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#18419 Summary

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Title and Abstract

Title	Photovoltaic Allocation with Tangent Vector Sensitivity

Abstract

Indonesia has abundant energy potential from renewable energy resources, especially from the sun but until now, the utilization is not optimal. This paper presents a new methodology for determining the effective location of Photovoltaic (PV) integration into the power system. The proposed scheme consists of two steps: first, determining the area with good irradiance from SOLARGIS and second, calculating the PV-Tangent Vector Sensitivity (PV-TVS) to determine the area that has the greatest impact in increasing network voltage stability and minimizing losses. PV-TVS is developed based on the Continuation Power Flow (CPF) technique which is a voltage stability evaluation tool in the quasi-static analysis methodology. For effectiveness, PV-TVS will be calculated only for good exposure areas. The region that has the highest PV-TVS means that it has the best sensitivity in enhancing system voltage stability and it is recommended for PV placement. The simulation results have been carried out on the South Sulawesi power system in Indonesia, which is a priority location for PV integration in Indonesia, and the results show that this method is effective in determining the location for PV integration.

Indexing

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Title and Abstract

Title	Photovoltaic Allocation with Tangent Vector Sensitivity
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Photovoltaic Allocation with Tangent Vector Sensitivity

Ardiaty Arief[1]*, Muhammad Bachtiar Nappu[2] and Sitti Marwah Rachman[3]

Abstract – *Indonesia has an abundant energy potential from renewable energy resources, especially from the solar but until now, its applications are not substantial. This paper presents a new methodology for determining the effective location of Photovoltaic (PV) integration into a power system. The proposed scheme consists of two steps which are: firstly, the determination of areas with good irradiance from SOLARGIS and secondly, the computation of PV-Tangent Vector Sensitivity (PV-TVS) to determine areas that have the biggest impact in improving network voltage stability and minimizing losses. The PV-TVS is developed based on the Continuation Power Flow (CPF) technique which is a voltage stability evaluation tool in quasi-static analysis methodology. For its effectiveness, the PV-TVS will be computed only for good irradiance areas. The region that has the highest PV-TVS means that it has the best sensitivity in enhancing the system's voltage stability and it is recommended for PV placement. Simulation results were done on the Southern Sulawesi power system in Indonesia which becomes a priority location for PV integration in Indonesia and the results show that this method is effective in deciding the location for PV integration.* ***Copyright © 2019 Praise Worthy Prize S.r.l. - All rights reserved.***

Keywords*: Continuation Power Flow, Irradiance, Losses reduction, Photovoltaic allocation, Tangent Vector Sensitivity, Voltage stability*

I. Introduction

Until now, Indonesia faces challenges in achieving developments in the field of energy. Indonesia still has a high dependence on fossil fuels to meet its domestic energy consumption that is equal to 96%, of which 48% is oil, 18% is gas and 30% is coal, of the total national energy consumption [1]. One of the main reasons of the high consumption of fossil energy is that the public tends use energy wastefully because of the cheap energy prices due to subsidies. Furthermore, Indonesia confronts the problem of declining reserves of fossil energy that has not been compensated by the discovery of new reserves of fossil energy. Many attempts to maximize the use of new and renewable energy (NRE) still faces some obstacles and cannot be performed as planned. Therefore, the Indonesian Government has launched a policy of conservation and diversification of energy [2]. One of them is the development of new renewable energy use as a complementary use of fossil energy. The Government of Indonesia has issued Law No. 30 of 2007 on energy, which mandates that the development and utilization of new and renewable energy should be improved and Law No. 30 of 2009 on electricity also mandates that the use of primary energy sources must be implemented by prioritizing new and renewable energy sources. Indonesia has plenty of new and renewable energy resources such as water, ocean waves, wind, solar, geothermal, biofuels, nuclear or waste. Table I shows the new and renewable energy resources owned by Indonesia.

TABLE I
NEW AND RENEWABLE ENERGY RESOURCES IN INDONESIA [1]

No	Type	Resources	Installed Capacity (MW)	Ratio (%)
1	**2**	**3**	**4**	**5 = 4/3**
1	Hydro	75.000 MW	7.573	10.1 %
2	Geothermal	28.910 MW	1.344	4.65 %
3	Biomass	32.654 MW	1.717	5.26 %
4	Solar	4,80 kWh/m^2/day	48	-
5	Wind	3-6 m/s	1.87	-
6	Sea	49 GW***)	0,01****)	0 %
7	Uranium	3.000 MW**)	30*)	0%

*) Only in Kalan – West Kalimantan
**) As research center, non-energy
***) National Energy Council
****) BPPT's Prototype

As can be seen in Table I, Indonesia has a great renewable energy potential, especially for solar but its utilizations is still insignificant. Since Indonesia is located on the equator, it means that Indonesia receives stable solar irradiation throughout the year hence, Indonesia has abundant solar energy potential with the solar irradiation intensity resources of 4.8 kWh/m^2/day on average. Furthermore, solar energy has the highest potential among renewable energy resources and the development of photovoltaic integration in Indonesia has an immense potential in reducing the carbon dioxide emissions in the world. A PV system for power generation resources for small islands have been initiated from the 1970s, nevertheless, it was stopped because of the 1997 financial

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crisis that hit Indonesia at that time [3]. Fig. 1 shows the Global Horizontal Irradiation (GHI) solar map for Indonesia. Furthermore, development of photovoltaic integration in Indonesia has an immense potential in reducing the carbon dioxide emissions in the world.

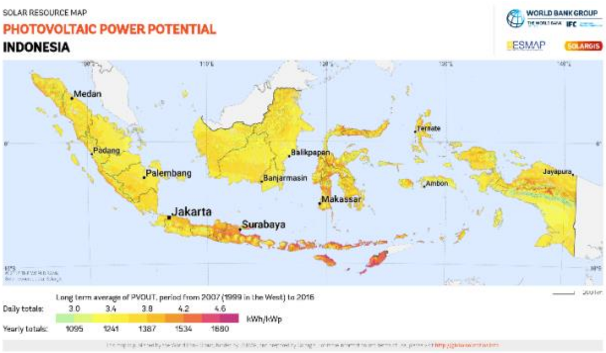


Fig. 1. Photovoltaic power potential map for Indonesia [4]

Nowadays, many countries are targeting the expansion of power supply generated from renewable energy resources. According to Razykov et al., the current world's energy consumption is about 10 terawatts per year and it is estimated to be 30 terawatts per year by 2050 [5]. For the balance of carbon dioxide in the atmosphere, the world needs energy generation by 20 terawatts which is derived from the non-carbon dioxide (non-CO_2) or renewable energy in the middle of this century. The simplest scenario proposed for the electrical energy is power generated from photovoltaic (PV) and other renewable energy such as wind, ocean waves, hydro, fuel cells and others by 10 terawatts [6]. Therefore, PV will play an important role in meeting the world's future energy needs. Presently, it is regarded as the turning point for the development of PV [7].

Serrano-Luján et al. conducted a research and placed Indonesia into the level 2 country group category together with United Arab Emirates, Western USA and Eastern China that have irradiance and electricity mix which will allow the CO_2 reduction of 15-20 tonnes for a 1 kWp PV capacity during its lifetime [8]. Fig. 2 shows the avoidable CO_2 emissions for the 1 kWp installed PV during its lifetime in the countries where the study was undertaken.

Proper PV allocation into a power system is crucial to optimize the voltage stability enhancement. Research have proven that the appropriate renewable energy generation installation in the transmission or distribution network can reduce network losses significantly and improve the voltage [9-11], improve power quality [12], minimizing emissions [13], reduce costs for utilities [14] as well as transmission and distribution network congestion release [15]. Furthermore, with proper connection of energy storage, cascading tripping of renewable energy generations is expected to be prevented [16]. Nevertheless, PV creates more challenges to the distribution system protection and stability because of its limited impact to short-circuit currents [17], probability of reverse power flow to transmission system [18] and the system becomes more susceptible to voltage collapse due to the high R/X ratio of distribution network [19]. In addition, the Government needs to design a policy and procedure to avoid potential financial losses due to non-technical losses [20, 21].

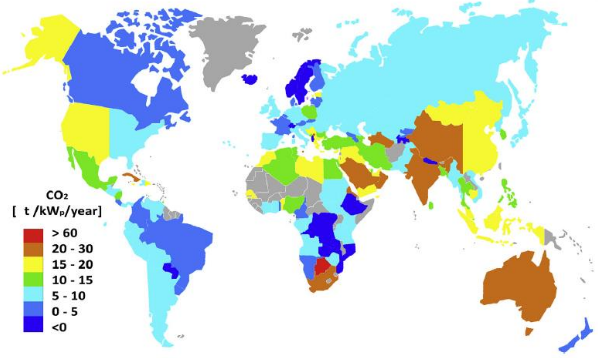


Fig. 2 Avoidable CO_2 emissions per kWp PV/year [8]

Southern Sulawesi region is one of the areas in Indonesia that is prioritized for PV integration in Indonesia since Southern Sulawesi has good irradiation. Therefore, the contribution of this paper is to develop a new methodology to determine the optimal location of PV based on the irradiation data and the network's configuration with Southern Sulawesi as the case study.

II. The Proposed Methodology

The proposed methodology consists of two stages, which are: firstly, the determination of areas with good irradiance from SOLARGIS, and secondly, the computation of PV-Tangent Vector Sensitivity (PV-TVS) to determine areas that have big influence in improving network voltage stability and minimizing losses. The PV-TVS is developed based on the quasi-static method of the Continuation Power Flow (CPF). This section will explain the proposed methodology in detail.

II.1. Solar Irradiation

Solar irradiation is the dispersion of solar energy derived from the thermonuclear process that occurs in the sun. Solar irradiation is a very important element for PV cells, since it functions like a conventional power plant fuel that makes the photovoltaic systems able to work. The more irradiation, the better the resulting current. Currently, the PV system is the best approach for producing electricity directly from the solar irradiation, since the solar PV has cost-competitive construction. However, it is important to assess the solar irradiance for maintaining system's reliability and stability considering the PV's intermittent features [22].

II.2. Continuation Power Flow (CPF) Method

After the determination of selected areas with good solar irradiation, then the second step which is the computation of the PV-Tangent Vector Sensitivity (PV-TVS). PV-TVS, is derived from the tangent vector calculation of the predictor-corrector procedure of the continuation power flow (CPF) method. This method is a quasi-steady-state voltage stability analysis developed by Ajjarapu and Christy [23]. CPF method modifies the conventional power flow equation. It uses a prediction and correction technique to find power flow solutions from basic loads to stable or critical stability states to determine a critical point. In addition, the CPF method can be employed to identify the most influential bus to voltage instability/collapse and also increase or reduce the network losses [24], which is based on the transferred active and reactive power from transmission or distribution lines. Figure 2 describes the prediction and correction procedure of the CPF method. As shown in Fig. 3, the analysis procedure starts from a known outcome, and then it predicts the next solution for different load parameter values.

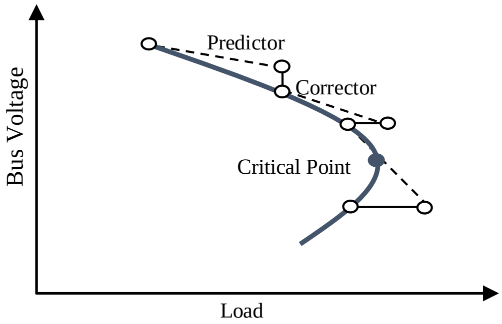


Fig. 3 Predictor-corrector scheme of the CPF [23]

Firstly, a load parameter, denoted by φ is defined by:

$$0 \leq \varphi \leq \varphi_{critical}$$

where $\varphi = 0$ corresponds to the base load and $\varphi = \varphi_{critical}$ corresponds to critical load. This load parameter is then integrated into the active and reactive power equations then:

$$0 = P_{Gi0}(1 + \lambda k_{Gi}) - P_{Li0} - \varphi\,(k_L\, S_{\Delta base} \cos\theta_i) - P_{Ti} \quad (1)$$

$$0 = Q_{Gi0} - Q_{Li0} - \varphi\,(k_{Li}\, S_{\Delta base} \sin\theta_i) - Q_{Ti} \quad (2)$$

where,

P_{Li0}, Q_{Li0} are the original load at bus i, active and reactive power

k_{Li} is the multiplying constant to entitle the rate of load change at bus i as φ changes

θ_i is the bus i power angle of load change

$S_{\Delta base}$ is the base quantity of apparent power

P_{Gi0} is the base case active power generated at bus i

k_{Gi} is the multiplying constant to state the rate of change in generation as φ varies

$P_{Ti},\ Q_{Ti}$ are the active and reactive power injected at bus i.

Then a continuation algorithm is implemented at the modified power flow equations. The above equations can be rewritten in a simple form such that:

$$F\,(\delta, V, \varphi) = 0 \quad (3)$$

where δ represents the generator angle vector, V represents the bus voltage magnitude vector and φ is the loading parameter.

