Determination of PV Hosting Capacity in Rural Distribution Network: A Study Case for Bantul Area

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Abstract- Research on the determination of PV hosting capacity in a specified distribution system or feeder is popular recently because of many factors such as the energy policy from the government, low capital cost of PV panel and the modern society lifestyle. PV hosting capacity determination should consider not only the potential resource and the economic aspect but also the technical consideration based on the static and dynamic performance of the distribution system. In this paper, the PV hosting capacity determination is calculated based on the existing distribution feeder using an iterative method considering the voltage regulation, system power factor, and apparatus loading. A novel method based on static analysis is proposed for the installation guidance in the rural area. The result shows that driving the PV location into the centre of the load and adjusting the reactive power support by PV producer may increase the hosting capacity size.

Keywords hosting capacity; distribution feeder; reactive power support; PV injection location; voltage regulation.

1. Introduction

Variable renewable energy (VRE) such as solar, micro-hydro and wind power plant, utilization becoming one of the solutions not only for the energy adequacy but also the environmental effect as mentioned in the Kyoto Protocol [1] and Paris Agreement [2] which consider the climate change effect. Furthermore, the electricity roadmaps for 100% VRE are conducted in Australia [3] Europe and North Africa [4].

Based on the power system configuration, the integration of VRE might affect the transmission system planning (partial shading effect [5]) and operation, which the impact has been evaluated in the requirement of the flexibility as presented in [6], ancillary services and planning issue [7] and the necessity of energy storage [8]. Moreover, the distribution system might also be affected, which energy storage is also needed [9] and the implementation of islanded areas for improving system reliability [10].

Indonesia is one of a special area in the world that has 17.504 islands, which most of the electricity network is built as an isolated system [11], [12]. Most of the isolated systems were connected in the distribution system, which is mainly connected to the medium voltage level [13] as a microgrid, distributed generation system or in the secondary voltage level [14], smart/microgrids [15],[16] or even in the rooftop [17] depending on the power market model. Distributed generation has some advantages to the power system such as overcoming under voltage problems, reduce the transmission congestion, and delay the transmission line investment period [18]. It also had been verified in the deployment process by installing in the public services system on the project presented in [19]. On the other hand, the power system should maintain its power quality. Overvoltage, harmonic, system stability, and protection evaluation are some issues related to the distributed generation which should be considered in the optimization process as presented in [20].

Considering the VRE integration, the utilities, especially distribution system operator (DSO), need to consider their operational performance. The performance of the system will be different depending on their distribution network, load and generation characteristic. Even though the common effect of the penetration is the same, the acceptability (hosting capacity) of the VRE could be totally different, which can be analyzed using sensitivity analysis [21] or optimization computation approach [22]. For example, in the Indonesian power system (distribution system) consisting of large island area the characteristic can be different as presented in the national planning document [11], and the investment analysis guide [23]. For that reason, the general rule of VRE determination has been determined as presented in

[24]. Moreover, in Indonesia, the new VRE installation guide existed as presented in the national document [25]. However, most of the regulations are based on the deterministic approach. To evaluate such regulation, the numerical approach reflecting the static and dynamic system's performance is necessary.

Indonesia is located at 6° N–11° S and 95°–141° E, which is in the tropical equator area, which makes the solar power plant becomes the prospective VRE source with the average solar radiation during the daytime is between 3.8 – 4.8 kWh/m2 [26]. On the other hand, the prospect of the wind power plant is relatively lower than the solar power plant, with the average wind speed are not more than 5 m/s [27]. The PV system becomes the solution for the rural area with high production costs such as in Kupang [28], Likupang [29], and Karampuang [30]. The installation of PV can support energy adequacy and system reliability. However, if a power system depends much on PV, like in Kupang (33% capacity), the power system may become unstable when the PV's power suddenly loss such as in the cloudy situation.

