Analysis of unbalanced voltage due to varying amounts penetration of rooftop PV in distribution network with balanced load

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Abstract. The increased penetration of rooftop PV on distribution networks is triggered by the decreasing prices of solar panels which will get closer to reach the grid parity. However, the massive rooftop PV without storage at medium and low voltages will cause power quality problems, namely increased of voltage fluctuations, unbalanced voltages and harmonics, as well as the emergence of active load fluctuations and power factors on the nearest bus. This paper analyzes the increase in unbalanced voltages in the distribution network due to the massive rooftop PV without storage. In a balanced load configuration, the presence of rooftop PV in certain phases with varying amounts penetration will cause voltage imbalances in the distribution network. From the results of this simulation, it can be concluded that with a higher number of rooftop PVs, the spread of rooftop PVs on a higher number of phases results in a smaller voltage imbalance than if the rooftop PV is only concentrated in one particular phase. Then, longer network lengths provide greater imbalance compared to networks with shorter distances.

1. Introduction
The use of photovoltaic (PV) power plants has been widely applied globally with a larger addition of installed capacity than other types of plants. According to Frankfurt school-UNEP center and BNEF the addition of PV capacity in 2018 is almost twice that of wind power plants. Increasing the level of penetration of rooftop PV is driven by the cheaper prices of PV panels (due to the cheaper PV production cost) and free energy sources from the sun, so it is getting closer to the price of grid parity. The International Technology Roadmap for Photovoltaics (ITRPV) states that the PV market share is expected to grow to 40% in 2028.

In many literary works mentioned that Renewable Energy Source (RES) integration in the power system network will cause some problems. Voltage fluctuations, power factor violations, increasing voltage imbalance and harmonics are usually found on the grid with high penetration of photovoltaic (PV) power plants [1]. On a grid scale, intermittent from resources due to integration Intermittent Renewable Energy Sources (IRES) should be considered maintaining network stability and reliability by consider IRES penetration rates in each voltage level [2,3].

The scope of this research is limited in increasing of unbalanced voltage in a distribution network relative to the difference concentration in the phase with balanced load. Multiple penetration scenarios (high, medium, and low) were analyzed to obtain a comprehensive result on the magnitude of voltage fluctuations. It will also be seen the influence of the length of the distribution network on increasing voltage imbalance.
2. Methodology
This section describes the research methodology that used in this paper. It consists of the PV rooftop installation scale definition, PV rooftop penetration level, voltage imbalance, and the system modelling.

2.1. Rooftop PV installation scale
PV generation can be connected to either the transmission or distribution system. Based on the PV generation scale can be classified into three categories [4]:

- The utility-scale PV is connected to either the distribution substation or high voltage consumers on the transmission system with size 1–100 MW (Large scale) or even more than 100 MW (very Large scale). This type of PV generator is usually three-phase and requires several interconnect transformers to connect to the power system in parallel.
- Medium scale PV is from 10 to 1000 kW and is connected at the distribution level. Medium-scale PV generation is installed in small or large buildings such as government sites, commercial buildings or residential complexes.
- Small scale PV up to 10 kW and connected to home voltage levels. Because of the low voltage level of small-scale PV generators, transformers are not required for installation. These types of PV are usually single phase and most include distributed rooftop PV.

2.2. Rooftop PV penetration level
In the existing literature, the level of PV penetration is defined according to the interests and objectives of the research carried out so that there is no uniform definition for this. The PV penetration level is defined as the ratio of PV installed capacity compared to annual peak loads [5], whereas the PV penetration level is defined as the ratio of the total PV power generated compared to the power generated by other generators on the grid [6]. Another definition of PV penetration level is the ratio of the maximum power ratio of PV to the peak load in the range of time the PV operates [7]. In this study the penetration level of rooftop PV used formula are as follows: [8].

\[
PV \text{ penetration} = \frac{\text{Peak PV power}}{\text{Peak load apparent power}}
\]

This means that on a rooftop PV without batteries, this comparison only applies to real time when the rooftop PV produces active power compared to the load at the same time. Thus, it is possible that the penetration level of rooftop PV is more than 100% due to the tendency of low loads and high rooftop PV production during the day and will result in a reverse power flow in the distribution network.

