Optimal placement of wind turbine in distribution grid to minimize energy loss considering power generation probability

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ABSTRACT

This research proposes an algorithm to determine the optimal position of wind turbines in a distribution grid for minimizing its annual energy loss. In this paper, the probability distribution of power generation at each wind turbine node is considered and the nonsimultaneous occurrence of the power generation at wind turbine nodes is also interested. Moreover, we also consider the wind energy exploitability at each node in the grid. This algorithm is coded in MATLAB environment and it is verified via a sample IEEE 33 bus distribution grid with a sample data of power generation probability. The verifying results indicated that the optimal number of wind turbines at each node to obtain a minimal annual energy loss. Results also indicated that the node voltage is varied because of the change of power generation; however, the voltage at all nodes is in normal operation range and its median value is between about 1.01 pu to 1.05 pu. The power factor of wind turbines has an impact on the optimal number of wind turbines at nodes and the efficiency of wind turbine installation.

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1. INTRODUCTION

The energy of wind has been ultilized to generate electricity in many countries on the world and it has been meet a significant percentage of demand [1]. For areas with the high potential of wind energy, the wind energy is exploited as large scale wind farms while for normal potential ones, only a few small wind turbines is used. Depending on the wind farm capacity, wind turbines can be connected to a transmission grid or a distribution grid. In the case of a connected distribution grid, changes in power flow can lead to the increase in the power loss in this grid [2].

Until now, researchers proposed many algorithms to determine the optimal position of distributed generator (DG) in a distribution grid with many kinds of cost function [3]-[18]. In these researches, authors did not consider the wind energy exploitability of each node and the optimal size of wind turbine at nodes is hard to suitable with wind turbine capacity in practice. For example, algorithms gave us the optimal size of DG is 2613 kW; with this optimal size, it is not easy to choose wind turbine such that the capacity in total is 2613 kW because wind turbine capacity is designed by manufacture such as 100 kW, 400 kW, and so on [19]. Moreover, available land for wind energy exploitation is an obstruction for practical application.

For wind turbine, there is a lite difference from other DGs. The wind turbine output cannot remain at the rated value during operating interval because the power generation of wind turbine is heavily depending on wind speed [20]-[22]. Therefore, the wind speed variation has an impact on the power loss of the connected grid. Moreover, the wind speed value at this node is hardly equal to other nodes. Therefore, determining the position of wind turbine to reduce the annual energy loss should take care the probability of wind speed. The wind speed probability was considered to determine the optimal placement of wind turbines [7], [10]. However, in these researches, one probability of wind speed is used for all wind turbine nodes. Practically, the wind speed probability at different nodes may be different. For example, at the i^{th} wind turbine node, the probability of rated wind speed is 30% while at the j^{th} node its data may be 20%. Therefore, using a wind speed probability for all nodes may be inaccuracy.

This paper proposes an algorithm to determine the optimal position and optimal size of wind turbines at nodes such that the annual energy loss becomes minimal. This research, we consider the probability of wind speed or power generation at nodes and we also consider the nonsimultaneous occurrence of wind speed at all nodes. Moreover, the wind energy exploitability at nodes is considered. We are going to use MATLAB software to code this algorithm and the IEEE-33 bus distribution grid is used to verify. The efficiency of this algorithm will be annalized from the verifying results.

2. ANNUAL ENERGY LOSS MINIMIZATION CONSIDERING TO POWER GENERATION PROBABILITY AND WIND ENERGY EXPLOITABILITY

A distribution grid often supplies to customers in a quite narrow area. In this grid, the length of each feeder is several kilometers, the rating voltage is several kV or ten of kV, and load demand is quite low, about several MW. This grid often consists of radial feeders or closed grid that is often in the opened operation. In this grid, the integration of wind turbines can lead to the increase in the energy loss. The annual energy loss of this grid depends on the position of wind turbines, the wind energy exploitability, the wind speed probability and the nonsimultaneous occurrence of wind speed at nodes.

