Community-Based Solar Photovoltaic Distributed Generation and its Effect on Distribution

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ABSTRACT

Utilization of solar home system (SHS) can be increased through government policies implemented on residential customers with an R3 rating, urging them to invest in solar photovoltaic (PV) power plants using 5%, 10%, and 15% of the standard total house construction price. The selection of customers with an R3 rating is due to the high initial cost of installing solar PV and insufficient financing opportunities for renewable energy projects exist due to the lack of adequate resources allocated by local banks. But there were other things that must be considered in regard to SHS penetration's impact on the distribution network, which could result in negative impacts, namely effect on voltage, power factor, and loads. The study would like to determine the impact of PV system penetration on the distribution network, identify the level of PV system penetration that is compliant with prevailing regulations, and determine whether the investment policy of PV systems for R3 rating customers can be implemented without disrupting the distribution network. In the study, power penetration was simulated using ETAP software to determine the impact on distribution network. Simulation uses the distribution network data of Bantul Power Station feeder, coded BNL and using BNL1, BNL2, BNL3, BNL5, BNL14, and BNL17 as the network test, and electricity customers in the region especially with an R3 rating. The simulation was carried out by adding solar PV generation to the feeder with an investment of 5%, 10%, and 15% of USD 35,000, assuming all distribution network expenses come from R3 customers. Result shows that the solar PV investment policy was considerable safe at 5% investment in all feeders even though power penetration affects the voltage, power factor, and conducting load. However, four feeders at 10% investment and all feeders at 15% investment exceed the power factor tolerance, thus give alert to distribution network.

1. INTRODUCTION

Indonesia's policy on renewable energy (RE) has not been firmly established. Rather than increasing RE contributions, the alteration in policy has decreased the RE investment in Indonesia since 2015 [1]. It is further supported by the newly approved policy stating that exporting electricity from community rooftop photovoltaic (PV) systems to the distribution network operator will not be compensated. Although in previous policy, community rooftop PV systems was allowed to sell their electricity to Perusahaan Listrik Negara (PLN), the sole distribution network operator in Indonesia.

Several studies have been made to support policy on RE [2]–[5], which has proposed energy conservation by reducing energy consumption. However, with the rise in technology and people mobility, reducing energy consumption will prove challenging due to the rapid population mobility and extensive utilization of technological advances, which will require extensive energy. Meanwhile, research proposing energy substitution and its policy regulation has been conducted to fulfill the energy demand [6], [7], which aims to propose and investigate various investment scenarios in installing PV generation based on total average house price. It has been demonstrated that the proposed scenario is feasible for on-grid systems, but not for off-grid systems due to the extra costs for batteries.

Also, Pepermans *et al.* [8] described policy issues that should be concerned resulting from distributed generation investments, and [9], [10] examines the impacts of a grid-connected solar PV generation to the distribution network. Some of the negative effects that can occur include reverse power flow, network feeder over voltage, power losses, phase imbalance,

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problematic voltage control, problematic power quality, and reactive power increase. Thus, this study aims to determine the impact of PV system penetration on the distribution network, identify the maximum level of PV system penetration that is compliant with prevailing regulations, and ascertain whether the PV system investment policy for the middle-class and above can be implemented without disrupting the distribution network.

2. DESCRIPTION OF STUDY AREA

Geographical variables were found to be a big barrier during the study. Therefore this study was limited to a specific area in Bantul, Yogyakarta.

2.1 Geographical Background

PV generation has been proven to contribute to global energy demand as one of the main renewable energy sources, and best applied in the equatorial region. As also the case in other region of Indonesia, sun rays can be harvested throughout the year and proven to be sustainable [11]. Bantul is one of five districts in Yogyakarta Province, located in the southern region with a relatively flat landscape. Yogyakarta lies between the Merapi Volcano to the north and the Indian Ocean to the south, mainly situated in the center of Java Island. Owing to this condition, Bantul is an ideal location for PV generation installation.

2.2 Economical Background

Energy provision through solar PV generation is proposed due to its long life cycle and abundance of solar radiation. Accordingly, various schemes for reducing poverty by providing access to renewable energy, including solar PV generation, have been investigated [12]–[14]. Rural community electrification project on solar PV generation, has experienced problems with its financing mechanisms, which only about installation costs, but fails to consider maintenance and operational costs, as well as a lack of competence amongst local communities and inadequate project evaluation. Also, the primary resource for solar PV is free, but the initial generation costs are high. Thus, the high initial costs and the inadequate financing opportunities for renewable energy projects, due to the lack of sufficient resources allocated by local banks, are the reasons why only the upper class has been considered in this study.