2.3. Voltage imbalance
With the existence of a PV generator in the distribution network both medium voltage and low voltage will cause voltage fluctuations in the distribution network if there is a reverse power flow from the customer to the PLN grid. This is due to the fluctuating power supply from PV following the intermittent nature of solar radiation. The change in voltage value on a network follows the following equation.

\[
\Delta V = \frac{(P_G - P_L)R + (Q_G - Q_L)X}{V}
\]

where \( P_G, Q_G \) is the active and reactive power of Rooftop PV in kW, kVAr respectively. The value of \( \Delta V \) will increase along with the escalation of \( P_G, Q_G \). While \( P_L, Q_L \) is the active and reactive power of Rooftop PV in kW, kVAr respectively. The value of \( \Delta V \) will decrease along with the deflation of \( P_G, Q_G \). \( V \) is the voltage at the connection point in Volt. \( R, X \) is the resistance and reactance between the main station and the connection point in \( \Omega \) [9].

With the power injection in the distribution network, the voltage tendency in the distribution network will increase along with the increasing level of PV penetration. The rooftop PV close to a load can cause a reduction in power supply from the grid, and the effect is increasing the voltage profile (fluctuating according to the intermittent rooftop PV power supply). The correlation of increasing stress with penetration level is mentioned in [10] as follows:
At low levels of PV penetration (5%), rooftop PV does not make a significant impact on the distribution network voltage. At the middle level of PV penetration (10%) the role of voltage increase due to PV can reduce the role of capacitors used to increase the distribution network voltage by up to 40%. At high levels of PV penetration (30-50%), the role of PV in increasing distribution voltage is very significant and can replace capacitors. Limits that are used as a reference in assessing the voltage quality on the distribution network follow the rules of the network (Grid code of Java-Madura-Bali System) that is not allowed to exceed the upper limit of 105% and the lower limit of 90% of network voltage.

Voltage unbalance in a three-phase system is a condition where the voltage phase differs in amplitude and or does not have a normal phase angle difference of 120°. Voltage imbalances are caused by unbalanced loads between phases. The magnitude of the Voltage Unbalanced Factor (VUF) or imbalance factor can be calculated with the following equation:

\[ VUF\% = \frac{V^-}{V^+} \times 100\% \]  

where \( V^- \) and \( V^+ \) are negative sequence voltages and positive sequence voltages. The limit of voltage imbalance follows the SPLN standard D5.004-1: 2012 which is equal to 2% of nominal voltage on medium voltage networks and low voltage networks.

The rooftop PV model used in this study is a battery-free rooftop PV, so that the power supply generated by the rooftop PV will be forwarded to the distribution grid when the house load needs are met and is only active in the morning to the afternoon according to sunlight irradiation. However, at night, the house load is only supplied from the distribution network.

The greater the injection of active and reactive power on the distribution network, the voltage will increase more, especially if the load on the customer side has decreased or tends to remain. While the lower voltage level will cause voltage fluctuations that are further from the original voltage value.

2.4. System modelling

The system modelling and simulation are performed using power system analysis software in order to simplify the calculation of voltage imbalance by considering distribution network characteristics. The rooftop PV is modelled 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.

There are four models used to simulate the impact of a rooftop PV on voltage imbalances with a similar picture in Figure 1 as follows:

- Model 1, rooftop PV is only concentrated in one phase with a penetration level of 250% so that in that phase a reverse power flow occurs which supplies active power to a single-phase network
- Model 2, rooftop PV is spread over two phases with the same penetration level (200%) while in the third phase there is no rooftop PV at all
- Model 3, rooftop PV is spread over all three phases with different penetration levels, at phase A 60%, phase B 285% and phase C 170%
- Model 4, using model 3 configuration with longer distribution line 50 km (model 1, 2 & 3 have 20 km distribution line)
Figure 1. The distribution grid model- rooftop PV is spread over all three phases with different penetration levels.

Because the electricity bill of consumers in only charged by the active power, it is assumed that consumers will maximize the production of active power on the rooftop PV. 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, Node 1 is the closest to the transformer, while node 10 is the furthest from the transformer.

3. Results and discussion

The voltage imbalance factor is calculated using equation 3. According to IEEE & SPLN D5.004-1: 2012 the limit for voltage unbalance is 2% in medium and low voltage of distribution networks. The simulation results are presented in Table 1, Table 2, Table 3 and Table 4 for models 1, 2, 3 and 4 respectively.