CPF method develops the prediction and correction steps scheme to achieve a solution track of a modified power flow equation. In the prediction step, the tangent vector is calculated from derivation of both sides of the power flow equation, hence:

$$[F_\delta \quad F_V \quad F_\varphi]\begin{bmatrix} d\delta \\ dV \\ d\varphi \end{bmatrix} = 0 \quad (4)$$

In addition to the direction of the solution track, the tangent vector also provides information for sensitivity analysis to determine the weak buses. The tangent vector gives ratio of degree of difference in the voltage change to degree of difference in the active power load change. Since photovoltaic only produces active power, hence this sensitivity given by the tangent vector is suitable in finding the PV placement. Therefore, in this study, the ratio of degree of difference in the voltage change to the degree of difference in the active power load change is called the Photovoltaic – Tangent Vector Sensitivity (PV-TVS). The PV-TVS at bus *j* becomes:

$$PV - TVS_j = \left|\frac{dV_j}{dP_{total}}\right| = \left|\frac{dV_j}{Cd_\emptyset}\right|$$

$$= \max \left\|\left|\frac{dV_1}{Cd_\emptyset}\right|, \left|\frac{dV_2}{Cd_\emptyset}\right|, \ldots\ldots \left|\frac{dV_n}{Cd_\emptyset}\right|\right\| \quad (5)$$

Because the value $Cd_\emptyset$ is the same, therefore the weakest bus is the bus with the highest dV_j. Hence, buses with the highest PV-TVS are then proposed for PV placement, since these buses have high irradiance and have good sensitivity in improving the system's voltage.

After a power flow study, the next step is to run CPF and calculate the PV-TVS in determining the most sensitivity location in improving stability in the system at the locations that have high irradiance. The buses with the highest PV-TVS were then recommended as the priority of PV placement.

II.3. Flowchart of the Proposed Method

Fig. 4 shows a proposed photovoltaic placement flowchart diagram using solar irradiance obtained from SOLARGIS and CPF method. After a power flow study, the next step is to run CPF and calculate PV-TVS in determining the most sensitivity location in improving stability in the system at locations with high irradiance. The buses with high PV-TVS is then recommended as the priority of PV placement. Fig. 4 shows the flowchart of the proposed DG placement by using CPF method and tangent vector.

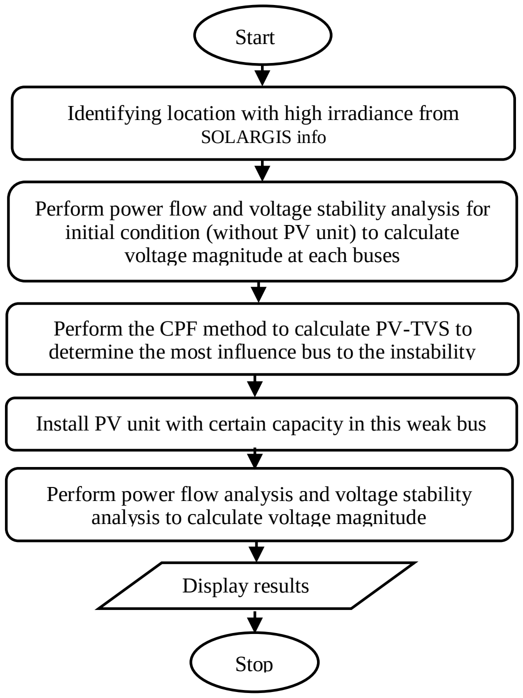


Fig. 4 Flowchart of the proposed PV placement

III. Test results and analysis

III.1. Solar Irradiation Results

The proposed method was simulated on the Southern Sulawesi interconnected power system in Indonesia that consists of 44 buses (substations), 7 major power plants and 47 transmission lines. The simulations were done by assessing the PV placement for the sizes of 1 MWp, 3 MWp and 5 MWp PV capacities.

The first stage is the identification of the areas with good irradiance. Based on the SOLARGIS data, the Southern Sulawesi region has good irradiance, which is shown in Fig. 5. From this data, Makassar City, Jeneponto, Sidrap, Bone, Palopo, Polmas, Pinrang and Poso regions were identified to have high irradiance of approximately 1607 kWh/m^2/year. Makassar city as the capital of the South Sulawesi province is very dense and since it is one of the areas that has good irradiance, the computation of PV-TVS was calculated in several substations as representations, which are; Bontoala, Panakukang, Tallo Lama and Daya. Therefore, those buses were the selected buses whose PV-TVS were calculated.

Fig. 5 Solar Global Horizontal Irradiation map for Southern Sulawesi [4]

III.2. PV-TVS Computation

In this research, PV-TVS values were calculated only for areas with good irradiance. The PV-TVS values computed for these selected areas were for the PV capacities of 1 MWp, 3 MWp, 5 MWp. Based on the areas with good irradiance, the PV-TVS for these areas were calculated for the 1 MWp PV capacity.

Fig. 6 informs the PV-TVS for each substation with good irradiance of the system in the descending order. The results show that Tallo Lama substation has the highest PV-TVS with the value of 0.9081. This means that Tallo lama substation has the largest influence in improving the system's stability. Panakukang, Bontoala and Daya substations also have good PV-TVS, which also mean that these buses have good influence in improving the system's voltage stability. On the other hand, Poso substation has the lowest PV-TVS value which implies that this region has small influence in improving the system's voltage stability.

III.3. Voltage Profile Improvement

Fig. 7 shows the voltage profile improvement for all PV placements. It can be seen from Fig. 7, when the PV of 1 MWp is placed at bus Tallo Lama, the voltage profile improved significantly and if it is integrated at Poso, the voltage profile just improve slightly compare to that without PV integration.

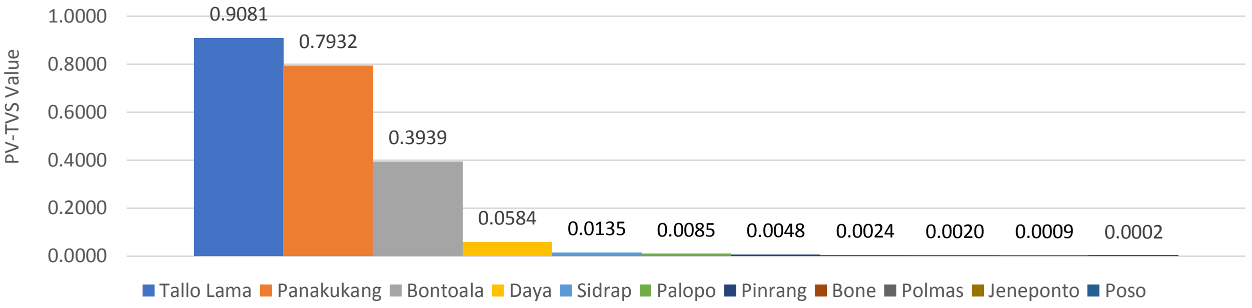


Fig. 6 PV –TVS values for 1 MWp Photovoltaic Capacity

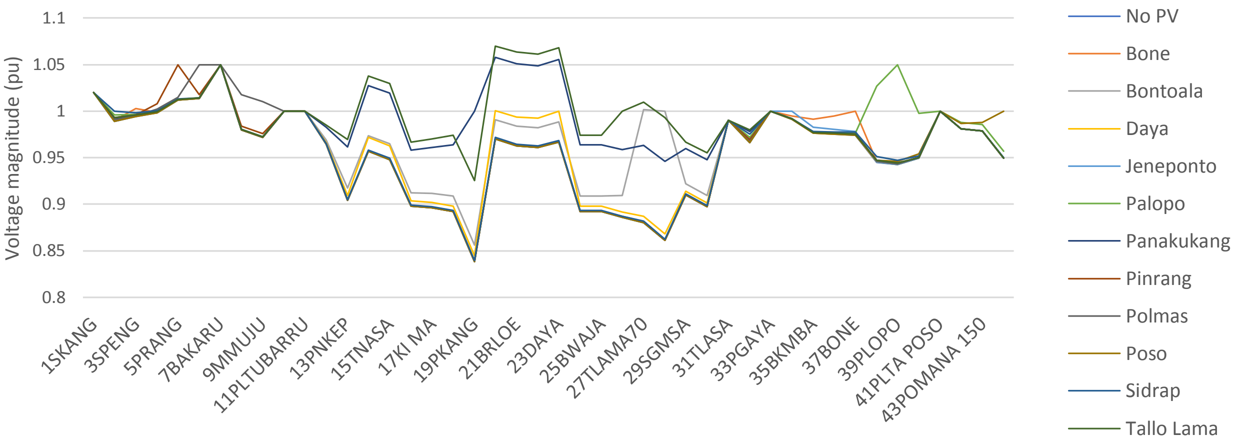
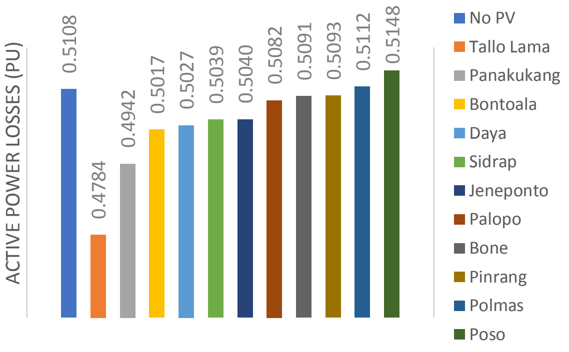


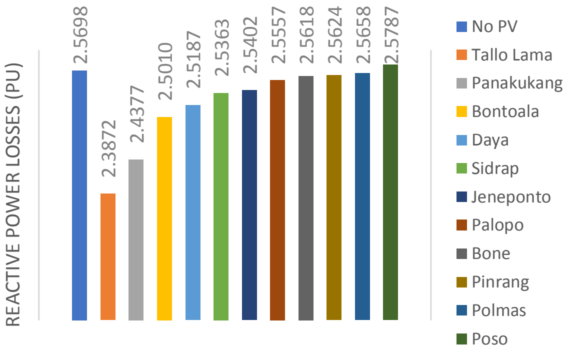
Fig. 7 Voltage profile for all PV placement of 1 MWp

III.4. Network Power Losses

Figs. 8 (a) and (b) illustrates the active and reactive power losses for the 1 MWp PV placements at each area, respectively. Table II provides information on the percentage of the decrease or increase of network losses for all the PV placements. The negative sign indicates the decrease in network losses, whereas the positive sign implies the losses addition.



(a) Active Power Losses



(b) Reactive Power Losses

Fig. 8 Power losses calculation for 1 MWp PV placement at each area

The initial active and reactive power losses of the system were 0.5108 p.u. and 2.5698 p.u., correspondingly. If the PV is placed in the Tallo Lama area, it results in the lowest system's active and reactive power losses. In contrast, placing the PV of 1 MWp in the Poso area, both the active and reactive power losses increased. The active power losses increased from 0.5108 p.u. to 0.5148 p.u. and the reactive power losses increased from 2.5698 p.u. to 2.5787 p.u. It can be seen from Table II, that the active power losses if the PV is placed in Tallo Lama, it

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decreased to around 6.33%, whereas placing the 1 MWp PV at Poso will result in an increase of active power to 0.79%.

TABLE II
NETWORK LOSSES FOR EACH PV PLACEMENT OF 1 MWp

1 MWp PV Location	Active Power Losses		Reactive Power Losses	
	pu	% decrease	pu	% decrease
No PV	0.5108	0	2.5698	0
Tallo Lama	**0.4784**	**-6.33**	**2.3872**	**-7.10**
Panakukang	0.4942	-3.25	2.5010	-2.68
Bontoala	0.5017	-1.76	2.5187	-1.99
Daya	0.5027	-1.58	2.4377	-5.14
Sidrap	0.5040	-1.32	2.5363	-1.30
Jeneponto	0.5082	-0.49	2.5557	-0.55
Palopo	0.5091	-0.32	2.5618	-0.31
Bone	0.5093	-0.29	2.5624	-0.29
Pinrang	0.5039	-1.34	2.5402	-1.15
Polmas	0.5112	0.10	2.5658	-0.16
Poso	**0.5148**	**0.79**	**2.5787**	**0.34**

III.5. PV-TVS and Network Losses Analysis for 1 MWp, 3 MWp and 5 MWp PV

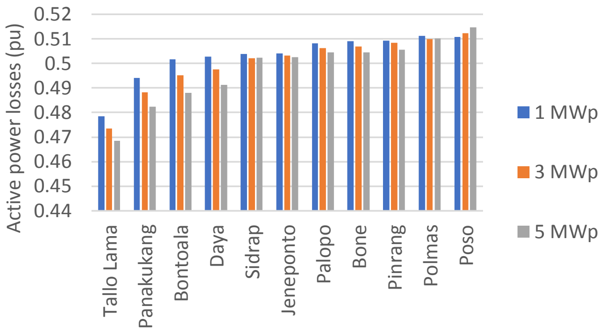
Table III informs the PV-TVS calculation for each PV placements of 1 MWp, 3 MWp and 5 MWp. For all of these simulations, Tallo Lama has the highest PV-TVS value whereas Poso has the smallest PV-TVS value. Furthermore, Poso has a negative value of PV-TVS for the 3 MWp and 5 MWp PV capacities. The negative value suggests that this can deteriorate the system's performance.