In this paper, the PV hosting capacity for a specific distribution system is determined using some criteria such as voltage profile, line flow, and short circuit. Options for installing PV scattered, in the middle or edge of feeder are also be considered in this paper. The special area of Indonesian Utility (PT. PLN) in Yogyakarta, Bantul I substation consists of BNL 1 to BNL5 feeders which are radial is used for the test system study. Voltage regulation is used as the main criterion for determining the PV hosting capacity [22] since the overvoltage will occur in the distribution line during the daytime when the active power transfer to the feeder is very small. Short circuit and stability analysis are used as the verification of the PV hosting capacity. The result shows that the voltage regulation is the main factor to be considered in the PV hosting capacity determination.

2. Profiles of Bantul Area

2.1. Topography of Bantul Area

Bantul area is part of the special region of Yogyakarta representing the rural condition of Indonesia. Bantul area is 506,86 km2 and the population for about 911,50 (by citizenship survey in 2011) thousand people. There are no generation sources near the Yogyakarta area, which the powers are supplied from Pacitan, Ungaran or Cilacap area. So, the Bantul area completely depends on the other region.

The primary distributions of the Bantul area are supplied by the two 150 kV transmission line (SUTT) as presented in "**Error! Reference source not found.**". The northern part covers 5 feeders called BNL01, BNL02, BNL03, BNL04, and BNL05, which BNL represents Bantul region. On the other hand, the southern part cover 7 feeders called BNL06 to BNL12. Both have supplied by two 150/20 kV transformer. In this research, the observation area is focused in the Northern part of Bantul.

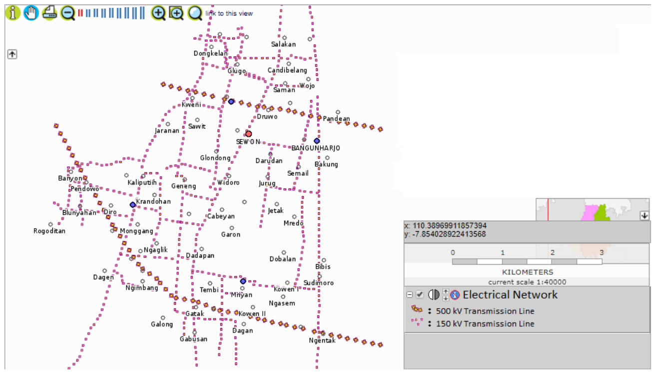

Fig. 1. 20 kV Electricity Network of Bantul Area

2.2. Potential Resources

Located in the equator area, which has abundant resources of solar energy. This situation related to the government program in the energy sector that Indonesia should produce the electricity 23% by 2025 as presented in [31]. For this purpose, further observation of the RES potential in Indonesia is required. Based on the information from the Indonesian ministry of energy, the solar and wind potential in Java and Bali is presented in "Table 1" which shows that the area has full of potential of solar and wind power [32]. Even if the potential of wind is greater than solar, wind power plan is not suitable to be installed in this region.

Table 1. PV and Wind Potential in Java Bali

Region	PV Potential (MW)	Wind Potential (MW)	Remarks
West Java	9099	7036	
Jakarta and Banten	2686	1757	Capital Area
Central Java	8753	5213	
Special Region Yogyakarta	996	1079	Bantul belong to this area
East Java	10335	7907	
Special Region Bali	1254	1079	Different Island

