Analysis of Distributed Generation Integration Effect on Active Power Losses in Distribution Networks

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***Abstract*—Distributed Generation (DG) is commonly used to reduce active power losses on a distribution network. The optimal location and size of DG will result in minimum active power losses and voltage profile improvement. This research proposes Novel Voltage Sensitivity Index (NVSI) and Stability Index (SI) methods to determine the optimal location and analytical expression to find optimal size and location of DG in Makassar distribution system, Feeder Kima, 76 buses to minimize active power losses and to improve voltage profile. Therefore, DG interconnection has a significant effect on improving the quality of the distribution network. The results show that the sensitivity method does not lead to the best placement DG in reducing active power losses. However, it is an analytical expression, which is very effective in determining optimal location and size of DG to reduce active power losses and to improve voltage profile in Makassar distribution system, Feeder Kima, 76 buses. The most optimal location for DG placement is on Bus 73 (Mega Sakti Pyramid), with a DG size of 0.8515MW. These combinations reduce 45.77% active power losses and increase 1.7336% voltage profile.**

***Index Terms*—Active power losses, distributed generator, voltage profile, distribution networks, optimal location, novel voltage-sensitive index**

I. Introduction

Electricity consumption in Indonesia increases every year as the national economic growth rises (Ministry of Energy and Mineral Resources, January 9, 2020). Generally, conventional power plants are designed on a large scale, centralized, and built far from the load center. Thus it requires extensive transmission and distribution networks to supply electricity. The longer the distance, the higher the power losses and voltage drops. In a distribution system, the X/R ratio (ratio of system reactance to system resistance) is higher than in a transmission system. Therefore, a significant voltage drop will result in power losses and the distribution network [1], [2]. Distributed Generation (DG), a smaller power size generator, is installed along with the network to overcome this problem. The general definition of DG is a distributed generation, which produces small-scale electrical energy and is directly connected to the distribution network, or it is close to the customer [3], [4].

Optimal placement of DG in the distribution network will reduce power system losses, improve voltage profile, increase reliability, and delay the investment of new construction on a distribution network. Otherwise, misplacement of DG will cause higher power losses [5], [6]. Installation of DG is one of the best alternatives to overcome several problems, such as high power losses, low reliability, and poor power quality. These problems often occur in electrical power distribution systems to meet the increasing demand. The small size of DG is easier and faster to be installed rather than conventional generation. To gain advantages of DG integration, such as lower power losses, higher voltage profile, and quality, DG must have proper size and location [7].

Optimal DG placement can be seen as optimal active power compensation, as capacitor placement for reactive power compensation, but DG placement is a relatively novel study, and it is different from capacitor placement. It used the power flow algorithm to determine optimal DG size on each load bus and assumed that each load bus could have a DG source. However, this method is less efficient because it employs load flow on its most calculation [8]. Determination of DG size and location by genetic algorithm (GA) method has been studied by several researchers, GA is suitable for multipurpose problems such as DG placement and gives optimal results, but it requires more complex computations and slower convergence [9]. The analytical method is also applied to place DG in the radial grid system to minimize power losses. The method has a different expression for a radial system based on a complex procedure of proposed phasor current to find DG location, but this method only optimizes location while DG size remains constant [10].

This research uses SI (Stability Index) and NVSI (Novel Voltage Sensitivity Index) methods to determine the most optimal DG location, while the analytical method is applied to find not only optimal DG location but also the size of DG. The analytical method is not computationally demanding, DG is assumed to be in the primary distribution system, and the purpose of placing DG is to reduce system power losses. The costs of DG

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and other related benefits are not considered in determining the location and size. The proposed methodology is using single DG in the distribution network and it is capable of supplying active power.

II. Distributed Generation (DG)

The International Energy Agency (IEA) defines DG as a generator that serves customers on-site or supports network-connected distribution systems. The International Council of Large Electric System (CIGRE) defines DG as a generator that is not planned to be connected to a distribution system, or centrally distributed and has a small size of 50MW to 100MW. Other organizations, such as the Electric Power Research Institute (EPRI), define DG as generation from a few kilowatts to 50MW. In general, DG is a small-scale generation that directly connects consumers and producers [11].

