

Optimal Capacity and Location Wind Turbine to Minimize Power Losses Using NSGA-II

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Abstract—Voltage deviations and power losses in the distribution network can be handled in various ways, such as adding diesel power plants and wind turbines. Adaut Village, Tanimbar Islands Regency, Maluku Province has installed a diesel power plant with a capacity of 1,200 kW, while the average hourly electricity load is 374.9 kW. Adaut Village has high wind potential that can be used for distributed generations namely wind turbine (WT). WT can be used to improve power quality in terms of power losses and voltage deviations. In adding WT, the capacity and location must be determined to get good power quality in terms of power loss and voltage deviation. The research applied an optimization technique for determining the capacity and location of WT using non-dominated sorting genetic algorithm II (NSGA-II) with an objective function of power losses and voltage deviation. In addition, the economic aspects of the power plant were calculated using the levelized cost of energy (LCOE). The research used scenarios based on the number of WT installed. The best results were obtained in scenario IV or 4 WT with 1.38 kW on Bus 2, 422.43 kW on Bus 15, 834.33 kW on Bus 30, and 380.81 kW on Bus 31 which could reduce power losses by 80% with an LCOE value of Rp7,113.15/kWh. The addition of the WT could also increase the voltage profile to close to 1 pu, which means it can minimize the voltage deviation in the distribution network.

Keywords—Wind Turbine, Non-Dominated Genetic Algorithm II, Power Loss, Voltage Deviation, Levelized Cost of Energy.

I. INTRODUCTION

The distribution network is part of the electric power system that distributes electrical energy from large power sources to loads or consumers. These consumers are, for example industries, factories, and households both in urban areas and in the outermost islands [1]. The distribution network has an inductive load that can cause voltage deviation and power losses. Voltage deviation is indicated by the voltage value below or above of nominal voltage value at each bus in the network system. While power losses are the loss of power in the process of sending electrical power from the source to the load [2]. The large voltage deviation and power losses can cause a decrease in power quality. It can be detrimental to both consumers and electricity producers. The loss from the consumer side is poor voltage quality caused by excess or lack of the nominal value or standard, while the loss from the producer side is voltage deviation and power losses which can cause wasted power leading to revenue reduction [3].

Voltage deviation and power losses in the distribution network can be handled in various ways such as adding distributed generation (DG) [4], [5]. DG is a small-scale power plant installed in the distribution network [6]. Power plant includes electric steam power plant, hydroelectric power plant,

gas power plant, diesel power plant, wind power plant, and nuclear power plant. The selection of the power plant is based on the location, purpose of generation, and potential of an area [1]. Diesel power plant can be added to the distribution network due to its fast response to load [7]. Adaut Village, Tanimbar Islands District, Maluku Province has a diesel power plant with a capacity of 1,200 kW, while the average hourly electricity load is 374.9 kW accumulated based on one-year data. In addition, Adaut Village has high wind potential that can be used for distributed generations namely wind turbine (WT). WT can be used to improve power quality in terms of power losses and voltage deviations.

In adding WT, the capacity and location must be determined to get good power quality in terms of power loss and voltage deviation. There are several studies on methods to determine the capacity and location of a power plant, namely analytic, classical (non-heuristic), meta-heuristic optimization, and mixed methods. The analytical method is more suitable for small and simple networks, and less suitable for large and complex networks. Then, the analytical method also does not work well if the load varies, it is more suitable to use if the load state has the same value [8]. The classical method can provide a solution even though the computational load is high. Sometimes, the solutions given are not decent because there is a convergence problem. The meta-heuristic optimization method is more suitable and works better in terms of convergence and accuracy when used on large and complex networks. The meta-heuristic optimization method can increase power quality and reduce power losses [9], [10].

The meta-heuristic optimization methods include genetic algorithm (GA), tabu search (TS), bat algorithm (BA), shuffled frog leaping algorithm (SFLA), artificial bee colony (ABC), particle swarm optimization (PSO), cuckoo search, bacterial foraging optimization, ant colony optimization, flower pollination algorithm, firefly algorithm, ant-lion optimization, oppositional krill herd optimization, intelligent water drop, and invasive weed optimization.

This research used multiple objectives, namely minimizing power losses and voltage deviations, so the authors used the non-dominated sorting genetic algorithm II (NSGA-II) based on GA model to obtain more optimal results. It was selected because it is simpler, does not require complex mathematical formulations, works well under varying load conditions, and reduces power losses [8], [11]. The test system used was the IEEE 33 bus radial distribution network with a case study of Adaut Village, Tanimbar Islands District, Maluku Province. In addition, the research also planned cost aspects. Cost calculation used levelized cost of energy (LCOE). There are other studies using LCOE in calculating the cost of WT. The study with a 2 MW WT capacity was conducted in the Catanduva region, São Paulo City, Brazil, with an LCOE value of US\$46.71/MW. While in the Birigui region, São Paulo City, Brazil, the LCOE value was US\$55.26/MW [9].

