Optimal Photovoltaic Placement at the Southern Sulawesi Power System for Stability Improvement

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Abstract-This paper presents a new method in determining the optimal location of Photovoltaic (PV) based on the location's irradiance from SOLARGIS and network system for voltage stability improvement and losses minimization. The analytical method is developed based on the Continuation Power Flow (CPF) which is an assessment to analyze the voltage stability in quasi-static technique. To optimize the allocation process, firstly, areas which have good irradiance based on SOLARGIS will be selected and only those areas will be the input data on the determination of optimal PV placement where PV-Sensitivity of each of these buses will be calculated. The bus that has the highest PV-Sensitivity is a bus that has a good sensitivity to improve the voltage stability of the system as well as has good irradiance and will be recommended for optimal PV placement. Simulation results on the Southern Sulawesi power system show that this method is effective in determining the PV location. In this work, voltage magnitude and network losses are evaluated to compare the stability for each PV placement scenarios. This study provides locations who have good irradiance and PV-Sensitivity, which the results of this research can become recommendations for the power system utility or PLN in Indonesia in planning for PV integration.

Keywords—Photovoltaic placement, voltage stability, losses minimization, irradiance, Continuation Power Flow.

I. INTRODUCTION

The term voltage stability is closely related to the ability of a power system to maintain the voltage of each bus whether in an abnormal conditions or because of interference [1]. A power system will experience voltage instability that occurs due to increased demand or changes in the system. This situation will impact the voltage profile down and power losses becomes greater, hence may be uncontrollable [2-4].

Expectation for significant reductions in fossil fuels and increased reforestation impacts make the whole world interested in alternative energy [5-10]. With the rapidly growing renewable energy resources around the world, such as solar, hydro, wind, ocean and geothermal energy, this has become an alternative power generation. On the other hand, this can also increase reliability in reducing power outages or blackouts in the surrounding areas [11]. Voltage on the distribution system network is one of the power quality issues that needs to be taken into account because it greatly affects the performance of the system when distributing energy to the consumers [12-13].

Among the existing renewable energy resources, the photovoltaic (PV) market from solar energy resources is growing very rapidly compared to other technologies. In 2009, PV production in the world reached up to 10.66 GW [14]. In Indonesia, a PV system as a source of electricity for small islands have been implemented since the 1970s, but unfortunately in 1997, it was stopped due to the financial crisis at that time [15].

PV units can be installed close to load centers. At the present, a PV system can convert 1 kW of solar energy that falls on a 1 meter-square area to 100 W of electricity, which can drive most of the household appliances such as: television, stereo, electric typewriter or lamp [16]. Based on data from the National Energy Board, the potential of solar energy in Indonesia reaches an average of about 4.8 kWh permeter-square or equivalent to 112,000 GWp [17].

The radiation of sunlight to the surface of the earth's atmosphere is not entirely accepted by the surface of the earth as it is being processed by clouds or other particles present in the atmosphere. To stabilize carbon dioxide (CO_2) in the atmosphere in the middle of this century, PV is proposed to be used for 10 TW of electricity, hydrogen of 10 TW for transportation and fossil fuels for housing and industry for 10 MW. Thus, PV will play a very important part in meeting world's future energy demand. This time is considered as a "tipping point" for PV development [18-19].

In a research by L. Serrano-Luján, et.al, the writers divided the countries around the world into categories of CO_2 amount that can be avoided for integration of 1 kWp PV during its lifetime [22]. In this division, avoided CO_2 emissions by PV in the first group of countries is about 35-40 tons. The first group of countries are; Turkmenistan, Iraq, Ethiopia, Kuwait, Saudi Arabia, Oman, South Africa, Australia, Cuba, India and Western China. These countries have the highest potential in CO_2 reduction [20-21]. While the countries of Morocco, Cambodia, Israel, Indonesia, Jamaica, Yemen, United Arab Emirates, Western United States, East China and the Dominican Republic fall into the second group of avoided CO_2 emission for 25-30 tons of CO_2 reductions per 1 kWp PV during its lifetime [22].