Distributed generators (DG) can be grouped into four types according to their ability to inject active and reactive power as follows [12], [13]:

- Type 1: DG can inject active power only (e.g., Photovoltaic, microturbines, fuel cells).
- Type 2: DG can inject reactive power only (e.g., synchronous compensators)
- Type 3: DG can inject both active and reactive power (e.g., cogeneration, gas turbine)
- Type 4: DG can inject active power but consumes reactive power (e.g., induction generators in wind farms)

DG's primary function is to anticipate power grid disconnection or as a unit installed during peak load hours. In other words, DG is a stand-by unit. The characteristics of DG are small scale, scattered and close to the load center (closed to load), interconnected with the distribution system, limiting the construction of transmission networks, and having one-way power flow. These generations are environmentally friendly, reliable in responding to load changes, reducing fossil fuels, and deregulation in the electricity market, and some other advantages [14].

III. Optimal Location and Size of Distributed Generators

DG integration with proper planning is needed to improve network performance related to active power losses and voltage profiles. However, misplacement and wrong size of DG will result in increased power losses, voltage imbalances, and power quality problems [15]. Therefore, the best location and appropriate DG size must be found before connecting to the distribution system. There are many methods proposed by researchers for optimal placement, including:

- Numerical based approach
- Analytical approach
- Meta-heuristic approach
- Sensitivity-based approach

For this research, analytical and sensitivity-based approaches are considered for the optimal size and location of DG using the SI and NVSI methods.

A. Optimal Location DG Using the Sensitivity Method

The most advantageous placement of DG is to place it on the bus, which has the lowest voltage. In this study, two different sensitivity indices are used for optimal placement of DG locations; there are NVSI and SI [16], [17].

NVSI is expressed as

$$\text{NVSI} = \frac{2X\sqrt{P_r^2 + Q_r^2}}{2Q_r X - V_S^2} \tag{1}$$

where X is the line reactance, V_s is the voltage at the sending end, P_r is the real power at the receiving end, and Q_r is the reactive power at the receiving end.

NVSI shows that the maximum value is considered the most susceptible value to voltage collapse. Therefore, the bus with a maximum sensitivity index value is considered a candidate bus for DG installation.

SI is expressed as

$$\text{SI} = 2V_S^2V_r^2 - V_r^4 - 2V_r^2\left(P_rR + Q_rX\right) - Z^2\left(P_r^2 + Q_r^2\right) \tag{2}$$

where V_r is the voltage at the receiving end, R is the line resistance, and Z is the line impedance.

For the sensitivity index, the bus with the minimum SI value is considered the most susceptible value to voltage collapse. Thus, the bus that shows the smallest/minimum SI is considered the optimal DG location [18], [19].

B. Optimal Location and Size Using Analytical Methods

Active power loss P_{loss} in an electrical power system can be determined using equation (3), which is often known as the "exact loss formula" [20].

$$P_{\text{loss}} = \sum_{i=1}^{n}\sum_{j=1}^{n}\left[a_{ij}\{P_iP_j + Q_iQ_j\} + b_{ij}\left\{Q_iP_j - P_iQ_j\right\}\right] \tag{3}$$

where

$$a_{ij} = \frac{r_{ij}}{v_iv_j}\cos\left\{\delta_i - \delta_j\right\} \tag{4}$$

$$b_{ij} = \frac{r_{ij}}{v_iv_j}\sin\left\{\delta_i - \delta_j\right\} \tag{5}$$

and r_{ij} is the ijth real element of the Z_bus matrix, v_i and δ_i is the voltage and angle on bus i, v_j and δ_j is the voltage and angle on bus j, P_i and P_j is the active power on buses i and j, and Q_i and Q_j is the reactive power on buses i and j.

