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Quasi-dynamic hosting capacity in radial distribution feeder

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Abstract

The target of massive installation of renewable energy is the focus of this research. Several industrial sectors continue to install photovoltaic rooftop to support green energy. One of the main objectives of this research is to see the maximum impact of installing a photovoltaic rooftop at 1 point of customer and spread capacity for each customer. This research uses a radial distribution network system that closely resembles the distribution network in Indonesia, where the load profile considers the load characteristics of industrial, commercial, and residential loads. This study uses the line equation theorem method to calculate the voltage rises by considering two current measurement points: the current at the end and the current at the base. The obtained voltage rise is then accumulated to be summed up with the customer afterward. The results are obtained by considering three scenarios: 1) voltage limits, 2) voltage limits and line loading, and 3) voltage limits, thermal, and harmonics in accordance with regulations. The obtained results are closely aligned with the simulations performed on the hosting capacity software such as DIgSILENT.

Keywords: photovoltaic rooftop; line equation theorem; hosting capacity.

I. Introduction

The installation of renewable energy distributed generators continues to increase until 2025 by 23 % based on the 2023-2030 national electricity supply business plan (RUPTL) [1]. This is to reduce the existence of a carbon tax of IDR 30 per kilogram [2]. Based on Indonesian Ministry of Energy and Mineral Resources (ESDM) regulation [3], kWh exports have been expanded from the previous limit at 65 % to 100 % of the power capacity that can be generated per customer. The increase in the allowed installation capacity of photovoltaic is an appreciation of the growing for users of clean industrial services with green energy. To find out the maximum limit capacity of customer installation without causing a violation, the hosting capacity approach theorem is used for this research.

According to research [4][5], hosting capacity is a high penetration limit regarding new renewable energy (EBT) without causing a violation. Some problems and limitations in the customer's operations include voltage below the limit, network losses, overload on transformers and feeders, protection failures, and harmonics exceeding grid code standard limits [6][7].

The update in this research is to calculate the hosting capacity at the limits of each customer. This method considers the measurement of the load current at the end customer and the load current at the first customer by the line equation theorem method [8]. Furthermore, for the system to be implemented close to the real system, the results of each customer's hosting capacity are calculated and validated within 24 hours [9][10][11].

II. Materials And Methods

Hosting capacity is a limiting curve for installing DG capacity that can still be accepted based on performance indication criteria on the system [12][13]. The concept and idea of contributing to this research are shown in Figure 1, which explains the concept of dynamic hosting capacity by calculating the amount of capacity per 24 hours for each customer. In the spread of the capacity, both in a

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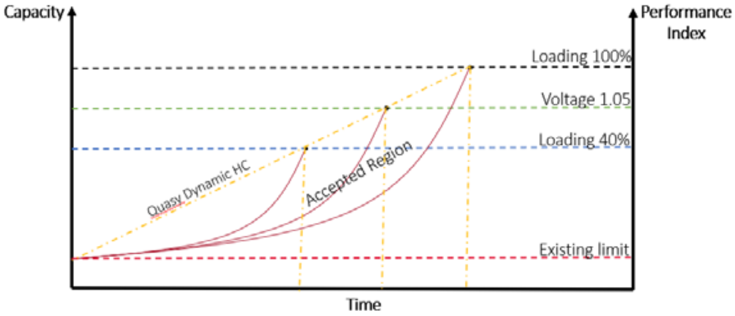

Figure 1. Dynamic Hosting capacity concept

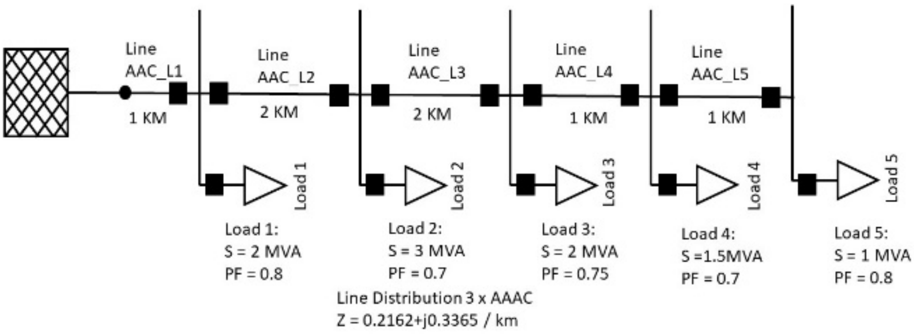

Figure 2. Radial distribution system 20 kV

maximum at one customer point and each customer as a maximum simultaneous capacity.

The radial distribution system modeling closely represents the real network system, as shown in Figure 2, which consists of five customers, with each customer having a different distance. This model also has different customer capacities.

This model is used as a model close to the real distribution system in Indonesia based on the type and capacity of customers. The network voltage system used in the simulation is 20 kV, following the standard medium voltage distribution network [14].

A. Voltage increase calculation

In the hosting capacity equation, equation (1) is used to calculate the amount of distributed generation (DG) capacity for each customer based on the voltage increase (△V) with the line equation theorem approach. This voltage increase calculation considers the two measurement points, namely at the beginning current and at the end current of the customer's load [15]. Equation (2) was used to calculate each Node where the tangent line meets. Equation (2) is calculated using the theorem of the derivative function, which then obtains equation (3) as the final derivative function. In equation (3), the value of the increase in the voltage difference due to PV injection on the customer bus is obtained.

$$y_1 - y_2 = m(x_2 - x_1) \quad (1)$$

$$dy = I_p + \frac{I_u - I_p}{d}\, d\, dx \quad (2)$$

$$\Delta V = Z\frac{d}{2}(I_p + I_u) \quad (3)$$

where y_1, y_2, x_1, x_2 are points between parts that adopt from the line equation theorem. y_1, and y_2 represent points on the vertical axis y, and x_1, x_2 represents points on the horizontal axis x. while m represents the gradient. dy is the derivative of equation (1) with to dx function.