We suppose that in the distribution grid, $\aleph$ is the set of nodes where wind energy can be exploited, and the exploitability at the i^{th} node in $\aleph$ is n^i_{max}. The power generation at each node has p states. The probability to generate an active power P_j of wind turbine at the i^{th} node is denoted $Ч^i_j$. If m is the number of wind turbine nodes, the combinatory number of power generations is p^m. We suppose that the probability of the k^{th} combinatory is $\wp^k_m$ which is calculated from the probability of all states in that combinatory. Here, ΔE^h_i is denoted the annual energy loss in the distribution grid when the h^{th} wind turbine is installed at the i^{th} node and the grid has m wind turbine nodes. This energy loss is computed.

$$\Delta E^h_i = \tau \sum_{k=1}^{k=p^m} \Delta P_{m,k}\, \wp^k_m \tag{1}$$

where $\Delta P_{m,k}$ is the power loss when the power generation at m nodes occur as the k^{th} combination; and τ is the maximum power loss duration of grid. Hence, the optimization problem is stated as (2):

$$\Delta E = f(n^i) \rightarrow min \tag{2}$$

subject to:

$$n^i \leq n^i_{max} \tag{3}$$

$$U_{min} \leq U^j \leq U_{max} \tag{4}$$

$$I^{lj} \leq I^{lj}_{max} \tag{5}$$

where, n^i is the number of wind turbines at the i^{th} node in the set $\aleph$; $U^j, U_{min}, and\ U_{max}$ are the voltage at the j^{th} node in the grid, minimum and maximum allowance voltage at nodes; $I^{lj}\ and\ I^{lj}_{max}$ are current and allowable current on the line connecting from the l^{th} node to the j^{th} node.

To solve (2), we use iterative method. In the h^{th} iteration, we must determine the optimal position of the h^{th}wind turbine. To obtain the optimal position of the h^{th} wind turbine, we have an optimization problem in which the cost function is:

$$\Delta E^h = f(i) \rightarrow min \tag{6}$$

and constraints are the same as (3) to (5). We also use the iteration method to solve the optimization problem (6). The condition to stop the iteration is that either energy loss in the grid is increased or the number of turbines at all nodes is over their allowance $\Delta E^h \geq \Delta E^{h-1}$ or $n^i = n^i_{max}\ \forall i \in \aleph$. Noted that as the h^{th} wind turbine is supposed to connect to the i^{th} node, we can know the number of wind turbine node in total, m.

3. ALGORITHM PROPOSAL

To obtain the minimal energy loss in a distribution grid, we determine the optimal position of wind turbine step-by-step. It means we must determine the optimal location of each wind turbine in order. The optimal position of wind turbine is the node where if we connect wind turbine to that node, the annual energy loss in the grid will be the lowest compared to the case of connecting to other nodes and this energy loss is lower than without it. The algorithm is shown in Figure 1.

3.1. Main algorithm

The aim of this algorithm is to determine the position of wind turbine in the grid or the number of wind turbines at nodes in the set $\aleph$ such that the annual energy loss becomes minimal. In this algorithm, we suppose h is the order of considered wind turbine. The h^{th}wind turbine is only connected to its optimal position if the annual energy loss is reduced comparing to without it. Algorithm is proposed as Figure 1(a).
Step 1: we read input data including load data, line data, the set $\aleph$, and allowable wind turbine number, the probability of power generation of each node in the set $\aleph$. We start the first wind turbine $h = 1$.
Step 2: we determine the optimal position of the h^{th}wind turbine. This step is carried out as subsection 3.2.
Step 3: we check the stop condition. If the annual energy loss is higher than the previous iteration or all nodes in set $\aleph$ are exploited with maximum capability, the algorithm is finished. Otherwise, we go to step 4.
Step 4: we move to next wind turbine $h = h + 1$ and we return step 2. We finish this algorithm.