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The structure of this paper is organized as follows. Section II discusses the proposed method. Section III shows the simulation setup. Section IV discusses and analyses the simulation results. Section V describes the conclusion.

II. PROPOSED METHOD

The aim of the research is to reduce power loss and voltage deviations in the distribution network by installing WT and diesels. However, the size of the capacity and the installation location must be considered. In this research, the location and capacity of WT and diesel were optimized using NSGA-II. At the end of the research, the generation cost was calculated using the LCOE method.

A. Objective Function

This research determined the capacity and location with the aim of reducing power losses and voltage deviations in the distribution network, therefore the objective function is formulated as follows:

$$OF = \min \sum_{t=1}^T (P_{tLoss} + V_{tDi}) \quad (1)$$

with P_{tLoss} is the active power losses at time t and V_{tDi} is the deviation of voltage at time t . T is the total time and t is the index of time. The total active power losses in the distribution network can be calculated using an equation known as the "exact loss formula" written in (2).

1) *Power Loss*: The following is the formula used to calculate the power loss.

$$P_{tLoss} = \sum_{i=1}^N \sum_{j=1}^N [\alpha_{ij}(P_{ti}P_{tj} + Q_{ti}Q_{tj}) + \beta_{ij}(Q_{ti}P_{tj} - P_{ti}Q_{tj})] \quad (2)$$

$$\alpha_{ij} = \frac{r_{ij}}{v_i v_j} \cos(\delta_i - \delta_j) \quad (3)$$

$$\beta_{ij} = \frac{r_{ij}}{v_i v_j} \sin(\delta_i - \delta_j) \quad (4)$$

with α_{ij} and β_{ij} are coefficient of magnitude and phase voltage, respectively. P_{ti} dan P_{tj} are injection of active power on bus i and bus j when time t . Q_{ti} dan Q_{tj} are injection of reactive power on bus i and bus j when time t . N is number of buses. $V_i < \delta_i$ is complex voltage of bus i . Then the $r_{ij} + jx_{ij} = Z_{ij}$ is the element i - j of impedance matrix (Z bus).

If a WT was added to the distribution network, the power injection at bus i is as follows:

$$P_i = P_{Di} + P_{Li} - P_{WTi} \quad (5)$$

with P_{Li} was ignored, then:

$$P_i = P_{Di} - P_{WTi} \quad (6)$$

P_i is the power injection in line i . P_{Di} is the power demand in line i . P_{Li} is the power loss in line i . P_{WTi} is the power injection of WT in line i .

2) *Voltage Deviation*: The research observed the effect when a WT was added in terms of voltage changes on the network bus obtained through the following equation:

$$V_{tDi} = \sum_{i=1}^N |1 - V_{ti}| \quad (7)$$

where V_{tDi} is the change in the initial voltage value or the difference between the initial voltage (1 pu) and the actual voltage on bus i when time t . V_{ti} is the voltage on bus i when time t . The value of 1 indicates 1 pu, while N denotes the number of buses.

B. Constraint

1) *Voltage*: In this research, the simulation was given restraints so that the voltage from the optimization results was in the range of standard stress limits. Based on the regulation of the Minister of Energy and Mineral Resources of the Republic of Indonesia Number 20 of 2020 concerning the Regulation of the Electric Power System Network (Grid Code), the voltage standard is within the limits of +5% and -10%, so that the voltage constraints of this study are as follows:

$$V_{ti} \min < V_{ti} < V_{ti} \max \quad (8)$$

$$0.95 \text{ pu} < V_{ti} < 1.05 \text{ pu} \quad (9)$$

with V_{ti} is the voltage on bus i when time t .

2) *Capacity of Wind Turbine*: The research carried out optimization to get the minimal power losses and voltage deviation by applying the optimal value of the WT capacity. The value of the WT capacity also considers the magnitude of the load value. Here is the equation of the capacity constraint:

$$P_{\min} < P_i^{\text{capacity}} < P_{\max} \quad (10)$$

$$0 \text{ MW} < P_i^{\text{capacity}} < 4 \text{ MW}$$

with P_i^{capacity} is the active power capacity of the installed WT.

C. Load Flow Calculation

Load flow is carried out to calculate the four variables associated with nodes, namely bus voltage magnitude (V), voltage angle (δ), real power (P), and reactive power (Q) [10], [11]. In this research, load flow was calculated by Newton Raphson. The calculation began by forming an impedance matrix with the following formula:

$$Z_{ij} = R_{ij} + jX_{ij} \quad (11)$$

with Z_{ij} , R_{ij} , and jX_{ij} are the impedance, resistance, and reactance between bus i and bus j . After that, the network impedance was converted to admittance matrix:

$$Y_{ij} = Yr_{ij} + jYx_{ij} \quad (12)$$

with

$$Yr_{ij} = \frac{R_{ij}}{R_{ij}^2 + X_{ij}^2} \quad (13)$$

$$Yx_{ij} = \frac{X_{ij}}{R_{ij}^2 + X_{ij}^2} \quad (14)$$

Subsequently, the Y bus admittance matrix was formed with components consisting of network admittance, line capacitance, and transformer tapping change. The Y bus admittance matrix

formed in rectangular form was converted into polar form, where, previously, the Y bus admittance matrix was separated into components of the G matrix and the B matrix. The scheduled power on each bus could be calculated using (15) and (16).

