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 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.* ***Copyright © 2020 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 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.

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

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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.

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

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].

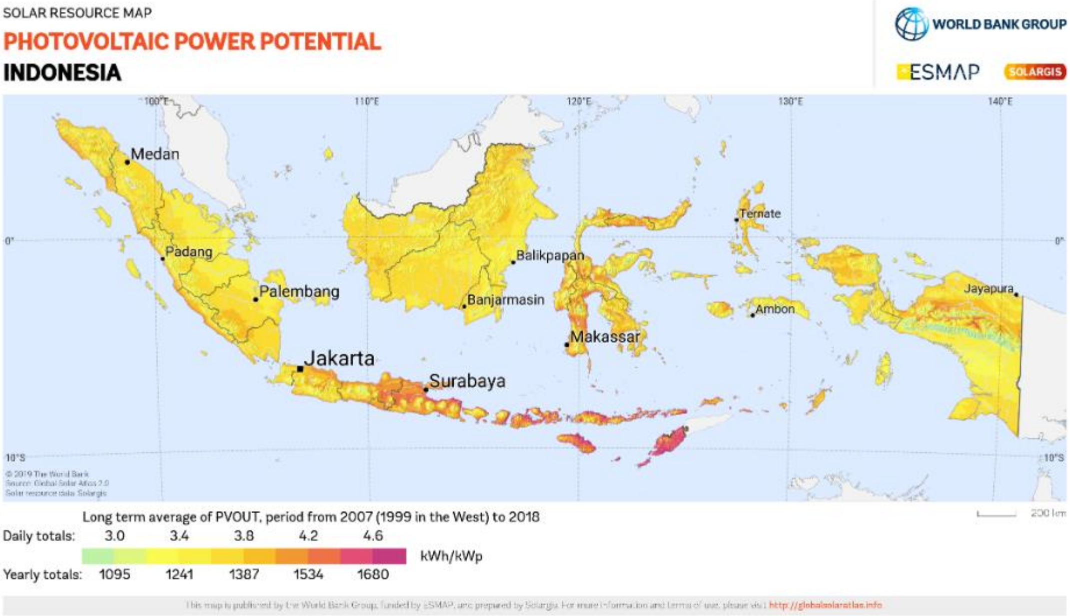

Fig. 1. Photovoltaic power potential map for Indonesia [25]

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:

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

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

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

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

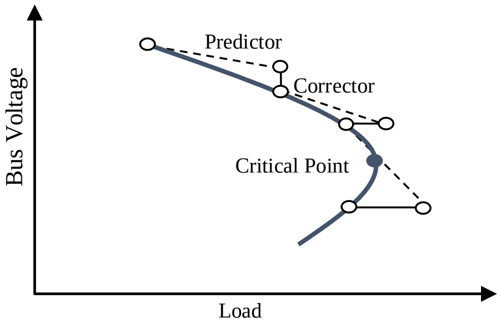

Fig. 2 Predictor-corrector scheme of the CPF [37]

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

$$F\ (\delta, V, \varphi) = 0 \tag{3}$$

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:

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

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:

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

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

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 then 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.

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.

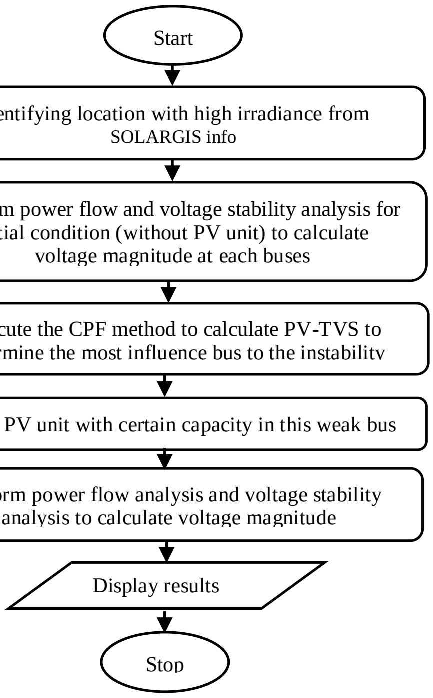

Fig. 3 Flowchart of the proposed PV placement

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.