Figure 3 is a sample from two customer measurement points. The modeling of several customers is shown in Figure 4. The equation formula was given for the value of the total voltage increase based on equation (4), which is used based on the total number of subscribers to the voltage increase of each installed PV.

$$\Delta V_{tot} = Z_1 \int y_1 + Z_2 \int y_2 + Z_3 \int y_3 + Z_4 \int y_4 + Z_5 \int y_5 \quad (4)$$

where ΔV is the increase in voltage due to injection of the spread generator (Volt), Z is the network impedance value (Ω), d is the total distance of the end customer to the substation (km), I_p is base current (A), and I_u is the end current (A).

B. Calculation of dynamic hosting capacity

According to papers [11][16][17], using hosting capacity calculations based on Kirchhoff Voltage Law (KVL) calculations can be applied to find voltage solutions on the point of common coupling (PCC). PCC is a connected point due to the installation of photovoltaic. By representing resistance and

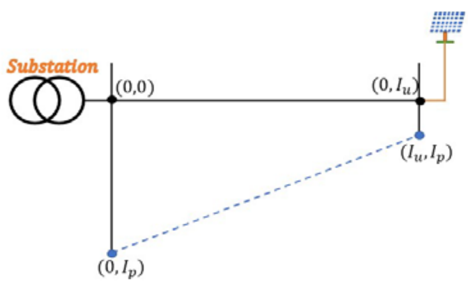

Figure 3. PV injected into the bus

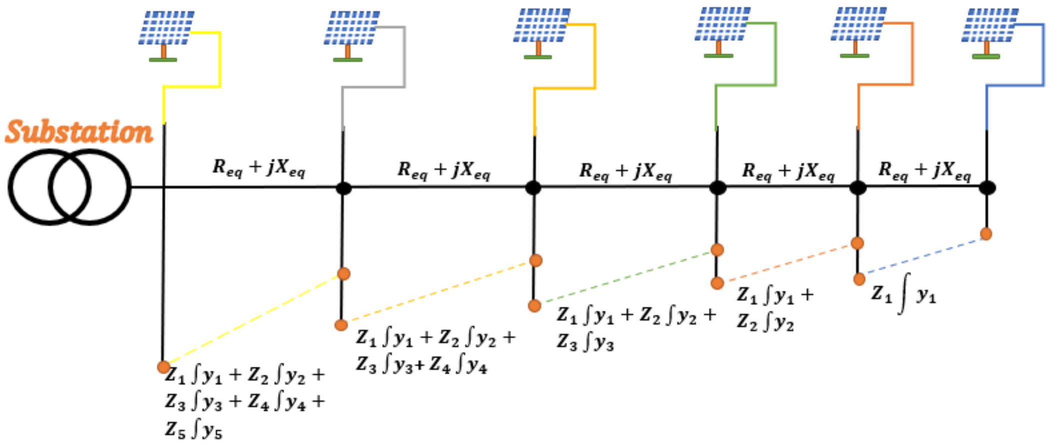

Figure 4. PV injected in each of the customers

reactance in terms of R_{eq} and X_{eq}, considering $U_{grid}\angle 0^0$ or as a slack bus. it can be written in equation (5),

$$P_g^{max,1} = \sum_{h=1}^{h=24} \frac{V_n^{max,1}(V_n^{max,1} - V_g^1)}{R_{eq} + X_{eq}\tan(\varphi)} \tag{5}$$

where $P_g^{max,1}$ is the maximum capacity of the injected hosting capacity (kWp), $V_n^{max,1}$ is the voltage on the slack bus from the grid (kV), V_g^1 is the voltage rise due to DG injection (kV), R_f is the conductor resistance/km (ohm), X_f is the conductor reactance/km (ohm), and $\tan(\varphi)$ is the power factor value at PCC.

C. Short circuit contribution current

Calculation of short circuit current considers based on calculations in the DIgSILENT software. This short circuit current is calculated based on the IEC 61909 standard in 2021. Research [18], the calculation of the short circuit contribution current is calculated based on equation (6),

$$1 - \left(\frac{I_p}{E_s}\right) * ZB \tag{6}$$

where, I_p is the pickup relay current, E_s is the value of the phase–neutral voltage from the source, and ZB is the value of the branch impedance.

D. Harmonic contribution

Harmonics is one of the constraints in this research. This constraint is used to maintain maximum capacity limits that are still safe and reliable when customers install their respective rooftop solar capacity. Moreover, the existence of harmonics, besides distorting the voltage and current waves, will cause heat to occur in equipment components such as transformers. The calculation of the harmonic limit of the total distortion demand is as in equation (7) [19][20],

$$TDD_i = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_L} \tag{7}$$

$$THD_i \; x \; i_1 = THD_i \; x \; I_L \tag{8}$$

where TDD_i is total demand distortion, I_n^2 is nominal current (A), I_L is current in each of the customers (A).

To calculate the amounts of harmonics from the total harmonic distortion (THD), it is formulated in equation (8).

E. Flowchart of this research

The research flowchart in Figure 5 is a simulation of workflow steps to calculate the amount of voltage increase due to distributed generation (DG) injection. The capacity of each customer is calculated based on the voltage increase on the PCC bus. The maximum allowable voltage increase is the reference for the purpose of hosting capacity. The data used to calculate this voltage increase is based on the current on the customer's end and the current on the customer's base.

F. Profile characteristic

The type of profile curve is presented in Figure 6, which contains three types of loads. The data is taken with the average data for one year. The data presented is the average peak load time. The value presented is the expense on weekdays, namely on Mondays.