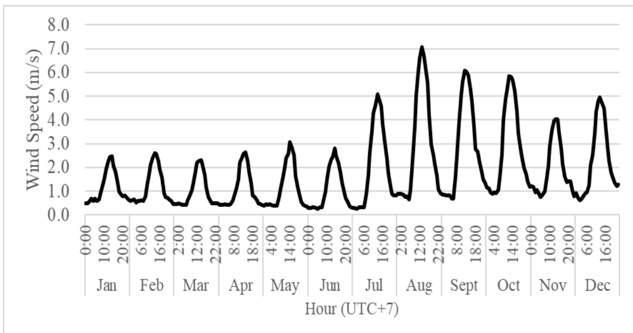

Fig. 2. Seasonal wind speed profiles in Yogyakarta Region

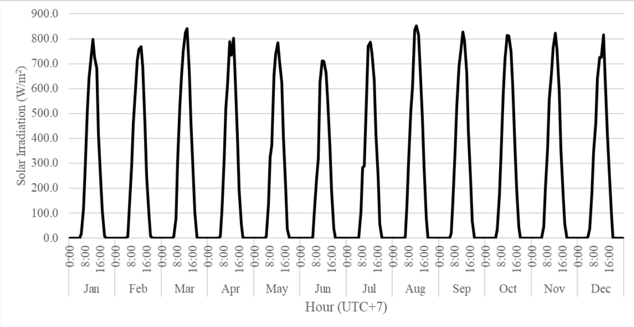

Fig. 3. Seasonal solar irradiation profiles in Yogyakarta Region

The average wind speed profiles for the 4 years historical data in each month are presented in "**Error! Reference source not found.**" with the average wind speed is 1.8 m/s [33]. Maximum wind speed is obtained during August–October.

On the other hand, the solar irradiation data for this region is relatively high which the maximum value approximately 850 W/m2. This situation means the Bantul region having a high potential for solar energy. The average annual seasonal data is presented in "**Error! Reference source not found.**".

3. Technical Consideration of the System Hosting Capacity

3.1. Hosting Capacity

Hosting capacity for a specified power system can be defined as the amount of generation capacity (usually for distributed generation), integrated into the power system, above which the system operating condition become violated [22]. In the distribution system PV can be connected through the low and medium voltage and for the hosting capacity purpose the size of PV is assumed controllable by the regulator. The hosting capacity need to be determined for warranting the security of the power system operation and control, since a specified power system will have their capability to host the PV (farms) based on constraints described in the following standard.

3.2. Technical Standard

Integrating PV in the distribution system affecting the system operation condition such as the voltage profile, short circuit current, power factor correction or reserve power. In order to ensure the quality of the power systems, the following standards need to be evaluated in the planning process.

Voltage Regulation

PV injection in the distribution affects the system's voltage profile depending the injection's magnitude. Voltage deviation as the function of active and reactive power injection is presented in (1)

$$\Delta U \cong \frac{P.R+QX}{|Un|} \qquad (1)$$

where ΔU is voltage deviation, P is active power, Q is reactive power, R is resistance, X is reactance, and $|U_n|$ is magnitude of nominal voltage. There are four variables which can be controlled in order to keep the voltage regulation within standard, which is typically between 0.90–1.05 p.u. as presented in the power quality standar [34], and the national power quality guidelines [35]. Other than the active power, the reactive power system can also be controlled using the methods presented in [36].

Current Flow Increment

PV penetration in the distribution system may increase the loading of a feeder. In order to keep the system security within the safe operation standard, the continuous feeder loading should be kept within 80% from the rated capacity as presented in [32]. The current flow increment may occur in the condition when PV suddenly lost their power due to the cloudy and rainy conditions.

PV rooftop or farm tend to operate in unity power factor, which make the active power contribution into the distribution network increase. This situation makes the distribution transformer (substation) work in very low power factor, since the reactive power load should be fulfilled by the grid. More PV in the distribution system will lower the substation power factor.

For some cases in Indonesian, when the power system is isolated which directly served by small scale synchronous generator, the issue will become more severer if the power factor is very low. Synchronous generator, which normally operated in over exited mode is take the direct effect of this situation. In addition, the Indonesian Utility (PLN) also has the regulation for maintaining the power factor greater than 0.85 [37], which the customer has the PF lower than this should compensate with the penalty cost [38].

Reverse Power

Huge PV penetration in the distribution feeder may cause the reverse power to the distribution transformer. This condition makes the system utility to evaluate the protection systems, additional directional relay is necessary for handle this condition. If the reverse power occurs, it also causes the system losses increment and production cost increment in the generation sites. Due to the complexity, the PV installation regulation do not allow the reversed power occur in their system operation.