3.2. Determine optimal position of the hth wind turbine

The objective of this algorithm is to determine the optimal position of the h^{th}wind turbine in step 2 in the subsection 3.1 by solving the optimization problem (6). To obtain this objective, we connect step-by-step this wind turbine to each node in the set $\aleph$ and calculate the energy loss. Noted that if the number of wind turbines at the i^{th} node is reached to its allowance value, we move to next node in the set $\aleph$. The optimal position is the node in which the annual energy loss is minimal. The algorithm is shown in Figure 1(b) and it is described in detail as:
Step 2.1: we start the first node ($i = 1$) in the set $\aleph$.
Step 2.2: we compare the number of wind turbines at the i^{th} node, n^i, to its allowable value, n^i_{max}. If $n^i \geq n^i_{max}$ we move to step 2.3, otherwise we move to step 2.4.
Step 2.3: we cannot connect the h^{th}wind turbine to the i^{th} node, and hence, we set $\Delta E^h_i = inf$ and then we move to step 2.6.
Step 2.4: we connect the h^{th}wind turbine to the i^{th} node.
Step 2.5: we calculate the annual energy loss, ΔE^h_i. Noted that calculating the annual energy loss ΔE^h_i is described as subsection 3.3.
Step 2.6: we check $i = i_{max}$ which i_{max} is the node number in total in the set $\aleph$. If it is wrong, we move to Step 2.7, otherwise, we move to step 2.8.
Step 2.7: we move to next node in the set $\aleph$, $i = i + 1$, and we return to step 2.2.
Step 2.8: we determine the optimal position of the h^{th}wind turbine. The optimal position is the i^{th} node if $\Delta E^h_i = \min\{\Delta E^h_1, \dots, \Delta E^h_{i_{max}}\}$.
Step 2.9: we increase the number of wind turbines at the i^{th} node to $n^i + 1$. The algorithm is finished.

3.3. Calculating the annual energy loss

The objective of this algorithm, shown in Figure 1(c), is to calculate the annual energy loss in the grid as the h^{th} wind turbine is connected to the i^{th} node in the set $\aleph$. Here, we must consider the generation state of wind turbine at different nodes. When the h^{th} wind turbine is connected to the i^{th} node, the number of wind turbine nodes is m and each wind turbine node has p generation states, it means we have p^mcombinatories of power generation. Probability of each combinatory is calculated from the probability of generation state of wind turbine nodes. We calculate the power loss in the grid for each generation state combinatory, and then, we obtain the annual energy loss by accumulating the production of power loss and probability of combinatory.
Step 2.5.1: we create the set of generation state combinatories from m wind turbine nodes, and depending on the generation state of nodes, we calculate the probability of each combinatory. We start the first combinatory, $k = 1$.