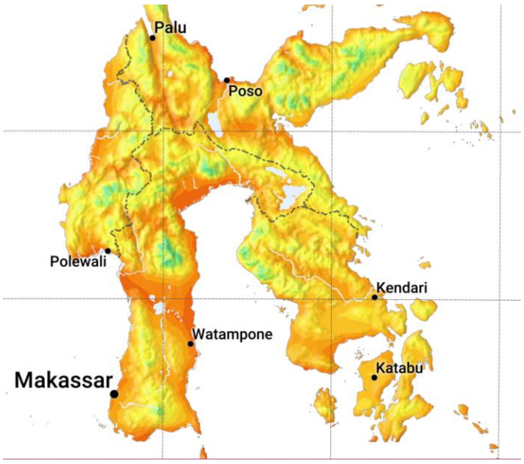

Fig. 4 Solar GHI map for Southern Sulawesi [25]

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.

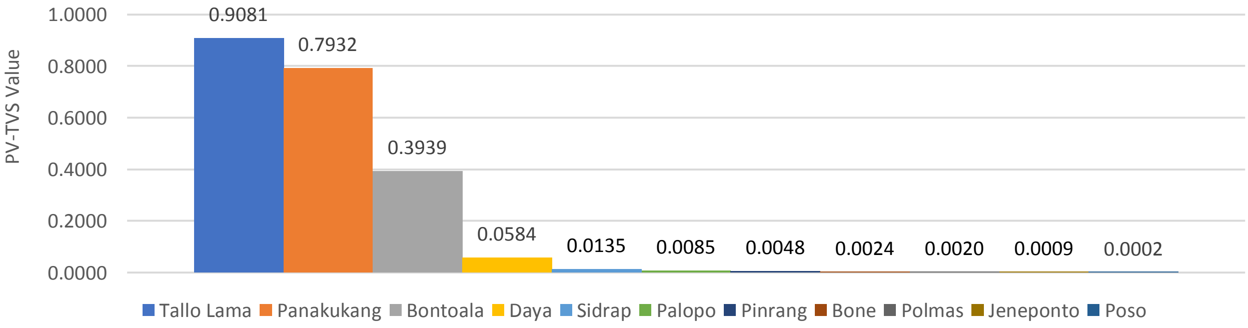

Fig. 5 PV –TVS values for 1 MWp Photovoltaic Capacity

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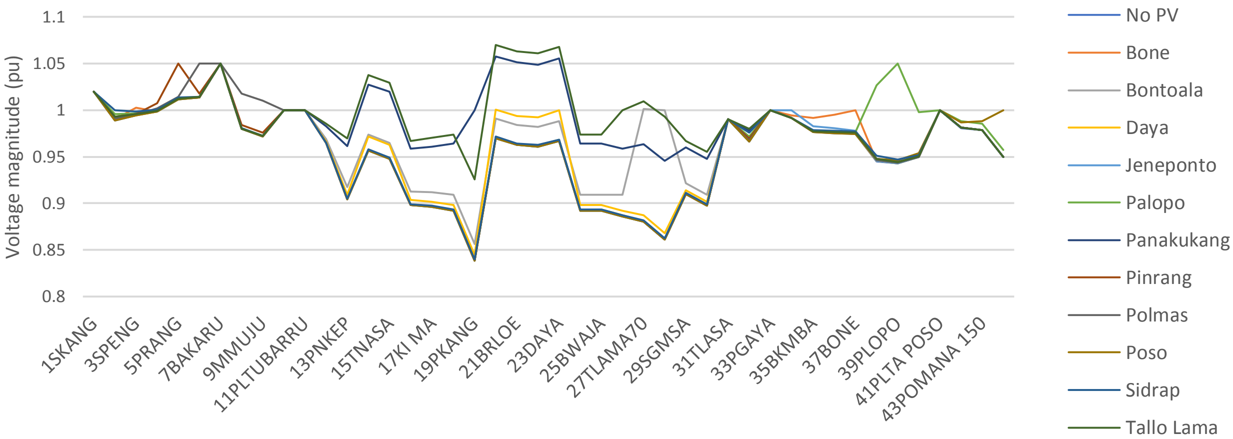
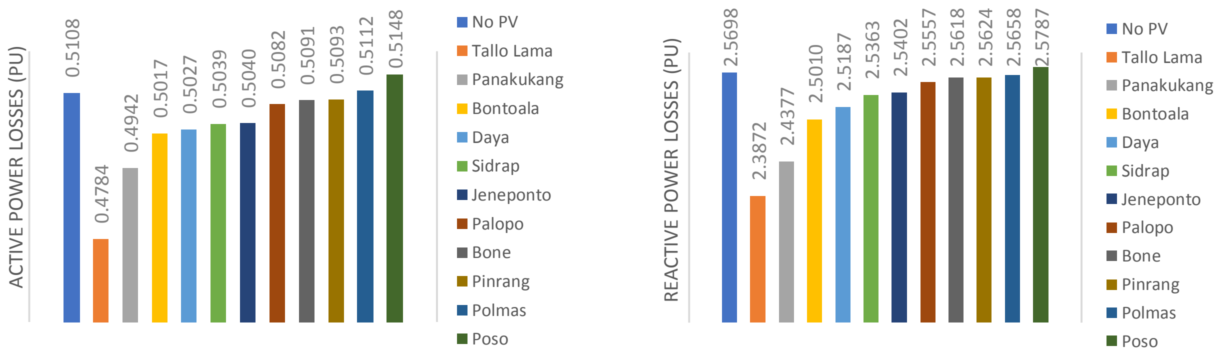


