Optimal Placement of Distributed Generation Using Analytical Approach to Minimize Losses in a University

Pisey Heng, Unchittha Prasatsap, Jirawadee Polprasert, and Suwit Kiravittaya*

Abstract— *This paper presents an analytical approach to determine the optimal location and size of distributed generation (DG) in the electrical distribution system of Naresuan University (NU). Based on available data of the system, the single line diagram is first drawn and line impedances among buses are estimated. The latter values are calculated based on the distance between bus locations and the electrical conductor characteristics. According to the power transformer rates and the maximum total load of the NU system (13.60 MW), the load consumptions of all main loads connected to the NU buses can be assumed. The optimal size and location of DG have been determined to minimize the transmission losses in the system. Placement of a photovoltaic source known as type-I DG has been considered for injecting the real power into the system. The analytical approach is based on the exact loss formula. The effects of optimal size and location of DG are considered and examined in detail in order to find minimum losses at various bus locations. The results show that the proposed analytical approach can reduce the transmission loss to 17.65 kW at the optimum size of DG of 7.58 MW at the bus no. 13, which is located near the main load (the NU hospital). This work enhances our understanding of the current system performance and allows us to plan for future improvement of the distribution system.*

Keywords— **Distributed Generation, Type-I DG, Exact Loss Formula, Loss Reduction.**

1. INTRODUCTION

In any electrical power distribution systems, the transmission loss is one of the major losses in the system. Engineers, who design the system, must consider it by forecasting the load and suitably placing the transformer/bus in the distribution system. For an existing system, this transmission loss is typically increased due to the monotonically increase of the electricity demand. Concept of distributed generation (DG) system has been introduced in order to reduce this loss and optimization techniques come to play an important role. Typically, DG is an electric power source connected directly to the distribution network or to the end customer [1]. DG is also referred as Dispersed Generation or Embedded Generation or Decentralized Generation. DG can be classified as a new technology, which is economical and gives operational benefits comparing with traditional large generators in power distribution networks [2]. Due to the economic reasons, the optimal allocation of DG is an interesting research area in a radial distribution system [3]. DG can be categorized into four major types [4] on the basis of their terminal characteristics. Normally, DG can be classified according to its sizes those are Micro, Small, Medium, and Large DGs [1]. Many former studies have indicated that the proper location and size of DG are very important factor for reducing loss in a distribution system [5, 6, 7]. Otherwise, the improper location and size of DG would lead to a higher loss even higher than the loss in the case of no DG installation [8]. For optimum allocation of DG can be provided the advantages such as reduction in the system losses, improvement of voltage regulation, and enhancement of supply reliability [9,10]. In this work, we consider the 22-kV electrical distribution system of Naresuan University (NU). A placement of single type-I DG known as photovoltaic DG has been considered. Single line diagram with the system parameters is first estimated. An analytical approach [11, 12] is applied to determine the optimal size and location of DG.

2. CHARACTERISTICS OF ELECTRICAL DISTRIBUTION SYSTEM OF NU

2.1 The Investigated System

The NU campus is located at Tambon Tha Pho, Amphoe Muang Phitsanulok, Phitsanulok province. It is in the lower North of Thailand (latitude of 16.7386 and longitude of 100.1947). The main NU substation is in the NU campus and it receives electrical power from the main grid of Provincial Electricity Authority (PEA) of Thailand. Two power lines of PEA main grid, which are the transmission system (voltage rate of 115 kV) and the distribution system (voltage rate of 22 kV), are connected to the power lines of NU system at the NU substation. The voltage rate 115 kV is reduced to 22 kV in the NU substation. In the NU power system has two main feeders to transfer power (voltage rate 22 kV) to all 3-phase 22 kV-to-380 V transformers in the university. The electric power system is supplied to 47 loads, which

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are mostly the main buildings of the university. Figure 1 shows a map of NU together with the location of NU substation and the location of the step-down transformers in the feeder no. 1. This feeder is the main feeder for the load in the university. Note that the hospital is also located inside the university and requires about 40% of the total electrical load energy. Singe line diagram of the NU system is extracted from the available data [13,14] and shown in Fig. 2. We consider only the feeder no. 1 because of it is the main feeder. The placement of DG will not be affected by the feeder no. 2 because of the star topology of the system. For extracting the line impedances, the distances between each transformer/bus are measured. The line impedances are listed in the Appendix. The values of the impedance are calculated based on the distance between the bus locations and the electrical conductor characteristics as stated in the Appendix.