4. Proposed Method

The procedures are required for determining the maximum penetration of PV in the distribution systems. The procedures require performing iterative load flow analysis subject to some standards. The complete procedure for determining PV hosting capacity in a specific distribution feeder is presented in "**Error!**

Reference source not found." showing three main criteria for allowing a penetration level.

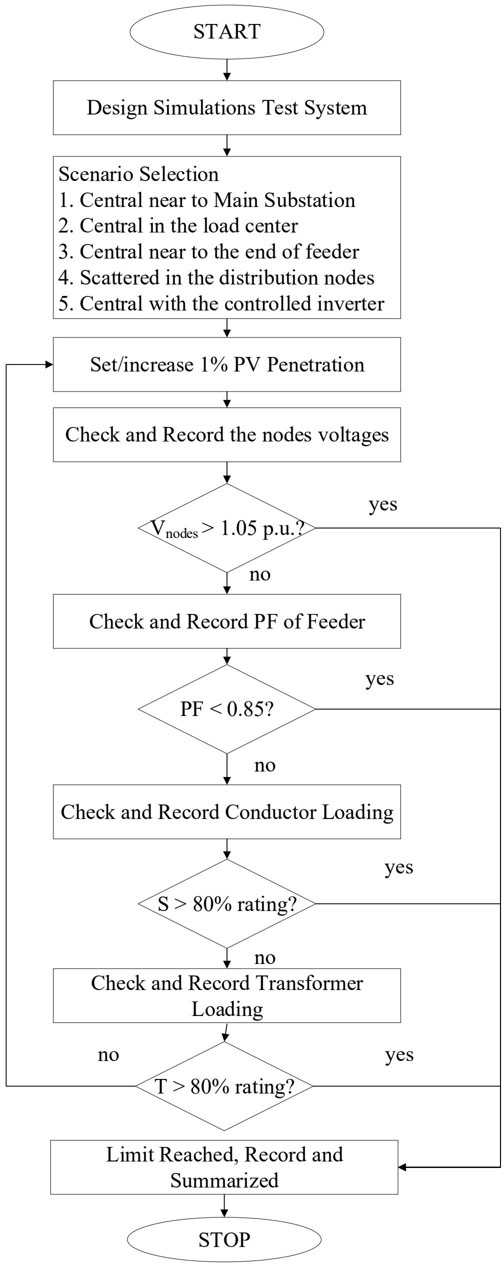

Fig. 4. Procedure for determining the PV Hosting Capacity

4.1. PV Injection Model

PV is modelled as the constant power source without any voltage controlled. As consequence, the voltage in the bus which PV connected becomes uncontrollable. PV penetration is modelled as the negative load.

$$P_{Dj} = P'_{Dj} - P_j^{PV} \qquad (2)$$

with P_{Dj}, P'_{Dj}, and P_j^{PV} are active power netload, actual load and PV output at bus-j.

4.2. Power Flow Equation

Power flow analysis are used for obtaining the operating condition as presented as follow with j and m representing the system busses.

$$P_{Gj} - P_{Dj} = V_j^k \sum_{m=1}^{NB} V_m^k \left(G_{jm}^k \cos\theta_{jm}^k + B_{jm}^k \sin\theta_{jm}^k \right) \qquad (3)$$

$$Q_{Gj}^k - Q_{Dj} = V_j^k \sum_{m=1}^{NB} V_m^k \left(G_{jm}^k \sin\theta_{jm}^k - B_{jm}^k \cos\theta_{jm}^k \right) \qquad (4)$$

4.3. Line Constraint

$$S^k_{jm} \leq 80\% x S_{max} \qquad (5)$$

PV penetration affects line loading profile of the distribution systems. Effect on the line loading is varied depending on the system configuration and PV location.

4.4. Transformer Capacity Constraint

$$T_L \leq 80\% x T_{max} \qquad (6)$$

As presented in the distribution system code, distribution transformer loading should be kept under 80% of its rated capacity.

4.5. Power Factor Constraint

$$PF \geq 0.85 \qquad (7)$$

Typical distribution feeder requires power factor at least 0.85 to ensure the power quality in the systems based on the Indonesian utility policy [37].