The load profile characteristic is displayed in Figure 6. The data was obtained from the typical data of each customer load. The data was inputted into the load profile in software simulation.

The characteristics of the photovoltaic rooftop profile used in this study are based on the measurement points on the Indonesian solar map, which are presented in Figure 7. At the point of measurement results, an approach is used to be input as a parameter for the characteristics of solar panels based on the load profile category, namely residential, industrial, and commercial. The data was taken on March 22, 2022.

G. Constraint

1) Voltage

The distribution voltage constraint in the standard distribution system is set based on the voltage level. In a distribution system with a voltage of 20 kV, the system voltage is maintained based on the grid code or network interconnection rules: $0.9 \; or \; 18 \; kV \le V_{grid} \le 1.05 \; or \; 21 \; kV$ [3].

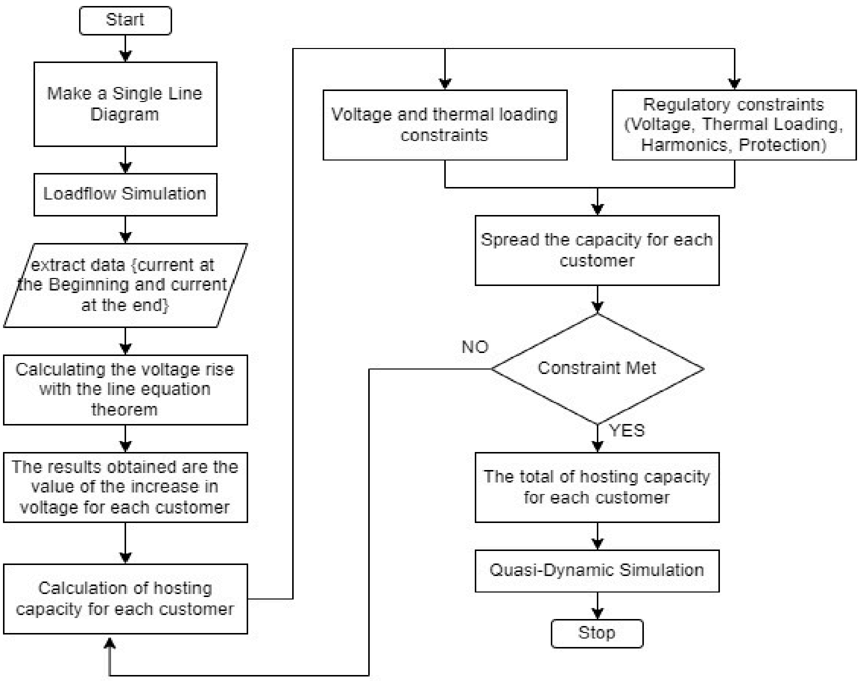

Figure 5. Flowchart of the research

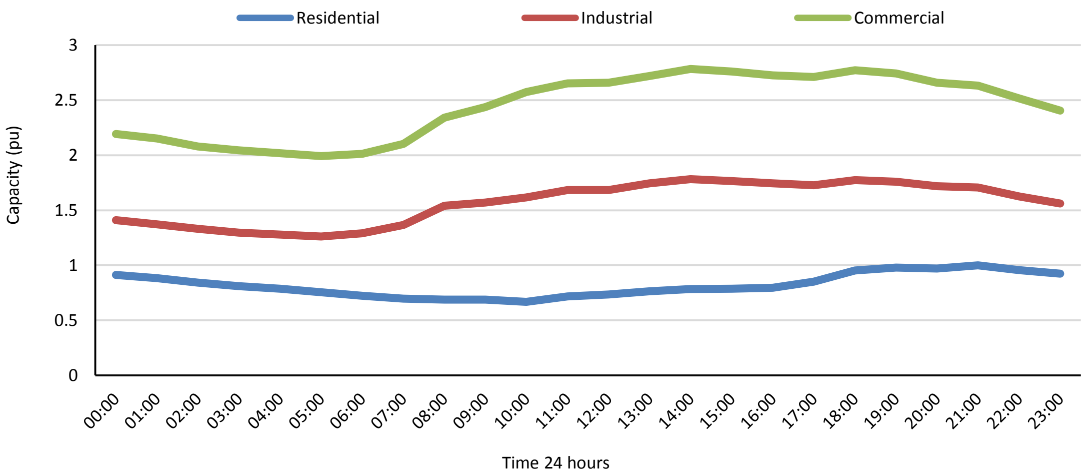

Figure 6. Load profile characteristic

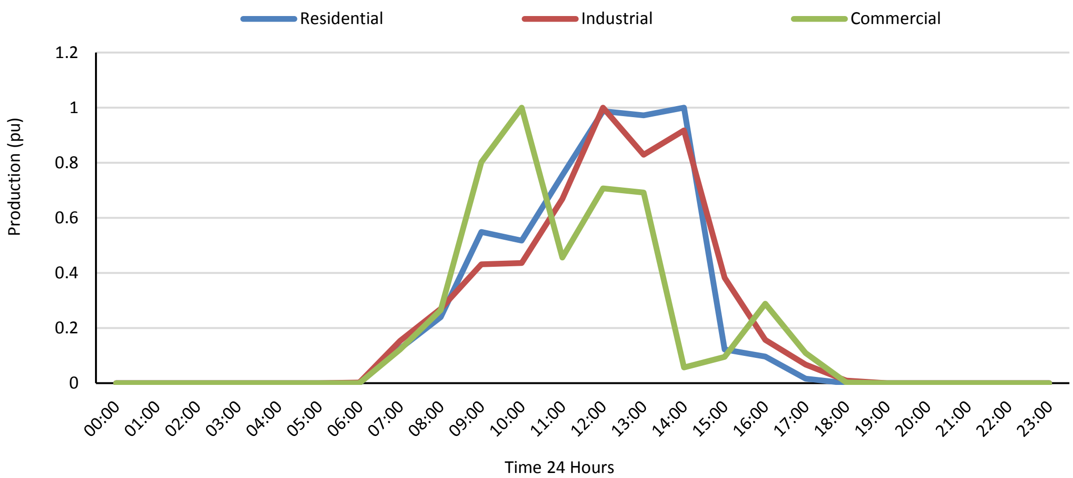

Figure 7. Photovoltaic profile characteristic

2) Thermal loading

The thermal loading limit is based on the maximum integration standard of renewable energy, set to maintain line loading, and the temperature in the distribution feeder is maintained. It is necessary to limit the influence of the installation capacity that enters and is connected to the distribution network. Based on the grid code [3], the value of the thermal loading limit $Line_{\_Loading} \leq 40\ \%$