Government of Indonesia (GoI) differentiates the electricity tariff for residential depend on the registered installed capacity and subsidy allocation for each household. There are three rating categories, namely R1, R2, and R3 rating, three categories for subsidy allocation, and four different electricity tariff per kilowatt hour (kWh). As a reference, residential tariff can be found in Table 1.

According to Statistics Indonesia, Yogyakarta indicated a negative growth during the second quarter of 2021, including Bantul, amidst the devastating COVID-19 pandemic. However, Indonesia's economy has grown gradually, indicating a recovery for the population [16], [17]. Along with it, residential customers with the highest rating, R3, have been increasing over the decade and are projected to continue increasing. Yogyakarta also showed a similar increase of 16% in its R3 rating, with Bantul consistently having a lower increase than the province average [18].

Table 1. Tariff category in residential. [15]

Rating	Installed Capacity	Cost per kWh
R1	450 VA	lowest tariff, highest subsidy
R1	900 VA	lower tariff, lower subsidy
R1	1300-2200 VA	average tariff, no subsidy
R2	3500-5500 VA	higher tariff, no subsidy
R3	6600 VA and above	higher tariff, no subsidy

3. METHODOLOGY

3.1 Technology

Distributed generation has been proposed and investigated in many research, including [19] and [20], which analyzed distributed generation from several power plants to reduce power losses using fuzzy theories. Theoretically, this method could result in significant power losses reductions. Other research has investigated that distributed generation needs to be regulated to promote economic efficiency and ease of use while avoiding potential negative impact that may arise during operation [21]–[23]. Moreover, distributed generation has several parameters that must be kept in balance for performance considerations, including voltage, current, and frequency. Delfanti *et al.* [24] and Mahat *et al.* [25] concluded that distributed generation could potentially give poor performance due to the frequency difference generated by multiple power plants.

3.2 Data Preparation

Power distribution networks are typically divided into two parts: medium-voltage and low-voltage distribution, while high-voltage distribution is generally referred to as transmission system. Medium-voltage distribution uses three-phase, four-wire systems with a potential difference between neutral and each phase of 20 kV. In Indonesia, the standard of low-voltage distribution is using 220 V potential difference with three-phase, four-wire systems or one-phase systems. This information was available in PLN as per request.

Data for the study was obtained from PT PLN UP 3 Yogyakarta in the form of load distribution, length of distribution lines, and secondary data of distribution network diagram. The data was then entered, re-drawn and simulated in Electric Transient and Analysis Program (ETAP) 12.6 software. The distribution network diagram was developed according to transformer capacity, feeder load, and feeder length. The main components utilized in the ETAP 12.6 software for creating single line diagrams were grids, power transformers, transmission cables, loads, and PV generation, with the following specifications:

- Grid: 150 kV
- Power transformer: 60 MVA 150/20 kV
- Transmission Cable: 240 mm2 AAAC

The diagram was created using the ANSI project standard with a network frequency of 50 Hz. The load along the feeder line was distributed with a load concentration system in three distinct locations (zones) as depicted in Figure 1. The load was divided into three zones to represent load positions, *i.e.* close to the feeder, the middle load, and the end of the feeder. Distance between each zone was obtained by dividing feeder length into three for an equal distance between each zone in a single feeder. However, the distance between zones in different feeders will vary depending on the length of the feeder. The load installed was based on the PLN's load data, which included transformer load in distribution networks, then distributed among three load concentration zones receiving one-third of the total load of the feeder, as shown in Table 2.