2.2 *Estimated Load Consumption*

For the NU electrical power system, it has a total maximum load power of 13.6 MW in 2016 [13,14]. As mentioned previously, the high demand load known as the NU hospital is located in the feeder no. 1. According to the maximum load consumption of the NU power system, we can estimate the distribution of the total demand load for all main buildings in the feeder no. 1. The estimation of total maximum load in the feeder is 9.39 MW. For demand load distribution, the loads are distributed based on the capacity of each transformers at various bus locations. Due to the existing capacity of these transformers are large, so the total loads are estimated with the extension factor and simultaneous factor in this calculation. In order to obtain the total demand loads which are approximated to the total maximum load, we initially assume the values of both factors to be 0.6 for all main buildings. Due to the fact that majority of the NU load is inductive load (air-conditioning system), the lagging power factor of 0.8 is assumed [15].

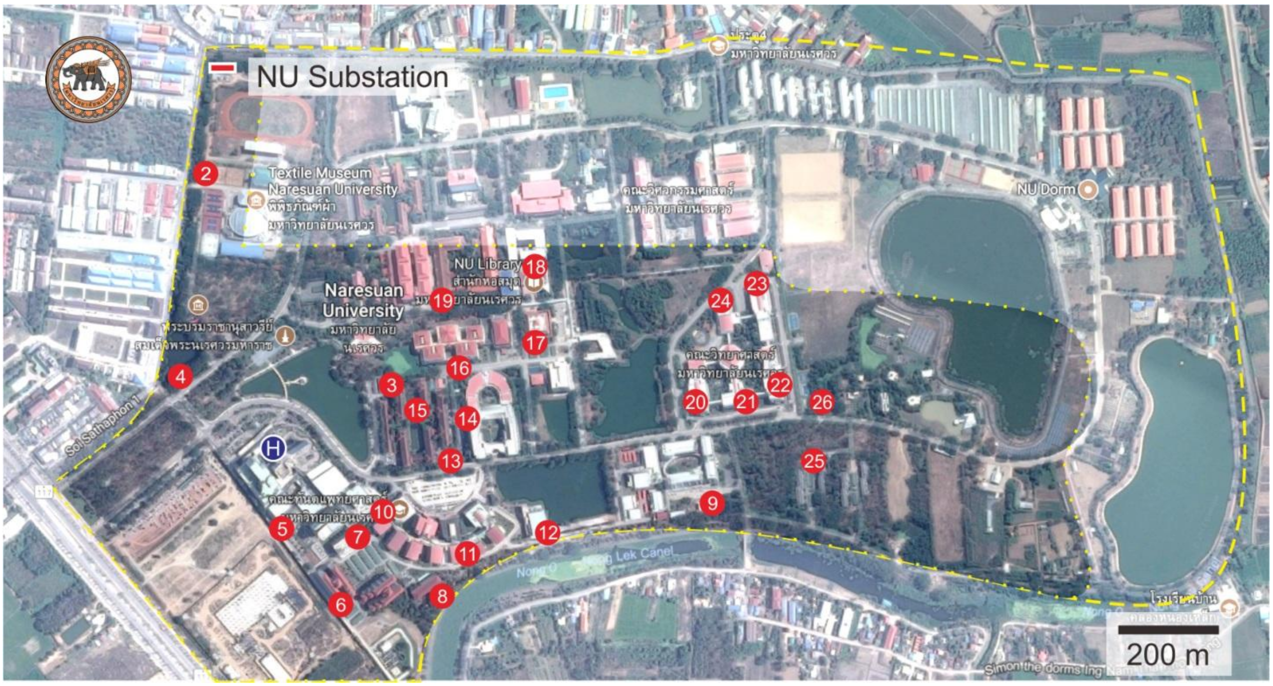

Fig. 1 Map of Naresuan university (NU). The NU substation and the location of the transformers of the feeder no. 1 are marked as a red rectangle and red circles, respectively. The bus numbers are labeled by the numbers. The location of NU hospital is marked by H.