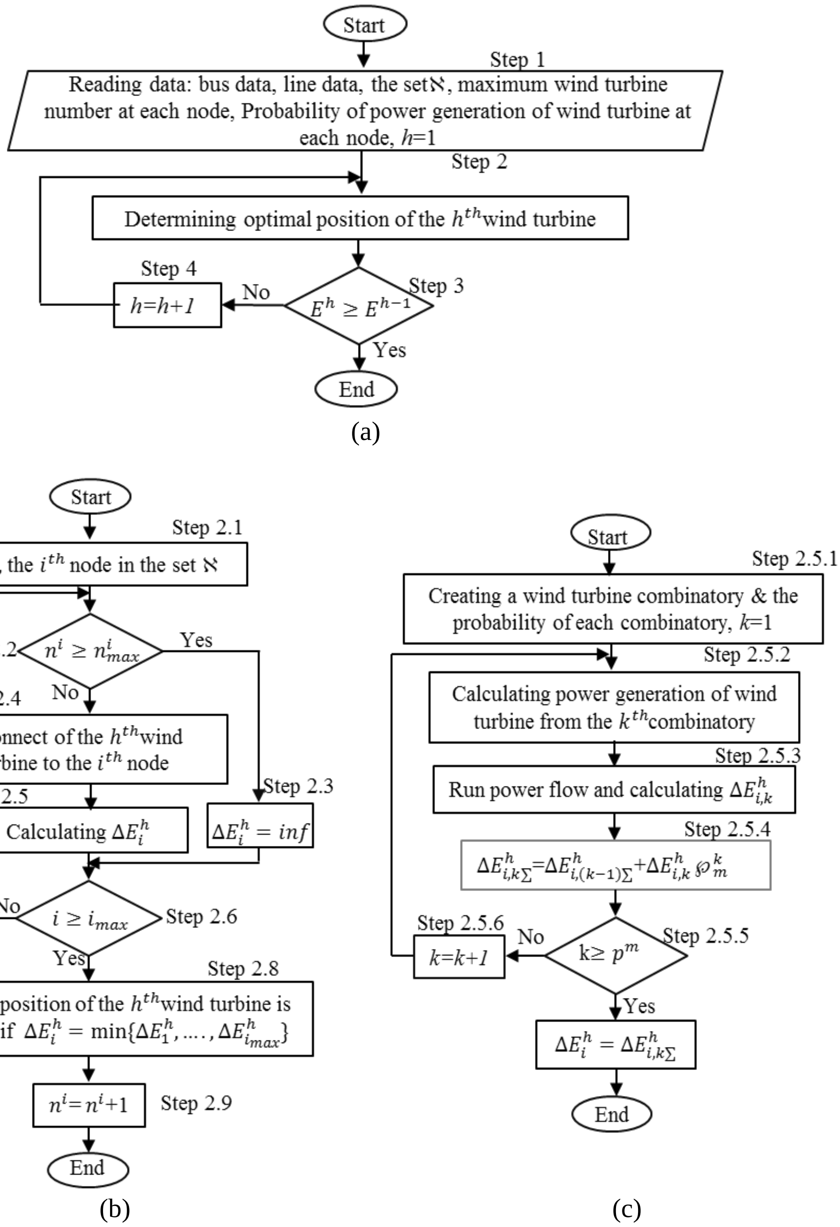

Figure 1. Algorithm to calculate the best position of wind turbine: (a) main algorithm, (b) algorithm to calculate the wind turbine's optimal position, and (c) algorithm to compute the annual energy loss

Step 2.5.2: we calculate the power generation at each wind turbine node corresponding to the power generation state in the k^{th}combinatory.
Step 2.5.3: we run the load flow algorithm [23] to obtain the power loss on the grid, and then, we calculate the annual energy loss corresponding to the k^{th}combinatory.
Step 2.5.4: we accumulate the energy loss at the k^{th}combinatory.

$$\Delta E^k_{h,i\Sigma} = \Delta E^{k-1}_{h,i\Sigma} + \Delta E^k_{h,i}\,\wp^k_m \quad (7)$$

Step 2.5.5: we check whether all combinatories are considered ($k \geq p^m$). If it is wrong, we move to step 2.5.6, otherwise, we finish this algorithm.
Step 2.5.6: we move to the next combinatory by increasing $k = k + 1$ and then, we move to step 2.5.2. We finish algorithm.

4. VERIFICATION

To verify the suggested algorithm, we use the sample distribution network as shown in Figure 2. The data of this grid is listed in [24]. Here, we suppose that nodes in the set ℵ are the 6th, 15th, 18th, 25th, and 33rd node, and their maximum wind turbine number are listed in Table 1. Each node has 5 generation-states and the probability of each state is list in Table 2. Here, we verify the different cases of power factor of wind turbines. We mainly focus the case of 0.95 power factor of all wind turbines and other cases' result is compared to that of the case of 0.95 power factor.