4.6. Reverse Power Constraint

Due to the complexity in modifying the protection system, the reverse power constraint is considered. The power from the customer side is not allowed flowing to the distribution transformer side.

4.7. Simulation Set Up

The simulation is conducted in two test systems, the real case at Bantul feeder. The simulation are conducted using Matpower toolbox [39] and ETAP software. Load flow analysis in iterative manner is used for analyzing the voltage deviation, power factor, losses and distribution transformer loading.

For understanding the effect of the PV size and location, all simulations are conducted in some different scenario that the location is set:
(2)

a. centralized near to the distribution transformer ("head'), at bus 1
b. centralized center of the load ("center") at bus 8
c. centralized edge of radial system ("edge") at bus 15
d. distributed proportionally along the feeder ("distributed").

In obtaining the penetration level, the PV penetration level is increased by 1% (relative to the daytime peak load). The voltage regulation is kept between 0.9–1.05 p.u. Line loading, transformer loading, and system power factor should be above 80%, 80% and 0.85, respectively.

5. Results and Dicussion

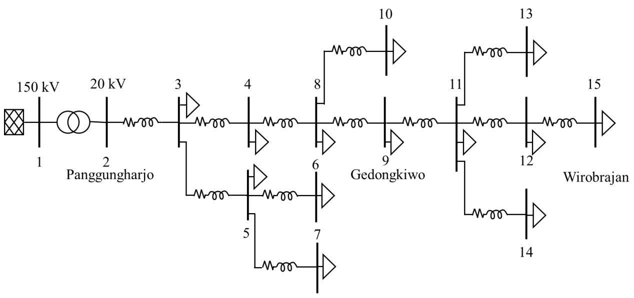

Fig. 5. Bantul No 05 20 kV Distribution Feeder

To demonstrate the effectiveness of the proposed method, the simulation under different scenarios are conducted. PV installation method are evaluated by the locations, installation method and the reactive power support.

System daytime peak load is within 11.00 – 11.40 with 20.5 MW and 10.7 Mvar (power factor 0.89). The Bantul 05 test system case, are simplified as shown in "**Error! Reference source not found.**", having 14 buses. The load in those 14 buses are supplied by the 30 MVA distribution transformer.

5.1. Centralized PV Location

Assuming the PV installation location can be controlled, there are three options for PV locations. In this situation, the PV producer will provide the farm for PV installation. PV location effect is observed in three different busses under various penetration PV level among those 14 buses, that are "Panggungharjo", "Gedongkiwo" and "Wirobrajan". Those location represent the bus location relative to the distribution transformer, which are near, moderate and far, respectively.

For head scenario, increasing 1% penetration case cause the voltage at buses "Panggungharjo", "Gedongkiwo" and "Wirobrajan" increase 0.0042 p.u as presented in "**Error! Reference source not found.**". The voltage increments are proportional for all of the obtained buses showing the characteristic of radial system effect.

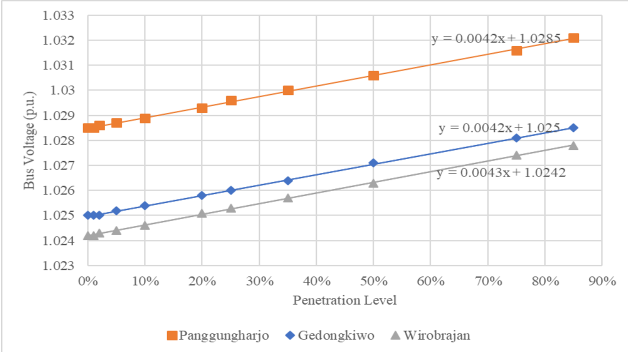

Fig. 6. Obtained Operating Voltage at Buses in Head Scenario

For the center scenario, the sensitivities for Gedungkiwo and Wirobrajan are increase to 0.0163 and 0.164 p.u. respectively as presented in "Fig. 7". PV penetration in the center of load does not have significant effect in the head buses (Penggungharjo). Moreover, the voltage sensitivities in edge scenario is increase in the bus Wirobrajan at 0.0247 p.u. while the other two buses are not affected much as presented in "Fig. 8".