$$P_i^{jd} = P_{Gi} - P_{Li} \quad (15)$$

$$Q_i^{jd} = Q_{Gi} - Q_{Li} \quad (16)$$

with P_i^{jd} and Q_i^{jd} are the active and reactive scheduled power, respectively. P_{Gi} and Q_{Gi} are the active and reactive power generation. P_{Li} and Q_{Li} are active and reactive power demand. Iteration process by Newton Raphson was looking for calculated power using (17) and (18).

$$P_i = \sum_{n=1}^N |Y_{in} V_i V_n| \cos(\theta_{in} + \delta_n - \delta_i) \quad (17)$$

$$Q_i = -\sum_{n=1}^N |Y_{in} V_i V_n| \sin(\theta_{in} + \delta_n - \delta_i) \quad (18)$$

with P_i and Q_i are the active and reactive power calculated. V_i and θ_i are the voltage magnitude and phase angle on bus i , meanwhile V_j and θ_j are the magnitude and phase angle on bus j . Y_{in} and θ_{in} are the magnitude and phase angle of admittance matrix element Y . Then, the power mismatch, which was the difference between the scheduled power and the calculated power, could be obtained using the following equations:

$$\Delta P_i = P_i^{jd} - P_i^{hit} \quad (19)$$

$$\Delta Q_i = Q_i^{jd} - Q_i^{hit} \quad (20)$$

with ΔP_i and ΔQ_i are the active and reactive power mismatch on bus i . After the power mismatch value was obtained, then a Jacobian matrix was formed, as shown in (21).

$$J = \begin{bmatrix} \frac{\partial P_2}{\partial \delta_2} & \dots & \frac{\partial P_2}{\partial \delta_n} |V_2| \frac{\partial P_2}{\partial |V_2|} & \dots & |V_n| \frac{\partial P_2}{\partial |V_n|} \\ \vdots & H = J_1 & \vdots & \vdots & N = J_2 \\ \frac{\partial P_n}{\partial \delta_2} & \dots & \frac{\partial P_n}{\partial \delta_n} |V_2| \frac{\partial P_n}{\partial |V_2|} & \dots & |V_n| \frac{\partial P_n}{\partial |V_n|} \\ \frac{\partial Q_2}{\partial \delta_2} & \dots & \frac{\partial Q_2}{\partial \delta_n} |V_2| \frac{\partial Q_2}{\partial |V_2|} & \dots & |V_2| \frac{\partial Q_2}{\partial |V_2|} \\ \vdots & M = J_3 & \vdots & \vdots & L = J_4 \\ \frac{\partial Q_n}{\partial \delta_2} & \dots & \frac{\partial Q_n}{\partial \delta_n} |V_2| \frac{\partial Q_n}{\partial |V_2|} & \dots & |V_n| \frac{\partial Q_n}{\partial |V_n|} \end{bmatrix} \quad (21)$$

The Jacobian matrix consists of four submatrixes, namely the H , N , M , and L submatrixes which can be expressed by other names, namely J_1 , J_2 , J_3 , and J_4 . The submatrix J_1 or H can be calculated by the following equation: calculation for off diagonal component and diagonal component in (22) and (23).

$$\frac{\partial P_i}{\partial \delta_j} = -|V_i V_j Y_{ij}| \sin(\theta_{ij} + \delta_j - \delta_i) \quad (22)$$

$$\frac{\partial P_i}{\partial \delta_j} = \sum_{n=1, n \neq i}^N |V_i V_n Y_{in}| \sin(\theta_{in} + \delta_n - \delta_i). \quad (23)$$

Then, the diagonal component was compared with Q_i^{hit} so that it obtained the following equation.

$$\frac{\partial P_i}{\partial \delta_j} = -Q_i - |V_i|^2 B_{ii} \quad (24)$$

The submatrix J_3 or M can be calculated by the following equation: calculation for off diagonal component and diagonal component in (25) and (26).

$$\frac{\partial Q_i}{\partial \delta_j} = -|V_i V_j Y_{ij}| \cos(\theta_{ij} + \delta_j - \delta_i) \quad (25)$$

$$\frac{\partial Q_i}{\partial \delta_i} = \sum_{n=1, n \neq i}^N |V_i V_j Y_{ij}| \cos(\theta_{ij} + \delta_j - \delta_i) = \sum_{n=1, n \neq i}^N \frac{\partial Q_i}{\partial \delta_n}. \quad (26)$$

The diagonal component of J_3 or M was then compared with P_i^{hit} so that it obtained (27).

$$\frac{\partial Q_i}{\partial \delta_i} = P_i - |V_i|^2 G_{ii}. \quad (27)$$

The submatrix J_2 or N can be calculated by the following equation: calculation for off diagonal component and diagonal component in (28) and (29).