Placement of PV at the appropriate location on the transmission system is essential for maintaining voltage stability

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[23-24] and may defer the transmission network development [25]. The installation of a PV generator in the distribution network shows an improvement in the voltage profile and reduction of power losses [26]. Since the Southern Sulawesi region is one of the areas that have good radiation, so it becomes the object of PV integration in Indonesia. Therefore, this study was conducted to determine the optimal location of PV placement in the Southern Sulawesi power system based on the system configuration and irradiation data. Areas with good irradiation are determined from the SOLARGIS data, which then becomes the input in the Continuation Power Flow (CPF) method to calculate the PV-Sensitivity value. Buses with high irradiation as well as good PV-Sensitivity are recommended for optimal PV placement.

The structure of this paper is as follow. Section 2 explains about PV Potential in Indonesia including the basic theory of photovoltaic, irradiance in Indonesia and maximum power point tracking (MPPT) of PV . Section 3 elaborates about the proposed method. Results and analysis are presented in Section 4. Section 5 summarizes the main findings of this study.

II. PV POTENTIAL IN INDONESIA

A. *Overview of PV Technology*

PV is a device that can convert solar energy directly into electrical energy. PV technology is much observed by engineers as one of the ideal energy resources because its performance does not cause pollution in generating electricity. This technology converts solar radiation into direct-current electricity (DC) by using semiconductors. DC currents generated from sunlight, can be directly used for DC electrical equipment or to recharge the batteries. To convert the DC current to an AC current, an inverter is required, then distributed through the indoor distribution panel.

A PV module is a number of solar cells that are coupled in series and/or parallel connection, to increase the resulting voltage and current so that it is sufficient to supply the power system's load. To obtain maximum electrical power output then the surface of the solar module should always be facing the sun. The main component of a PV system is the module which consist of some PV solar cells. Crystal and thin film technology are mostly used for PV modules fabrication [27].

B. *Irradiance in Indonesia*

Indonesia is a country on the equator, so its solar energy's potential is high, because the sun continues to exist throughout the year. The average of the sun that has the potential to produce energy in the western part of Indonesia is around 4-5 hours per-day. In Aceh, Western Sumatra, Northern Sumatra, Riau and Jambi provinces have average energy potential of 4.5 kWh/m^2/day, while the eastern part of Indonesia covers all of Papua, Maluku, East Nusa Tenggara, West Nusa Tenggara, and parts of Sulawesi have average energy potential of 5.1 kWh/m^2/day [17].

Hence, utilization of renewable energy sources, especially in Indonesia is an effective approach in addressing the increasing energy demand as well as dealing with the worsening ecological environment [28]. Solar energy that reaches the earth's surface is usually calculated by Global Horizontal Irradiation (GHI). Furthermore, for the long-term average value of Photovoltaic Power Production Potential (PVOUT) is determined by various factors including latitude, elevation, landform and many other meteorological variables. The amount of PVOUTs in 2017 in Indonesia is shown in Fig. 1 that was predicted by SOLARGIS [29].

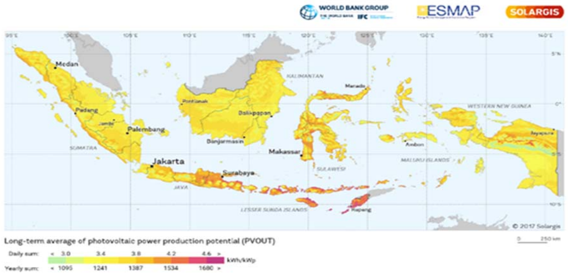


Fig. 1. Long-term average of photovoltaic power production potential (PVOUT) in Indonesia [29]

C. *Maximum Power Point Tracker (MPPT)*

MPPT is a technique used in solar/photovoltaic systems to maximize sun power extraction under all conditions. As the amount of sunlight varies, the load characteristics change so that the efficiency of the system is optimized to preserve power transferred at highest efficiency. MPPT devices are often integrated into electrical power converter systems that they can adjust current settings to drive the load [30].