3) Harmonic

Harmonics is one aspect of electric power quality in distribution feeders. Harmonics arise from non-linear loads or power electronic components connected to the network. In this research, the harmonics aspect is limited due to the installation of photovoltaic capacity in the distribution system. Based on network rules (grid code), total harmonic distortion (THD) ≤ 5 % [3].

4) Harmonic data simulation

In modeling harmonics caused by solar photovoltaic injection, the pulse-6 harmonic model is used in this paper [21]. The harmonic frequency values are presented in Table 1, which is the dummy data used in the injection of harmonics in the generator is the fundamental current harmonics for balanced and unbalanced.

The 2-pulse bridge data is used because this type of harmonics for solar photovoltaic has a sequential order of harmonics starting from the 3rd order. The 2-pulse bride order used, as shown in Table 2, has a maximum order of harmonics up to the 50th order. This research uses these data as content data for generator harmonic distortion.

Table 1.
Load harmonic data

Harmonics order	Ia_h (%)	Ib_h (%)	Ic_h (%)
1	100	100	100
2	20	20	20
3	10	10	10
5	80	80	80
7	60	60	60
9	30	30	30

Table 2.
Photovoltaic harmonic data

Harmonics order	Ia_h (%)	Ib_h (%)	Ic_h (%)
3	33.333	33.333	33.333
5	20.000	20.000	20.000
7	14.286	14.286	14.286
9	11.111	11.111	11.111
11	9.091	9.091	9.091
13	7.692	7.692	7.692
15	6.667	6.667	6.667
17	5.882	5.882	5.882
19	5.263	5.263	5.263
21	4.762	4.762	4.762
23	4.348	4.348	4.348
25	4.000	4.000	4.000
27	3.704	3.704	3.704
29	3.448	3.448	3.448
31	3.226	3.226	3.226
33	3.030	3.030	3.030
35	2.857	2.857	2.857
37	2.703	2.703	2.703
39	2.564	2.564	2.564
41	2.439	2.439	2.439
43	2.326	2.326	2.326
45	2.222	2.222	2.222
47	2.128	2.128	2.128
49	2.041	2.041	2.041

III. Results and Discussions

The time used in this calculation is 14.00, during peak load times of the day. Because when the calculation is done, namely estimating the current on the end side customer and the current on the base side customer. The data used for calculations are based on the peak load current during overload conditions.

A. Scenario 1: Voltage constraint

The hosting capacity calculation in this scenario is determined by the voltage limit standard. This scenario uses grid code rules with a minimum voltage of 0.9 p.u. and a maximum voltage of 1.05 p.u., It is important to note that the case study used a distribution system close to the real system on a 20 kV distribution network in Indonesia.

1) Quasi-dynamic simulation in customer 1

The installed capacity of the first customer is 328.26 MWp. The Quasi-dynamic simulation results, shown in Figure 8, indicate that the highest voltage recorded is 1.05 p.u. at 14:15. Furthermore, the peak voltage value observed on customer 1 at 14:00 is determined by the characteristic curve in photovoltaic 1.

2) Quasi-dynamic simulation in customer 2

The maximum capacity for customer 2 is 118.38 MWp. The highest voltage value at the maximum point on the 2nd customer is 1.05 p.u at 10:00. Installation of photovoltaic rooftop capacity for the 2nd customer is shown in Figure 9, when the highest voltage profile curve on the 2nd customer where the PV was installed.

3) Quasi-dynamic simulation in customer 3

The maximum installation capacity of photovoltaic rooftop for customers is calculated to obtain a maximum capacity of 75.038 MWp. At the voltage limit, the peak voltage value is still in the maximum range of 1.05 p.u at system voltage, as shown in Figure 10.

4) Quasi-dynamic simulation in customer 4

Calculation of the capacity of the 4th customer taking into account the voltage limit; the result is 62.285 MWp. These results are simulated for 24 hours. The highest voltage results are shown in Figure 11, which shows a maximum voltage of 1.049 p.u.