$$|V_j| \frac{\partial P_i}{\partial |V_j|} = |V_j| |V_i Y_{ij}| \cos(\theta_{ij} + \delta_j - \delta_i) \quad (28)$$

$$|V_i| \frac{\partial P_i}{\partial |V_i|} = \frac{\partial Q_i}{\partial \delta_i} + 2|V_i|^2 G_{ii} = P_i + |V_i|^2 G_{ii}. \quad (29)$$

The submatrix J_4 or L can be calculated by the following equation: calculation for off diagonal component and diagonal component in (30) and (31).

$$|V_j| \frac{\partial Q_i}{\partial |V_j|} = -|V_j| |V_i Y_{ij}| \sin(\theta_{ij} + \delta_j - \delta_i) = \frac{\partial P_i}{\partial \delta_j} \quad (30)$$

$$|V_i| \frac{\partial Q_i}{\partial |V_i|} = -\frac{\partial P_i}{\partial \delta_i} - 2|V_i|^2 B_{ii} = Q_i - |V_i|^2 B_{ii} \quad (31)$$

with $\frac{\partial P_i}{\partial \delta_i}$ and $\frac{\partial P_i}{\partial \delta_j}$ are the elements of the J_1 submatrix or H . $\frac{\partial P_i}{\partial \delta_j}$ and $\frac{\partial Q_i}{\partial \delta_i}$ are the elements of the J_3 submatrix or M . $|V_j| \frac{\partial P_i}{\partial |V_j|}$ and $|V_i| \frac{\partial P_i}{\partial |V_i|}$ are the elements of the J_2 submatrix or N . $|V_j| \frac{\partial Q_i}{\partial |V_j|}$ and $|V_i| \frac{\partial Q_i}{\partial |V_i|}$ are the elements of the J_4 submatrix or L . V_i and θ_i are the voltage magnitude and phase angle on the bus i . V_j and θ_j are the voltage magnitude and phase angle on the bus j . P_i and Q_i are active and reactive power on the bus i . Y_{in} and θ_{in} are the magnitude and phase angle admittance on the bus i to n . G_{ii} and B_{ii} are the conductance and susceptance on the bus i .

After obtaining the results of the calculation of each element in the Jacobian submatrix, then the Jacobian matrix was formed by combining four Jacobian submatrixes so that the power flow equation was formed, as in (32).

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & N \\ J & L \end{bmatrix} \begin{bmatrix} \frac{\Delta \delta}{|V|} \\ \frac{\Delta |V|}{|V|} \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \frac{\Delta \delta}{|V|} \\ \frac{\Delta |V|}{|V|} \end{bmatrix} \quad (32)$$

The Jacobian matrix formed was then inverted. Next, the phase angle and voltage magnitude values on each bus were recalculated or updated using the following equation:

$$\begin{bmatrix} \Delta \delta_2 \\ \vdots \\ \Delta \delta_n \\ \frac{\Delta |V_2|}{|V_2|} \\ \vdots \\ \frac{\Delta |V_n|}{|V_n|} \end{bmatrix} \begin{bmatrix} \frac{\partial P_2}{\partial \delta_2} & \dots & \frac{\partial P_2}{\partial \delta_n} |V_2| \frac{\partial P_2}{\partial |V_2|} & \dots & |V_n| \frac{\partial P_2}{\partial |V_n|} \\ \vdots & H = J_1 & \vdots & \vdots & N = J_2 \\ \frac{\partial P_n}{\partial \delta_2} & \dots & \frac{\partial P_n}{\partial \delta_n} |V_2| \frac{\partial P_n}{\partial |V_2|} & \dots & |V_n| \frac{\partial P_n}{\partial |V_n|} \\ \frac{\partial Q_2}{\partial \delta_2} & \dots & \frac{\partial Q_2}{\partial \delta_n} |V_2| \frac{\partial Q_2}{\partial |V_2|} & \dots & |V_2| \frac{\partial Q_2}{\partial |V_2|} \\ \vdots & M = J_3 & \vdots & \vdots & L = J_4 \\ \frac{\partial Q_n}{\partial \delta_2} & \dots & \frac{\partial Q_n}{\partial \delta_n} |V_2| \frac{\partial Q_n}{\partial |V_2|} & \dots & |V_n| \frac{\partial Q_n}{\partial |V_n|} \end{bmatrix}^{-1} \begin{bmatrix} \Delta P_2 \\ \vdots \\ \Delta P_n \\ \Delta Q_2 \\ \vdots \\ \Delta Q_n \end{bmatrix} \quad (33)$$

The results of the multiplication were then separated and the change in the phase angle of the voltage and the bus voltage i could be calculated as in (34) and (35).

$$\Delta\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^k \quad (34)$$

$$\begin{aligned} |V_i|^{(k+1)} &= |V_i|^{(k)} + \Delta|V_i|^{(k)} \\ &= |V_i|^{(k)} \left(1 + \frac{\Delta|V_i|^{(k)}}{|V_i|^{(k)}}\right) \end{aligned} \quad (35)$$

with $\partial\delta_i$ is the change in phase angle voltage on the bus i and $\Delta|V_i|$ is the change in voltage magnitude or voltage deviation on the bus i .