Fig. 6 Voltage profile for all PV placement of 1 MWp



(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%.

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 PV-TVS 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 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**

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.

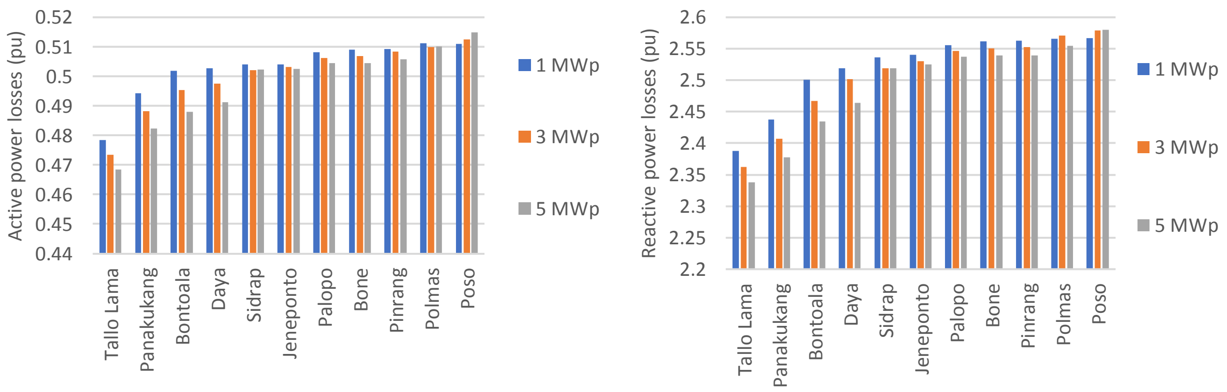
TABLE III
PV-TVS CALCULATION FOR EACH PV PLACEMENT OF 1 MWP, 3 MWP AND 5 MWP

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 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].

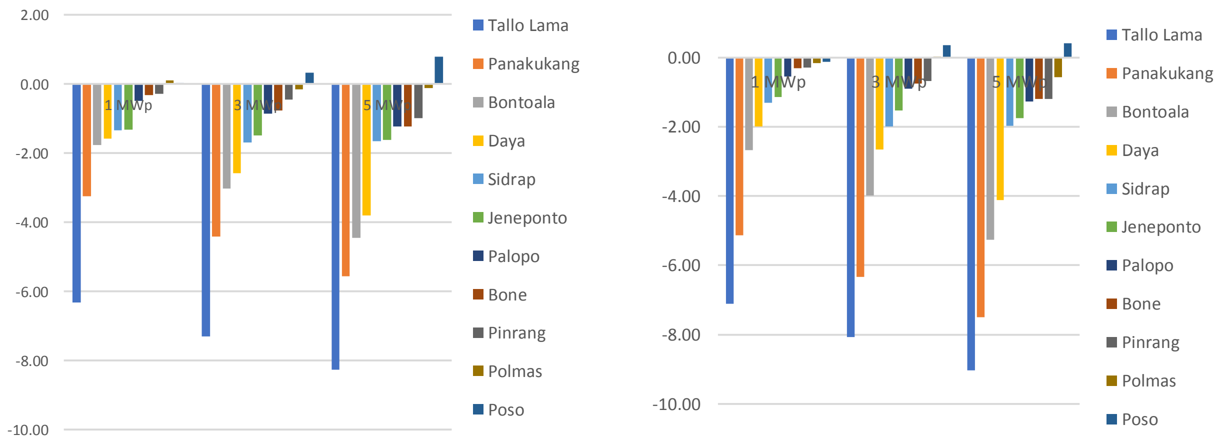
IV. Conclusions

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.



(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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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.

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