Analysis of the impact of harmonic increase due to penetration of variations in the number of roof PV in the distribution network during the Covid-19 pandemic

D R Jintaka*, N W Priambodo, A S Habibie, K M Tofani and M Ridwan
Transmission and Distribution Department, PLN Research Institute, Jakarta, Indonesia

*dhandis.jintaka@pln.co.id

Abstract. The increased penetration of rooftop PV in the distribution network was triggered by the reason for free energy obtained from the sun and an incremental decrease in prices for solar panels. These were bringing it closer to grid parity. However, massive rooftop PVs without storage at medium and low voltages will cause power quality problems, namely increased voltage fluctuation, unbalanced voltage, and harmonics, in addition to active load fluctuations and power factor on nearby buses. The use of an inverter to convert DC to AC will increase the number of non-linear loads on the network so that it will increase the presence of harmonics. In early 2020 the Coronavirus pandemic was spread over the world and brought people to have activities from home. This condition shifts the portion of power consumption for each sector and increases the probability of rooftop PVs usage. This paper analysed the comparison of the use of two inverters with different harmonic characteristics with various levels of rooftop PV penetration in the distribution network. From the simulation results, it can be concluded that the existing harmonic characteristics of the inverter used has a more significant impact than the PV rooftop penetration level on the increase of harmonics in the distribution network.

1. Introduction
The use of photovoltaic (PV) power plants has been widely applied globally with the addition of installed capacity that is greater than other types of generation. The increase in the penetration rate of PV rooftops is driven by lower prices for PV panels and free energy sources from the sun so that the price of grid parity is getting closer. According to [1] the additional PV capacity is almost double that of wind power generation. The use of PV is getting bigger because it is supported by cheaper PV production costs. The International Technology Roadmap for Photovoltaics (ITRPV) states that the PV market share is expected to grow to 40% by 2028. Besides those reasons, in early 2020 the Coronavirus pandemic was spread over the world and brought people to isolate in their homes which means people do the majority of their activity from home. In Indonesia, this Covid-19 pandemic has shifted the portion of energy consumption growth in the household, business, and industry sectors. From January to Mei 2020, household’s energy consumption is growing 9.25% different from business and industry sectors which have negative growth of -5.97% and -8.92% respectively.

In many literary works, it is stated that the integration of Renewable Energy Sources (RES) in the electric power system network will cause several problems. Voltage fluctuation, power factor violation, increased voltage imbalance, and harmonics are commonly found in high penetration photovoltaic (PV) power plants [2]. On a network scale, intermittency due to the integration of Intermittent Renewable Energy Sources (IRES) should be considered to maintain network stability and reliability by taking into account the IRES penetration rate at each voltage level [3,4].
The scope of this research is limited to the increase in the harmonic phenomenon caused by the increasing level of penetration of the PV rooftop on the distribution network by comparing the impact caused by the use of inverters that have different harmonic order characteristics.

2. Rooftop PV Installation Scale, Penetration Level, and Harmonics Phenomena

2.1. Rooftop PV installation scale
The PV power plant can be connected to a transmission or distribution system. Based on the scale of the PV generation it can be classified into three categories [5]:

a. Utility-scale PV is connected to distribution substations or high-voltage consumers in transmission systems with sizes 1–100 MW (Large Scale) or even more than 100 MW (Very Large Scale). This type of PV generator is typically three-phase and requires multiple interconnect transformers to be connected to the electric power system in parallel.

b. Medium-scale PV is from 10 to 1000 kW and is connected at the distribution level or medium voltage. Medium-scale PV power plants are installed in small or large buildings such as government sites, commercial or residential buildings.

c. Small scale PV up to 10 kW and connected to a low voltage level. Due to the low voltage level of small-scale PV generators, a transformer is not required for installation. This type of PV is typically a single phase and mostly includes distributed rooftop PV.

2.2. Rooftop PV penetration level
In the existing literature, the PV penetration rate is determined according to the interests and objectives of the research carried out so that there is no uniform definition for it. In [6] the PV penetration rate is defined as the ratio of the installed PV capacity to the annual peak load, whereas in [7] the PV penetration rate is defined as the ratio of the total PV power generated to the power generated by the overall generator on the grid. Another definition of the PV penetration rate is the ratio of the maximum PV power to peak load in the operating period of the PV [8]. In this study, the formula for the PV rooftop penetration rate used is as follows: [9].

\[
PV\ penetration = \frac{Peak\ PV\ power}{Peak\ load\ apparent\ power}
\] (1)

That is, in a rooftop PV without batteries, this ratio only applies to real-time when the rooftop PV is generating active power compared to the load at the same time. Thus, it is likely that the rooftop PV penetration rate is more than 100% due to the tendency of low loads and high rooftop PV production during the day and will result in reverse power flow to the distribution network.