TABLE III
PV-TVS CALCULATION FOR EACH PV PLACEMENT OF 1 MWP, 3 MWP AND 5 MWP

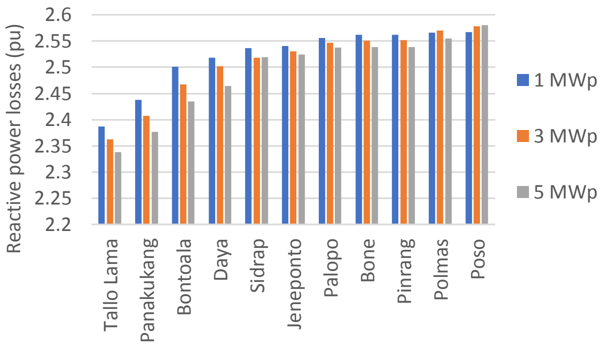
Location	PV-TVS		
	1 MWp	3 MWp	5 MWp
Tallo Lama	**0.908138**	**0.908851**	**0.909554**
Panakukang	0.793209	0.793744	0.794234
Bontoala	0.393857	0.399379	0.404696
Daya	0.058354	0.066072	0.073616
Sidrap	0.013496	0.013443	0.013390
Jeneponto	0.008470	0.008374	0.008269
Palopo	0.004815	0.004827	0.004834
Bone	0.002443	0.002911	0.003373
Pinrang	0.001991	0.002010	0.002024
Polmas	0.000853	0.001997	0.003109
Poso	**0.000205**	**-0.000048**	**-0.000321**

Figs. 9 (a) and (b) show the active and reactive power losses for the 1 MWp, 3 MWp and 5 MWp capacities. For all substations, the trend in the active and reactive power losses value tend to decrease as the capacity of PV increased. In contrast, the active and reactive power losses increased as the PV capacity increased if the PV is placed at Poso. From the system's structure, Poso is located in the northern part of the system, whereas the load centers are located in Makassar City, where it is located in the southern part of the system. Therefore, placing the PV at Poso, is not effective in improving the system's stability and reducing losses, but placing the PV at Tallo Lama, Panakukang, Bontoala or Daya (which are substations in Makassar City) have significant impact in improving the stability and reducing losses.

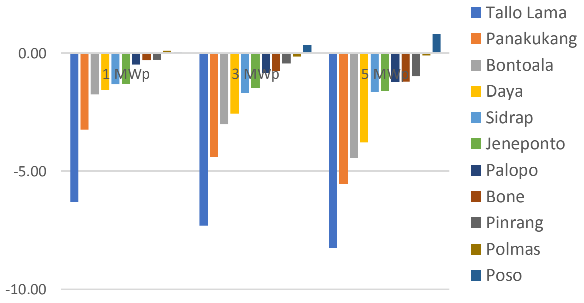
Figs. 10 (a) and (b) show the percentage of losses decrease or increase. Placing the PV at Tallo Lama will give the highest losses reduction for all simulations. The other way around, placing PV at Poso will give losses addition as the PV capacity increases. Since PV's only produce active power, hence research on the PV and reactive power compensating devices for Southern Sulawesi should be done, especially with the integration of wind power plants [25].



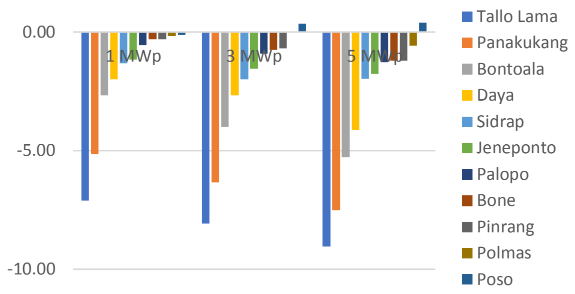
(a) Active Power Losses



(b) Reactive Power Losses
Fig. 9 Power losses for all simulations



(a) Active Power Losses



(b) Reactive Power Losses

Fig. 10 Power losses reduction/addition percentage for all simulations

IV. Conclusions

This paper proposes a new analytical method for the PV placement. The proposed method consisted of two stages, which are: the identification of areas with good irradiance from SOLARGIS, then compute the PV-Tangent Vector Sensitivity (PV-TVS) for those areas. The PV-TVS provides information about the sensitivity of each location to the change of active power. From SOLARGIS, it has been determined that 8 regions have good irradiance.

The results of this study verify that substations in the city of Makassar have high irradiance and high PV-TVS. Therefore, these areas (Panakukang, Tallo Lama, Bontoala, and Daya) are recommended for the PV allocation, however, since Makassar City is quite dense and the PV plants installation require extensive large area of land, hence further research needs to be done to find suitable locations or other solutions in Makassar City. Other regions such as: Jeneponto, Sidrap, Bone, Palopo, Pinrang and Polmas also have good irradiance but smaller PV-TVS. PV can also be placed at these regions, even though it is not as effective as if it is placed in Makassar. Nevertheless, the Poso region tends to have small and even negative PV-TVS. Based on these results, it informs that placing the PV at Poso is not effective since it does not have any significant effect in improving voltage profile and furthermore it may be increasing more network losses into the system.

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#18419 Review

SUMMARY **REVIEW** EDITING

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Section	Articles
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Photovoltaic Allocation with Tangent Vector Sensitivity

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Abstract – *Indonesia has abundant energy potential from renewable energy resources, especially from the sun but until now, the utilization is not optimal. This paper presents a new methodology for determining the effective location of Photovoltaic (PV) integration into the power system. The proposed scheme consists of two steps: first, determining the area with good irradiance from SOLARGIS and second, calculating the PV-Tangent Vector Sensitivity (PV-TVS) to determine the area that has the greatest impact in increasing network voltage stability and minimizing losses. PV-TVS is developed based on the Continuation Power Flow (CPF) technique which is a voltage stability evaluation tool in the quasi-static analysis methodology. For effectiveness, PV-TVS will be calculated only for good exposure areas. The region that has the highest PV-TVS means it has the best sensitivity in enhancing system voltage stability and is recommended for PV placement. The simulation results were carried out on the South Sulawesi power system in Indonesia which is a priority location for PV integration in Indonesia and the results show that this method is effective in determining the location for PV integration.* ***Copyright © 2019 Praise Worthy Prize S.r.l. - All rights reserved.***

***Keywords**: Continuation Power Flow, Irradiance, Losses reduction, Photovoltaic allocation, PV-Tangent Vector Sensitivity, Voltage stability*

Nomenclature

CPF	Continuation Power Flow
GHI	Global Horizontal Irradiation
k_{Li}	Multiplying constant to entitle the rate of load change at bus i as φ changes
k_{Gi}	Multiplying constant to state the rate of change in generation as φ varies
NRE	New and Renewable Energy
P_{Gi0}	Base case active power generated at bus *i*
P_{Li0}	Original active load at bus *i*
P_{Ti}	Active power injected at bus *i*
PV	Photovoltaic
PV-TVS	Photovoltaic-Tangent Vector Sensitivity
Q_{Li0}	Original reactive load at bus *i*
Q_{Ti}	Reactive power injected at bus *i*
$S_{\Delta base}$	Base quantity of apparent power
V	Bus voltage magnitude vector
ΔP	Difference in the active power load
ΔV	Difference in the voltage change
θ_i	Power angle of load change at bus *i*
δ	Generator angle vector
φ	Loading parameter
$\varphi = 0$	Loading parameter corresponds to the base load
$\varphi = \varphi_{critical}$	Loading parameter corresponds to critical load

I. Introduction

Until now, Indonesia faces challenges in achieving developments in the energy sector. Indonesia still has a high dependency on fossil fuels to meet its domestic energy consumption which is 96%, of which 48% is oil, 18% is gas and 30% is coal, of the total national energy consumption [1].

One of the main reasons for the high consumption of fossil energy is that public tends to spend energy wastefully because of low energy prices due to subsidies. Furthermore, Indonesia faces the problem of decreasing fossil energy reserves that have not yet been compensated by the discovery of new fossil energy reserves. Many attempts to maximize the use of NRE still face several obstacles and cannot be performed according to plan. Therefore, the Government of Indonesia has launched a policy of conservation and diversification of energy [2].

One of them is the development of the use of renewable energy as a complement to the use of fossil energy. The Government of Indonesia has issued Law No. 30 of 2007 concerning energy, which mandates that the development and utilization of NRE must be increased and Law No. 30 of 2009 concerning electricity also mandates that the use of primary energy sources must be implemented by prioritizing NRE sources. Indonesia has many NRE resources such as water, ocean waves, wind, solar, geothermal, biofuels, nuclear or waste. Table I shows the NRE resources owned by Indonesia.

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TABLE I
NEW AND RENEWABLE ENERGY (NRE) RESOURCES IN INDONESIA [1]

No	Type	Resources	Installed Capacity (MW)	Ratio (%)
1	**2**	**3**	**4**	**5 = 4/3**
1	Hydro	75.000 MW	7.573	10.1 %
2	Geothermal	28.910 MW	1.344	4.65 %
3	Biomass	32.654 MW	1.717	5.26 %
4	Solar	4,80 kWh/m^2/day	48	-
5	Wind	3-6 m/s	1.87	-
6	Sea	49 GW***)	0,01****)	0 %
7	Uranium	3.000 MW**)	30*)	0%

*) Only in Kalan – West Kalimantan
**) As research center, non-energy
***) National Energy Council
****) BPPT's Prototype

As can be seen in Table I, Indonesia has a large NRE potential, especially for solar power but its utilization is still insignificant. Because Indonesia is located at the equator, it means that Indonesia receives stable solar irradiation throughout the year hence Indonesia has abundant solar energy potential with an average solar irradiation intensity resource of 4.8 kWh/m^2/day.

Furthermore, solar energy is an attractive clean renewable energy [3] and has the highest potential among renewable energy resources hence the development of photovoltaic integration in Indonesia has immense potential in reducing carbon dioxide emissions in the world. The PV system for power generation resources for small islands in Indonesia had been started since the 1970s, nevertheless was stopped due to the 1997 financial crisis that hit Indonesia at that time [4]. Fig. 1 shows a GHI solar map for Indonesia.

Nowadays, many countries are targeting expansion of power supplies generated from NRE resources. According to Razykov et al., the current world energy consumption is around 10 terawatts per year and an estimated 30 terawatts per year in 2050 [5]. To balance carbon dioxide in the atmosphere, the world needs 20 terawatt of energy generation that comes from non-carbon dioxide (non-CO$_2$) or NRE in the middle of this century. The simplest scenario proposed for electrical energy is power generated from PV and other NRE such as wind, sea waves, hydro, fuel cells and others as much as 10 terawatt [6]. Therefore, PV will play an important role in meeting the world's energy needs in the future. At present, this is considered a turning point for PV development [7].

Serrano-Luján et al. conducted research and placed Indonesia in the category of level 2 country groups together with the United Arab Emirates, Western USA and Eastern China which have a combination of electricity and irradiation that will allow CO$_2$ reduction of 15-20 tons for PV capacity of 1 kWp over its lifetime [8]. Fig. 2 shows the avoidable CO$_2$ emissions for 1 kWp installed PV over its lifetime in the countries where the study was conducted.

Proper PV allocation into the power system is very important to optimize the increase in voltage stability [9]. Research has proven that the installation of a suitable renewable energy generation in a transmission or distribution network can significantly reduce network losses and improve voltage [10-14], improve power quality [15], minimize emissions [16], reduce costs for utilities [17] as well as the transmission and distribution network congestion release [18-20]. Furthermore, with proper connection of energy storage, load shedding or cascading tripping of renewable energy generations is expected to be prevented [21, 22]. Nevertheless, PV creates more challenges for the protection and stability of the distribution system due to its limited impact to short-circuit currents [23] as well as probability of reverse power flow to transmission system [24].