The active and reactive power injected on bus i, where DG is installed, can be written as follows:

$$P_i = P_{\text{DG}} - P_{Di} \tag{6}$$

$$Q_i = Q_{\text{DG}} - Q_{Di} = \left(\text{apf} \cdot P_{\text{DG}}\right) - Q_{Di} \tag{7}$$

where P_{DG} and Q_{DG} are the active and reactive power of injected DG, P_{Di} and Q_{Di} are the active power load and reactive power load on bus i, and apf is defined as

$$\text{apf} = \{\text{sign}\}\tan\left\{\cos^{-1}\left(\text{PF}_{\text{DG}}\right)\right\} = \begin{cases} 1 & \text{if DG injected reactive power} \\ -1 & \text{if DG absorbed reactive power} \end{cases} \quad (8)$$

here PF_{DG} is the DG power factor.

Substituting (6) and (7) into (3), the active power loss with DG is obtained as follows:

$$P_{\text{loss}} = \sum_{i-1}^{n}\sum_{j=1}^{n}\begin{bmatrix} a_{ij}\left\{P_{\text{DG}i} - P_{Di}\right\}P_j + \left(\left(\text{apf}\cdot P_{\text{DG}i}\right) - Q_{Di}\right)Q_j\} + \\ b_{ij}\left\{\left(\left(\text{apf}\cdot P_{\text{DG}i}\right) - Q_{Di}\right)P_j - \left(P_{\text{DG}i} - P_{Di}\right)Q_j\right\} \end{bmatrix} \quad (9)$$

where $P_{\text{DG}i}$ and $Q_{\text{DG}i}$ are the active power and reactive power of injected DG into bus i.

The system's active power losses can reach a minimum value by partial differentiating of (7) on the active power from DG on the bus i ($P_{\text{DG}i}$) to zero.

$$\frac{\partial P_{\text{loss}}}{\partial P_{\text{DG}i}} = 2\sum_{j=1}^{n}\left\{a_{ij}\left(P_j + \left(\text{apf}\cdot Q_j\right)\right) + b_{ij}\left(\left(\text{apf}\cdot P_j\right) - Q_j\right)\right\} = 0 \quad (10)$$

Equation (10) can be written as follows:

$$\begin{aligned} & a_{ii}\left\{P_i + \left(\text{apf}\cdot Q_i\right)\right\} + b_{ii}\left\{\left(\text{apf}\cdot P_j\right) - Q_i\right\} + \\ & \sum_{j=1,\neq i}^{n}\left(a_{ij}P_j - b_{ij}Q_j\right) + \text{apf}\sum_{j=1, j\neq i}^{n}\left(a_{ij}Q_j + b_{ij}P_j\right) = 0 \end{aligned} \quad (11)$$

For example:

$$X_i = \sum_{j=1,\neq i}^{n}\left(a_{ij}P_j - b_{ij}Q_j\right) \quad (12)$$

$$Y_i = \sum_{j=1,\neq i}^{n}\left(a_{ij}Q_j - b_{ij}P_j\right) \quad (13)$$

From (6), (7), (11), (12), and (13), we obtain:

$$\begin{aligned} & a_{ii}\left\{P_{\text{DG}i} - P_{Di} + \text{apf}^2\cdot P_{\text{DG}i} - \text{apf}\cdot Q_{Di}\right\} + \\ & b_{ii}\left\{Q_{Di} - \text{apf}\cdot P_{Di}\right\} + X_i + aY_i = 0 \end{aligned} \quad (14)$$

From equation (14), the optimal size of DG on the bus i to minimize power loss is written as in equation (15):

$$\begin{aligned} P_{DGi} = \frac{1}{\text{apf}^2\cdot a_{ii} + a_{ii}} & \left[a_{ii}\left(P_{Di} + \text{apf}\cdot Q_{Di}\right) + \right. \\ & \left. b_{ii}\left(\text{apf}\ P_{Di} - Q_{Di}\right) - X_i - \text{apf}\cdot Y_i\right] \end{aligned} \quad (15)$$

Reduction of active power loss after DG integration to the system is given on the following equation:

$$\text{Active Power Loss Reduction} = \frac{P_{\text{loss}} - P_{\text{loss}}^{\text{DG}}}{P_{\text{loss}}}100\% \quad (16)$$

Active power losses of the system can reach the minimum value by partial differentiating of (7) on the active power from DG on the bus i ($P_{\text{DG}i}$) to zero.

