the results of load flow analysis under various rooftop PV penetration levels at sections 1, 2, 3, 4, 5, and 6. It can be seen that reverse power flow begins at 20% penetration, as shown by the appearance of negative active power values, and becomes more significant as the penetration level increases.

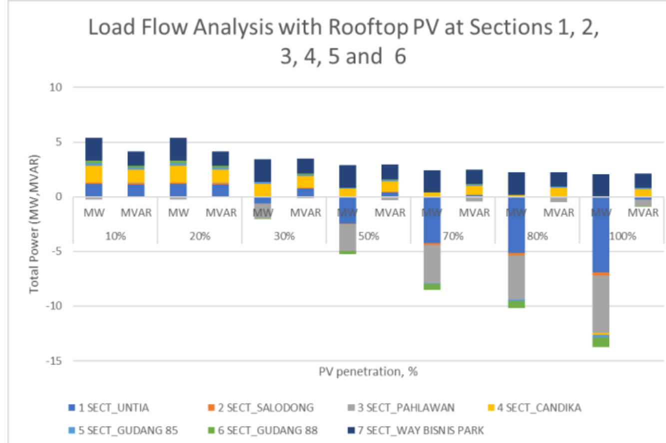

Figure 20. Load flow analysis with rooftop PV at sections 1 - 6

C.6. Condition with Rooftop PV at Sections 1 - 7

Figure 20 presents the results of load flow analysis under various rooftop PV penetration levels at sections 1, 2, 3, 4, 5, 6, and 7. It can be seen that reverse power flow begins at 10% penetration, as shown by the appearance of negative active power values, and becomes more significant as the penetration level increases.

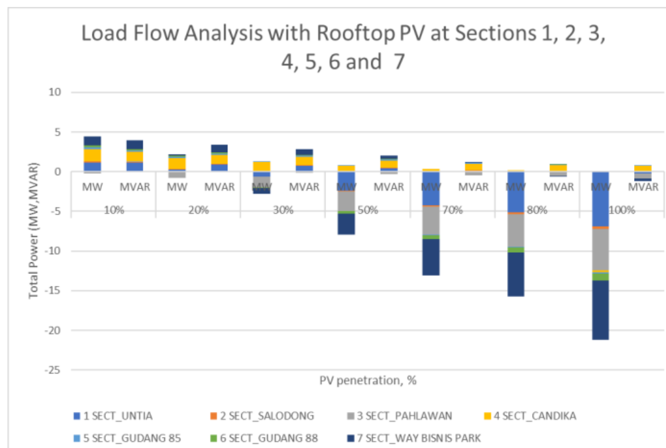

Figure 21. Load flow analysis with rooftop PV at sections 1 - 7

Based on the load flow analysis results, it was found that when rooftop PV penetration reaches 100% at Section 1, the highest reverse power occurs compared to other sections. This is due to the characteristics of Section 1, which represents the largest load on the feeder. Therefore, when the rooftop PV system supplies a large amount of power, any surplus not consumed locally flows back to the main distribution network. Reverse power begins to be detected when rooftop PV penetration reaches 30%. Section 1 exhibits a significant shift in power flow at this point.

For lower penetration levels (0% to 20%), Section 1 still draws power from the grid (positive MW values). However, at 30% penetration, the active power value becomes negative, indicating the onset of reverse power flow at that section. From this point onward, the rooftop PV connected to Section 1

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generates more power than the local load demand, resulting in excess power flowing back into the distribution system. It confirms that at 30% penetration, Section 1 transitions from importing to exporting power, and the reverse power level increases sharply with higher PV penetration levels.

A similar pattern was observed in Section 6, which also began to experience reverse power flow at 30% penetration. Data show that Section 6 was still importing 0.098 MW at 20% penetration but shifted to exporting approximately –0.053 MW at 30%. This trend aligns with Section 1, reinforcing the evidence that at 30% rooftop PV penetration, a transition in power flow direction occurs at the PV-connected locations from power absorption to power injection into the grid.

Meanwhile, sections without rooftop PV systems, such as Sections 2, 3, 4, 5, and 7, continued to show positive power flow even at 100% penetration, indicating that reverse power primarily occurs at the points where PV is installed. The 30% level marks the threshold at which this effect becomes significant. The reverse power phenomenon is also observable as early as 10% penetration when four rooftop PV units are introduced into the system, indicating that higher PV penetration levels increase the likelihood of reverse power flow due to an imbalance between generation and local consumption [24].

The occurrence of reverse power flow can have several technical implications. It may interfere with conventional protection schemes designed for unidirectional current, potentially leading to maloperation or failure to detect faults. Voltage regulation equipment may also respond incorrectly, as traditional systems assume power flows from the substation to the load. Additionally, if not properly managed, reverse power can cause coordination issues between feeders, impact transformer tap settings, and contribute to system instability. These challenges underscore the importance of reviewing protection and voltage regulation strategies when planning for higher rooftop PV penetration.

V. CONCLUSION

The study indicates that the Salodong Feeder can accommodate rooftop photovoltaic (PV) penetration levels of up to approximately 30% of its installed capacity without exceeding acceptable limits for voltage deviation, harmonic distortion, or inducing significant reverse power flow. In light of these findings, it is recommended that a rooftop PV penetration level of 30% be considered the preliminary technical hosting capacity for distribution feeders with similar characteristics. For higher levels of PV integration, advanced mitigation strategies such as smart inverter controls, Volt-VAR optimization, or the integration of battery energy storage systems should be implemented to maintain power quality and system reliability. Additionally, protection systems must be reviewed and upgraded with bidirectional relays to effectively handle potential reverse current scenarios. These findings can assist PLN in planning rooftop PV installation quotas more accurately while ensuring the distribution network operates within technical limits. By adopting the 30% penetration threshold as a technical reference, PLN can support the acceleration of rooftop PV adoption across similar feeders without compromising grid stability. Furthermore, this strategy will contribute significantly toward achieving Indonesia's national renewable energy mix target of 23% by 2025.

ACKNOWLEDGMENT

The authors thank PT PLN (Persero) for supporting this research.

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