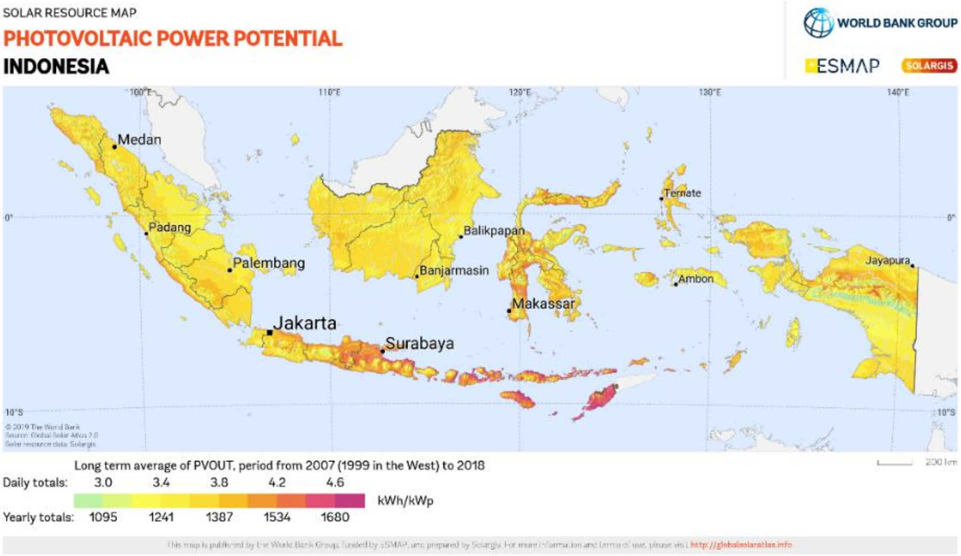


Fig. 1. Photovoltaic power potential map for Indonesia [25]

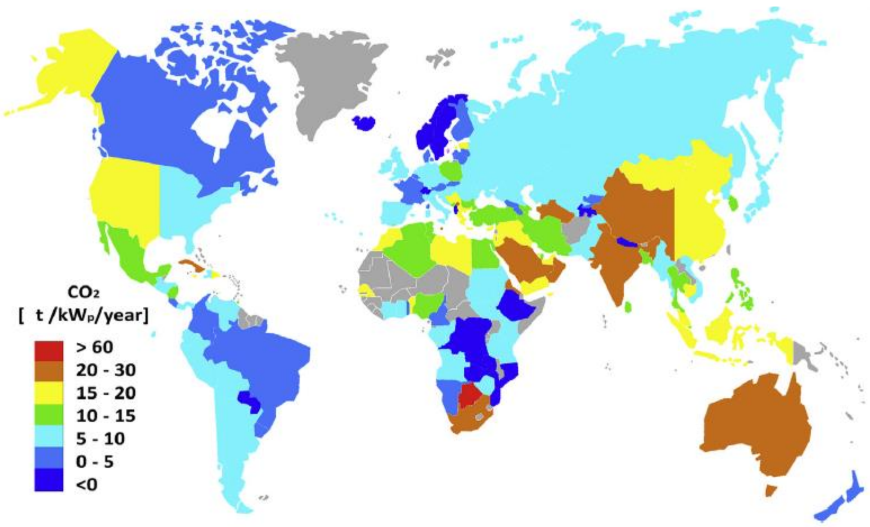


Fig. 2 Avoidable CO_2 emissions per kWp PV/year [8]

In recent years, various methodologies have been developed for PV placement. The authors in [26] created a new strategy for optimizing PV systems with the shortest path algorithm. The Voltage Stability Index (VSI) was developed to investigate the impact of PV on the transmission network system by considering the system voltage stability [24]. Paper [27] analyzes the penetration of PV in a distribution system using modified Monte Carlo simulation. Furthermore, the metaheuristic optimization method has become one of the popular techniques for solving many optimization problems because of its flexibility, free derivation process, ability to handle complicated problems and the ability to escape from local targets. Genetic algorithm (GA) based on Newton-Raphson power flow is employed in [28] for PV placement with the aim of minimizing losses. Hybrid methods based on GA and optimal reactive control are also applied to [29]. Optimal PV allocation is proposed by using self-organizing hierarchical binary particle swarm optimization (SHBPSO) in [30] and Binary Particle Swarm Optimization (BPSO) in [31]. However, both GA and PSO techniques are time-consuming and may be less effective in escaping from local optimal values. The authors in [32] developed the quantum-inspired binary lightning search algorithm (QBLSA) for optimal PV placement. An improved gravitational search algorithm (IGSA) is proposed to determine the optimal PV location and size in [33].

In the placement of PV, solar irradiation is an important parameter to consider, because it functions like a fuel for conventional power plants. The more irradiation, the better the current generated. Therefore, it is crucial to choose an area for PV placement with good irradiation. Therefore, the contribution of this paper is to:

1. Develop a two-step methodology where in the first step is the selection of areas with good radiation.
2. Formulate Photovoltaic-Tangent Vector Sensitivity (PV-TVS) which provides information about areas that have a high impact in increasing voltage stability.

The South Sulawesi region is one of the regions in Indonesia that is prioritized for PV integration in Indonesia because South Sulawesi has good irradiation. Therefore, the contribution of this paper is to develop a new methodology for determining the optimal PV location based on irradiation data and network configuration with South Sulawesi as a case study.

The remaining sections of this paper are organized as follows. Section II provides an overview of the proposed methodology which is an explanation of solar irradiation, elaboration of the Continuation Power Flow (CPF) method and the proposed PV placement flowchart. Section III provides results and analysis, and Section IV summarizes the main findings of the research.

II. The Proposed Methodology

The proposed methodology consists of two stages, namely: first, the determination of areas with good radiation from SOLARGIS, and second, the calculation of PV-Tangent Vector Sensitivity (PV-TVS) to determine areas that have a major influence in increasing network voltage stability and minimizing losses. PV-TVS is developed based on the quasi-static method of Continuation Power Flow (CPF). This section will explain the proposed methodology in detail.

II.1. Solar Irradiation

Solar irradiation is the dispersion of solar energy derived from thermonuclear processes that occur in the sun. Solar irradiation is a very important element for PV cells, because it functions like a conventional power plant fuel that makes the photovoltaic system work. The more irradiation, the better the current generated. At present, PV systems are the best approach to generate electricity directly from solar irradiation, because solar PV has a cost competitive construction. However, it is important to assess solar radiation to maintain the reliability and stability of the system given the intermittent features of PV [34-36].

II.2. Continuation Power Flow (CPF) Method

After determining the selected area with good solar irradiation, the second step is the calculation of PV-Tangent Vector Sensitivity (PV-TVS). PV-TVS, derived from the calculation of tangent vectors from the predictor-corrector procedure of the continuation power flow (CPF) method. This method is a quasi-steady-state voltage stability analysis developed by Ajjarapu and Christy [37].

The CPF method modifies conventional power flow equations. It uses prediction and correction techniques to find power flow solutions from the base load to stable or critical stability conditions to determine the critical point. In addition, the CPF method can be used to identify the bus that has the greatest influence on voltage instability/collapse and also increase or decrease network losses [13], which is based on active and reactive power transferred from a transmission or distribution line. Fig. 3 explains the procedure of prediction and correction of the CPF method. As shown in Fig. 3, the analysis procedure starts from the known results, and then predicts the next solution for different load parameter values.

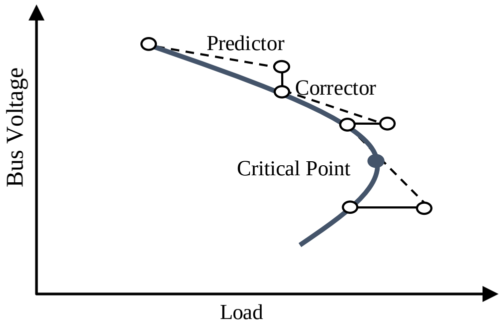


Fig. 3 Predictor-corrector scheme of the CPF [37]

First, the load parameter, denoted by φ is defined by:

$$0 \leq \varphi \leq \varphi_{critical}$$

This load parameter is then integrated into the active and reactive power equations then:

$$0 = P_{Gi0}(1 + \lambda k_{Gi}) - P_{Li0} - \varphi\,(k_L\, S_{\Delta base} \cos\theta_i) - P_{Ti} \quad (1)$$

$$0 = Q_{Gi0} - Q_{Li0} - \varphi\,(k_{Li}\, S_{\Delta base} \sin\theta_i) - Q_{Ti} \qquad (2)$$

Then the continuation algorithm is implemented in the modified power flow equation. The above equations can be rewritten in such a simple form:

$$F\,(\delta, V, \varphi) = 0 \qquad (3)$$

The CPF method develops a scheme of prediction and correction steps to achieve the solution path of the modified power flow equation. In the prediction step, the tangent vector is calculated from the derivation of both sides of the power flow equation, hence:

$$\begin{bmatrix} F_\delta & F_V & F_\varphi \end{bmatrix} \begin{bmatrix} d\delta \\ dV \\ d\varphi \end{bmatrix} = 0 \qquad (4)$$

In addition to the direction of the solution pathway, the tangent vector also provides information for sensitivity analysis to determine sensitive buses. The tangent vector gives a ratio of the degree of difference in voltage changes to the degree of difference in changes in active power load. Because photovoltaics only produce active power, the sensitivity given by this tangent vector is suitable for finding PV placement. Therefore, in this study, the ratio of the level of difference in voltage change (ΔV) to the level of difference in active power load (ΔP) changes is called Photovoltaic-Tangent Vector Sensitivity (PV-TVS). PV-TVS on bus *j* becomes:

$$PV - TVS_j = \left|\frac{dV_j}{dP_{total}}\right| = \left|\frac{dV_j}{Cd_\emptyset}\right|$$

$$= \max\left|\left|\frac{dV_1}{Cd_\emptyset}\right|, \left|\frac{dV_2}{Cd_\emptyset}\right|, \ldots \ldots \left|\frac{dV_n}{Cd_\emptyset}\right|\right| \qquad (5)$$

Because the value of $Cd_\emptyset$ is the same, the most sensitive bus is the bus with the highest dV_j. Therefore, the bus with the highest PV-TVS is then proposed for PV placement, since this bus has high radiation and has good sensitivity in increasing the system voltage.

After the power flow study, the next step is to run CPF and calculate PV-TVS in determining the most sensitive location in increasing system stability in locations that have high radiation. The bus with the highest PV-TVS is then recommended as a PV placement priority.

II.3. Flowchart of the Proposed Method

Fig. 4 shows a flowchart diagram of the proposed photovoltaic placement using solar radiation obtained from SOLARGIS and the CPF method.

The computational procedure for determining the location of a PV is explained in detail below:

Step 1 Identify locations with high radiation from SOLARGIS info. This step is the first selection step. PV-TVS will only be calculated for areas with good irradiation.

Step 2 Perform power flow and voltage stability analysis for initial conditions (without PV units) to calculate the magnitude of the voltage on each bus and evaluate the stability of the system.

Step 3 Execute the CPF method to calculate PV-TVS to determine the most influential bus to improve system stability. The buses with the highest PV-TVS are then proposed for PV placement, because these buses have high radiation and have good sensitivity in increasing the system voltage.

Step 4 Install PV units with certain capacities on this sensitive bus. In this study, the simulation was carried out by assessing the placement of PV for PV capacity of 1 MWp, 3 MWp and 5 MWp.

Step 5 Perform power flow analysis and voltage stability analysis to calculate the voltage magnitude after PV placement for each size.

Step 6 Showing results, i.e. voltage profile and network power losses.

Step 7 Process stopped.

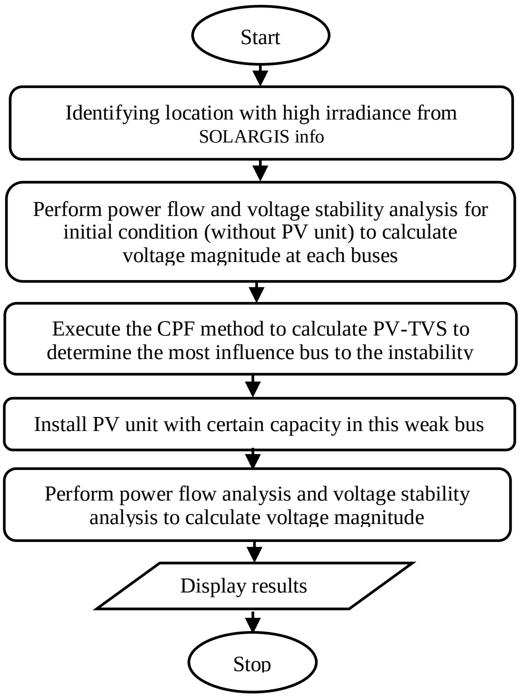


Fig. 4 Flowchart of the proposed PV placement

III. Test results and analysis

III.1. Solar Irradiation Results

The proposed method was simulated on the South Sulawesi interconnection power system in Indonesia which consists of 44 buses (substations), 7 main power plants and 47 transmission lines. This simulation was done by assessing the placement of PV for capacity sizes of 1 MWp, 3 MWp and 5 MWp.

The first step is identification of areas with good radiation. Based on SOLARGIS data, the South Sulawesi region has good radiation, which is shown in Fig. 5. From this data, Makassar City, Jeneponto, Sidrap, Bone, Palopo, Polmas, Pinrang and Poso were identified as having high levels of radiation around 1607 kWh/m^2/year. Makassar City as the capital of South Sulawesi Province is very dense and because it is one of the regions that has good radiation, the calculation of PV-TVS is calculated in several substations as a representation, namely; Bontoala, Panakukang, Tallo Lama and Daya. Therefore, these buses are the selected buses that are calculated for PV-TVS.