Power factor of DG depends on operating conditions and type of DG When DG power factor is known, the optimal size of DG on the bus i to minimize power losses can be determined in the following ways [21]:

- DG Type 1; Power factor is 1, therefore apf = 0, from equation (15), the optimal capacity of DG on the bus i to minimize power losses can be given by the equation:

$$P_{Gi} = P_{Di} + \frac{1}{a_{ii}}\left\{b_{ii}Q_i - \sum_{\substack{j=1\\ j\neq i}}^{n}\left(a_{ij}P_j - b_{ij}Q_j\right)\right\} \quad (17)$$

- DG Type 2; Power factor is assumed to be 2 and apf = ∞ , from equation (15), the optimal size of DG on the bus i to minimize power loss is given on the following equation:

$$Q_{DGi} = Q_{Di} + \frac{1}{a_{ii}}\left\{b_{ii}P_i - \sum_{\substack{j=1\\ j\neq i}}^{n}\left(a_{ij}Q_j - b_{ij}P_j\right)\right\} \quad (18)$$

- DG Type 3; Power factor is between 0 and 1, sign = +1, and apf is constant, thus the optimum capacity of DG on the bus i to minimize power losses is given in equations (9) and (17).
- DG Type 4; Power factor is between 0 and 1, sign = −1, and apf is constant, thus the optimum capacity of DG on the bus i to minimize losses is given in equations (7) and (15).

After optimal DG size on each bus is obtained, the next step is to find active power losses by consecutively using the optimal DG size on each bus. Calculation of active power losses when DG is placed requires several power flow solutions, such as the number of buses in the system. When DG is installed in the system, the value of the losses coefficient will change since it depends on the voltage and phase angle variables. Therefore, an approach method is needed to find the estimated power losses, which will give the best DG placement location. [22], [23].

IV. Result and Discussion

To analyze the performance of the proposed method, the Makassar Distribution System, Feeder Kima, 76 bus, as a tested system, is constructed in Fig. 1. Direct load flow analysis is applied to calculate power losses, voltage magnitudes, and phase angles in various buses.

DG Type 1 is used in this research, and it only injects active power into the system. Based on the analytical method's proposed approach, the optimal DG size for each bus in the Makassar distribution system, Feeder Kima, 76 buses is given in Fig. 2.

Fig. 2 indicates that the size of DG varies and does not depend on the location of the bus. After connecting DG on each bus (one at a time consecutively), the minimum active power losses will be obtained on the corresponding bus. In the Makassar Distribution System, Feeder Kima, 76 buses, optimal DG size ranges from 0.019MW to 5.438MW.