In model 1, conditions beyond the standard are found in node 7, node 8, node 9 & node 10, while in model 2, conditions beyond the standard are found in node 8, node 9 and node 10. From model 3, conditions beyond the standard are obtained at node 9 and node 10, while in model 4, conditions beyond the standard are obtained at node 3 to node 10.

Voltage is one of the parameters of the quality of electrical energy supplied. With the active power supply from the PV rooftop on the distribution network, the voltage will tend to increase, especially at the node at the end of the feeder. Rooftop PV connected to low and medium networks can cause an increase in voltage imbalances in the distribution network. The result will be an extra loss in the distribution network.
### Table 1. Model 1, rooftop PV is only active in one phase with a penetration level of 250%.

| Name   | u1, Magnitude (p.u.) | u1, Magnitude (kV) | u2, Magnitude (p.u.) | u1, Magnitude (kV) | VUF (%) |
|--------|----------------------|--------------------|----------------------|--------------------|---------|
| Node10 | 0.9923               | 11.4587            | 0.0215               | 0.2482             | 2.1661  |
| Node9  | 0.9924               | 11.4592            | 0.0213               | 0.2459             | 2.1456  |
| Node8  | 0.9925               | 11.4600            | 0.0209               | 0.2412             | 2.1050  |
| Node7  | 0.9926               | 11.4612            | 0.0203               | 0.2343             | 2.0443  |
| Node6  | 0.9927               | 11.4626            | 0.0195               | 0.2251             | 1.9640  |
| Node5  | 0.9928               | 11.4642            | 0.0185               | 0.2138             | 1.8650  |
| Node4  | 0.9930               | 11.4661            | 0.0174               | 0.2005             | 1.7483  |
| Node3  | 0.9932               | 11.4681            | 0.0160               | 0.1853             | 1.6160  |
| Node2  | 0.9934               | 11.4703            | 0.0146               | 0.1687             | 1.4711  |
| Node1  | 0.9936               | 11.4726            | 0.0131               | 0.1513             | 1.3190  |
| 20 kV  | 0.9938               | 11.4749            | 0.0116               | 0.1341             | 1.1688  |
| 150 kV | 1.0000               | 86.6025            | 0.0003               | 0.0259             | 0.0300  |

### Table 2. Model 2, rooftop PV active in two phases with a penetration level of 200%.

| Name   | u1, Magnitude (p.u.) | u1, Magnitude (kV) | u2, Magnitude (p.u.) | u1, Magnitude (kV) | VUF (%) |
|--------|----------------------|--------------------|----------------------|--------------------|---------|
| Node10 | 1.0008               | 11.5580            | 0.0211               | 0.2383             | 2.1057  |
| Node9  | 1.0007               | 11.5549            | 0.0209               | 0.2410             | 2.0856  |
| Node8  | 1.0005               | 11.5527            | 0.0205               | 0.2363             | 2.0454  |
| Node7  | 1.0002               | 11.5492            | 0.0199               | 0.2293             | 1.9855  |
| Node6  | 0.9998               | 11.5444            | 0.0191               | 0.2201             | 1.9062  |
| Node5  | 0.9993               | 11.5384            | 0.0181               | 0.2086             | 1.8082  |
| Node4  | 0.9986               | 11.5310            | 0.0169               | 0.1952             | 1.6926  |
| Node3  | 0.9979               | 11.5227            | 0.0156               | 0.1801             | 1.5632  |
| Node2  | 0.9971               | 11.5134            | 0.0142               | 0.1638             | 1.4230  |
| Node1  | 0.9962               | 11.5033            | 0.0127               | 0.1468             | 1.2766  |
| 20 kV  | 0.9953               | 11.4922            | 0.0113               | 0.1302             | 1.1326  |
| 150 kV | 1.0000               | 86.6025            | 0.0003               | 0.0252             | 0.0291  |