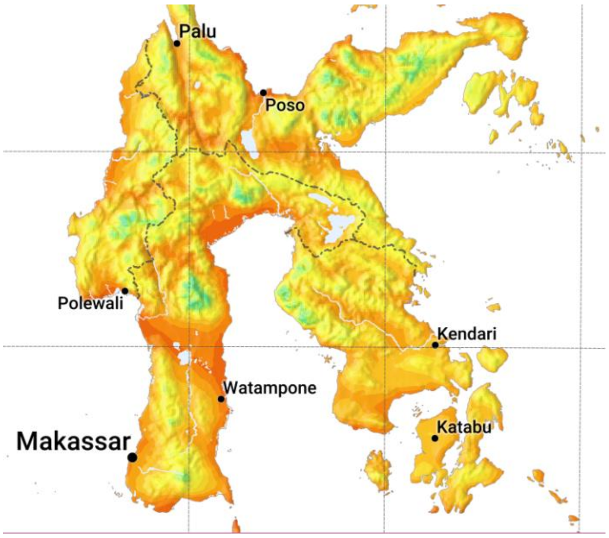


Fig. 5 Solar GHI map for Southern Sulawesi [25]

III.2. PV-TVS Computation

In this research, PV-TVS values were calculated only for areas with good radiation. PV-TVS values computed for these selected areas are for PV capacity of 1 MWp, 3 MWp and 5 MWp. Based on areas with good irradiance, PV-TVS for these areas were calculated for a PV capacity of 1 MWp.

Fig. 6 informs PV-TVS for each substation with good irradiance from the system in descending order. The results showed that the Tallo Lama substation had the highest PV-TVS with a value of 0.9081. This means that the Tallo Lama substation has the biggest influence in increasing system stability. The Panakukang, Bontoala and Daya substations also have good PV-TVS, which also means that these buses have a good influence in increasing the stability of the system voltage. On the other hand, Poso substation has the lowest PV-TVS value which implies that this region has small influence in improving system voltage stability.

III.3. Voltage Profile Improvement

Fig. 7 shows an increase in voltage profile for all PV placements. It can be seen from Fig. 7, when a 1 MWp PV was placed on the Tallo Lama bus, the voltage profile improved significantly and if integrated in Poso, the voltage profile only increased slightly compared to the one without PV integration.

III.4. Network Power Losses

Figs. 8 (a) and (b) illustrates active and reactive power losses for the placement of 1 MWp PV in each region. Table II provides information about the percentage of decrease or increase in network losses for all PV placements. A negative sign indicates a decrease in network losses, while a positive sign implies additional losses.

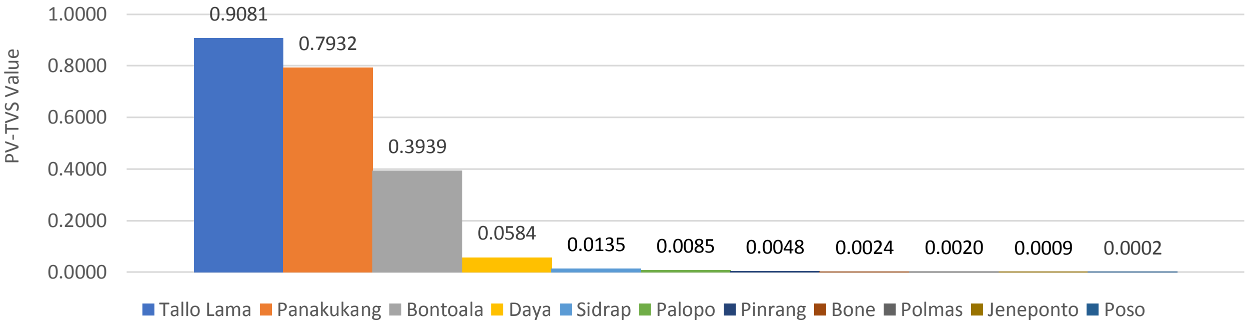


Fig. 6 PV –TVS values for 1 MWp Photovoltaic Capacity

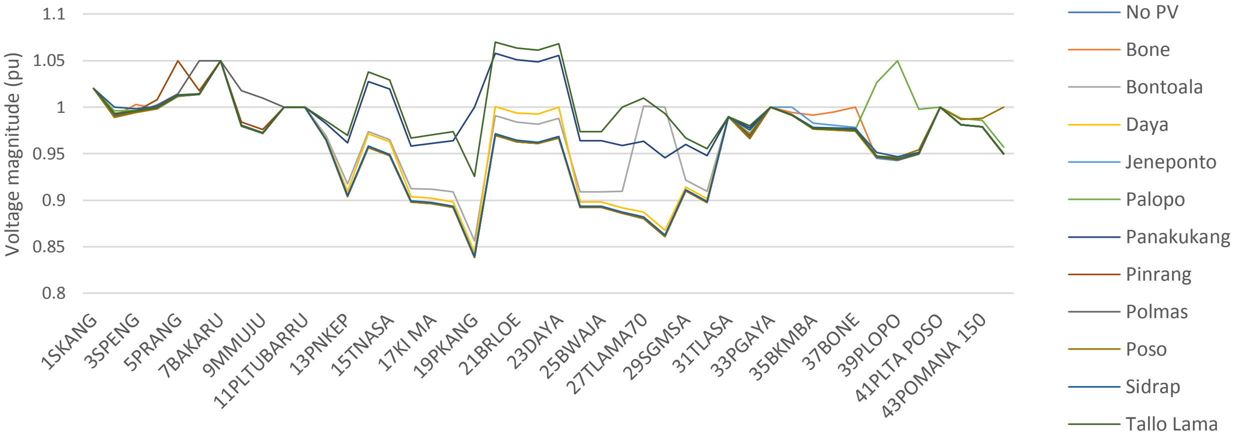
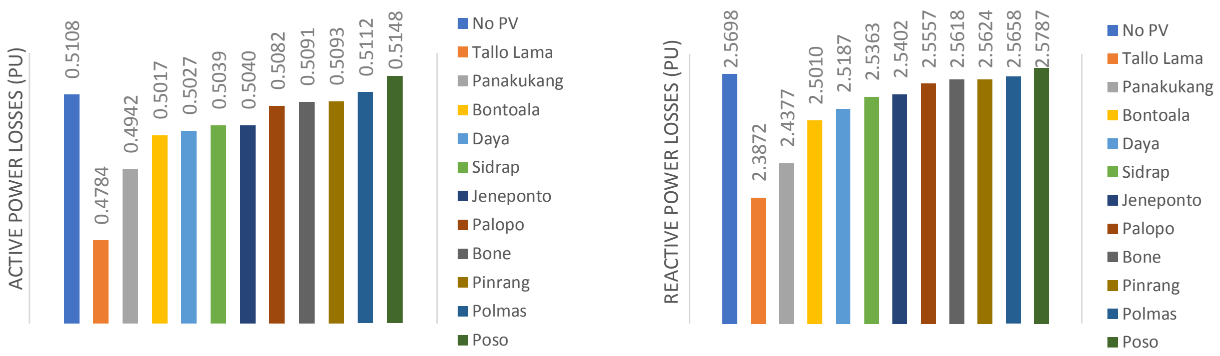


Fig. 7 Voltage profile for all PV placement of 1 MWp



(a) Active Power Losses (b) Reactive Power Losses

Fig. 8 Power losses calculation for 1 MWp PV placement at each area

The initial active and reactive power losses of the system were 0.5108 p.u. and 2.5698 p.u., correspondingly. If PV is placed in the Tallo Lama area, it results in the lowest system active and reactive power losses. Conversely, placing PV 1 MWp in Poso area, both active and reactive power losses increased. Active power loss increased from 0.5108 p.u. to 0.5148 p.u. and reactive power losses have increased from 2.5698 p.u. up to 2.5787 p.u. It can be seen from Table II, that the active power losses if PV is placed in Tallo Lama, drops to around 6.33%, while placing 1 MWp PV in Poso will result in an increase in active power losses to 0.79%.

TABLE II
NETWORK LOSSES FOR EACH PV PLACEMENT OF 1 MWp

1 MWp PV Location	Active Power Losses		Reactive Power Losses	
	pu	% decrease	pu	% decrease
No PV	0.5108	0	2.5698	0
Tallo Lama	**0.4784**	**-6.33**	**2.3872**	**-7.10**
Panakukang	0.4942	-3.25	2.5010	-2.68
Bontoala	0.5017	-1.76	2.5187	-1.99
Daya	0.5027	-1.58	2.4377	-5.14
Sidrap	0.5040	-1.32	2.5363	-1.30
Jeneponto	0.5082	-0.49	2.5557	-0.55
Palopo	0.5091	-0.32	2.5618	-0.31
Bone	0.5093	-0.29	2.5624	-0.29
Pinrang	0.5039	-1.34	2.5402	-1.15
Polmas	0.5112	0.10	2.5658	-0.16
Poso	**0.5148**	**0.79**	**2.5787**	**0.34**

III.5. PV-TVS and Network Losses Analysis for 1 MWp, 3 MWp and 5 MWp PV

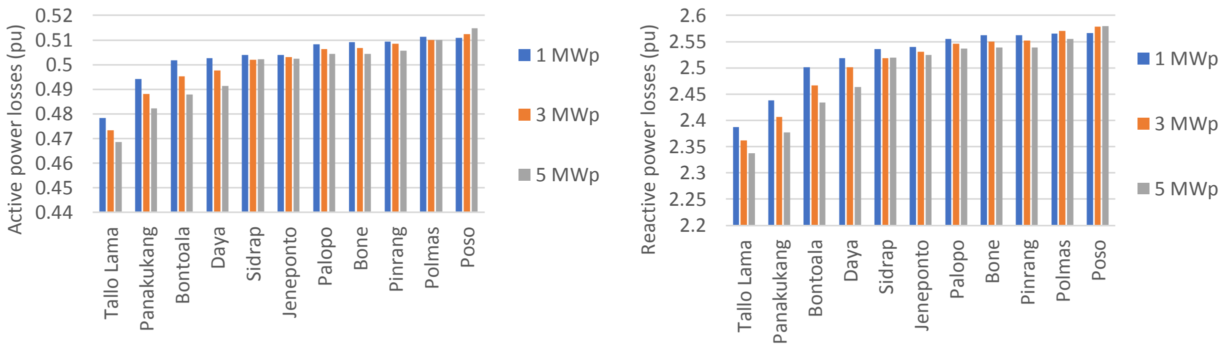
Table III informs PV-TVS calculations for each PV placement of 1 MWp, 3 MWp and 5 MWp. For all of these simulations, Tallo Lama has the highest PV-TVS value while Poso has the smallest PV-TVS value. In addition, Poso has negative PV-TVS values for 3 MWp and 5 MWp PV capacities. A negative value indicates that this can worsen system performance.

TABLE III
PV-TVS CALCULATION FOR EACH PV PLACEMENT OF 1 MWP, 3 MWP AND 5 MWP

Location	PV-TVS		
	1 MWp	3 MWp	5 MWp
Tallo Lama	**0.908138**	**0.908851**	**0.909554**
Panakukang	0.793209	0.793744	0.794234
Bontoala	0.393857	0.399379	0.404696
Daya	0.058354	0.066072	0.073616
Sidrap	0.013496	0.013443	0.013390
Jeneponto	0.008470	0.008374	0.008269
Palopo	0.004815	0.004827	0.004834
Bone	0.002443	0.002911	0.003373
Pinrang	0.001991	0.002010	0.002024
Polmas	0.000853	0.001997	0.003109
Poso	**0.000205**	**-0.000048**	**-0.000321**

Figs. 9 (a) and (b) indicate active and reactive power losses for PV capacities of 1 MWp, 3 MWp and 5 MWp. For all substations, trends in the value of active and reactive power losses tend to decrease due to increased PV capacity. In contrast, active and reactive power losses increase when PV capacity increases if PV is placed in Poso. From the system structure, Poso is located in the northern part of the system, while the load centers are located in Makassar City, in the southern part of the system. Therefore, placing PV in Poso, is not effective in increasing system stability and reducing losses, but placing PV in Tallo Lama, Panakukang, Bontoala or Daya (which are substations in Makassar City) has a significant impact in improving stability and reducing losses.

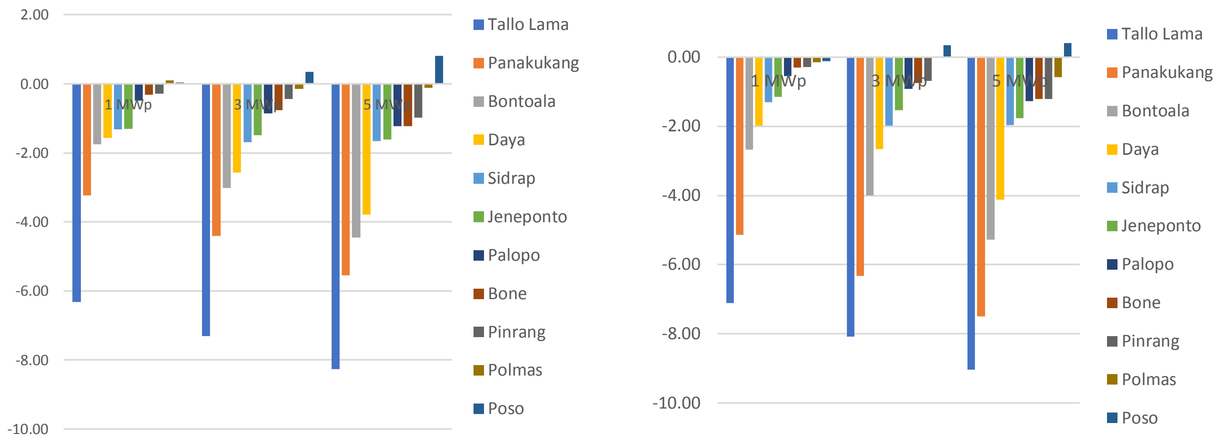
Figs. 10 (a) and (b) show the percentage of losses decreased or increased. Placing PV in Tallo Lama will provide the highest loss reduction for all simulations. On the contrary, placing PV in Poso will give additional losses as PV capacity increases. Because PV only produces active power, research on PV and reactive power compensation devices for South Sulawesi should be carried out, especially with the integration of wind power plants [38].