3. METHODOLOGY

3.1 *Problem Formulation*

Minimization of power losses by placing optimal size and location of DG are investigated using analytical approach. The analytical approach is based on exact loss formula [11,12]. The real power loss in a distribution system is given by:

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\alpha_{ij}\left(P_iP_j + Q_iQ_j\right) + \beta_{ij}\left(Q_iP_j - P_iQ_j\right)\right] \tag{1}$$

where $\alpha_{ij} = \dfrac{R_{ij}}{|V_iV_j|}\cos\left(\delta_i - \delta_j\right)$, (2)

$$\beta_{ij} = \frac{R_{ij}}{|V_iV_j|}\sin\left(\delta_i - \delta_j\right), \tag{3}$$

and $Z_{ij} = R_{ij} + jX_{ij}$. (4)

P_i (P_j) is the real power injected at the i^{th} (j^{th}) bus. Q_i (Q_j) is the reactive power injected at the i^{th} (j^{th}) bus. Z_{ij} is the impedance of the line between the i^{th} and j^{th} bus. V_i (V_j)

and δ_i (δ_j) are the voltage magnitude and phase angle at the i^{th} (j^{th}) bus and N is the number of buses in the feeder (= 26). The problem is subjected to the power balance constraint:

$$\sum_{i=1}^{N} P_{DG,i} = \sum_{i=1}^{N} P_{D,i} + P_L \tag{5}$$

and the voltage constraint:

$$V_i^{\min} \le V_i \le V_i^{\max},\ i = 1,2,3,...,N\ , \tag{6}$$

where $P_{DG,i}$ is the real power injection from all DGs, $P_{D,i}$ is the load demand at the i^{th} bus, $V_i^{\min}$ and $V_i^{\max}$ are minimum and maximum voltage limit of the i^{th} bus. In this work, the voltage constraint (Eq. (6)) plays no role due to the small system size.

3.2 Optimum Size of DG

The exact loss formula given in Eq. (1) is considered. The total power loss of the system is minimum if the partial derivative of Eq. (1) with respect to the injected power P_i from DG at the i^{th} bus equals zero [11], i.e.,

$$\frac{\partial P_L}{\partial P_i} = 2\sum_{j=1}^{N}\left(\alpha_{ij}P_j - \beta_{ij}Q_j\right) = 0 \tag{7}$$

It follows that:

$$P_i = -\frac{1}{\alpha_{ii}}\left[\sum_{j=1, j\neq i}^{N}\left(\alpha_{ij}P_j - \beta_{ij}Q_j\right)\right], \tag{8}$$

where P_i is the real power injection at the i^{th} bus. The difference between real power generation and the real power demand is also P_i and it can be determined as follows:

$$P_i = P_{DG,i} - P_{D,i}\ , \tag{9}$$

where $P_{DG,i}$ is the real power injection from DG placed at the i^{th} bus, and $P_{D,i}$ is the load demand at the i^{th} bus.
From Eq. (9), P_{DGi} can be determined as follows:

$$P_{DG,i} = P_{D,i} - \frac{1}{\alpha_{ii}}\left[\sum_{\substack{j=1\\ j\neq i}}^{N}\left(\alpha_{ij}P_j - \beta_{ij}Q_j\right)\right] \tag{10}$$

The Eq. (10) gives the optimal size of DG at each bus [4]. If the type-I DG is placed at the i^{th} bus and it gives the minimum loss compared to the case that the same type of DG is placed at any other bus, then the i^{th} bus is the optimal location for placing the optimal type-I DG.

3.3 Computational Procedure

The computational procedure to find the optimal location and size of single DG using the analytical approach is described below.

Step 1: Run the base case load flow.

Step 2: Find the base case total power loss using Eq. (1)

Step 3: Find the optimum size of DG for each bus location using Eq. (10).

Step 4: Place the optimum DG size at each bus and calculate the loss using Eq. (1).

Step 5: After DG placement, the optimal bus locates at a minimum loss. This is optimal location for DG installation.