III. THE PORPOSED METHOD

A. *The Continuation Power Flows*

In this paper, optimal PV analytical placement employs Continuation Power Flow (CPF) method. But for its effectiveness, only buses with good irradiance whose sensitivity will be calculated. In general, the methods for voltage stability analysis are classified into 3 categories, ie; 1) Static (steady-state) voltage stability analysis; 2) Quasi-Steady-State Voltage Analysis; and 3) Dynamic Voltage Stability Analysis [31-34]. One method of a well-recognized quasi-static is the CPF method introduced by Ajjarapu and Christy [35]. CPF method is a voltage stability analysis method that remodels the conventional power flow equation to find power flow solutions ranging from basic loads to stable or critical stability states which uses a predictor and corrector scheme. In addition, the CPF method can be used to detect the most sensitive bus to voltage collapse and also increase or decrease the power losses in the system [36-37], which based on active and reactive power being transferred from distribution or transmission lines.

Fig. 2 shows the graph of the predictor-corrector scheme where in the analytical procedure begins with a known result then will predict the next solution with different loads.

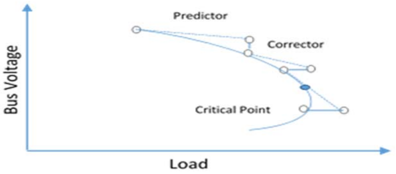


Fig. 2. Predictor-corrector scheme of the CPF method [35].

Firstly a loading parameter (∅) is defined as:

$$0 \leq \quad \emptyset \leq \quad \emptyset_{critical} \qquad (1)$$

Where ∅ = 0 has the relationship with the base load and ∅ = ∅critical corresponds to the critical load. This load parameter is then inserted into the active and reactive power equation, so that:

$$0 \ = P_{Gi0}(1 + \lambda k_{Gi}) - P_{Li0} - \emptyset(k_{Li}S_{\Delta base})\cos\theta i) - P_{Ti} \quad (2)$$

$$0 \ = \ Q_{Gi0} - \ Q_{Li0} \ - \ \emptyset \ (k_{Li}S_{\Delta base}\sin\theta i) - Q_{Ti} \qquad (3)$$

Where,

$P_{Li0,}$	is active load at bus *i*
Q_{Li0}	is reactive load at bus *i*
k_{Li}	is the rate of change indicator of load at bus *i* to change ∅
θ_i	is the power angle of the load changes at bus *i*
$S_{\Delta base}$	is the quality of the apparent power chosen to inject the exact scale of ∅
P_{Gi0}	is the active power generation at bus *i*
Q_{Gi0}	is the reactive power generation at bus *i*
k_{Gi}	is a constant value in the generator to determine the varying degres of change in the generator to ∅
$P_{Ti,}\ Q_{Ti}$	are parameters of active and reactive power, respectively, that are provided in the system.

After the first step is done then proceed with computation on the algorithm using the following power flow equation as;

$$F\ (\delta, \quad V, \quad \emptyset) = 0 \qquad (4)$$

Where δ is angle vector of the generator, V is vector of bus voltage magnitude and ∅ is loading parameter.

The CPF method describes a predictor corrector step scheme to find the solution of the reformulated power flow equation. Then, by deriving both sides of the power flow equation, hence:

$$[F_\delta \quad F_V \quad F_\emptyset]\begin{bmatrix} d\delta \\ dV \\ d\emptyset \end{bmatrix} = 0 \qquad (5)$$

By extending the parameterization that has been identified from each solution that was obtained after the computation process from Eq. 5, then the results achieved will show the sensitivity of every bus in the system. The most sensitive bus has a ratio of the magnitude of the differential voltage changes to the differential change of the load. Therefore, in this study we are presenting PV-Sensitivity to determine the PV location as follows:

$$\begin{aligned} PV - Sensitivity_j &= \left|\frac{dV_j}{dP_{total}}\right| = \left|\frac{dV_j}{Cd_\emptyset}\right| \\ &= \max\left|\left|\frac{dV_1}{Cd_\emptyset}\right|, \left|\frac{dV_2}{Cd_\emptyset}\right|, \ldots\ldots \left|\frac{dV_n}{Cd_\emptyset}\right|\right| \qquad (6) \end{aligned}$$

Eq. 6 shows the sensitivity of each locations with high irradiance, where the PV-Sensitivity is calculated based on the ratio of the magnitude of the differential voltage changes to the differential change of the load, specified to the voltage magnitude improvement in buses with low voltages. Hence, buses with high PV-Sensitivity are then proposed for PV placement, since these buses have high irradiance and have good sensitivity in improving the system's voltage.