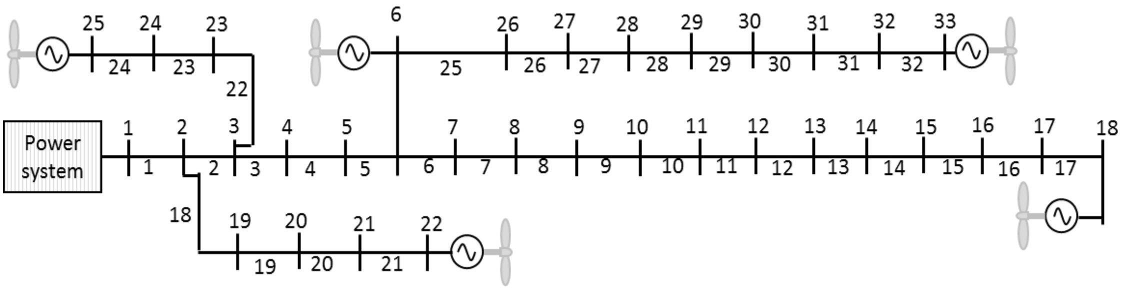

Figure 2. The sample distribution network, IEEE-33 bus, with wind energy potential node

Table 1. Maximum number of wind turbine at nodes

Node	6th node	18th node	22nd node	25th node	33rd node
Maximum number of WT	10	15	6	14	17

Table 2. Probability of generation state at nodes

Generation state (%)	6th node (%)	18th node (%)	22nd node (%)	25th node (%)	33rd node (%)
100	12	15	10	8	17
75	20	17	20	22	2
50	30	18	22	24	33
25	20	32	28	20	18
0	18	18	20	26	12

4.1. Power factor of 0.95

In this section, we suppose that all wind turbines operate at the 0.95 power factor. After running the recommended algorithm, the verifying results are performed as Table 3. The data in this table indicated the number of wind turbines, which we should install to obtain a minimal energy loss. The number of wind turbines in total is 25 wind turbines of 100 kW and the total energy loss is 727 MWh, which is cut down about 855 MWh comparing to the case of no wind turbine installation. Majority of wind turbines are recommended to install at the 33rd and 18th node. Only a few of wind turbines are suggested to install at the 25th and 22nd node. The number of wind turbines at all nodes has not yet over their exploitability.

Table 3. Number of wind turbine at nodes

Node	6th	18th	22nd	25th	33rd
Number of wind turbine	5	6	1	2	11

By installing 25 wind turbines at 5 nodes and the probability of power generation at nodes in Table 2, the boxplot of voltage at nodes in the grid is shown as Figure 3. Obviously, the voltage at nodes in the grid is varied with a large range, taking the 18th node as an example. The voltage at this node is varied from 0.968 pu to approximate 1.05 pu. This variation is caused by the change in power generation of wind turbines. In the case of no wind or no generation from wind turbines at all nodes, the voltage at the 18th node is minimum but in the case of all wind turbines generating the rated value, the voltage at this node is approximate to 1.05 pu. The median value of voltage at all nodes is often over 1 pu. This indicated that the installation of wind turbines, the voltage on the grid is varied but it is still in operation range, between 0.95 pu to 1.05 pu.

Depending on the position and the existence of wind turbine in the grid, the installation effective of wind turbine can be different. Therefore, in the case of limited investment, we can invest step-by-step and the priority order is listed as Table 4. In this table, we can see that the 33rd node and 18th node are prioritized to install wind turbines. The reason is that they are far from the source, the installation of wind turbines at these nodes leads to reducing the power flow on line segments in the up-stream side, and hence, the power loss on lines is reduced. We can see that the higher priority order of wind turbine is, the lower its efficiency. For the first wind turbine, the annual energy loss is reduced over 4.04% while the last wind turbine, this data is only 0.55%, as Figure 4. For first 22 wind turbines, the installation efficiency of wind turbine is quite high, the annual energy loss reduction is over 2.5% for each installed wind turbine while for the last wind turbine, the efficiency is sharply reduced, from 1.88% to 0.55%, as Figure 4. It means the contribution of the last wind turbine to the energy loss reduction is insignificant. Therefore, depending on the investment ability, we can determine the number of wind turbine to obtain a high investment profit.