2.3. Harmonics phenomena
With the penetration of PV rooftop in the distribution network, the harmonics of current and voltage become an important issue considering the inverter used in the conversion of direct current voltage to alternating current voltage. Harmonics can increase the skin effect on the conductors thereby reducing the conductivity of the phase conductors. Besides, harmonics also increase neutral current, thereby increasing network losses. The limits for the harmonic distortion of voltage and current in the distribution network are described in [16,17] as in Error! Reference source not found. and Table 1.

The total voltage harmonic distortion or \( THD_{V_n} \) can be calculated according to the following formula.

\[
THD_{V_n} = \frac{\sqrt{\sum_{h=2}^{63} V_h^2}}{V_n}
\] (2)

Where \( V_h \) is the magnitude of the individual voltage harmonic components (rms volts), \( h \) is the order of harmonics and \( V_n \) is the nominal voltage of the system (rms volts).
Table 1. Harmonic Current distortion Limits

| $\frac{I_{SC}}{I_L}$ | $V_n \leq 66kV$ | Maximum Harmonic Current Distortion in Percent of $I_L$ | TDD |
|----------------------|----------------|-------------------------------------------------------|-----|
|                      |                 | Individual Harmonic Order (Odd Harmonics)             |     |
|                      | $h < 11$        | $11 \leq h < 17$ | $17 \leq h < 23$ | $23 \leq h < 35$ | $35 \leq h$ |
| $< 20^*$             | 4.0%            | 2.0%                                                  | 1.5%| 0.6% | 0.3% | 5.0% |
| 20 – 50              | 7.0%            | 4.5%                                                  | 2.5%| 1.0% | 0.5% | 8.0% |
| 50 – 100             | 10.0%           | 4.0%                                                  | 4.0%| 1.5% | 0.7% | 12.0%|
| 100 – 1000           | 12.0%           | 5.5%                                                  | 5.0%| 2.0% | 1.0% | 15.0%|
| $> 1000$             | 15.0%           | 7.0%                                                  | 6.0%| 2.5% | 1.4% | 20.0%|

The voltages included in the table above refer to SPLN No. 1 of 1995 concerning Standard voltages. The things of concern include,

a. Even harmonics are limited to 25% of the odd harmonics above;

b. Direct current (DC) distortion is not allowed;

c. The application of all power generation equipment is limited by the above current distortion values regardless of the $\frac{I_{SC}}{I_L}$ ratio;

d. $I_{SC}$ is the maximum short circuit current at the customer connection point;

e. $I_L$ is the maximum load current (calculated based on the power contract);

f. TDD is total demand distortion, current harmonic distortion (%) of the maximum load current (measured for 15 minutes).

The value of short circuit current ($I_{SC}$) can be calculated using the following formula.

$$I_{SC} = \frac{kVA_{TF}}{Z_{pu} \times \sqrt{3} \times kV - \theta}$$  \hspace{1cm} (3)

Where $kVA_{TF}$ is the installed power kVA, $Z_{pu}$ per unit of transformer impedance at installed power, and kV is the nominal voltage.

Triple-N harmonics or triple-order harmonics have a significant effect on the increase in neutral phase currents, especially at low voltage levels that only use a single-phase neutral system. As a result of the triple-N harmonics, there tends to be an increase in current in the neutral phase arithmetic, compared to only zero values such as in a balanced three-phase system or other harmonic orders. The calculation of the addition of current to the neutral phase can be done using the IEC 60364-5-52 method with the standards as shown in Table 2.