The difference or change in the value of the phase angle and the magnitude of the voltage between the old and the new was then compared with the predetermined accuracy value. If the accuracy value had not been reached, then it was continuously iterated until the accuracy value was obtained and converged. After convergence was obtained, the power on the slack bus was calculated using the following equation:

$$P_i = \sum_{n=1}^N |Y_{in} V_i V_n| \cos(\theta_{in} + \delta_n - \delta_i) \quad (36)$$

$$Q_i = \sum_{n=1}^N |Y_{in} V_i V_n| \sin(\theta_{in} + \delta_n - \delta_i) \quad (37)$$

with P_i and Q_i are the active and reactive power on the slack bus. Then, the power flow between buses could be calculated using the following equation:

$$S_{ij} = V_i (V_{ij}^* Y_{ij}^* + V_i^* Y_{cij}^*) \quad (38)$$

$$P_{ij} - jQ_{ij} = V_i^* (V_i - V_j) Y_{ij} + V_i^* V_i Y_{cij} \quad (39)$$

with S_{ij} , P_{ij} , Q_{ij} are the complex, active, and reactive power flow from bus i to bus j . V_i and V_j are the voltage vector on the bus i and j . V_{ij} , Y_{ij} , and Y_{cij} are the voltage vector, admittance, and admittance line charging between bus i and bus j .

Calculation of power flow could determine the value of the power losses on the network. Power losses between buses could be calculated using the following equation:

$$S_{ij}(losses) = S_{ij} + S_{ji} \quad (40)$$

with $S_{ij}(losses)$ is the complex power losses from bus i to bus j . S_{ij} is the complex power from bus i to bus j . Meanwhile, S_{ji} is the complex power from bus j to bus i .

D. Non-Dominated Sorting Genetic Algorithm II

NSGA-II is a method used to solve a value search in an optimization problem. This method was developed based on a GA that uses the principles of genetics and the natural selection process of Darwin's evolution theory. The development of generations in natural populations follows the principle of "only the strong survives" natural selection. The GA can be used to find solutions to real-world problems by imitating the theory of evolution [12].

In this research, the capacity and location of WT were determined with the aim of reducing power losses and voltage deviations using the NSGA-II based on the GA. The method was chosen as it is simpler, does not require complex mathematical formulations, works well under varying load conditions, and is able to reduce power losses [13], [14]. This research used a population value of 100, iteration of 200, crossover probability of 0.8, and mutation probability of 0.3.

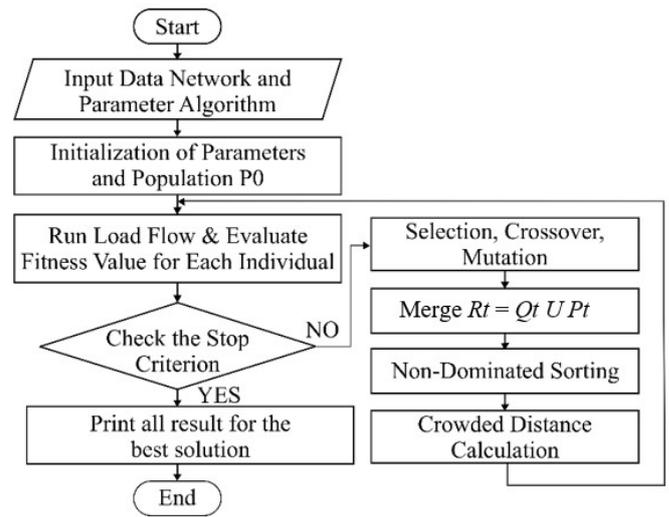


Fig. 1 Optimization method stages.

Based on Fig. 1, the process of the proposed method is as follows:

1. Input network data (line data, bus data, load, and wind speed) and algorithm parameters (population number, number of chromosomes or individuals, crossover, and mutation probabilities).
2. Initialization of parameter and population. Generate initial population P_0 or generation $t = 0$.

$$P_0 = [x_1 \ x_2 \ x_{N_{pop}}] \quad (41)$$

$$x_i = [WT_{loc} \ WT_{size}] \quad (42)$$

with x_i is an individual.

$$WT_{loc} = [\text{randsrc}(1, \text{no_of_wt}, \text{minval1}:\text{maxval1})]$$

$$WT_{size} = [\text{randsrc}(1, \text{no_of_wt}, \text{minval2}:\text{maxval2})]$$

with minval1 and maxval1 are bus 1 and bus 33, while minval2 and maxval2 are 0 and 4 MW. The randsrc means the random number is uniformly distributed.