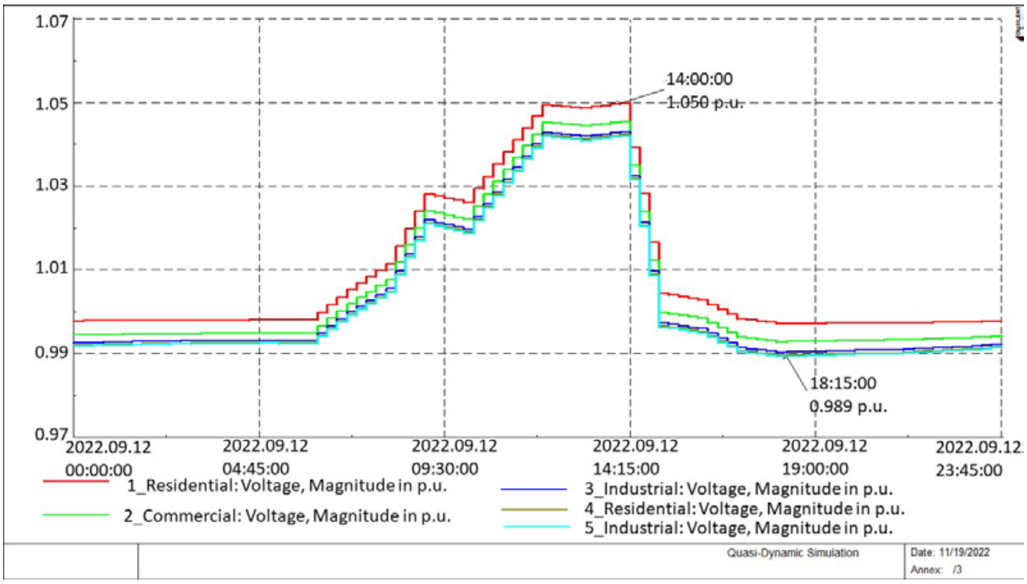

Figure 8. Voltage profile in customer 1

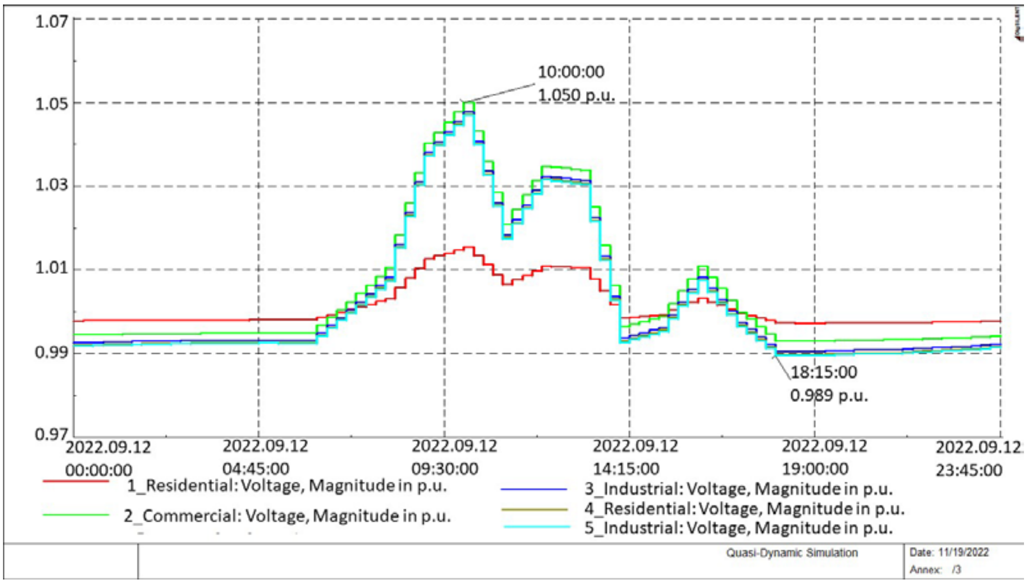

Figure 9. Voltage profile in customer 2

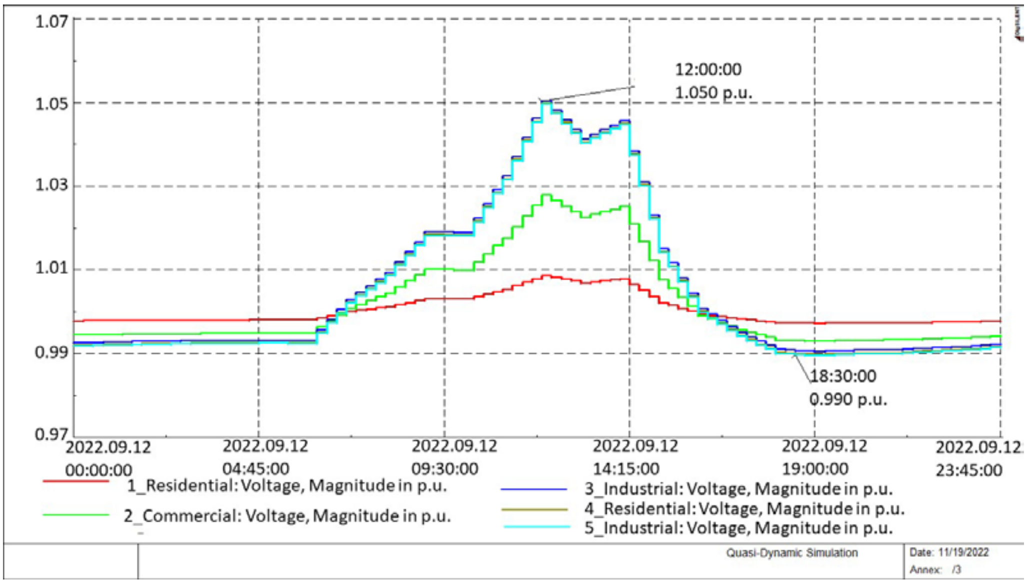

Figure 10. Voltage profile in customer 3

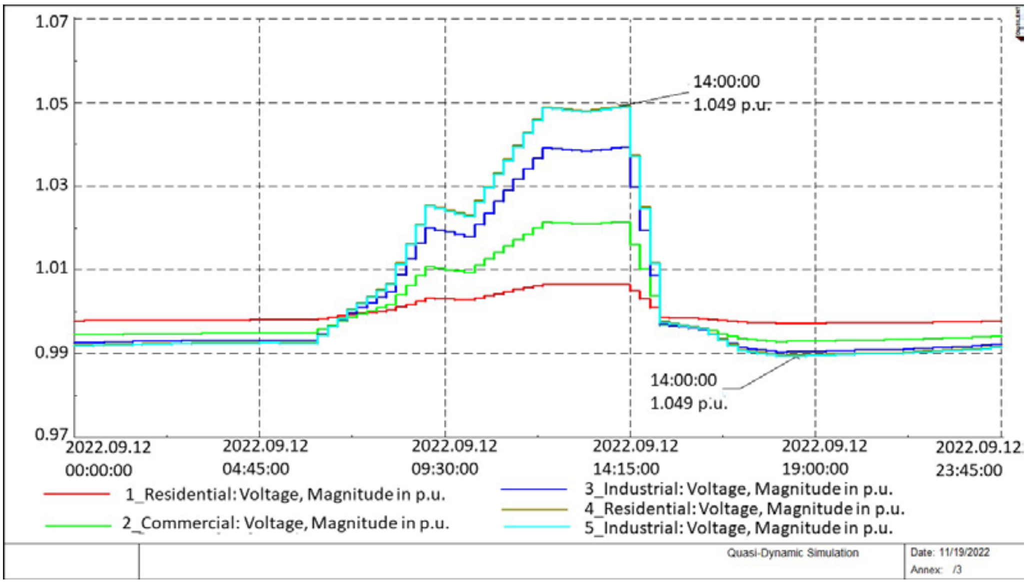

Figure 11. Voltage profile in customer 4

5) Quasi-dynamic simulation in customer 5

Calculations performed on the 5th customer obtained a maximum capacity of 38.535 MWp. In Figure 12, the highest voltage value is 1.034 p.u. it is to be noted that the last customer does not experience any additional voltage increase (△V) from other customers. As a result, the voltage value for the last customer has a different value from the results obtained from the simulation.

6) Spread capacity in each customer

The distribution of capacity in each customer is determined based on voltage considerations. Equation (9) outlines the distribution calculation, where the spread of capacity is divided from each maximum point in each customer to the total photovoltaic capacity.

$$PV\ capacity = \frac{Maximum\ 1\ point}{total\ PV\ capacity}\ x\ maximum\ pv\ capacity \quad (9)$$

The capacity of each customer is simultaneously simulated over a 24-hour period, as illustrated in Figure 13. The spread of capacity in each node can be seen in Table 3. The objective is to evenly allocate the total capacity among the customers. The capacity for each customer is calculated, and a single diagram modeling approach is employed to simulate the results. Based on the calculated capacities, the assumed distribution is implemented, and the results are run in the software.

Table 3.
Spread photovoltaic capacity in each customer

Customer at node	HC (MWp) DIgSILENT	HC (MWp) mathematics	Spread (MWp)
1	327.00	328.260	169.00
2	120.00	118.380	22.70
3	75.86	75.038	9.13
4	64.18	62.285	6.29
5	55.38	38.535	2.41