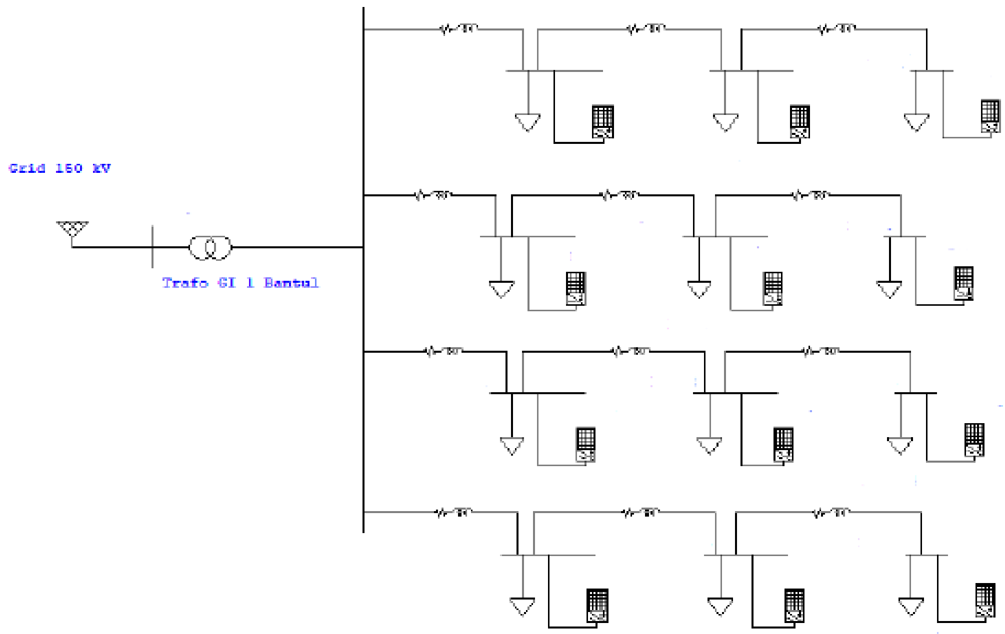

Fig. 1. Single line diagram for simulation.

Table 2. Load for each zone [26].

Feeder	Load (A)					
	Total			Zone		
	R	S	T	R	S	T
BNL01	120	89	116	40	29.67	38.67
BNL02	98	112	121	32.67	37.33	40.33
BNL03	115	103	121	32.67	34.33	40.33
BNL05	229	201	251	76.33	67	83.67
BNL14	84	56	65	28	18.67	21.67
BNL17	57	60	24	19	20	8
	Potential difference of phase – neutral: 11.55 V					

3.3 Solar Home System Assumption Design

An on-grid solar home system (SHS) was employed in the simulation, selected for its economic benefit when implemented on a home scale compared to an off-grid system, which requires expensive battery maintenance. According to the calculations, in order to achieve a 100% grid independent of R3 customers, the PV system must provide an average of 28 kWh/day, or investment of USD 24,000. However, this is more than half of what R3 customers usually pay to construct their home, so it would not be feasible for the majority of R3 homes [6]. Also, R3 customers maximum payment commitment is 15% of the total cost of house construction, which was assumed to be USD 35,000 [6]. Therefore, the study proposed 5%, 10%, and 15% of the total house construction and can be represented as USD 1,750, -, USD 3,500, -, and USD 5,250, -, respectively. The SHS installed capacity was obtained according to the level of investment, shown in Table 3.

The number of installed PV systems depends on the number of PLN customers in Class R3. To determine the number of PLN customers in Class R3, it is assumed that all loads on the feeder originate from R3 customers. Thus, the number of R3 customers can be determined by dividing existing load data by the R3 customer capacity. Due to this assumption, it is referred to as community-based solar PV distributed generation.

The existence of the solar PV distributed system on the single-line diagram is divided equally into three zones from its total capacity installed capacity and the total numbers of R3 customers on feeder line. The installation of the PV system also adheres to the zone of load installation, as indicated in Table 4.

Table 3. Cost and capacity assumption.

	5%	10%	15%
Number of panels	22	44	66
Number of inverters	2	4	6
Capacity	1,760 Wp	3,520 Wp	5,280 Wp

Notes:
1. PV panel cost USD 77 / panel
2. Inverter 1000 W cost USD 35
3. Price as of indicated when the research was done

Table 4. Total solar PV installed capacity per feeder.