In radial system, installing the PV near to the edge will help increasing the voltage profile in the edge of radial system. In this situation, for a distribution system having the high voltage drop in the afternoon may take advantage in placing PV in the edge. However, most power system having peak load in the evening/night. This situation may cause the overvoltage in the edge of the radial system, which presented by the high sensitivities in the edge bus.

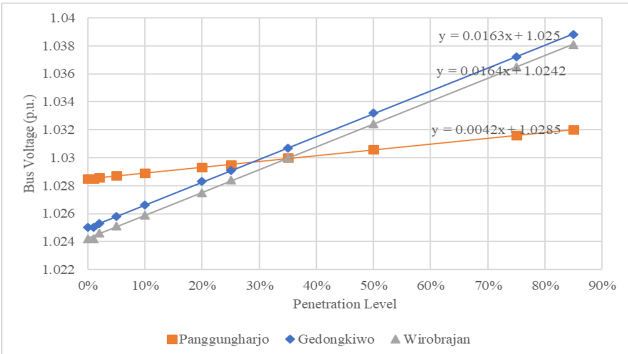

Fig. 7. Obtained Operating Voltage at Buses in Center Scenario

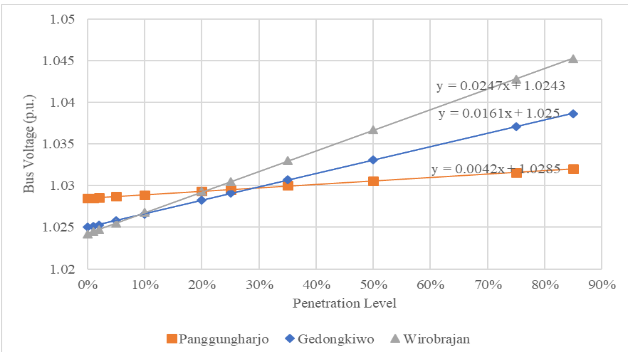

Fig. 8. Obtained Operating Voltage at Buses in Edge Scenario

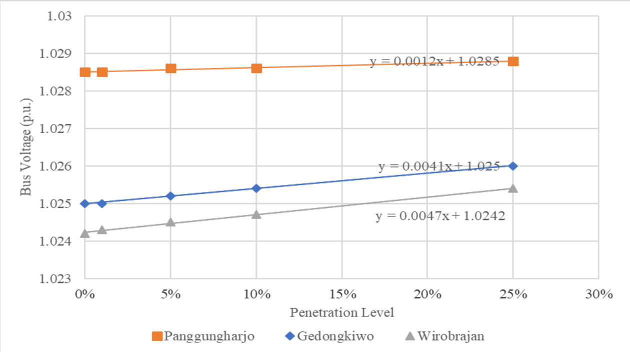

Fig. 9. Obtained Operating Voltage at Buses in Distributed Scenario

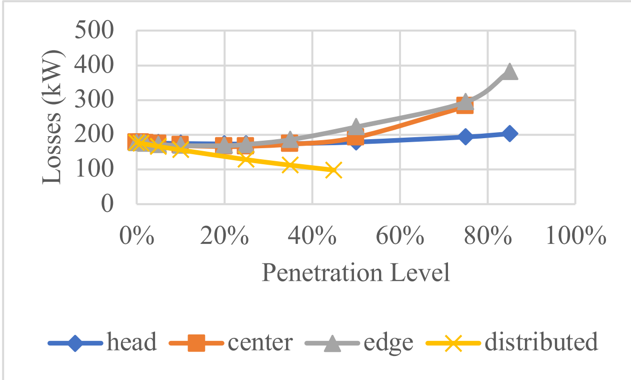

Fig. 10. System Losses under different Scenario

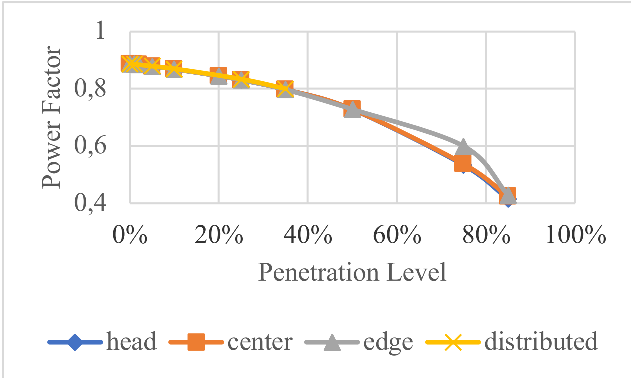

Fig. 11. System Power Factor under different Scenario

5.2. Distributed Locations

Another possibility is installing PV scattered in the distribution system, in PV rooftop cases. This scenario will be more natural and uncontrollable. Comparing to the centralized PV, the effect of distributed PV has different characteristic, as described in voltage sensitivity, losses and system power factor.

Voltage sensitivities in distributed scenarios are not so high as presented in "Fig. 9" especially at bus Penggungharjo is only 0.0012 p.u., while the other two buses are 0.0041 and 0.0047 p.u., respectively. Comparing to the centralized PV scenario, scattered PV will not have high voltage sensitivity issue.

From "**Error! Reference source not found.**", system losses for each scenario are presented. System losses for distributed scenario is lower than any scenario in centralized PV. Since the PV is distributed evenly in the distribution feeder, the system losses are decrease more significant in the same level of penetration. In this situation, PV is installed close to the load (customer) so the line congestion is decreasing.