*HC = Hosting Capacity

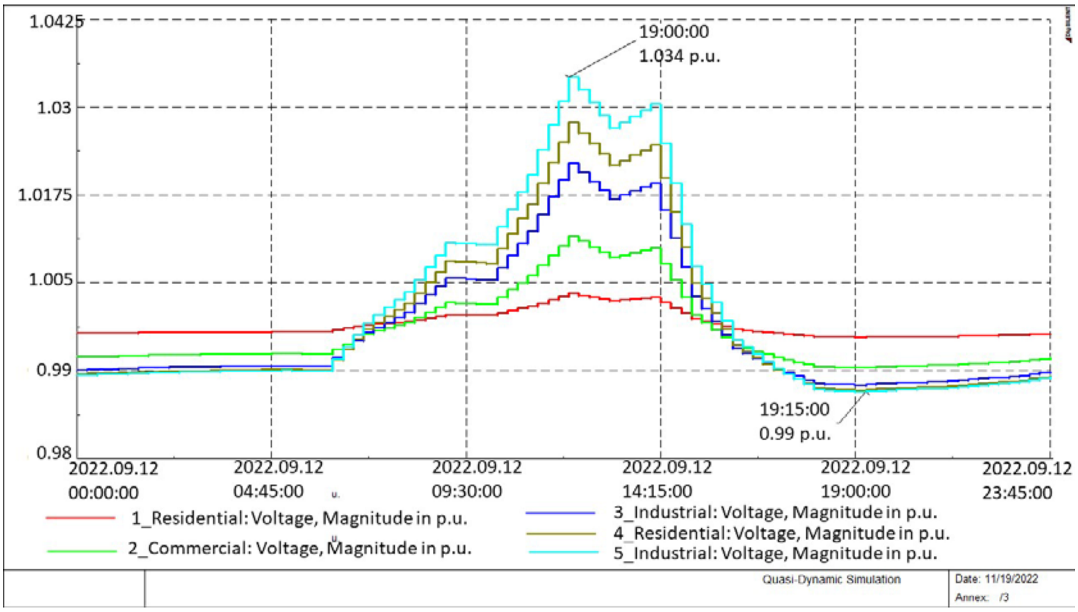

Figure 12. Voltage profile in customer 5

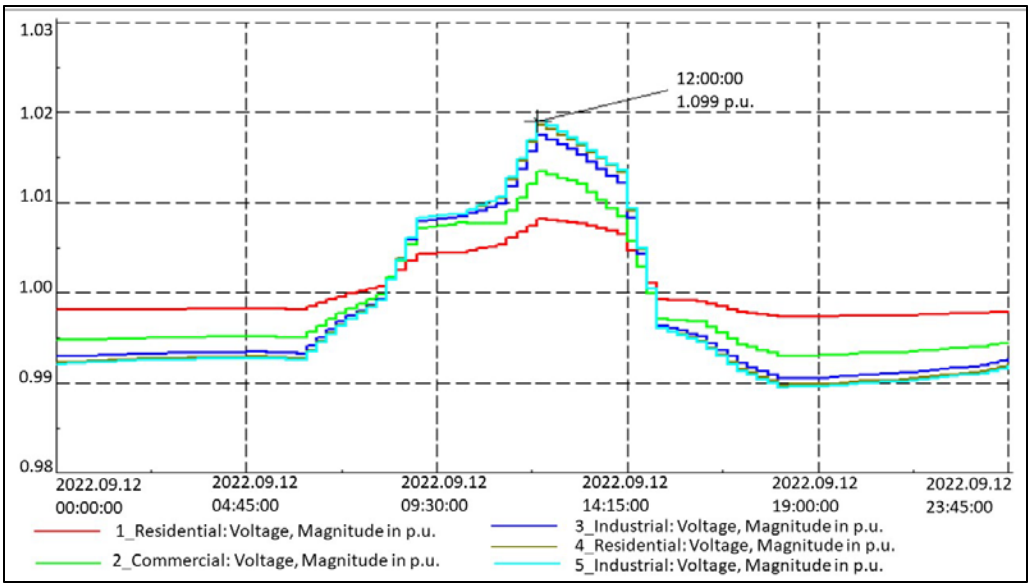

Figure 13. Quasi-dynamic in photovoltaic spread of customer

B. Scenario 2: Voltage, thermal loading, harmonic, and protection

This scenario considers the existence of renewable energy interconnection to the system based on regulations (grid code). The constraints determined are Voltage, Thermal Loading, and Harmonics. The calculation analysis takes into account the simulation results performed on the DIgSILENT software.

1) The difference between calculation and simulation results

The results obtained from calculations and comparisons in the software are presented in Table 4. In the calculations using equation (9), the results are not close or have many differences to the end customer. It is because the end customer does not have added value (ΔV). The spread capacity of each customer, multiplication of the maximum number of 1 point of photovoltaic rooftop capacity divided by the total photovoltaic rooftop multiplied by the highest maximum capacity. Table 4 also shows the spread of the capacity in each customer.

Table 4.
Spread photovoltaic capacity for each customer

Bus	HC (MWp) DIgSILENT	HC (MWp) mathematics	Spread (MWp)
1	23.96	23.5010	9.5500
2	13.28	13.2780	5.3961
3	8.36	8.3678	3.4005
4	7.07	7.1793	2.9174
5	6.11	5.5049	2.2370

*HC = Hosting Capacity

2) Quasi-dynamic results for scenario 2

The results of the simulation are shown in Figure 14. It can be seen for the highest voltage at industrial loads with a value of 1,003 p.u. Meanwhile, at the lowest voltage, the industrial load is also with a voltage value of 0.994 p.u. This highest rise is based

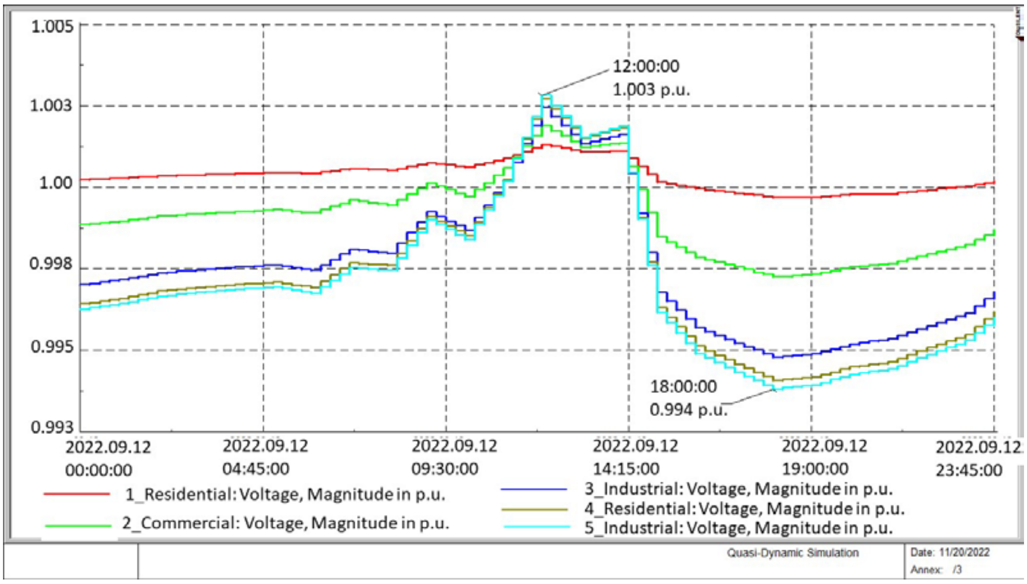

Figure 14. Voltage profile in 24 hours

on the highest load profile when the load characteristics are applied. The voltage values obtained are still in the range of standard PLN (SPLN), where the range of tolerance of the voltage with a minimum drop of 10 % and a maximum increasing 5 % from the basic nominal voltage value.

The results of the line loading values are shown in Figure 15, indicating that the highest loading values occur on cable 1 at 39.556 %. On the other hand, the value for the lowest thermal loading can be found on cable 5, which a value of 1.369 %. This discrepancy can be attributed to the fact that customer-1 has the largest generation capacity, resulting in a large channel load. The obtained results were compared to the standard grid code, and it was determined that the values are still in the range of safe operation. Therefore, it is suggested that the calculated capacity can be implemented in real cases.

According to the interconnection rules for renewable energy generators (grid code) [3], the allowable tolerance limit for harmonics when the voltage at the connection point ≤ 66 kV is 5 %. Figure 16 shows that the highest voltage distortion occurs at 0.04 s of 36,329 kV. In this case, the virtual voltage measurement point is installed on the bus for each customer.

Based on the obtained results, it is evident that the voltage is still within the safe range of harmonics. This is because the harmonics contained due to the injection of photovoltaics are still within the safe limits. Furthermore, Figure 16 also indicates the presence of a very few harmonic frequencies in 1 wavelength.