3. The new individuals then form the parent population at time t (P_t). Then, load flow for each individual is executed in P_t with the Newton Raphson. The fitness value is then evaluated by (1).
4. Generating the first offspring population. After that, check the constraints of load flow analysis and max generation. If the constraints are met, proceed to the next step, otherwise add a penalty term to the objective function.
5. Generating first offspring (Q_t) formed by selection, crossover, and mutation.
6. Combining the first offspring population (Q_t) and the parent population (P_t) into R_t .

$$R_t = Q_t \cup P_t \quad (43)$$

7. On the R_t , non-dominated sorting is then carried out by sorting the minimum objective function (OF) results. The highest-ranking is with the largest minimum OF.
8. A new population of P_{t+1} is formed in the N_{pop} population which is added from the ranking results. After that, a calculation based on the crowded distance

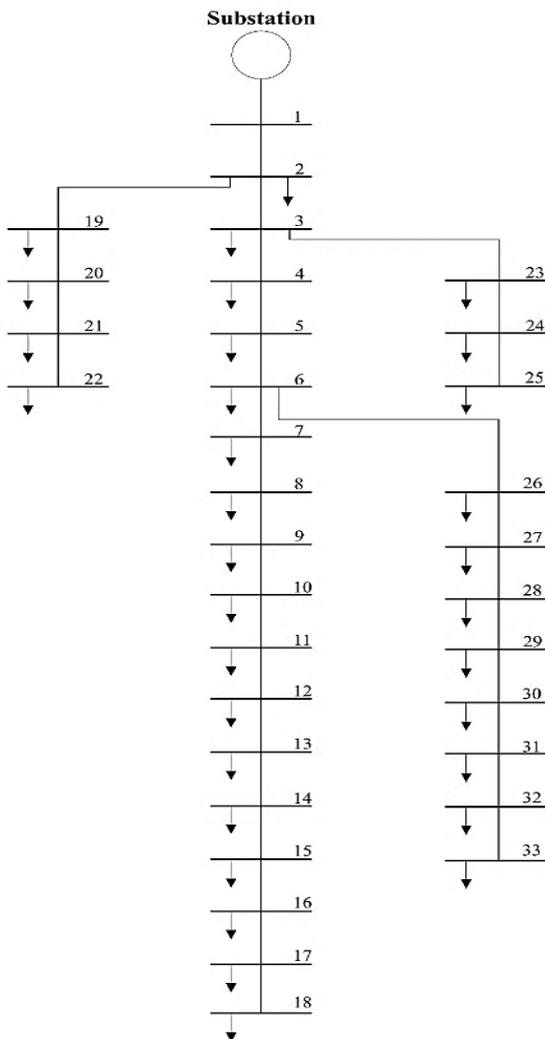


Fig. 2 IEEE 33 bus system.

is applied with a certain size limit. The greater the value of the crowded distance is better.

9. Looping or repetition of steps three to eight until it reaches the maximum population.
10. Getting the best results with the capacity and location of WT minimizing power losses and voltage deviations.

E. Economic Aspect

The economic aspect in this study was calculated to determine the recommended selling price of electricity when the minimum power losses and voltage deviations were reached. The cost of generating diesel and WT in the distribution network can be calculated using the LCOE. LCOE is the main cost of energy production so that the economic aspect of the distribution network can be analyzed. LCOE is the sum of investment costs, operation and maintenance costs, and fuel costs. The formula is shown in (44) obtained from (45)-(48).

$$\text{LCOE (\$/MWh)} = \frac{\text{FPM} \times \text{Cost}}{\text{Avail} \times 8,760} + \frac{\text{OM}}{\text{Avail} \times 8,760} + \frac{0,860 \times \text{BBB}}{\text{Eff}} \quad (44)$$

$$\text{FPM} = \frac{d \times (1+d)^{\text{Tekonom}}}{(1+d)^{\text{Tekonom}} - 1} \quad (45)$$

TABLE I
DATA BUS AND LINE DATA

Bus	P (kW)	Q (kVar)	From Bus-	To Bus-	R (Ohm)	X (Ohm)
1	0	0	1	2	0.0922	0.0470
2	100	60	2	3	0.4930	0.2511
3	90	40	3	4	0.3660	0.1864
4	120	80	4	5	0.3811	0.1941
5	60	30	5	6	0.8190	0.7070
6	60	20	6	7	0.1872	0.6188
7	200	100	7	8	0.7114	0.2351
8	200	100	8	9	1.0300	0.7400
9	60	20	9	10	1.0440	0.7400
10	60	20	10	11	0.1966	0.0650
11	45	30	11	12	0.3744	0.1238
12	60	35	12	13	1.4680	1.1550
13	60	35	13	14	0.5416	0.7129
14	120	80	14	15	0.5910	0.5260
15	60	10	15	16	0.7463	0.5450
16	60	20	16	17	1.2890	1.7210
17	60	20	17	18	0.7320	0.5740
18	90	40	2	19	0.1640	0.1565
19	90	40	19	20	1.5042	1.3554
20	90	40	20	21	0.4095	0.4784
21	90	40	21	22	0.7089	0.9373
22	90	40	3	23	0.4512	0.3083
23	90	50	23	24	0.8980	0.7091
24	420	200	24	25	0.8960	0.7011
25	420	200	6	26	0.2030	0.1034
26	60	25	26	27	0.2842	0.1447
27	60	25	27	28	1.0590	0.9337
28	60	20	28	29	0.8042	0.7006
29	120	70	29	30	0.5075	0.2585
30	200	600	30	31	0.9744	0.9630
31	150	70	31	32	0.3105	0.3619
32	210	100	32	33	0.3410	0.5302
33	60	40				