(a) Active Power Losses

(b) Reactive Power Losses

Fig. 9 Power losses for all simulations



(a) Active Power Losses (b) Reactive Power Losses

Fig. 10 Power losses reduction/addition percentage for all simulations

IV. Conclusions

This paper proposes a new analytical method for PV placement. The proposed method consists of two stages, namely: identification of areas with good irradiance from SOLARGIS, then calculating Vector-Tangent Vector Sensitivity (PV-TVS) for these areas. PV-TVS provides information about the sensitivity of each location to changes in active power. From SOLARGIS, it has been determined that 8 regions have good radiation.

The results of this study verify that the substations in Makassar have high radiation and high PV-TVS. Therefore, these areas (Panakukang, Tallo Lama, Bontoala, and Daya) are recommended for PV allocation. Nonetheless, since Makassar City is quite dense and PV plant installations require large tracts of land, further research needs to be done to find suitable locations or other solutions in Makassar City. Other regions such as: Jeneponto, Sidrap, Bone, Palopo, Pinrang and Polmas also have good radiation but PV-TVS is smaller. PV can also be placed in these areas, although it is not as effective if it is placed in Makassar. However, the Poso region tends to have small and even negative PV-TVS. Based on these results, it informs that placing PV in Poso is ineffective because it does not have a significant effect in increasing the voltage profile and may further increase the network losses into the system.

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Photovoltaic Allocation with Tangent Vector Sensitivity

Ardiaty Arief[1*], Muhammad Bachtiar Nappu[2] and Sitti Marwah Rachman[3]

Abstract – *Indonesia has abundant energy potential from renewable energy resources, especially from the sun but until now, the utilization is not optimal. This paper presents a new methodology for determining the effective location of Photovoltaic (PV) integration into the power system. The proposed scheme consists of two steps: first, determining the area with good irradiance from SOLARGIS and second, calculating the PV-Tangent Vector Sensitivity (PV-TVS) to determine the area that has the greatest impact in increasing network voltage stability and minimizing losses. PV-TVS is developed based on the Continuation Power Flow (CPF) technique which is a voltage stability evaluation tool in the quasi-static analysis methodology. For effectiveness, PV-TVS will be calculated only for good exposure areas. The region that has the highest PV-TVS means that it has the best sensitivity in enhancing system voltage stability and it is recommended for PV placement. The simulation results have been carried out on the South Sulawesi power system in Indonesia, which is a priority location for PV integration in Indonesia, and the results show that this method is effective in determining the location for PV integration.*

Keywords*: Continuation Power Flow, Irradiance, Losses reduction, Photovoltaic allocation, PV-Tangent Vector Sensitivity, Voltage stability*

Nomenclature

CPF	Continuation Power Flow
GHI	Global Horizontal Irradiation
k_{Li}	Multiplying constant to entitle the rate of load change at bus i as φ changes
k_{Gi}	Multiplying constant to state the rate of change in generation as φ varies
NRE	New and Renewable Energy
P_{Gi0}	Base case active power generated at bus *i*
P_{Li0}	Original active load at bus *i*
P_{Ti}	Active power injected at bus *i*
PV	Photovoltaic
PV-TVS	Photovoltaic-Tangent Vector Sensitivity
Q_{Li0}	Original reactive load at bus *i*
Q_{Ti}	Reactive power injected at bus *i*
$S_{\Delta base}$	Base quantity of apparent power
V	Bus voltage magnitude vector
ΔP	Difference in the active power load
ΔV	Difference in the voltage change
θ_i	Power angle of load change at bus *i*
δ	Generator angle vector
φ	Loading parameter
$\varphi = 0$	Loading parameter corresponds to the base load
$\varphi = \varphi_{critical}$	Loading parameter corresponds to critical load

I. Introduction

Until now, Indonesia has faced challenges in achieving developments in the energy sector. Indonesia still has a high dependency on fossil fuels in order to meet its domestic energy consumption which is 96%, of which 48% is oil, 18% is gas and 30% is coal, of the total national energy consumption [1].

One of the main reasons for the high consumption of fossil energy is that public tends to spend energy wastefully because of low energy prices due to subsidies. Furthermore, Indonesia faces the problem of decreasing fossil energy reserves that have not yet been compensated by the discovery of new fossil energy reserves. Many attempts to maximize the use of NRE still face several obstacles and cannot be performed according to plan. Therefore, the Government of Indonesia has launched a policy of conservation and diversification of energy [2].

One of them is the development of the use of renewable energy as a complement to the use of fossil energy. The Government of Indonesia has issued Law No. 30 of 2007 concerning energy, which mandates that the development and utilization of NRE must be increased and Law No. 30 of 2009 concerning electricity also mandates that the use of primary energy sources must be implemented by prioritizing NRE sources. Indonesia has many NRE resources such as water, ocean waves, wind, solar, geothermal, biofuels, nuclear or waste. Table I shows the NRE resources owned by Indonesia.

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TABLE I
NEW AND RENEWABLE ENERGY (NRE) RESOURCES IN INDONESIA [1]

No	Type	Resources	Installed Capacity (MW)	Ratio (%)
1	**2**	**3**	**4**	**5 = 4/3**
1	Hydro	75.000 MW	7.573	10.1 %
2	Geothermal	28.910 MW	1.344	4.65 %
3	Biomass	32.654 MW	1.717	5.26 %
4	Solar	4,80 kWh/m^2/day	48	-
5	Wind	3-6 m/s	1.87	-
6	Sea	49 GW***)	0,01****)	0 %
7	Uranium	3.000 MW**)	30*)	0%

*) Only in Kalan – West Kalimantan
**) As research center, non-energy
***) National Energy Council
****) BPPT’s Prototype

As it can be seen in Table I, Indonesia has a large NRE potential, especially for solar power but its utilization is still insignificant. Indonesia is located at the equator; it means that it receives stable solar irradiation throughout the year; hence, it has abundant solar energy potential with an average solar irradiation intensity resource of 4.8 kWh/m^2/day.

Furthermore, solar energy is an attractive clean renewable energy [3] and has the highest potential among renewable energy resources hence the development of photovoltaic integration in Indonesia has immense potential in reducing carbon dioxide emissions in the world. The PV system for power generation resources for small islands in Indonesia has been started since the 1970s, nevertheless it has been stopped due to the 1997 financial crisis that hit Indonesia at that time [4]. Fig. 1 shows a GHI solar map for Indonesia.

Nowadays, many countries are targeting the expansion of power supplies generated from NRE resources. According to Razykov et al., the current world energy consumption is around 10 terawatts per year and an estimated 30 terawatts per year in 2050 [5]. In order to balance carbon dioxide in the atmosphere, the world needs 20 terawatt of energy generation that comes from non-carbon dioxide (non-CO$_2$) or NRE in the middle of this century. The simplest scenario proposed for electrical energy is power generated from PV and other NRE such as wind, sea waves, hydro, fuel cells and others as much as 10 terawatt [6]. Therefore, PV will play an important role in meeting the world's energy needs in the future. At present, this is considered a turning point for PV development [7].

Serrano-Luján et al. have conducted a research and they have placed Indonesia in the category of level 2 country groups together with the United Arab Emirates, Western USA and Eastern China which have a combination of electricity and irradiation that will allow CO$_2$ reduction of 15-20 tons for PV capacity of 1 kWp over its lifetime [8].

Proper PV allocation into the power system is very important to optimize the increase in voltage stability [9]. The research has proven that the installation of a suitable renewable energy generation in a transmission or distribution network can significantly reduce network losses. improve voltage [10-14], improve power quality [15], minimize emissions [16], reduce costs for utilities [17] as well as the transmission and distribution network congestion release [18-20]. Furthermore, with proper connection of energy storage, load shedding or cascading tripping of renewable energy generations is expected to be prevented [21, 22]. Nevertheless, PV creates more challenges for the protection and stability of the distribution system due to its limited impact to short-circuit currents [23] as well as probability of reverse power flow to transmission system [24].

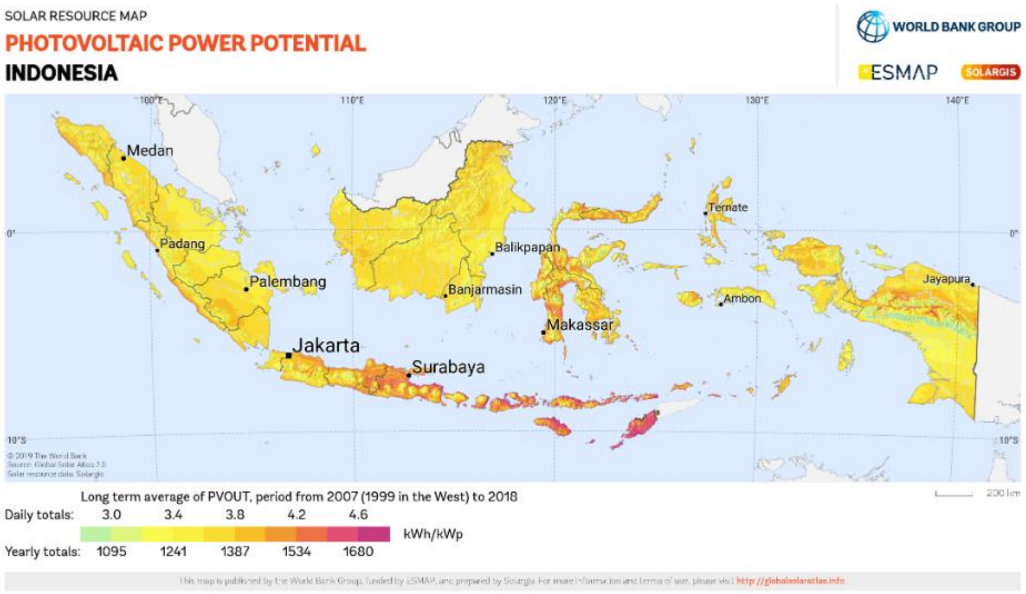


Fig. 1. Photovoltaic power potential map for Indonesia [25]

In recent years, various methodologies have been developed for PV placement. The authors in [26] have created a new strategy for optimizing PV systems with the shortest path algorithm. The Voltage Stability Index (VSI) has been developed to investigate the impact of PV on the transmission network system by considering the system voltage stability [24]. [27] analyzes the penetration of PV in a distribution system using modified Monte Carlo simulation. Furthermore, the metaheuristic optimization method has become one of the most popular techniques for solving many optimization problems because of its flexibility, free derivation process, ability to handle complicated problems and the ability to escape from local targets. Genetic algorithm (GA) based on Newton-Raphson power flow is employed in [28] for PV placement with the aim of minimizing losses. Hybrid methods based on GA and optimal reactive control are also applied in [29]. Optimal PV allocation is proposed by using self-organizing hierarchical binary particle swarm optimization (SHBPSO) in [30] and Binary Particle Swarm Optimization (BPSO) in [31]. However, both GA and PSO techniques are time-consuming and may be less effective in escaping from local optimal values. The authors in [32] have developed the quantum-inspired binary lightning search algorithm (QBLSA) for optimal PV placement. An improved gravitational search algorithm (IGSA) is proposed to determine the optimal PV location and size in [33].

In the placement of PV, solar irradiation is an important parameter to consider, because it functions like a fuel for conventional power plants. The more irradiation there is, the better the current generated is. Therefore, it is crucial to choose an area for PV placement with good irradiation. Therefore, the contribution of this paper is to:

1. Develop a two-step methodology where in the first step is the selection of areas with good radiation.
2. Formulate Photovoltaic-Tangent Vector Sensitivity (PV-TVS) which provides information about areas that have a high impact in increasing voltage stability.

The South Sulawesi region is one of the regions in Indonesia that is prioritized for PV integration in Indonesia because it has good irradiation. Therefore, the contribution of this paper is to develop a new methodology for determining the optimal PV location based on irradiation data and network configuration with South Sulawesi as a case study.

The remaining sections of this paper are organized as follows. Section II provides an overview of the proposed methodology, which is an explanation of solar irradiation, elaboration of the Continuation Power Flow (CPF) method and the proposed PV placement flowchart. Section III provides results and analysis, and Section IV summarizes the main findings of the research.