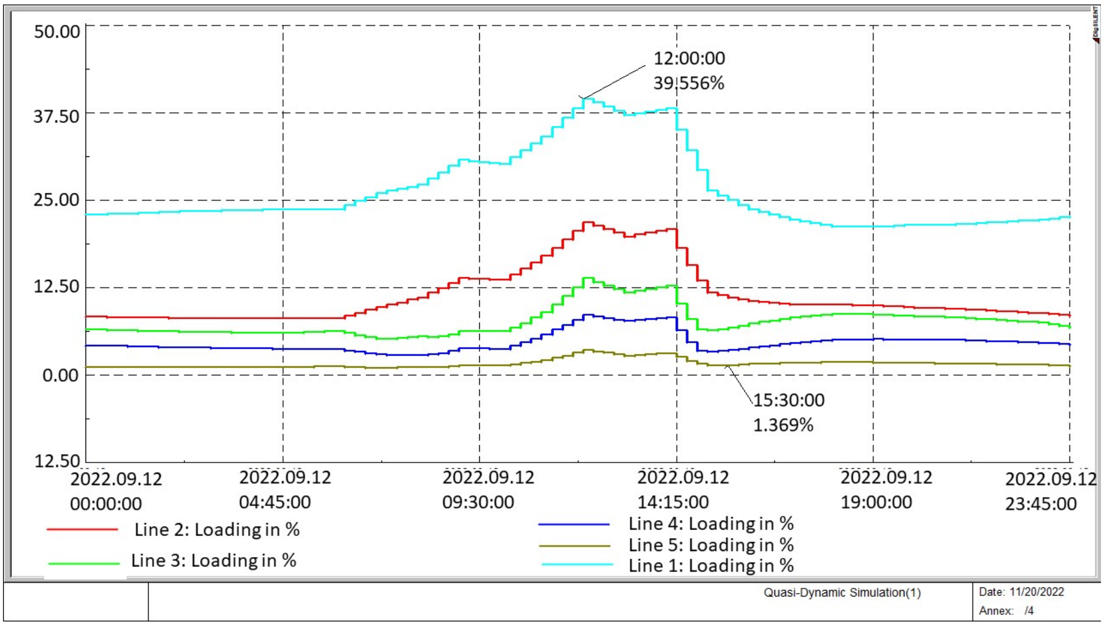

Figure 15. Thermal line loading

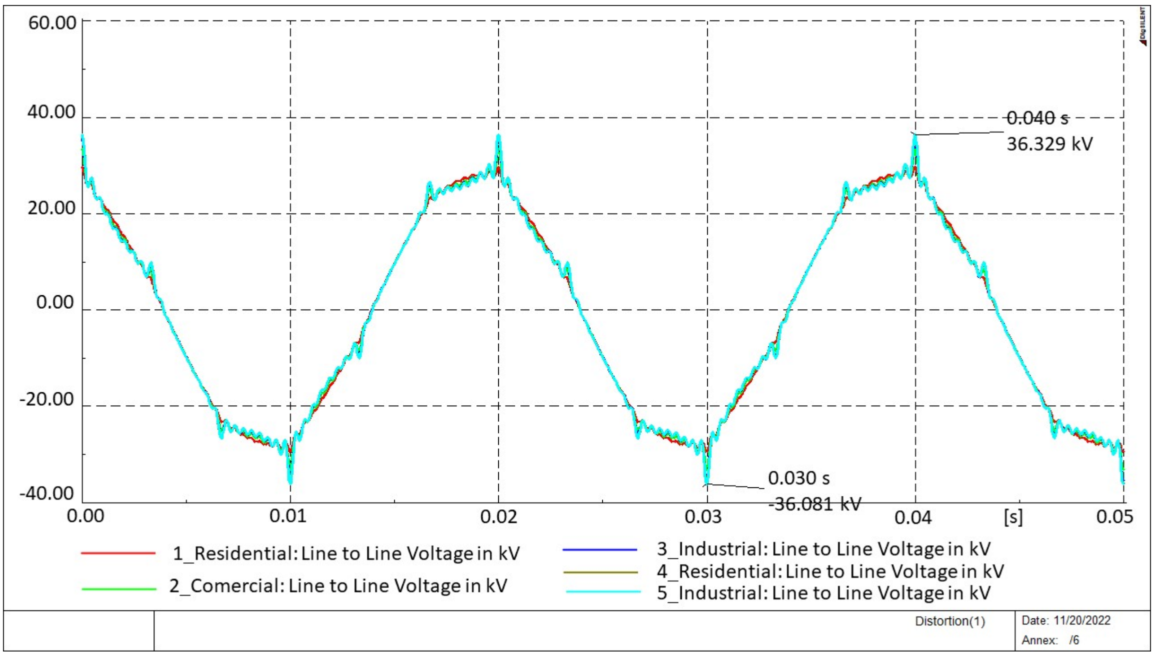

Figure 16. Voltage harmonic distortion

IV. Conclusion

In the simulation, the results for voltage limits were obtained. It was found that the photovoltaic capacity with voltage limit, with quasi-dynamic simulation for each customer, still met the +5 % and -10 % standards. The highest voltage value in Scenario 1 is 1.05 p.u. at customer 1, customer 2, and customer 3. In Scenario 2, the highest voltage result is 1.003 p.u. and the lowest is 0.994 p.u. The highest network load results were 39.558 %, and the lowest was 1.369 %, while the harmonics level with a line-to-line voltage of 36.329 kV. Both of these scenarios are still within the limits of network standards.

Declarations

Author contribution

R. Khomarudin, K.M. Banjar-Nahor, and N. Hariyanto contributed equally as the main contributor of this paper. All authors read and approved the final paper.

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Additional information

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