$$\text{Cost} = \text{FdLC} \times \text{LC} \quad (46)$$

$$\text{FdLC} = \sum_{i=1}^{\text{Tkonstr}} (\text{DisLC}_i \times (1+d)^{\text{Tkonstr}-i+0.5}) \quad (47)$$

$$\text{Avail} = \frac{\text{Av}}{100} \text{ or } \text{Avail} = 1 - \frac{\text{FO}}{100} - \frac{\text{SO}}{52} \quad (48)$$

with Av is the availability factor (%). Eff is the thermal efficiency (%). FO and SO are the force and scheduled outages (%). $Tekonom$ is the economic life (years). $Tkonstr$ is the development time (years). LC is the investment cost (US \$/kW). OM is the operation and maintenance cost (US \$/kW). BBB is the fuel cost (US\$/106 kcal). Variable d and DLC are the discount rate (%) and disbursement (%). The calculation parameters were obtained from the official publication of the Ministry of Energy and Mineral Resources [15].

III. SIMULATION SETUP

A. Test System

The test system used an IEEE 33 bus radial distribution whose topology and network data are shown in Fig. 2 and Table I. The simulation was carried out using MATLAB.

TABLE II
LOAD PROFILE OF THE ADAUT VILLAGE

Time	P (kW)	Q (kVar)
01:00 AM	406.9444	252.2015
02:00 AM	406.9444	252.2015
03:00 AM	405.5556	251.3408
04:00 AM	413.8889	256.5053
05:00 AM	409.7222	253.9230
06:00 AM	377.7778	234.1256
07:00 AM	358.3333	222.0751
08:00 AM	336.1111	208.3030
09:00 AM	316.6667	196.2524
10:00 AM	294.4444	182.4803
11:00 AM	270.8333	167.8474
12:00 PM	295.8333	183.3410
01:00 PM	315.2778	195.3916
02:00 PM	336.1111	208.3030
03:00 PM	358.3333	222.0751
04:00 PM	377.7778	234.1256
05:00 PM	419.4444	259.9483
06:00 PM	418.0556	259.0876
07:00 PM	416.6667	258.2268
08:00 PM	415.2778	257.3660
09:00 PM	411.1111	254.7838
10:00 PM	415.2778	257.3660
11:00 PM	409.7222	253.9230
12:00 AM	412.5000	255.6445

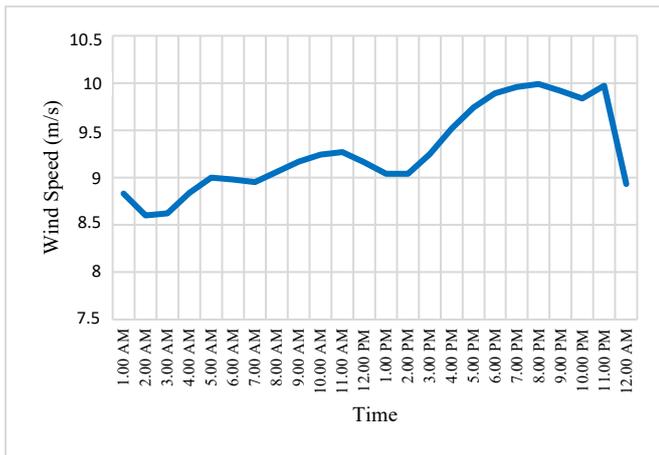


Fig. 3 Wind speed.

B. Case Study

Adaut Village, Tanimbar Islands Regency, Maluku Province was the case study used in this research. The Adaut Village load profile pattern was applied to each bus of IEEE 33 bus radial distribution that is shown in Table II which peak demand is at 05:00 PM with 419.4444 MW.

Previously, diesels were installed with a capacity of 200 kW, 250 kW, 250 kW, 250 kW or a total of 1,200 kW. The electricity production can be increased by utilizing wind potential there whose speed is shown in Fig. 3.

IV. RESULT AND DISCUSSION

This research was carried out with four scenarios, namely with the addition of 1 WT, 2 WT, 3 WT, and 4 WT scenarios.