II. The Proposed Methodology

The proposed methodology consists of two stages, namely: first, the determination of areas with good radiation from SOLARGIS, and second, the calculation of PV-Tangent Vector Sensitivity (PV-TVS) in order to determine areas that have a major influence in increasing network voltage stability and minimizing losses. PV-TVS is developed based on the quasi-static method of Continuation Power Flow (CPF). This section will explain the proposed methodology in detail.

II.1. Solar Irradiation

Solar irradiation is the dispersion of solar energy derived from thermonuclear processes that occur in the sun. It is a very important element for PV cells, because it functions like a conventional power plant fuel that makes the photovoltaic system work. The more irradiation there is, the better the current generated is. At present, PV systems are the best approach to generate electricity directly from solar irradiation, because solar PV has a cost competitive construction. However, it is important to assess solar radiation in order to maintain the reliability and stability of the system given the intermittent features of PV [34-36].

II.2. Continuation Power Flow (CPF) Method

After determining the selected area with good solar irradiation, the second step is the calculation of PV-Tangent Vector Sensitivity (PV-TVS). PV-TVS, derived from the calculation of tangent vectors from the predictor-corrector procedure of the continuation power flow (CPF) method. This method is a quasi-steady-state voltage stability analysis developed by Ajjarapu and Christy [37].

The CPF method modifies conventional power flow equations. It uses prediction and correction techniques to find power flow solutions from the base load to stable or critical stability conditions to determine the critical point. In addition, the CPF method can be used to identify the bus that has the greatest influence on voltage instability/collapse and also increase or decrease network losses [13], which is based on active and reactive power transferred from a transmission or distribution line. Fig. 2 explains the procedure of prediction and correction of the CPF method. As shown in Fig. 3, the analysis procedure starts from the known results, and then predicts the next solution for different load parameter values.

First, the load parameter, denoted by φ is defined by:

$$0 \le \varphi \le \varphi_{critical}$$

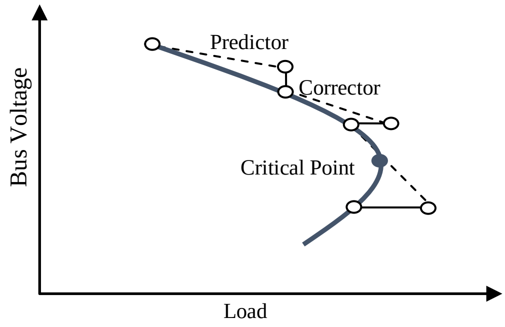


Fig. 2 Predictor-corrector scheme of the CPF [37]

Then this load parameter is integrated into the active and reactive power equations:

$$0 = P_{Gi0}(1 + \lambda k_{Gi}) - P_{Li0} - \varphi\,(k_L\, S_{\Delta base}\cos\theta_i) - P_{Ti} \quad (1)$$

$$0 = Q_{Gi0} - Q_{Li0} - \varphi\,(k_{Li}\, S_{\Delta base}\sin\theta_i) - Q_{Ti} \quad (2)$$

Then the continuation algorithm is implemented in the modified power flow equation. The above equations can be rewritten in the following simple form:

$$F\,(\delta, V, \varphi) = 0 \quad (3)$$

The CPF method develops a scheme of prediction and correction steps in order to achieve the solution path of the modified power flow equation. In the prediction step, the tangent vector is calculated from the derivation of both sides of the power flow equation, hence:

$$\begin{bmatrix} F_\delta & F_V & F_\varphi \end{bmatrix} \begin{bmatrix} d\delta \\ dV \\ d\varphi \end{bmatrix} = 0 \quad (4)$$

In addition to the direction of the solution pathway, the tangent vector also provides information for sensitivity analysis in order to determine sensitive buses. The tangent vector gives a ratio of the degree of difference in voltage changes to the degree of difference in changes in active power load. Since photovoltaics only produce active power, the sensitivity given by this tangent vector is suitable for finding PV placement. Therefore, in this study, the ratio of the level of difference in voltage change (ΔV) to the level of difference in active power load (ΔP) changes is called Photovoltaic-Tangent Vector Sensitivity (PV-TVS). PV-TVS on bus *j* becomes:

$$PV - TVS_j = \left|\frac{dV_j}{dP_{total}}\right| = \left|\frac{dV_j}{Cd_{\emptyset}}\right|$$

$$= \max\left\|\frac{dV_1}{Cd_{\emptyset}}\right|, \left|\frac{dV_2}{Cd_{\emptyset}}\right|, \ldots\ldots \left|\frac{dV_n}{Cd_{\emptyset}}\right\| \quad (5)$$

Since the value of $Cd_{\emptyset}$ is the same, the most sensitive bus is the one with the highest dV_j. Therefore, the bus with the highest PV-TVS is proposed for PV placement, since this bus has high radiation and has good sensitivity in increasing the system voltage.

After the power flow study, the next step is to run CPF and calculate PV-TVS in determining the most sensitive location in increasing system stability in locations that have high radiation. Then the bus with the highest PV-TVS is recommended as a PV placement priority.

II.3. Flowchart of the Proposed Method

Fig. 3 shows a flowchart diagram of the proposed photovoltaic placement using solar radiation obtained from SOLARGIS and the CPF method.

The computational procedure for determining the location of a PV is explained in detail below:

Step 1 Identify locations with high radiation from SOLARGIS info. This one is the first selection step. PV-TVS will only be calculated for areas with good irradiation.

Step 2 Perform power flow and voltage stability analysis for initial conditions (without PV units) in order to calculate the magnitude of the voltage on each bus and evaluate the stability of the system.

Step 3 Execute the CPF method to calculate PV-TVS in order to determine the most influential bus to improve system stability. Then the buses with the highest PV-TVS are proposed for PV placement, because these buses have high radiation and good sensitivity in increasing the system voltage.

Step 4 Install PV units with certain capacities on this sensitive bus. In this study, the simulation has been carried out by assessing the placement of PV for PV capacity of 1 MWp, 3 MWp and 5 MWp.

Step 5 Perform power flow analysis and voltage stability analysis in order to calculate the voltage magnitude after PV placement for each size.

Step 6 Showing results, i.e. voltage profile and network power losses.

Step 7 Process stopped.

III. Test results and analysis

III.1. Solar Irradiation Results

The proposed method has been simulated on the South Sulawesi interconnection power system in Indonesia, which consists of 44 buses (substations), 7 main power plants and 47 transmission lines. This simulation has been done by assessing the placement of PV for capacity sizes of 1 MWp, 3 MWp and 5 MWp.

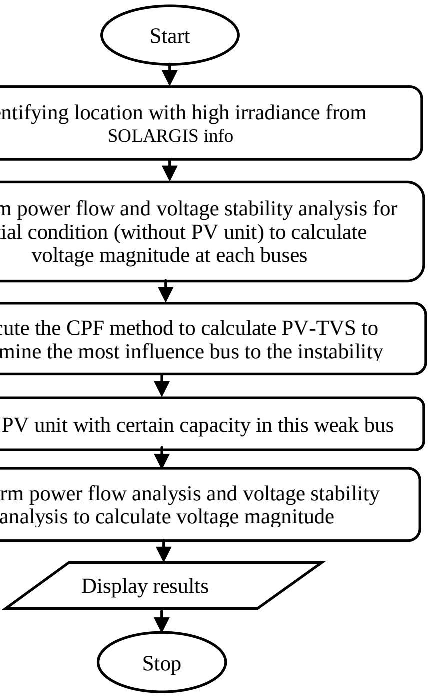


Fig. 3 Flowchart of the proposed PV placement

The first step is the identification of areas with good radiation. Based on SOLARGIS data, the South Sulawesi region has good radiation, which is shown in Fig. 4. From this data, Makassar City, Jeneponto, Sidrap, Bone, Palopo, Polmas, Pinrang and Poso have identified to have high levels of radiation around 1607 kWh/m^2/year. Makassar City as the capital of South Sulawesi Province is very dense and since it is one of the regions that has good radiation, the calculation of PV-TVS is done in several substations as a representation, namely; Bontoala, Panakukang, Tallo Lama and Daya. Therefore, these buses are the selected ones that are calculated for PV-TVS.

III.2. PV-TVS Computation

In this research, PV-TVS values have been calculated only for areas with good radiation. PV-TVS values computed for these selected areas are for PV capacity of 1 MWp, 3 MWp and 5 MWp. Based on areas with good irradiance, PV-TVS for these areas have been calculated for a PV capacity of 1 MWp.

Fig. 5 shows PV-TVS for each substation with good irradiance from the system in descending order. The results have showed that the Tallo Lama substation had the highest PV-TVS with a value of 0.9081. This means that the Tallo Lama substation has the biggest influence in increasing system stability. The Panakukang, Bontoala and the Daya substations also have good PV-TVS, which also means that these buses have a good influence in increasing the stability of the system voltage. On the other hand, Poso substation has the lowest PV-TVS value, which implies that this region has small influence in improving system voltage stability.

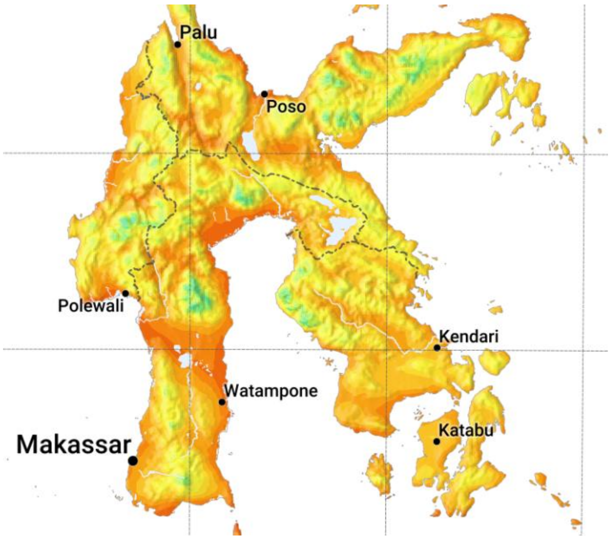


Fig. 4 Solar GHI map for Southern Sulawesi [25]

III.3. Voltage Profile Improvement

Fig. 6 shows an increase in voltage profile for all the PV placements. It can be seen from Fig. 6 that, when a 1 MWp PV has been placed on the Tallo Lama bus, the voltage profile has improved significantly and if integrated in Poso, the voltage profile has only increased slightly compared to the one without PV integration.

III.4. Network Power Losses

Figs. 7 (a) and (b) illustrate active and reactive power losses for the placement of 1 MWp PV in each region. Table II provides information about the percentage of decrease or increase in network losses for all the PV placements. A negative sign indicates a decrease in network losses, while a positive one implies additional losses.