B. Flowchart of the proposed method

Fig. 3 shows a proposed PV flow diagram using CPF and irradiance. After a power flow study, the next step is to run CPF and calculate PV-Sensitivity in determining the most sensitivity location in improving stability in the system at locations with high irradiance. The buses with high PV-Sensitivity is then used as the priority of PV placement.

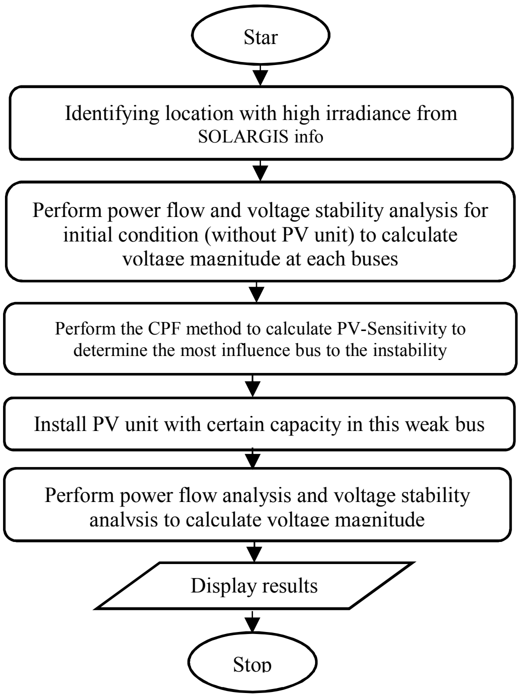


Fig. 3. Flowchart of the proposed PV allocation methodology with irradiance and CPF [38].

IV. RESULTS AND ANALYSIS

Based on the SOLARGIS data, Southern Sulawesi region has good irradiance, which is shown in Fig. 4. From here, several regions are identified with high irradiance of 1607 kWh/m^2/year, they are: Makassar, Sidrap, Jeneponto, Palopo, Bone, Pinrang, Polmas and Poso. Based on this data, Makassar city is one of the areas that have good irradiance. In Makassar itself there are several substations. Given Makassar is the capital of the province and very dense, so for this study, PV-Sensitivity calculations in Makassar City are represented by several substations, they are; Tallo Lama, Panakukang, Bontoala, and Daya, which are listed in Table I. Hence, these buses/substations will become the candidate for PV placement whose PV-Sensitivity will be calculated.

The proposed method is simulated on the Southern Sulawesi interconnected power system that consists of 44 buses (substations), 47 lines and 7 power plants that are modeled for PV placement research based on SOLARGIS data. The power generation output of each PV is simulated of 20 MW. Further detail of the Southern Sulawesi power system can be found at [39-40].

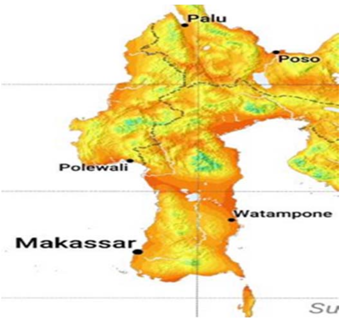


Fig. 4. Solar irradiance at Southern Sulawesi region

TABLE I. SUBSTATIONS WITH HIGH IRRADIANCE

Substations	
Tallo Lama	Palopo
Panakukang	Bone
Bontoala	Pinrang
Daya	Polmas
Sidrap	Poso
Jeneponto	

Fig. 5 displays the PV-Sensitivity value in each substation with good irradiance on the system in descending order. The results are that substations with good irradiance and the highest PV-Sensitivity is found in Tallo Lama and substation who has good irradiance but the worst PV-Sensitivity is Poso.

Overall, Tallo Lama Substation has the highest PV-Sensitivity that is 0.94158, followed by Panakukang of 0.79649, then Bontoala and Daya with PV-Sensitivity of 0.43834 and 0.12497, respectively. While areas that have low PV-Sensitivity are Bone with PV-Sensitivity of 0.00663, Pinrang (0.00472) and Polmas (0.00195). Area with the worst sensitivity is Poso with PV-Sensitivity of -0.00301. This value is even negative, meaning that installing PV at this substation may deteriorate the stability.