Furthermore, the penetration also decreases the system power factor, since the PV producer tend to operate the PV close to unity power factor as presented in "**Error! Reference source not found.**". All scenarios will have power factor below 0.85 after 20% penetration. The pattern of all scenario is relatively close since the power factor is affected by power and reactive power. For power quality issue, the DSO should maintain the power factor above 0.85.

5.3. Effect of Controllable Inverter

Central inverter in the PV farm control center can be controlled for reactive power compensation support. For this purpose, PV provider is assumed to operates the PV system not close to unity power factor depending on the system requirement, which is totally not economic. A term condition between the distribution system operator and the PV provider should be applied. Moreover, ancillary services market is existed in the world as presented in [40], which can make the reactive power flow more controllable.

Based on the load characteristic which tend to be inductive, the system power factor will become more inductive. For that reason, the reactive power compensation by the PV owner is necessary to simulate. Assuming that the power factor can be controlled by the owner, the various PV power factors are simulated under PF 0.85, 0.95 (leading) and close to unity for the "center" scenario. It is presented from "**Error! Reference source not found.**" that operating the leading power factor may increase the voltages (it presents the voltage at Gedongkiwo bus). In this situation, leading reactive power support will correct the voltage phasor.

Another effect is in the line loading effect, which makes operating the leading power factor will increase the severest line loading as presented in "Fig. 13". In scenarios with inverter power factor is set 0.85, there are overload condition when PV penetrate at 75 and 85 %.