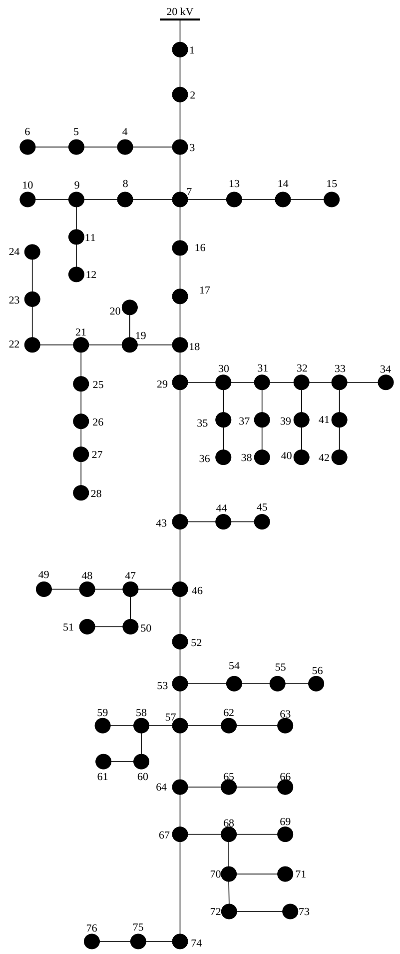

Fig. 1. Makassar Distribution System, Feeder Kima, 76 Buses

The optimal placement of DG in Makassar Distribution System, Feeder Kima, 76 buses, is conducted using (NVSI and SI sensitivity approaches. The result of the NVSI sensitivity index is given in Fig. 3, where bus 45 shows the highest NVSI value. Therefore bus 45 is considered the optimal location for DG, and the results of the SI sensitivity index are shown in Fig. 4, where it can be seen that bus 28 shows the minimum SI value. Thus bus 28 is considered the optimal DG location. In contrast, the optimal location for DG placement using the analytical method is located with minimum system power losses. Hence, determination of optimal DG location is carried out by placing DG on each bus at a time, consecutively, with a capacity as shown in Fig. 2, and the result is shown in Fig. 5. Based on Fig. 5, it can be seen that the minimum active power loss is on bus 73; therefore the optimal DG location is on bus 73.

As a result, there are three DG placement locations, and these locations (bus 28, bus 45, and bus 73) will be simulated. The simulation results are given in Table I and Table II.

TABLE I: ACTIVE POWER LOSS BEFORE AND AFTER DG IS INSTALLED ON THE CANDIDATE BUS

Bus Number	Size DG (MW)	Active Power Losses (MW)		Losses Reduction (%)
		Before DG is installed	After DG is installed	
28	0.29220	0.156100	0.161068	-3.183
45	0.19340	0.156100	0.150023	3.893
73	0.85150	0.156100	0.084638	45.770
Size DG (0.5DG) Bus 73		0.156100	0.093745	39.946
Size DG (2DG) Bus 73		0.156100	0.207772	-33.102
Size DG (3DG) Bus 73		0.156100	0.479453	-207.140

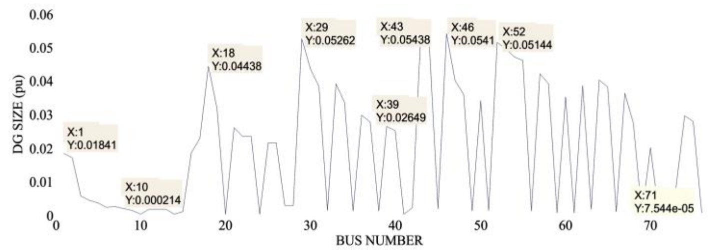

Fig. 2. Graph of DG Size on each bus of Makassar distribution system, feeder Kima, 76 buses

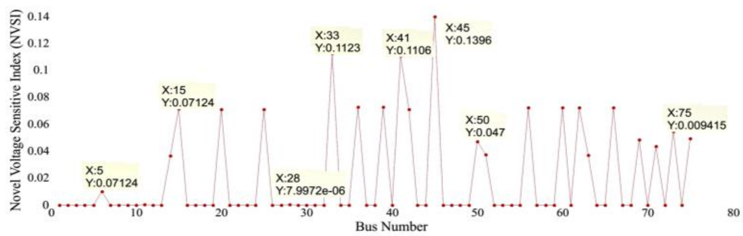

Fig. 3. NVSI Makassar distribution system, feeder Kima, 76 buses

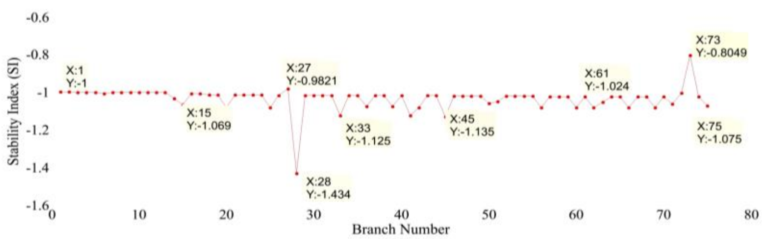

Fig. 4. SI, Makassar distribution system, feeder Kima 76 buses

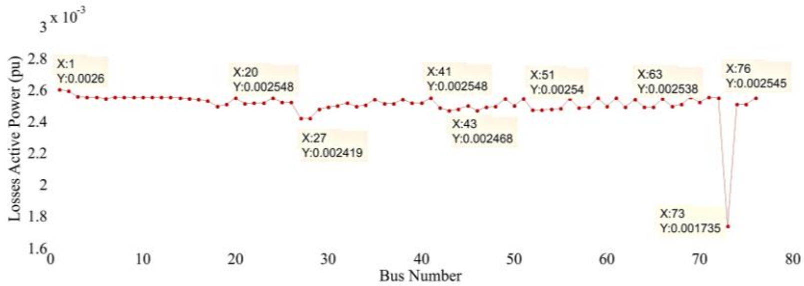

Fig. 5. Active power losses when DG is installed on each bus.