Table 2. Reduction factor of current conductivity due to Triple-N harmonics

| 3rd harmonic line current (%) | Value selected based on the line current | Value selected based on the neutral current |
|------------------------------|----------------------------------------|-------------------------------------------|
| 0-15                         | 1.00                                   |                                           |
| 15-33                        | 0.86                                   |                                           |
| 33-45                        | -                                      | 0.86                                      |
| > 45                         | -                                      | 1.00                                      |

The 3rd harmonic line current (%) is calculated using the following equation.

$$\frac{I_n}{I_p} = 300 \times \frac{\%THD}{\sqrt{10,000 + \%THD^2}} \text{ up to } 173\%$$  \hspace{1cm} (4)

For phase currents with triple-N harmonics less than 15%, there is no need to increase the cross-sectional area of the neutral conductor. Under these conditions, the neutral current is estimated to only reach a maximum of 45% of the phase current and generate about 6% additional heat from the rating temperature of the cable.
For phase currents with triple-N harmonics of 15% -33%, the neutral current may be equal to the phase current and the conductor is derating to 0.86 its nominal value. Whereas for phase currents with triple-N harmonics above 33%, the conductor rating is determined based on the neutral current.

3. Modeling and Simulation Results
This simulation using power system analysis software to simplify the calculation of harmonics by considering distribution network characteristics.

3.1. Distribution grid model
The rooftop PV is modeled as rooftop PV without using any batteries. Therefore, the rooftop PV will supply power to the grid if there is any excess of production. The grid model in this paper uses one external grid, one 150/20 kV distribution transformer, and one 20 kV feeder with balanced loads, and single-phase PVs rooftop are uniformly distributed. The distribution grid model is developed by using 10 balanced loads and 30 single-phase Rooftop PVs which are uniformly distributed in the feeder with different power output as shown in Figure 1.

Rooftop PVs are spread over all three phases with different penetration levels, at phase A 60%, phase B 285%, and phase C 170% in 20 km distribution line. Node 1 is the closest to the transformer, while node 10 is the furthest from the transformer. An inverter was used for every rooftop PV.

In the simulation of the impact of PV rooftop on the distribution network, the effect of two types of inverters (inverter A and inverter B) with different harmonic characteristic values is compared as shown in Table 3.

3.2. Simulation results
It was simulated distribution network model in Figure 1 using different harmonic order characteristic in inverter A and inverter B as in Table 3 to obtain the value of individual harmonic distortion, total current harmonic distortion, individual voltage harmonic distortion, total voltage harmonic distortion, and the impact of triple-N harmonics (triple harmonic order).
Table 3. Harmonic characteristics of inverter A and inverter B

| Harmonic Order | % phase A | % phase B | % phase C | Harmonic Order | % phase A | % phase B | % phase C | Harmonic Order | % phase A | % phase B | % phase C |
|----------------|----------|----------|----------|----------------|----------|----------|----------|----------------|----------|----------|----------|
| 2              | 0.710    | 0.710    | 0.710    | 2              | 0.355    | 0.272    | 0.388    | 2              | 0.173    | 0.148    | 0.199    |
| 3              | 1.850    | 1.850    | 1.850    | 3              | 0.233    | 0.527    | 0.323    | 3              | 0.125    | 0.120    | 0.107    |
| 4              | 0.570    | 0.570    | 0.570    | 4              | 0.248    | 0.214    | 0.226    | 4              | 0.153    | 0.120    | 0.167    |
| 5              | 0.100    | 0.100    | 0.100    | 5              | 0.172    | 0.147    | 0.156    | 5              | 0.155    | 0.134    | 0.128    |
| 6              | 0.070    | 0.070    | 0.070    | 6              | 1.229    | 1.011    | 0.914    | 6              | 0.120    | 0.097    | 0.120    |
| 7              | 0.070    | 0.070    | 0.070    | 7              | 0.198    | 0.221    | 0.257    | 7              | 0.147    | 0.093    | 0.111    |
| 8              | 0.250    | 0.250    | 0.250    | 8              | 0.269    | 0.409    | 0.242    | 8              | 0.106    | 0.113    | 0.125    |
| 9              | 0.120    | 0.120    | 0.120    | 9              | 0.171    | 0.241    | 0.227    | 9              | 0.132    | 0.119    | 0.117    |
| 10             | 0.240    | 0.240    | 0.240    | 10             | 2.275    | 2.809    | 2.627    | 10             | 0.095    | 0.099    | 0.097    |
| 11             | 0.080    | 0.080    | 0.080    | 11             | 0.121    | 0.134    | 0.128    | 11             | 0.122    | 0.114    | 0.112    |
| 12             | 0.160    | 0.160    | 0.160    | 12             | 1.880    | 1.657    | 1.568    | 12             | 0.113    | 0.105    | 0.106    |
| 13             | 0.250    | 0.250    | 0.250    | 14             | 0.211    | 0.153    | 0.217    | 14             | 0.078    | 0.085    | 0.080    |
| 15             | 0.050    | 0.050    | 0.050    | 15             | 0.164    | 0.214    | 0.203    | 15             | 0.103    | 0.090    | 0.098    |
| 16             | 0.050    | 0.050    | 0.050    | 16             | 0.131    | 0.150    | 0.155    | 16             | 0.092    | 0.093    | 0.096    |
| 17             | 0.060    | 0.060    | 0.060    | 17             | 0.515    | 0.144    | 0.432    | 17             | 0.078    | 0.072    | 0.083    |
| 18             | 0.040    | 0.040    | 0.040    | 18             | 0.109    | 0.100    | 0.113    | 18             | 0.102    | 0.086    | 0.096    |
| 19             | 0.050    | 0.050    | 0.050    | 19             | 0.085    | 0.340    | 0.534    | 19             | 0.084    | 0.080    | 0.083    |
| 20             | 0.040    | 0.040    | 0.040    | 20             | 0.212    | 0.131    | 0.193    | 20             | 0.072    | 0.083    | 0.085    |
| 21             | 0.050    | 0.050    | 0.050    | 21             | 0.272    | 0.205    | 0.182    | 21             | 0.083    | 0.074    | 0.083    |
| 22             | 0.030    | 0.030    | 0.030    | 22             | 0.156    | 0.165    | 0.168    | 22             | 0.075    | 0.078    | 0.084    |
| 23             | 0.070    | 0.070    | 0.070    | 23             | 0.236    | 0.264    | 0.300    | 23             | 0.082    | 0.067    | 0.064    |
| 24             | 0.000    | 0.000    | 0.000    | 24             | 0.095    | 0.095    | 0.096    | 24             | 0.070    | 0.071    | 0.067    |
| 25             | 0.000    | 0.000    | 0.000    | 25             | 0.205    | 0.142    | 0.164    | 25             | 0.060    | 0.049    | 0.058    |
| 26             | 0.000    | 0.000    | 0.000    | 26             | 0.129    | 0.114    | 0.137    | 26             |          |          |          |