TABLE III
THE CAPACITY AND LOCATION OF WT

Scenarios	Size (kW)	Location (Bus)
1 WT	709.98	18
2 WT	395.99	11
	611.19	18
3 WT	232.47	15
	254.24	18
	620.80	30
4 WT	1.38	2
	422.43	15
	834.33	30
	380.81	31

TABLE IV
COMPARISON OF ACTIVE POWER LOSSES

Time	Active Power Losses (kW)				
	Without WT	1 WT	2 WT	3 WT	4 WT
01:00 AM	194.910	109.67	89.680	72.669	41.914
02:00 AM	194.910	109.67	89.680	72.669	41.914
03:00 AM	193.494	108.69	88.813	71.880	41.383
04:00 AM	202.083	114.65	94.093	76.690	44.637
05:00 AM	181.749	102.53	83.109	66.731	38.956
06:00 AM	166.376	90.17	72.515	57.121	31.720
07:00 AM	148.753	78.40	62.279	47.936	26.023
08:00 AM	129.949	66.15	51.738	38.571	20.568
09:00 AM	114.641	56.44	43.508	31.350	16.701
10:00 AM	98.429	46.50	35.218	24.187	13.301
11:00 AM	82.671	37.24	27.686	17.827	10.857
12:00 PM	99.403	47.08	35.701	24.601	13.482
01:00 PM	113.588	55.79	42.956	30.868	16.457
02:00 PM	129.949	66.15	51.738	38.571	20.568
03:00 PM	148.753	78.40	62.279	47.936	26.023
04:00 PM	166.376	90.17	72.515	57.121	31.720
05:00 PM	207.927	118.72	97.715	79.996	46.899
06:00 PM	206.457	117.70	96.802	79.162	46.327
07:00 PM	204.668	116.43	95.667	78.124	45.599
08:00 PM	203.535	115.66	94.991	77.509	45.196
09:00 PM	199.196	112.64	92.313	75.067	43.534
10:00 PM	203.535	115.66	94.991	77.509	45.196
11:00 PM	197.762	111.65	91.430	74.263	42.989
12:00 AM	200.636	113.64	93.200	75.876	44.083
Total	3,989.750	2,179.80	1,760.600	1,394.200	796.050
Round	4,000.000	2,200.00	1,800.000	1,400.000	800.000

NSGA-II obtained the best result in which power losses and voltage deviations were significantly decreased which capacity and location of WT is shown in Table III.

C. Power Losses

The power losses in the scenario of adding 1 WT decreased by 45.4%, the scenario of adding 2 WT decreased by 56%, the scenario of adding 3 WT decreased by 65%, and the scenario of adding 4 WT decreased by 80%. Table IV shows the comparison of active power losses in each scenario.

D. Voltage Deviation

The effect of voltage deviation on the distribution network in the initial condition scenario, 1 WT, 2 WT, 3 WT, and 4 WT was observed in 24-hours simulation. Fig. 4 shows the

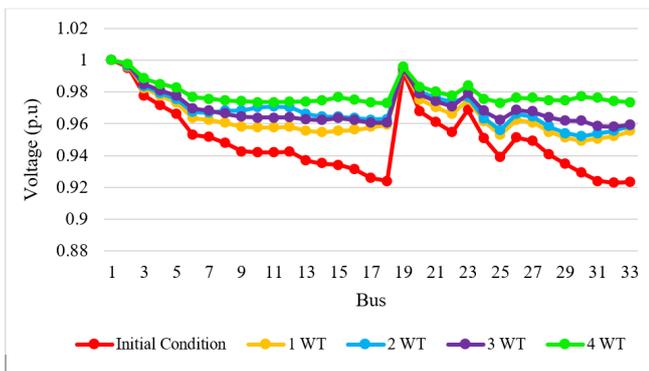


Fig. 4 Voltage profile.

TABLE V
LCOE BASED ON THE SCENARIO

Scenarios	Generation	Capacity (kW)	LCOE (\$cents/kWh)	LCOE (Rp/kWh)
I	Diesel	1,200	43.9539	6,181.87
	1 WT	800	4.0170	564.95
	Total		47.9709	6,746.82
II	Diesel	1,200	43.9539	6,181.87
	2 WT	400	1.8700	263.01
		750	5.5500	780.58
Total		51.3739	7225.46	
III	Diesel	1,200	43.9539	6,181.87
	3 WT	235	2.6900	378.33
		300	1.0380	145.99
		750	5.5500	780.58
Total		53.2319	7,486.77	
IV	Diesel	1,200	43.9539	6,181.87
	4 WT	2	0.0166	2.33
		400	1.8700	263.01
		450	2.1700	305.20
		1,000	2.5650	360.74
Total		50.5755	7,113.15	

occurrence of an increase in voltage where in scenario 4 WT get the best voltage profile. The increase in voltage is close to the nominal voltage of 1 pu so as to minimize voltage deviations. At the peak load hours at 05.00 PM, it can be observed that the best voltage improvement is obtained on Bus 32, which is from 0.92399 and increases to 0.9731. It means that voltage deviation can be minimized to 0.0269.

E. Economic Aspect

The cost of generating diesel and WT in the distribution network has been calculated using the LCOE. The location and capacity obtained from the optimization results and LCOE calculations are shown in Table V. The capacity used is rounded up before calculating using LCOE.

V. CONCLUSION

The research applied an optimization technique for determining the capacity and location of WT using NSGA-II

with an objective function of power losses and voltage deviation. The best results were obtained in scenario IV: 1.38 kW on Bus 2, 422.43 kW on Bus 15, 834.33 kW on Bus 30, and 380.81 kW on Bus 31 which can reduce power losses by 80% and minimum deviation voltage was 0.0269 with an LCOE value of Rp7,113.15/kWh.

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