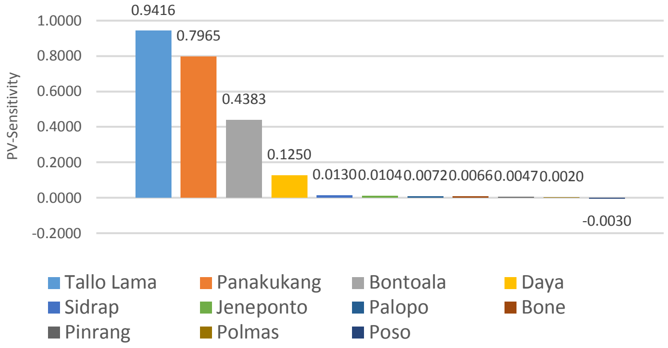


Fig. 5. PV – Sensitivity chart

To assess the results, we evaluated the voltage stability if PV is installed at each substation with good irradiance. Fig. 6 shows the voltage profile for all PV mounting scenarios. The system voltage for installation of 20 MW PV in Tallo Lama is shown in the graph with red line. For more details, Fig. 7 compares the voltage magnitude for initial conditions and for 20 MW PV at substations with the highest PV-Sensitivity (Tallo Lama) and the lowest PV-Sensitivity (Poso). It can be seen that the voltage magnitude of 20 MW PV installed at Tallo Lama is much better than voltage magnitude before PV installation and if PV is placed at Poso. In addition, it clearly shows that if PV of 20 MW is placed in Poso substations, it does not significantly improve the system's voltage and even voltage at some substations are still below the stability limit of 0.9 p.u. Most of the voltage under 0.9 p.u. are located in the capital of South Sulawesi province where these substations have high load.

After the installation of PV on the system based on SOLARGIS data, we also evaluated network losses in each substation used for the placement of PV in the Southern Sulawesi power system. Assessment of network losses is important in power system's planning [41-42].

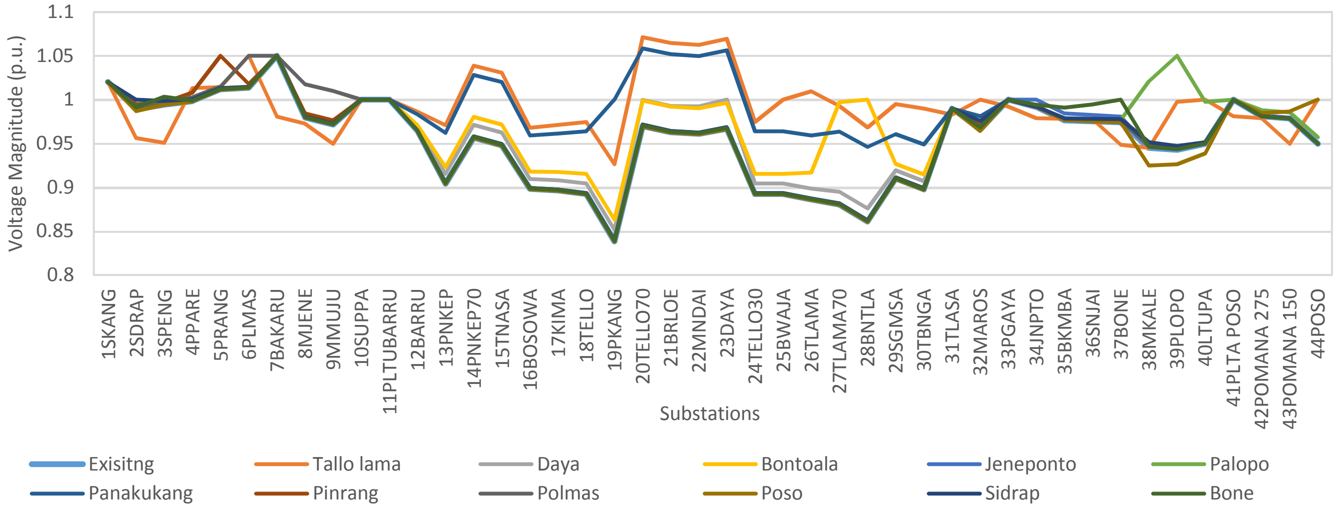
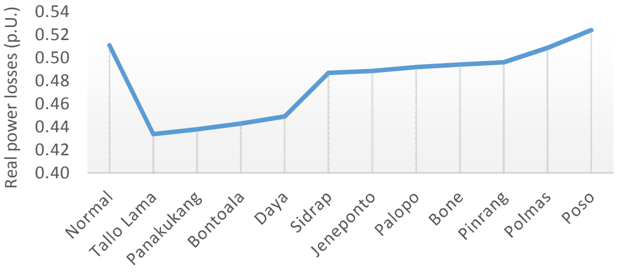