Feeder	Number of Customers	Total Capacity (Wp)		
		5%	10%	15%
BNL01	568	999,680	1,999,360	2,999,040
BNL02	580	1,020,800	2,041,600	3,062,400
BNL03	558	982,080	1,964,160	2,946,240
BNL05	1192	2,097,920	4,195,840	6,293,760
BNL14	360	633,600	1,267,200	1,900,800
BNL17	247	434,720	869,440	1,304,160

3.4 Simulation

Simulation was conducted using a single-line diagram and the load flow method on the ETAP 12.6 software, with several considerations applied, including:

- Solar radiation is 4.8 kWh/m^2/s [27]
- Daytime load data
- Simulations were carried out based on existing load data
- Load power factor: 0.95
- Maximum voltage increase is 5%
- The minimum network power factor was 0.90 lagging
- Maximum carrier load is 50% of the current-carrying capacity

The flowchart in Figure 2 was carried out to investigate the effect of distributed generation penetration on feeder parameters, including voltage on the feeder, power factor on the transformer, and the load on the transformer and conductor. The data obtained from the simulation were then analyzed and compared for each investment level.

4. SIMULATION RESULT

Although the value changes of each variable are relatively small, excessive investment will certainly lead to greater solar PV power penetration, effecting voltage, power factor, and carrier load. In the study, the variable tolerance limits refer to the Minister of Energy and Mineral Resources (MEMR) Regulation number 20 of 2020 about Grid Code concerning rules of Jawa-Madura-Bali electric power system network and rules of Bantul distribution systemm. For nominal voltage in 20 kV, the voltage tolerance range is within the lowest maximum of -10% and the highest maximum of 5%, the power factor tolerance limit is a minimum of 0.90 lagging, the carrier loading limits is a maximum of 50% of the conductor capacity usedacity used. The conductor used in Bantul distribution network is AAAC with a cross-section area of 240 mm2 which has a current-carrying capacity of 585 A, thus the limits of conductor loading are 292.5 A [28]. Data obtained from the simulation shows that several variables were affected by the PV generation penetration.

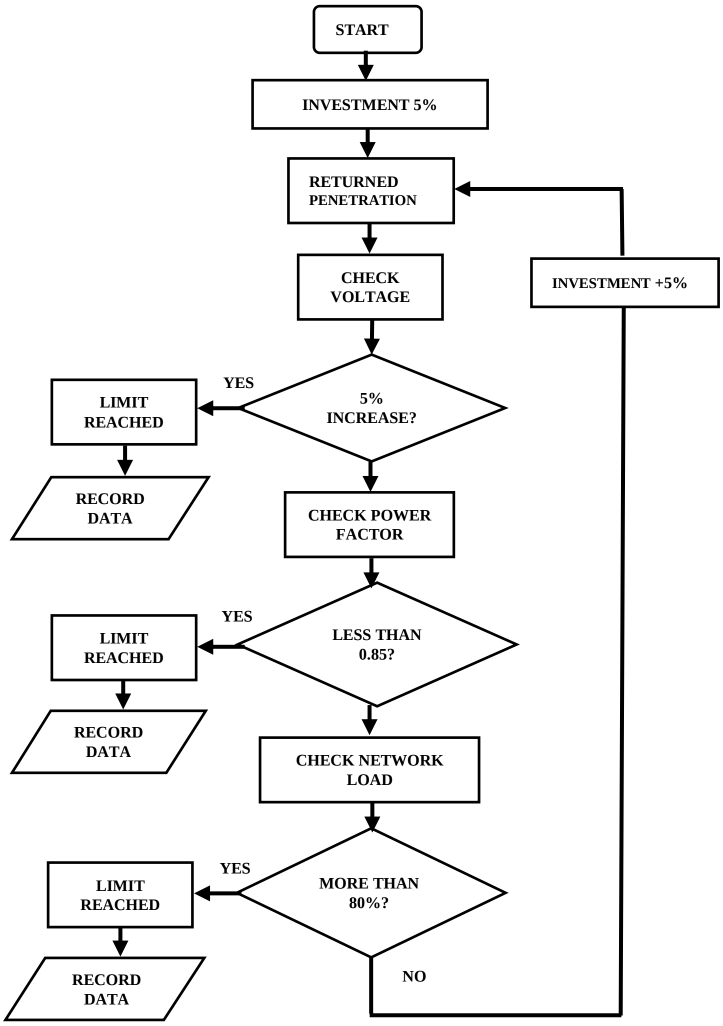

Fig. 2. Single line diagram for simulation.