TABLE II: VOLTAGE PROFILE AFTER DG IS INSTALLED ON SOME WEAK BUSES

Bus No.	Size DG (MW)	Voltage (pu) before DG is installed	Voltage After DG is Installed on					
			Bus 28 (pu)	Delta (%)	Bus 45 (pu)	Delta (%)	Bus 73 (pu)	Delta (%)
28	0.292	1.0040	1.004	0.012	1.004	0.013	1.004	0.051
42	0.214	0.9065	0.906	0.020	0.906	0.018	0.907	0.072
45	0.193	0.9326	0.932	0.016	0.932	0.017	0.933	0.080
56	0.116	0.9674	0.967	0.015	0.967	0.019	0.968	0.094
63	0.180	0.9673	0.967	0.015	0.967	0.019	0.968	0.099
73	0.851	0.8729	0.87	0.019	0.873	0.024	0.972	10.242
Average voltage rise (%)				0.0165		0.0187		1.7736

Table I gives the value of active power losses before and after DG is installed on bus 28 (SI sensitivity result), bus 45 (NVSI sensitivity result), and bus 73 (analytical method). It can be seen that among the three buses, minimum active power losses occurred on bus 73 with a DG size of 0.8515MW, and its value reached 0.084638MW. There is a significant decline in active power losses to 45.77%. Active power losses are significant when DG is placed on buses 28 and 45. Therefore, the most optimal location of DG is on bus 73 based on the analytical method. When DG size on bus 73 is doubled, active power losses increase to 33.102%, as well, when DG size is enlarged three times, increasing of active power losses reach 207.14%. Reducing DG size to half of its capacity (0.5 DG) will reduce active power losses, but not at the minimum value. Thus, a larger DG size does not always indicate a more considerable reduction of active power losses, nor smaller DG size indicates higher active power losses reduction. It can be concluded that the most optimal placement of DG in Makassar Distribution System, Feeder Kima, 76 Buses is on bus 73 (Mega Sakti Pyramid Bus) and optimal DG size is 0.8515MW. It will result in minimum active power losses of 0.084638MW and percentage reduction of 45.77%.

Table II shows voltage variations on several buses by placing DG on a selected bus: bus 28, bus 45, and bus 73 with DG capacity based on Fig. 2. The results show that voltage increases in each bus when DG is installed on bus 28, bus 45, and bus 73. DG 0.2922MW is installed on bus 28, the voltage profile increases by an average of 0.0165%; DG 0.1934MW installed on bus 45, the voltage profile increased by an average of 0.0187%; DG 0.8515MW is installed on bus 73, the voltage profile increases by an average of 1.7736%. The highest percentage on voltage profile gained has happened when DG is installed on bus 73. Therefore, the optimal location and size of DG will reduce active power losses and improve voltage profile.

V. CONCLUSION

This research has proposed sensitivity method, NVSI and SI, to determine the optimal location of DG and analytical methods to find the optimal size of DG and minimum active power losses of primary distribution for optimal DG placement. The results give the optimal candidate locations for the Makassar Distribution System, Feeder Kima, 76 buses are bus 28 (SI), bus 45 (NVSI), and bus 73 (analytical method). Active power loss based on the placement and size of DG is varied. Thus, the optimal location and size of DG are essential factors in DG application in reducing active power losses and improving voltage profiles. Bus 73 (Mega Sakti Pyramid) is the best location for DG placement, and DG size is 0.85150MW, it results in reducing active power loss to 45.77% and increasing voltage profile to 1.7736%.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS

Zaenab Muslimin and Indar Chaerah Gunadin conducted the research and preparation for the manuscript. Ansar Suyuti, Elyas Palantei, and Indrabayu helped to check the whole manuscript and approved the final version.

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