Step 6: Run load flow with the optimal DG size to obtain final result.

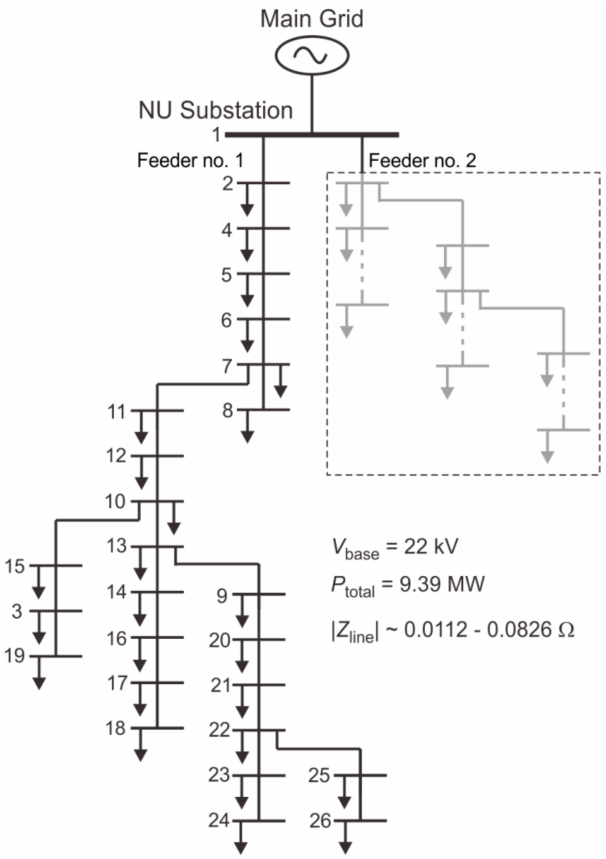

Fig. 2 Single line diagram of the NU power system.

4. RESULTS AND DISCUSSION

The analysis is carried out on the NU power system and it has a total estimated load of 9.39 MW and 7.04 Mvar (for the feeder no. 1). Due to the small system size, the computational results can easily be obtained from this analytical approach. However, this method might not be applicable to large scale system. According to the analytical approach [11], the optimum size of DGs are determined at various bus locations. Figure 3 shows the minimum transmission loss and the optimum DG size at the various bus locations when the optimal single DG is installed. Based on the load power and the impedance values, the estimated loss is 42.06 kW (without DG installation). For the solution shown in Fig. 3, we observed that the losses reduction can be reduced if the optimal DGs placement are placed at the appropriate bus locations. In addition, we also found that the reduced losses depend on the capacity of the DGs. In order to reduce the loss, a placement of single type-I DG is considered. The optimum size of DGs is identified at the various bus locations based on the minimum losses. Minimum losses and optimum DG size can be calculated and the latter is ranging from 4.65 to 9.43 MW. The minimum power loss is obtained when the DG size with optimal size is installed at the optimum location. The minimum loss is ~17.65 kW when the optimal DG size of 7.58 MW is installed at the bus no. 13 for our bus topology. The loss is reduced by 58% when the optimal DG is installed. The second suitable location is bus no. 10. It gives slightly higher total power loss as shown in Fig. 3(a). As observed in Figs. 3 (a) & (b), the results yield that the optimal DGs size at the various bus locations. They play an important role in reduction of the system loss. The proposed analytical approach for optimal placement of single DG not only minimize the line losses but also minimize the DG size. Note that the voltage becomes more stable when the DG is placed. The line voltage of 0.9940 p.u. at the bus no. 24 is changed to 0.9971 p.u. when the DG is installed at that bus. This result might be validated by adding a photovoltaic cell (type-I DG) at the optimum bus (bus 13) and observe the change of voltages at other buses.