4.1 Community-based Solar PV Penetration Effect on Voltage

Simulated data was obtained by observing the voltage in zones 1, 2, and 3 in each of the BNL1, BNL2, BNL3, BNL5, BNL14, and BNL17 feeders. Voltage fluctuations were observed periodically for each investment level.

From the test data recorded in the simulation, the voltage drop can be obtained by calculating the difference between the initial voltage and the voltage at the end of each feeder (receiver). For simplicity, the nominal secondary voltage of the substation transformer was assumed to be the initial voltage. The following formula is used for voltage drop calculation:

$$\Delta V = (Vs - Vr) / Vs \times 100 \quad (1)$$

For every feeder in Bantul Substation Transformer I, the same voltage drop calculation is carried out using Equation 1. Table 5 and Figure 3 indicate the voltage increase and the calculation results of the voltage drop on the feeder.

Based on Table 5, it can be observed that community-based solar PV penetration ranging from 0 to 15% can lead to an increase in the received voltage [29], [30], thus reducing the voltage drop in each feeder. The received voltage increase is progressive with community-based solar PV penetration, and occurs in all existing feeders. It has been reported that voltage regulation within the distribution network is challenging [29], [31].

Table 5. Average voltage increase.

Feeder	Average voltage increase		
	Zone 1	Zone 2	Zone 3
BNL01	0.057	0.088	0.103
BNL02	0.035	0.052	0.061
BNL03	0.069	0.107	0.126
BNL05	0.173	0.274	0.321
BNL14	0.085	0.134	0.158
BNL17	0.011	0.013	0.014

Based on the Figure 3, solar PV investment levels between 5% and 15% can cause an increase in voltage. The increase occurs continuously as the power penetration increases. The voltage increase also occurs in all existing feeders. Although there are increase, the voltage drop that occurs is still within the tolerance limit of the voltage drop prescribed in the grid code regulations, with tolerance of +5% and -10%.

4.2 Community-based Solar PV Penetration Effect on Power Factor

The power factor data was gathered from zone 1, 2, and 3 for each feeder. In addition to the voltage data, the power factor was observed directly from the distribution line at each feeder. Figure 4 illustrates the results of the power factor (pf) observation in zone 1 from the simulation with investment levels ranging from 0 to 15% in each zone.

Figure 4 indicated a decrease in power factor for each feeder and a similar decrease was observed in other zones. The decrease in power factor was attributed to the active power of the load supplied directly by community-based solar PV generation, thus decreasing the need for the supply from the PLN network. Yet, it was observed to be flowing in the distribution network. The reactive power value was high enough to cause a decrease in power factor [32]. Additionally, the power factor at 10% investment level was also seen to be decreasing and exceeding the tolerance. In the observation, the feeder that exceeded the tolerance was BNL5, which was due to it having the highest load. Hence, the reactive power supplied to BNL5 was also relatively larger than the other feeders.

Analysis shows that the power factor value decreases at each feeder due to the active power load being directly supplied by PV systems, thus reducing the need for PLN network supply. However, the reactive power load is still supplied by the PLN network, which causes reactive power to flow in the distribution network with a value that remains large, thus causing the power factor in the network to decrease. The decrease in power factor also exceeds the tolerance limit when the investment level of 10%. Only BNL 14 and BNL 17 did not violate the power factor tolerance, with 0.910 and 0.902, respectively.

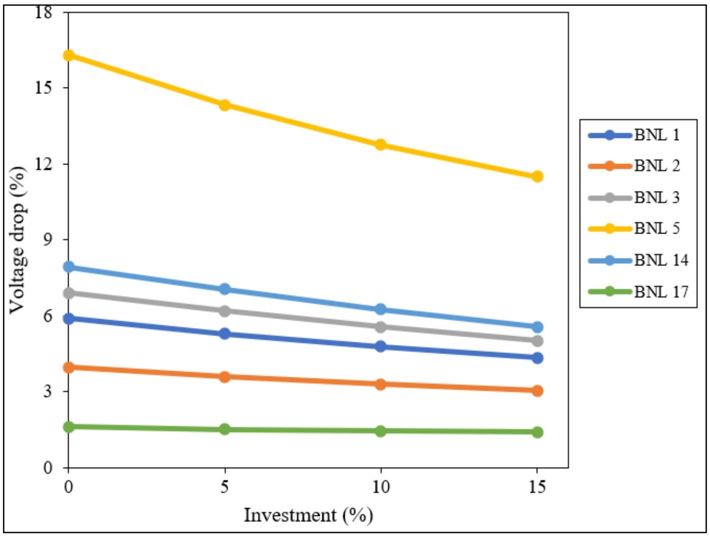

Fig. 3. Voltage drops.