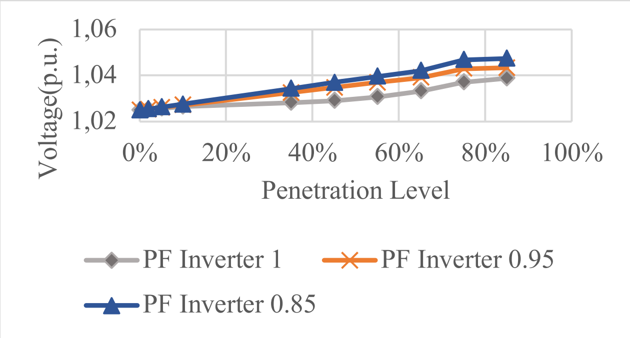

Fig. 12. Obtained Operating Voltage under different PV Power Factor

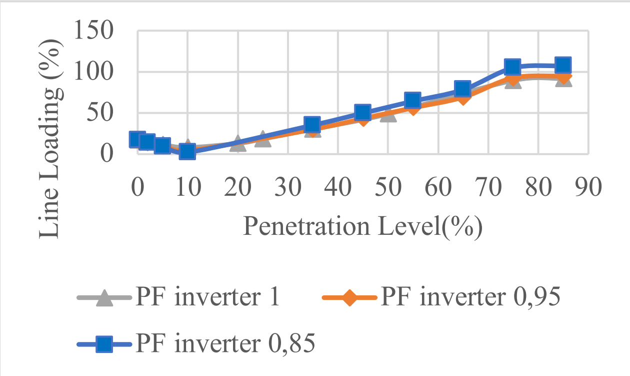

Fig. 13. Line Loading Profiles under different PV Power Factor

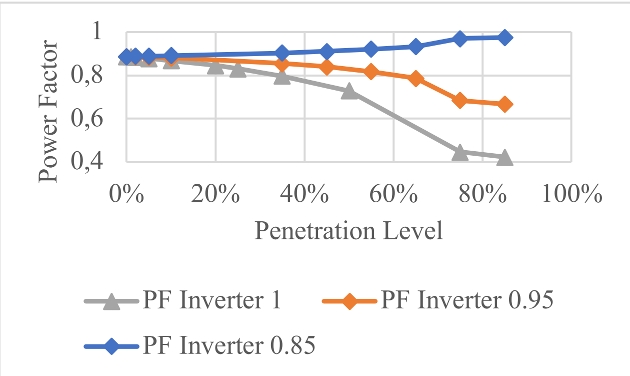

Fig. 14. System Power Factor under different PV Power Factor

However, the system power factor increases if the inverter power factor 0.85 as presented in "Fig. 14". If the inverter set at 0.85, the system power factor can be well maintained above 0.9 lagging, which made the hosting capacity of PV higher.

6. Discussion

PV penetration level different scenarios are summarized in "**Error! Reference source not found.**". Considering uncontrollable PV inverter, the maximum penetration level is obtained at "center" scenarios. All of the head, center, edge and distributed scenarios are violated in the power factor constraint, with the maximum penetration can be achieved in the "Center" scenario, which is 21 %.

Violation occurs in the system power factor which is limited to the 0.85. Even the PV power factor is unity, the system power factor for every scenario are different. Practically, the voltage at the substation can be controlled. In this simulation, the substation is set as swing bus with the voltage magnitude and angle is constant. For maintaining the constant voltage, some reactive power is generated in the substation side. For that reason, the location and the magnitude of generated PV active power triggering the required active power in the substation side.

Table 2. Maximum PV Penetration Under Different Scenario

Skenarios	Load Sensitivity ($x10^{-3}$ p.u.)			Losses	Penetration Level (%)
	Bus 2	Bus 9	Bus 15		
Head	4.2	4.2	4.3	Moderate	20.9
Center	4.2	16.3	16.4	Low	21
Edge	4.2	16.1	24.7	High	20
Distributed	2.7	7.6	8.7	Very Low	14.6
Center (PF inverter 0.95)	5.7	22.4	22.4	Low	41.3
Center (PF inverter 0.85)	7.0	27.3	27.2	Low	61.4

If the PV owner can participate in the reactive power support, the PV hosting capacity can be optimized more. The reactive power support is needed by the distribution system in order to keep the power factor within the permissible limit. However, line loading increment should be monitored.

7. Conclusion

The iterative PV hosting determination method considers the technical aspect in calculating the PV amount in the distribution system. For maximizing the hosting capacity, the utility should consider the PV location and the reactive power support from the PV producer. From the simulation result it can be concluded that installing the PV in the "center" resulted in more hosting capacity than in the "edge" or "head". Moreover, if the PV producer willing to participate the reactive power support it can increase the hosting capacity more. Distributed installation of PV rooftop in the distribution feeder also gives the positive impact to the system since it reduces the more distribution losses than the other location.

Acknowledgements

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