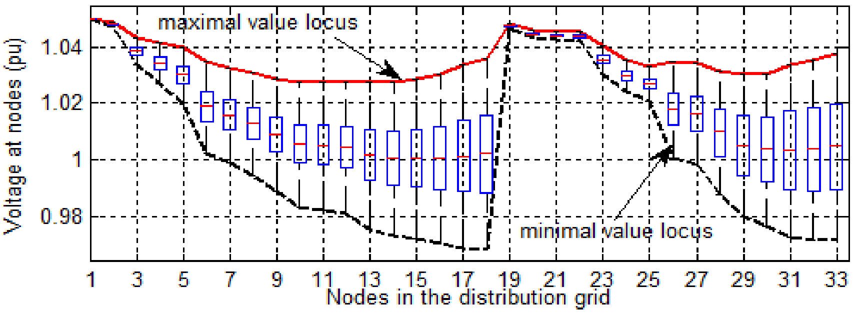

Figure 3. Operation voltage range at nodes

Table 4. Order to install wind turbine

Order	Node	ΔE (MWh)	Order	Node	ΔE (MWh)	Order	Node	ΔE (MWh)	Order	Node	ΔE (MWh)
1	33	1518	8	33	1157	14	18	942	20	6	799
2	33	1458	9	18	1115	15	33	914	21	6	779
3	33	1402	10	33	1076	16	18	889	22	6	759
4	18	1348	11	18	1039	17	33	864	23	25	745
5	33	1296	12	33	1004	18	6	842	24	25	731
6	18	1247	13	33	972	19	6	820	25	22	727
7	33	1201									

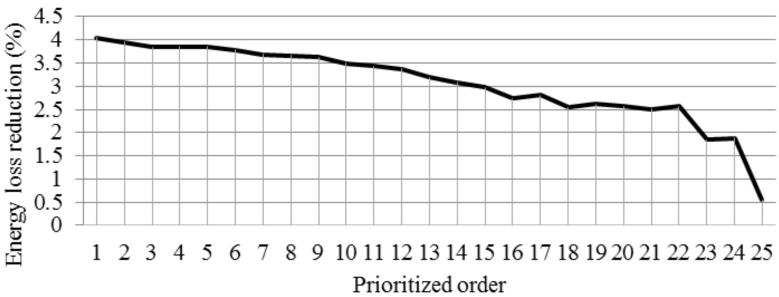

Figure 4. Efficiency of wind turbine installation

4.2. Other power factors

To reduce the energy loss in the grid, wind turbines should operate at leading power factors such that they generate the reactive power to supply the demand of local load. From the reactive power capability of variable speed wind turbines [25], at the rated active power, it can operate with the leading power factor between 0.9 and 1.0. Hence, in this section, we only test two cases of power factor including 0.9 power factor and unity power factor. Here, we compare the results in the case of 0.95 power factor to that in the case of 0.9 power factor and unity power factor, as Figure 5.

Figure 5(a) indicates that the higher power factor is, the higher the number of wind turbines in total. In term of the annual energy loss, by installing 25 wind turbines with the 0.95 power factor, the energy loss is lowest, 727 MWh. In three cases of considered power factor, many wind turbines are recommended to install at the 18th node and the 33rd node, the 22nd node and the 25th node, only a few of wind turbines are installed, Figure 5(b). Noted that, at the unity power factor, the number of wind turbines at the 6th node is approached to its exploitability, 10 wind turbines. Concerning to the prioritized order of wind turbines, the 33rd node and the 18th node are almost prioritized to install the first 16 wind turbines, other nodes are often prioritized the remaining wind turbines, Figure 5(c). From Figure 5(d), we can see that the efficiency of wind turbine installation is reduced gradually according to the prioritized order of wind turbines. The installation efficiency is reliant on the power factor of wind turbines heavily. Obviously, for the first 18 wind turbines, the lower power factor is the higher efficiency because the reactive power generation from wind turbines contributes the reduction of power loss on lines. However, when the number of wind turbines is high enough, the reactive power can be over the demand of vinicity loads and this makes the efficiency of wind turbine installation be reduced in comparing to the higher power factor cases. The case of 0.95 power factor, the efficiency of wind turbine installation is quite approximate to the case of 0.9 power factor but it is far higher than that of the unity power factor. From comparison, the 0.95 power factor should be used to obtain the lowest energy loss.