The graph of harmonic distortion at 100% PV rooftop penetration level with inverter A and inverter B can be seen in Figure 2 and Figure 3, respectively.

Figure 2. Harmonic characteristics with inverter A at 100% rooftop penetration level

Figure 3. Harmonic characteristics with inverter B at 100% rooftop penetration level
The harmonic simulation results of inverter A showed that the dominant harmonic orders were order 3 and order 14. While the simulation results of inverter B, the dominant harmonic orders were orders 7, 11, and 13. The simulation results using two different inverters and a PV penetration level of 20% to 300% were then compared with the current and current harmonic limits according to [16], [17].

### Table 4. Harmonic distortion of inverter A and inverter B at various levels of PV penetration

| Number of parallel inverter | PV penetration level (%) | Inverter A | Inverter B |
|-----------------------------|-------------------------|------------|------------|
|                            | Max HDv* | Max HDv* | THDv | Max HDv* | Max HDv* | THDv | TDD |
| 12                          | 20%      | 3.04    | 3.94 | 2.02    | 3.23    | 0.24 | 0.17 |
| 23                          | 40%      | 0.85    | 0.37 | 0.09    | 0.42    | 0.47 | 0.31 |
| 35                          | 60%      | 1.00    | 0.57 | 1.13    | 0.64    | 0.71 | 0.49 |
| 46                          | 80%      | 0.30    | 0.74 | 0.17    | 0.83    | 0.45 | 0.65 |
| 58                          | 100%     | 0.52    | 0.94 | 0.22    | 0.62    | 1.05 | 1.17 |
| 70                          | 120%     | 0.54    | 1.13 | 0.26    | 0.39    | 1.27 | 1.42 |
| 81                          | 140%     | 0.91    | 1.30 | 0.30    | 0.26    | 1.46 | 1.64 |
| 93                          | 160%     | 1.44    | 1.49 | 0.35    | 0.25    | 1.68 | 1.88 |
| 104                         | 180%     | 1.60    | 1.67 | 0.39    | 1.17    | 1.88 | 2.10 |
| 116                         | 200%     | 1.78    | 1.85 | 0.43    | 1.60    | 2.09 | 2.34 |
| 145                         | 250%     | 2.22    | 2.31 | 0.54    | 1.06    | 2.60 | 2.92 |
| 174                         | 300%     | 2.64    | 2.75 | 0.65    | 1.17    | 3.12 | 3.49 |