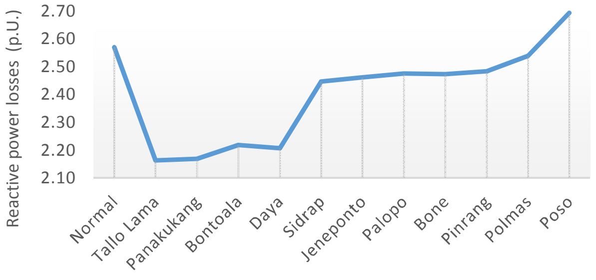
Fig. 6. Voltage Profiles for all scenarios

Fig. 7. Voltage profiles for initial condition, PV at Tallo Lama and PV at Poso

Figs. 8a and 8b demonstrate the network active and reactive power losses, respectively, if PV of 20 MW is installed at each substation with high irradiance. It is found that the highest total losses if PV is installed at Poso Substation, where for active power losses are 0.5236 p.u and reactive power losses are 2.6924 p.u. Nevertheless, if PV is placed at Tallo Lama (with the highest PV-Sensitivity) the network losses are the smallest compared to other scenarios, which are 0.4335 p.u for active power losses and 2.1625 p.u for reactive power losses.



(a) Real power losses



(b) Reactive power

Fig. 8. Network Power Losses

Table II informs the power losses reduction/addition of each scenario of PV installation compared to the initial condition losses. The negative sign (-) implies losses reduction, whereas the positive sign implies losses addition. PV integration at Tallo Lama will result in the biggest losses reduction whereas integrating PV at Poso area will create bigger network losses.

TABLE II. POWER LOSSES REDUCTION/ADDITION COMPARE TO BEFORE PV INSTALLATION

PV Location	Power losses reduction/addition	
	Real power [p.u.]	Reactive power [p.u.]
Tallo Lama	-0.07727	-0.40726
Panakukang	-0.07301	-0.40196
Bontoala	-0.06797	-0.35211
Daya	-0.06193	-0.36342
Sidrap	-0.024	-0.12416
Jeneponto	-0.02225	-0.10929
Palopo	-0.01904	-0.0948
Bone	-0.01683	-0.09765
Pinrang	-0.0148	-0.08749
Polmas	-0.00234	-0.03185
Poso	0.01284	0.12256

V. CONCLUSIONS

Proper PV placement in the Southern Sulawesi power system can reduce the power losses that occurs and improve system stability. This paper proposes a new algorithm for PV placement using SOLARGIS data. From SOLARGIS, 8 regions have good irradiance, where Makassar City is represented by 4 substations.

The results of this study confirm that substations in the city of Makassar (Tallo Lama, Panakukang, Bontoala, and Daya) have high irradiance and PV-Sensitivity, and based on these results become recommended places for PV placement as it can increase the voltage profile and reduce the network losses significantly. Nevertheless, the PV plants installation require extensive land, hence further research should be done to find appropriate area in these regions. Sidrap, Jeneponto, Palopo, Bone, Pinrang and Polmas regions also have good irradiance but smaller PV-sensitivity. PV can also be placed at these locations, even though not as effective as if placed at Makassar City area. Poso, with negative PV-Sensitivity, if adding PV at this region, is not effective, since it does not have significant effect in improving voltage profile and adding more network losses into the system.

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