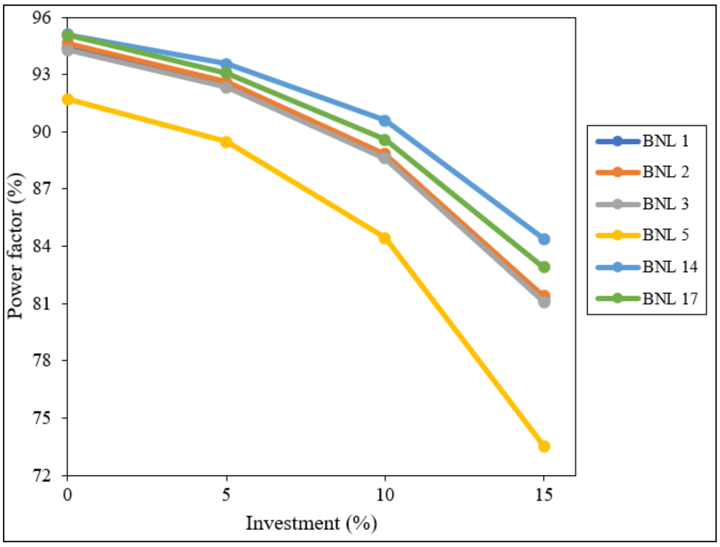

Fig. 4. Power factor in zone 2.

4.3 Community-based Solar PV Penetration Effect on Distribution Network

Data regarding the distribution network was obtained by observing the current in each zone. Figure 5 indicated a network load change in zone 3 for each investment scheme. Additionally, a similar decrease was also observed in other zones.

As indicated in Figure 5, the penetration of community-based solar PV caused a decrease in load current in the distribution network. The difference can be seen from the figure when comparing 0% investments to the other levels. For example, in zone 3, without installing PV systems on the BNL14 feeder, the load current was 22 A, which then dropped to 12 A at the 15% investment level. The decrease occurred because some of the load on the feeder was directly supplied by community-based solar PV generation, which does not pass through a 20 kV conductor [33]. Thus, resulting in a current decrease in power delivery from the network. It can also be seen in the figure that the greater the investment level, the lower the load current in the conductors.

4.4 Power Penetration Tolerance on Community-based Solar PV Generation to Distribution Network

Excessive community-based solar PV generation will certainly lead to greater power penetration. Furthermore, it would cause greater changes in voltage, power factor, and load in the power network. As depicted in Figure 2, simulation was carried out continuously by incrementing investment by 5% until the tolerance was violated. Therefore, BNL5 feeder was only using 5% of investment for installed on-grid SHS before exceeding the power factor tolerance. Referring to the observed conditions for BNL5, three simulation scenarios were proposed, as follows:

1) All feeders were installed with solar PV generation at 5% of investment.
2) BNL 14 and BNL 17 were installed with solar PV generation at 10% of investment, other using 5% of investment.
3) BNL 14 and BNL 17 were installed with solar PV generation at 15% of investment, other using 5% of investment.

Using the three scenarios mentioned above, power factor was the only parameter being violated on the feeders. Specifically, BNL14 and BNL17 violated power factor tolerance at 15% investment, or scenario 3. Thus, the investment limit was 5% for BNL1, BNL2, BNL3, and BNL5 and 10% for BNL14 and BNL17, emphasizing that there were no parameters being violated when simulating scenarios 1 and 2.

The total installed capacity of community-based solar PV in all feeders when using scenario 2 or the maximum investment with no parameters tolerance violation was 7,237,120 Wp, as detailed in Table 6.