### Table 3. Model 3, rooftop PV active in all three phases with different penetration levels.

| Name   | u1, Magnitude (p.u.) | u1, Magnitude (kV) | u2, Magnitude (p.u.) | u1, Magnitude (kV) | VUF (%) |
|--------|----------------------|--------------------|----------------------|--------------------|---------|
| Node10 | 1.0008               | 11.6400            | 0.0204               | 0.2356             | 2.0234  |
| Node9  | 1.0006               | 11.6467            | 0.0202               | 0.2334             | 2.0039  |
| Node8  | 1.0002               | 11.6417            | 0.0198               | 0.2290             | 1.9670  |
| Node7  | 1.0005               | 11.6341            | 0.0193               | 0.2224             | 1.9120  |
| Node6  | 1.0007               | 11.6239            | 0.0185               | 0.2138             | 1.8391  |
| Node5  | 1.0006               | 11.6112            | 0.0176               | 0.2031             | 1.7489  |
| Node4  | 1.0004               | 11.5958            | 0.0165               | 0.1904             | 1.6424  |
| Node3  | 1.0002               | 11.5777            | 0.0153               | 0.1761             | 1.5211  |
| Node2  | 1.0009               | 11.5571            | 0.0139               | 0.1604             | 1.3879  |
| Node1  | 0.9989               | 11.5338            | 0.0125               | 0.1439             | 1.2474  |
| 20 kV  | 0.9966               | 11.5079            | 0.0110               | 0.1275             | 1.1081  |
| 150 kV | 1.0000               | 86.6025            | 0.0003               | 0.0247             | 0.0285  |

### Table 4. Model 4, rooftop PV active in all three phases with different penetration levels and 50 km of line distribution length.

| Name   | u1, Magnitude (p.u.) | u1, Magnitude (kV) | u2, Magnitude (p.u.) | u1, Magnitude (kV) | VUF (%) |
|--------|----------------------|--------------------|----------------------|--------------------|---------|
| Node10 | 1.0397               | 12.0051            | 0.0351               | 0.4053             | 3.3757  |
| Node9  | 1.0391               | 11.9985            | 0.0346               | 0.3996             | 3.3307  |
| Node8  | 1.0384               | 11.9876            | 0.0336               | 0.3938             | 3.2943  |
| Node7  | 1.0359               | 11.9610            | 0.0322               | 0.3715             | 3.1057  |
| Node6  | 1.0332               | 11.9301            | 0.0302               | 0.3490             | 2.9254  |
| Node5  | 1.0298               | 11.8910            | 0.0278               | 0.3211             | 2.7002  |
| Node4  | 1.0257               | 11.8438            | 0.0249               | 0.2879             | 2.4305  |
| Node3  | 1.0209               | 11.7882            | 0.0216               | 0.2497             | 2.1185  |
| Node2  | 1.0154               | 11.7244            | 0.0180               | 0.2074             | 1.7690  |
| Node1  | 1.0091               | 11.6521            | 0.0141               | 0.1627             | 1.3962  |
| 20 kV  | 1.0021               | 11.5714            | 0.0104               | 0.1206             | 1.0426  |
| 150 kV | 1.0000               | 86.6025            | 0.0003               | 0.0233             | 0.0269  |
From the results of this simulation it can be concluded that with a higher number of rooftop PVs and the spread of rooftop PVs at a higher number of phases resulting in a smaller voltage imbalance than if rooftop PVs are only concentrated in one particular phase. The effect of longer network lengths provides greater voltage imbalance compared to networks with shorter distances.

Voltage imbalances in single phase distribution systems are difficult to control although in balanced load, especially with the active power supply from fluctuating rooftop PV. Moreover, the rooftop PV is only active when there is solar radiation; so if a transformer tap changer is maneuvered during the day to reduce the rising voltage due to the rooftop PV then at night it must be maneuvered again to adjust it to normal voltage. Battery usage and network reconfiguration are alternative efforts to balance the load between phases. Further research is needed to determine the capacity and location of battery placement on the distribution network with variable fluctuations in rooftop PV supply power in the distribution network.

4. Conclusion

Rooftop PV connected to the low and medium network can cause an increase in voltage imbalance in the distribution network. The higher number of rooftop PVs and the spread of rooftop PVs at a higher number of phases results in a smaller voltage imbalance than if the rooftop PVs are only concentrated in one particular phase. The effect of longer network lengths provides a greater voltage imbalance compared to networks with shorter distances. Voltage imbalances in one-phase distribution systems are difficult to control even in balanced loads, especially with active power supply from fluctuating rooftop PVs.

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