### Table 5. The individual harmonic distortion of inverter A at various levels of PV penetration

| Harmonic order | Penetration level (%) | Number of inverter |
|----------------|-----------------------|--------------------|
|                | 10%  | 40%  | 60%  | 80%  | 100% | 120% | 140% | 160% | 180% | 200% | 250% | 300% | SPLN |
| HDI            | 0.04 | 0.22 | 0.36 | 0.43 | 0.50 | 0.57 | 0.64 | 0.71 | 0.78 | 0.85 | 0.92 | 0.99 | D5.004-1 |
| HDII           | 0.02 | 0.06 | 0.04 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| HDIII          | 0.03 | 0.03 | 0.03 | 0.03 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |

### Table 6. The individual harmonic distortion of inverter B at various levels of PV penetration

| Harmonic order | Penetration level (%) | Number of inverter |
|----------------|-----------------------|--------------------|
|                | 10%  | 40%  | 60%  | 80%  | 100% | 120% | 140% | 160% | 180% | 200% | 250% | 300% | SPLN |
| HDI            | 0.04 | 0.11 | 0.25 | 0.56 | 1.36 | 1.85 | 0.85 | 0.57 | 0.44 | 0.38 | 0.33 | 0.28 | 0.25 |
| HDII           | 0.12 | 0.30 | 0.46 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 |
| HDIII          | 0.04 | 0.11 | 0.25 | 0.56 | 1.36 | 1.85 | 0.85 | 0.57 | 0.44 | 0.38 | 0.33 | 0.28 | 0.25 |

From Table 4, it can be seen that the individual current harmonics in inverter A, the individual current harmonic distortions were subject to conditions beyond the standard permissible limits at a penetration level of 80% to 140%. Meanwhile, B exceeded the standard at all penetration levels with
the highest gap at the 100% penetration level. While Table 5 and Table 6 provide more detailed HDi simulation results for each odd order. Distortion of individual harmonic currents in inverter A for odd orders above 23, is ignored because it is very small, close to 0.

The calculation of the addition of current to the neutral phase can be done using the IEC 60364-5-52 method with the standards as shown in Table 2. Then Table 7 shows the calculation results of the addition of current in the neutral phase using this method. The phase value with triple-N harmonics on both inverters is in the range of 15% -33% so that the neutral current may be equal to the phase current and the conductor is derating to be 0.86 its nominal value.

Table 7. The results of the calculation of the derating factor of the neutral conductor in inverter A and inverter B

| Name | Inverter A | Inverter B |
|------|------------|------------|
|      | THDi (%)   | %In        | THDi (%) | %In     |
| Line | 4.390      | 13.159     | 7.290    | 21.812  |
| Line_a | 4.453     | 13.347     | 7.402    | 22.146  |
| Line_b | 4.511     | 13.519     | 7.505    | 22.450  |
| Line_c | 4.563     | 13.675     | 7.596    | 22.724  |
| Line_d | 4.609     | 13.812     | 7.677    | 22.964  |
| Line_e | 4.648     | 13.929     | 7.747    | 23.170  |
| Line_f | 4.681     | 14.027     | 7.804    | 23.342  |
| Line_g | 4.706     | 14.103     | 7.850    | 23.478  |
| Line_h | 4.725     | 14.158     | 7.883    | 23.577  |
| Line_i | 4.735     | 14.190     | 7.904    | 23.640  |

4. Discussion
Harmonic distortion is one of the parameters of the quality of electrical energy supplied. With more nonlinear load such as inverter which is used by the PV rooftop on the distribution network, the harmonic distortion will tend to increase, especially if the harmonic order characteristic of the inverter itself is dominant at odd orders. The result will be an extra loss in the distribution network due to the presence of increasing current in the neutral phase.

In early 2020, the Covid-19 virus spread over the world. This virus caused millions of death victims and forced people to limit their activities especially those that raise the crowd. During this pandemic, there is a new adaptation method to prevent its transmission that is called activities at home such as work from home, study from home, pray from home, etc. As a result, the electric energy of every home was aroused. One of the attitudes that consumers can take to save electricity consumption is to install rooftop PVs in their homes. For economic reasons as well, consumers will choose the most affordable inverter price regardless of their harmonic characteristics. So that the probability of an increase in harmonic distortion as a result of the massive penetration of Rooftop PVs in the distribution network will increase. Some methods can be applied to reduce harmonic distortion such as modify the frequency response of the system by filters, inductors, or capacitors.