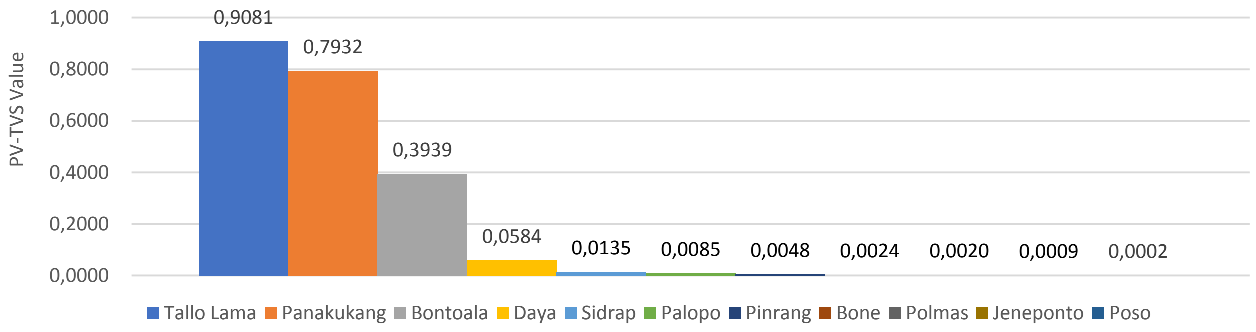


Fig. 5 PV –TVS values for 1 MWp Photovoltaic Capacity

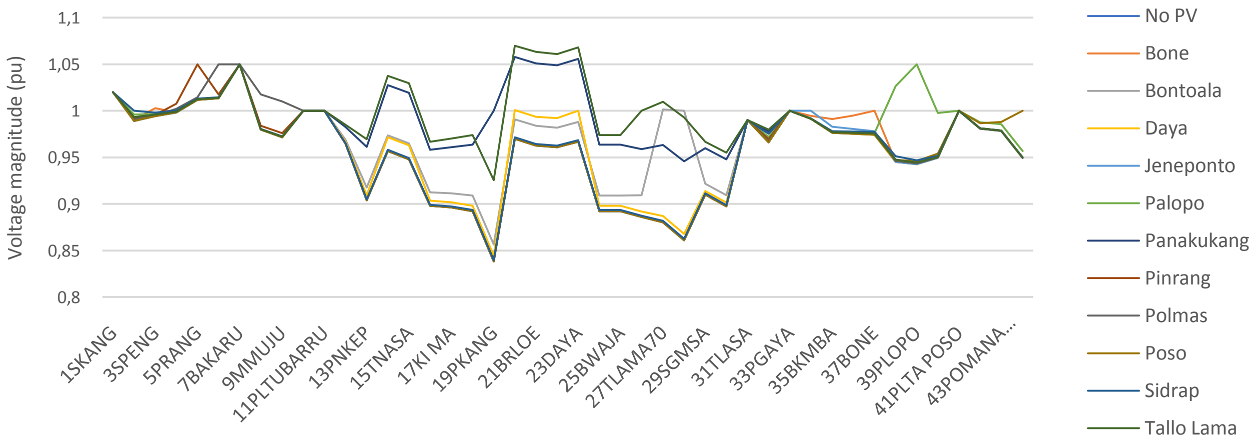
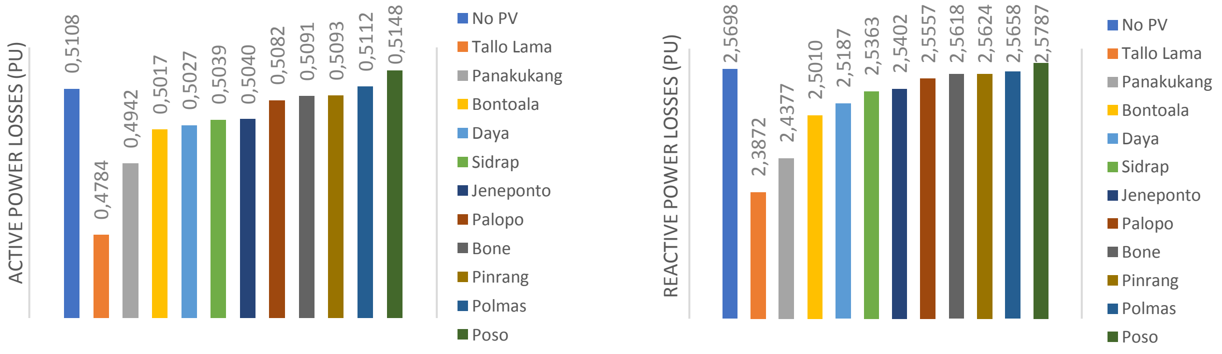


Fig. 6 Voltage profile for all PV placement of 1 MWp



(a) Active Power Losses (b) Reactive Power Losses

Fig. 7 Power losses calculation for 1 MWp PV placement at each area

The initial active and reactive power losses of the system have been 0.5108 p.u. and 2.5698 p.u., correspondingly. If PV is placed in the Tallo Lama area, it results in the lowest system active and reactive power losses. Conversely, placing PV 1 MWp in Poso area, both active and reactive power losses increase. Active power loss has increased from 0.5108 p.u. to 0.5148 p.u. and reactive power losses have increased from 2.5698 p.u. up to 2.5787 p.u. It can be seen from Table II, that the active power losses if PV is placed in Tallo Lama, drop to around 6.33%, while placing 1 MWp PV in Poso will result in an increase in active power losses to 0.79%.

Manuscript received January 2013, revised February 2013

TABLE II
NETWORK LOSSES FOR EACH PV PLACEMENT OF 1 MWp

1 MWp PV Location	Active Power Losses		Reactive Power Losses	
	pu	% decrease	pu	% decrease
No PV	0.5108	0	2.5698	0
Tallo Lama	**0.4784**	**-6.33**	**2.3872**	**-7.10**
Panakukang	0.4942	-3.25	2.5010	-2.68
Bontoala	0.5017	-1.76	2.5187	-1.99
Daya	0.5027	-1.58	2.4377	-5.14
Sidrap	0.5040	-1.32	2.5363	-1.30
Jeneponto	0.5082	-0.49	2.5557	-0.55
Palopo	0.5091	-0.32	2.5618	-0.31
Bone	0.5093	-0.29	2.5624	-0.29
Pinrang	0.5039	-1.34	2.5402	-1.15
Polmas	0.5112	0.10	2.5658	-0.16
Poso	**0.5148**	**0.79**	**2.5787**	**0.34**

III.5. PV-TVS and Network Losses Analysis for 1 MWp, 3 MWp and 5 MWp PV

Table III shows PV-TVS calculations for each PV placement of 1 MWp, 3 MWp and 5 MWp. For all of these simulations, Tallo Lama has the highest PV-TVS value while Poso has the smallest one. In addition, Poso has negative PV-TVS values for 3 MWp and 5 MWp PV capacities. A negative value indicates that this can worsen system performance.

TABLE III
PV-TVS CALCULATION FOR EACH PV PLACEMENT OF 1 MWP, 3 MWP AND 5 MWP

Location	PV-TVS		
	1 MWp	3 MWp	5 MWp
Tallo Lama	**0.908138**	**0.908851**	**0.909554**
Panakukang	0.793209	0.793744	0.794234
Bontoala	0.393857	0.399379	0.404696
Daya	0.058354	0.066072	0.073616
Sidrap	0.013496	0.013443	0.013390
Jeneponto	0.008470	0.008374	0.008269
Palopo	0.004815	0.004827	0.004834
Bone	0.002443	0.002911	0.003373
Pinrang	0.001991	0.002010	0.002024
Polmas	0.000853	0.001997	0.003109
Poso	**0.000205**	**-0.000048**	**-0.000321**

Figs. 8 (a) and (b) indicate active and reactive power losses for PV capacities of 1 MWp, 3 MWp and 5 MWp. For all the substations, trends in the value of active and reactive power losses tend to decrease due to increased PV capacity. In contrast, active and reactive power losses increase when PV capacity increases if PV is placed in Poso. From the system structure, Poso is located in the northern part of the system, while the load centers are located in Makassar City, in the southern part of the system. Therefore, placing PV in Poso is not effective in increasing system stability and reducing losses, but placing PV in Tallo Lama, Panakukang, Bontoala or Daya (which are substations in Makassar City) has a significant impact in improving stability and reducing losses.

Figs. 9 (a) and (b) show the percentage of losses decreased or increased. Placing PV in Tallo Lama will provide the highest loss reduction for all simulations. On the contrary, placing PV in Poso will give additional losses as PV capacity increases. Since PV only produces active power, research on PV and reactive power compensation devices for South Sulawesi should be carried out, especially with the integration of wind power plants [38].

IV. Conclusions

This paper proposes a new analytical method for PV placement. The proposed method consists of two stages, namely: identification of areas with good irradiance from SOLARGIS, then calculating Vector-Tangent Vector Sensitivity (PV-TVS) for these areas. PV-TVS provides information about the sensitivity of each location to changes in active power. From SOLARGIS, it has been determined that 8 regions have good radiation.

The results of this study verify that the substations in Makassar have high radiation and high PV-TVS. Therefore, these areas (Panakukang, Tallo Lama, Bontoala, and Daya) are recommended for PV allocation. Nonetheless, since Makassar City is quite dense and PV plant installations require large tracts of land, further research needs to be done in order to find suitable locations or other solutions in Makassar City. Other regions, such as Jeneponto, Sidrap, Bone, Palopo, Pinrang and Polmas, also have good radiation but PV-TVS is smaller. PV can also be placed in these areas, although it is not as effective if it is placed in Makassar. However, the Poso region tends to have small and even negative PV-TVS. Based on these results, it can be noticed that placing PV in Poso is ineffective because it does not have a significant effect in increasing the voltage profile and may further increase the network losses into the system.

Acknowledgements

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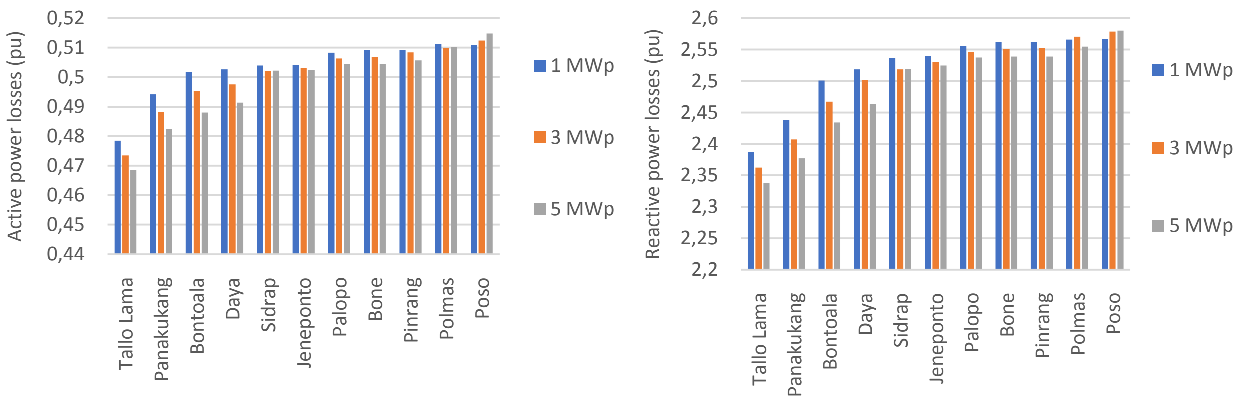
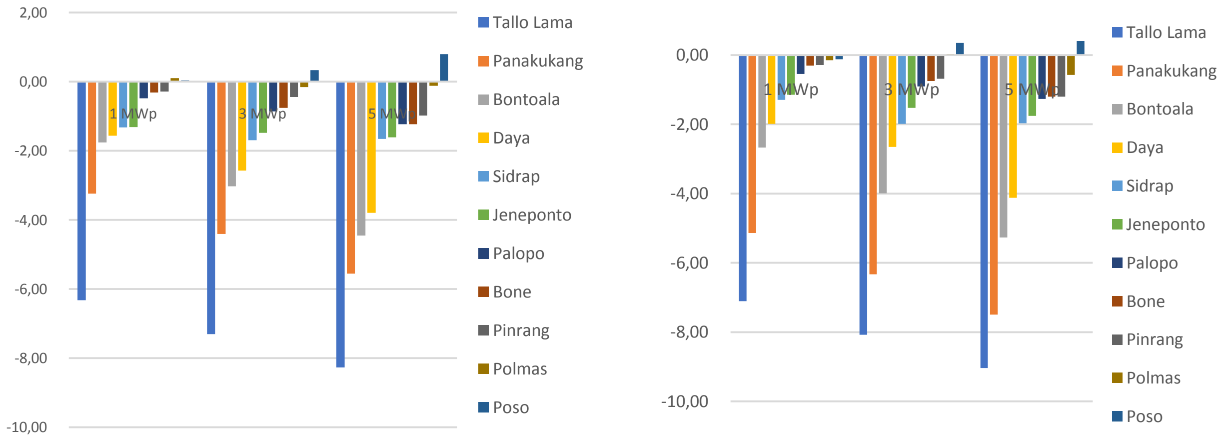


(a) Active Power Losses (b) Reactive Power Losses

Fig. 8 Power losses for all simulations



(a) Active Power Losses (b) Reactive Power Losses

Fig. 9 Power losses reduction/addition percentage for all simulations

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This is an opportunity for you to respond to their major concerns and to incorporate improvements in the paper according to their suggestions. It is also an opportunity for you to add new results.
We normally only permit one major revision before an accept or reject decision is made. So please take the concerns of the reviewers seriously. Therefore, I invite you to respond to the reviewer(s)' comments and revise your manuscript within four weeks from the date of this email.
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This paper proposes an interesting approach to estimate the effective location of PV integration into a power system. The proposal should be valuable for other users in other countries.

The manuscript needs, however, some additions clarifications:

1. One of the main lack is that the authors contribution is not well discussed and evaluated versus the literature. In this context, it is mandatory, in the Introduction section, to better highlight the contribution.

2. This evaluation should be made on a more relevant reference section that

should be enhanced with more relevant papers.

In addition, the manuscript needs to be deeply proofread.

Reviewer B:

- At the end of the Introduction add a paragraph on how the rest of the paper is organized and developed, typically a summary on the rest.

- The literature review needs to be expanded on the bases on 2017-2019 references.

- The references list is missing of more recent titles (2017-2019): we strictly encourage the authors to visit our wide database of titles where they could search for references, at the page http://www.praiseworthyprize.org /jsm/index.php?journal=index&page=search

- The paper is well developed and argued, the English is comprehensible, but it needs editing for grammatical errors and style. We suggest to use our service "English Language Editing". More information can be found to http://www.praiseworthyprize.com/english_service.htm.

- More discussion of the flowchart in figure 4 is advisable.

- At the beginning of the paper, before the Introduction section, a Nomenclature section, not numbered, should be added with a list, in alphabetic order, of all the used symbols/acronyms and their meaning.

- The quality of figure 5 should be improved.

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Subject: [IRECON] Editor Decision DELETE

Dr. Ardiaty Arief:

It is my great pleasure to inform you that your paper "Photovoltaic Allocation with Tangent Vector Sensitivity" has been accepted and will be published on the International Journal on Energy Conversion (IRECON) after English revision by PWP Staff.

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Sincerely,
Dr. Mohamed Benbouzid, Editor-in-Chief of International Journal on Energy Conversion (IRECON)
mohamed.benbouzid@univ-brest.fr

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