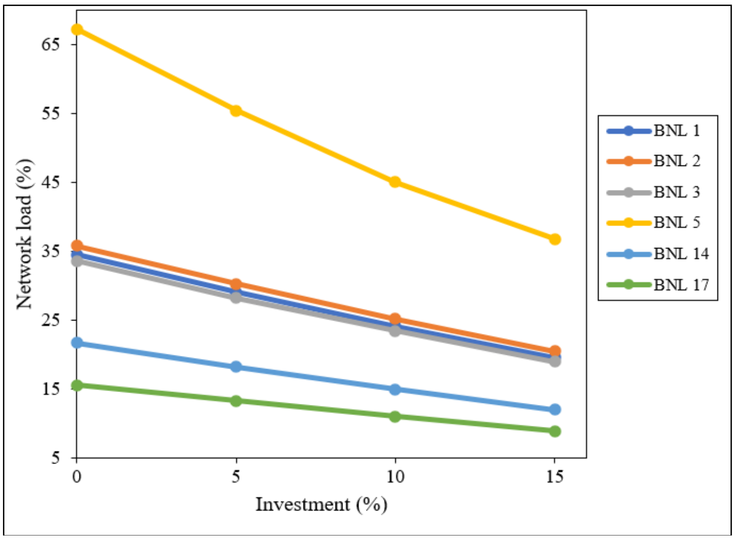

Fig. 5. Network load in zone 3.

Table 6. Maximum installed solar PV capacity for each feeder.

Feeder	Investment	Installed solar PV	
		Feeder	House
BNL01	5%	999,680 Wp	1,760 Wp
BNL02	5%	1,020,800 Wp	1,760 Wp
BNL03	5%	982,080 Wp	1,760 Wp
BNL05	5%	2,097,920 Wp	1,760 Wp
BNL14	10%	1,267,200 Wp	3,520 Wp
BNL17	10%	869,440 Wp	3,520 Wp
	Total (Wp)	7,237,120 Wp	

4.5 Community-based Solar PV Penetration Overload

Community-based solar PV penetration overload can be determined by subtracting the installed capacity of solar PV from the installed load. The solar PV installed capacity was calculated using the maximum investment, which is at 15%, to get a maximum overload that could occur. Table 7 below displays the calculated community-based solar PV capacity for all feeders and zones used in the simulation.

The overload was calculated by subtracting the total load of each zone on the feeder from the total PV generation capacity in each feeder zone. The result shown a negative value, indicating that there was no overload in all investment scenarios.

Table 7. Solar PV power capacity at 15% investment

Feeder	Solar PV power capacity (kW)		
	Zone 1	Zone 2	Zone 3
BNL01	587	587	587
BNL02	600	600	600
BNL03	577	577	577
BNL05	1233	1233	1233
BNL14	372	372	372
BNL17	255	255	255

4. CONCLUSION

Community-based solar PV distributed generation can affect voltage, power factor, and conductor load value. However, in the study, it can be observed that the power factor was the only parameter on the feeders that being on the feeders. Other parameters were also impacted with its effects were comparatively minor and within allowable limit.

From the analysis, it can be concluded that community-based solar PV penetration in Bantul distribution network are as follows:

1) Using an investment simulation which was carried out by continuously adding an investment value increment of 5%, the power factor tolerance on BNL1, BNL2, BNL3, and BNL5 feeders was violated when the investment level reached 10%.
2) Calculating the difference between the solar PV installed capacity at the maximum investment and the existing load capacity gave a negative result. Thus, no overload was occurring from solar PV.
3) The solar PV investment policy was still safe to carry out even though all the burdens were R3 customers with an investment level of 10% in BNL 14 and BNL 17, and 5% in other feeders. Meanwhile, using 15% investment has violated the parameters tolerance. The BNL5 feeder has the lowest initial power factor because it has the highest load among other feeders, thus the maximum investment is at 5% to comply with power factor tolerance.

The power factor condition in the 20 kV distribution network feeder in Bantul can be improved by the Optimal Capacitor Placement (OCP) method. Through the implementation of OCP in the network, it is expected to improve the power factor condition, voltage value, reduce current flow and reduce power losses in the feeders. Furthermore, with better load forecasts in the future, distribution network planning can be more accurate and real-time so that the carrier load does not become over-capacity like it is now, allowing for a greater than 50% in load capacity.

It is recommended for further study by utilizing a network modelling that is more closely aligned with reality, rather than being as simple as in this study.

NOMENCLATURE

ΔV = Voltage drops (%)
V_s = Initial voltage (Volt)
V_r = Received voltage (Volt)

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