5. Conclusion
The impact of the PV rooftop in terms of harmonics depends on the quality of the inverter used. The better the filter on the inverter, the smaller the harmonic characteristics will be. The harmonics that arise can amplify the skin effect on the conductor so this needs to be controlled to minimize shrinkage. Rules that limit the value of harmonic distortion need to be applied so that the harmonics at the connection point do not exceed the permitted standards.

6. References
[1] Frankfurt school-UNEP center and BNEF (2018)
[2] Jung J, Onen A, Arghandeh R, Broadwater RP. Coordinated control of auto- mated devices and photovoltaic generators for voltage rise mitigation in power distribution circuits. Renew
Energy 2014; 66:532–40.

[3] Tariq Aziz, Nipon Ketjoy. PV penetration limits in low voltage networks and voltage variations. IEEE Access 2017; 10.1109/ACCESS.2017.2747086

[4] S. Eftekharnejad, V. Vittal, G. T. Heydt, B. Keel, and J. Loehr, “Impact of Increased Penetration of Photovoltaic Generation on Power Systems,” IEEE Transaction on Power Systems, vol. 28, no.2, pp.893–901, 2013.

[5] H. B. Tambunan, A. A. Kusuma, and B. S. Munir, “Maximum Allowable Intermittent Renewable Energy Source Penetration in Java-Bali Power System,” in 2018 10th International Conference on Information Technology and Electrical Engineering (ICITEE), 2018, pp. 325–328

[6] D. R. Jintaka, K. M. Banjar-Nahor, V. Debusschere, and N. Sinisuka, "Assessment of Renewable Energy Potential in Eastern Sumba Microgrid based on Numerical Stochastic Power Flow," 2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe), Bucharest, Romania, 2019, pp. 1-5.

[7] E. Rakhshani, K. Rouzbeh, A. J. Sánchez, A. C. Tobar, and E. Pouresmaeil, “Integration of large scale PV-based generation into power systems: A survey,” Energies, vol. 12, no. 8, 2019.

[8] D. R. Jintaka, Suharto, K. G. H. Mangunkusumo and B. S. Munir, "Correlation of Harmonics Distorted Current to Current-Carrying Capacity in Different Cable Cross Section," 2019 International Conference on Electrical Engineering and Informatics (ICEEI), Bandung, Indonesia, 2019, pp. 320-323.

[9] Cheng, D.; Mather, B.A.; Seguin, R.; Hambrick, J.; Broadwater, R.P. Photovoltaic (PV) Impact Assessment for Very High Penetration Levels. IEEE J. Photovolt. 2016, 6, 295–300.

[10] Eftekharnejad, S.; Vittal, V.; Heydt, G.T.; Keel, B.; Loehr, J. Impact of increased penetration of photovoltaic generation on power systems. IEEE Trans. Power Syst. 2013, 28, 893–901.

[11] Hoke, A.; Butler, R.; Hambrick, J.; Kroposki, B. Steady-state analysis of maximum photovoltaic penetration levels on typical distribution feeders. IEEE Trans. Sustain. Energy 2013, 4, 350–357.

[12] Mohammadi, P.; Mehraeen, S. Challenges of PV Integration in Low-Voltage Secondary Networks. IEEE Trans. Power Deliv. 2017, 32, 525–535.

[13] Armendariz, M.; Brodén, D.; Honeth, N.; Nordström, L. Nordström, A method to identify exposed nodes in low voltage distribution grids with High PV penetration. In Proceedings of the 2015 IEEE Power & Energy Society General Meeting, Denver, CO, USA, 26–30 July 2015; pp. 1–5.

[14] Ghaflarianfar, M.; Hajizadeh, A. Voltage Stability of Low-Voltage Distribution Grid with High Penetration of Photovoltaic Power Units. Energies 2018, 11, 1960. [CrossRef]

[15] A. Hoke, R. Butler, J. Hambrick, and B. Kroposki, “Maximum Photovoltaic Penetration Levels on Typical Distribution Feeders,” IEEE Trans. Sustain. Energy, no. July, pp. 1–14, 2012.

[16] IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems," in IEEE Std 519-2014 (Revision of IEEE Std 519-1992), vol., no., pp.1-29, 11 June 2014.

[17] PT. PLN (Persero), SPLN D5.004-1: 2012 about power quality (harmonics, flicker, voltage unbalance regulation), Jakarta, 2012.