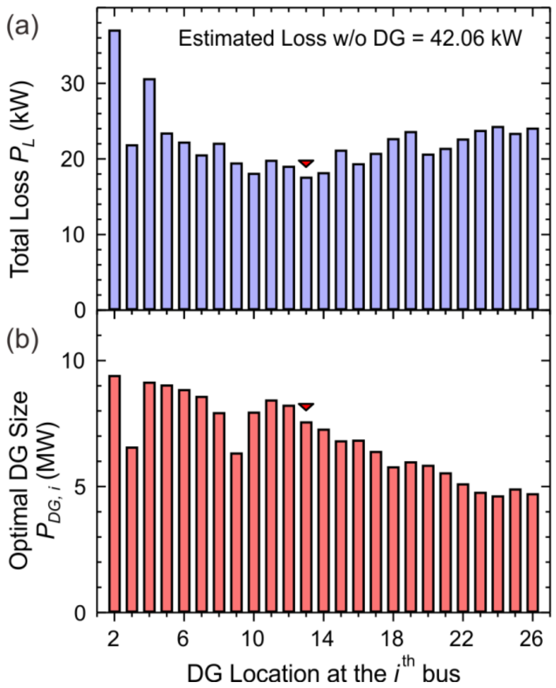

Fig. 3 (a) Total transmission loss and (b) the optimal DG size when the single DG with optimal DG size is installed at various bus locations

Concerning the spatial distribution of the load, one can clearly observe in Fig. 1 that the optimal DG location is at the bus no. 13, which is located in the mid of the main load area. The optimal DG position can therefore be predicted from this fact. However, the accurate position cannot be known without the calculation. In order to reduce the transmission loss inside the university, the DG is recommended to install at that bus. In practical, the best location of DG may not be always possible due to many constraints, ie., energy source, land restriction, installation/maintenance cost, and other factors.

5. CONCLUSION

This paper presents an estimation of the transmission loss in the NU power system. An installation of type-I DG is considered in order to minimize this loss. The analytical approach to determine the optimal size and location of DG for loss minimization in NU power system is applied. The proper location and size of DG are a very important factor for loss reduction. By using the proposed analytical approach, the results can be obtained the minimum system loss of 17.65 kW with the optimum size of DG of 7.58 MW at the bus no. 13 for our bus topology. This work improves our knowledge of the existing power system and allows us to further improve the system performance.

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APPENDIX

The bus parameters are listed in the Table I. For the calculation of the optimal DG size and the impedance values, we use the substation voltage V_{base} = 22 kV and the base apparent power = 100 MVA. The line impedance is

$$\left|Z_{ij}\right| = \sqrt{R_{ij}^2 + X_{ij}^2} \,. \tag{11}$$

Resistance per length r_{ij} between the bus i and j is

$$r_{ij} = \frac{23.7\ \Omega\ \text{mm}^2/\text{km}}{A_{ij}\left(\text{mm}^2\right)} \,, \tag{12}$$

where A_{ij} is the cross section area of the electrical line. The corresponding resistance is

$$R_{ij} = r_{ij} L_{ij} \,, \tag{13}$$

where L_{ij} is the measured distance between the i^{th} and j^{th} transformer/bus. The reactance X_{ij} is calculated from the length L_{ij} and the reactance per length of 0.08 Ω/km [15]. The load power $P_{L,j}$ at the j^{th} bus is estimated from the rated power of the installed transformer and listed in the Table A1.

Table A1. The list of bus parameters

From (i)	To (j)	R_{ij} (Ω)	X_{ij} (Ω)	$P_{Load,j}$ (kW)
1	2	0.0269	0.0218	432
15	3	0.0087	0.0070	288
2	4	0.0385	0.0312	72
4	5	0.0436	0.0354	1728
5	6	0.0119	0.0096	288
6	7	0.0186	0.0150	230
7	8	0.0117	0.0094	288
13	9	0.0642	0.0520	922
12	10	0.0183	0.0148	288
7	11	0.0094	0.0076	432
11	12	0.0131	0.0106	360
10	13	0.0230	0.0186	144
13	14	0.0109	0.0088	922
10	15	0.0335	0.0271	288
14	16	0.0160	0.0130	576
16	17	0.0173	0.0140	230
17	18	0.0272	0.0220	230
3	19	0.0222	0.0180	144
9	20	0.0301	0.0244	230
20	21	0.0207	0.0168	288
21	22	0.0336	0.0272	288
22	23	0.0277	0.0225	288
23	24	0.0125	0.0102	230
22	25	0.0153	0.0124	115
25	26	0.0148	0.0120	91