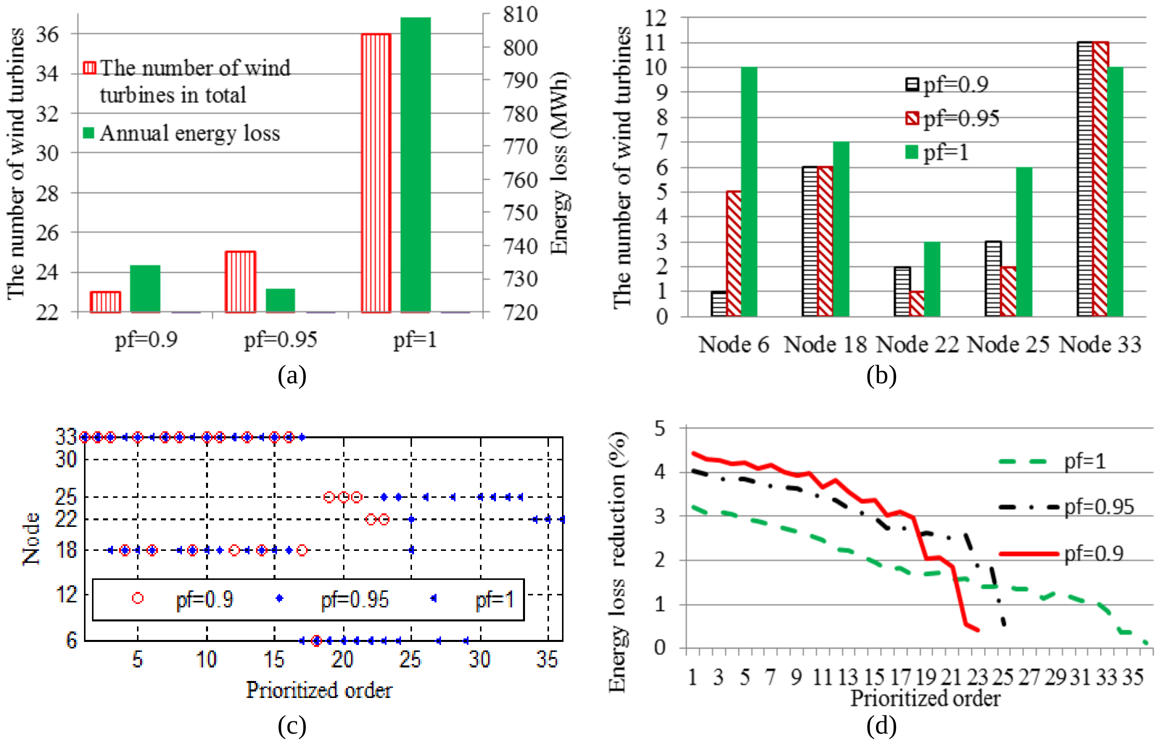

Figure 5. Comparison of calculating results at different power factors: (a) the wind turbine number and energy loss, (b) the wind turbine number at nodes, (c) the prioritized order to wind turbine installation, and (d) the efficiency of each wind turbine

5. CONCLUSION

This research proposed an algorithm to determine the optimal position of wind turbines such that the annual energy loss is minimal. This research considered the probability of power generation at different nodes and the wind energy exploitability at each node. The verifying results of IEEE-33 bus distribution grid indicated the optimal number of wind turbines at each node and the minimal annual energy loss after installing wind turbines. Results also indicated that the existence of wind turbines affects significantly on the variation of node voltage in the grid but the voltage at all nodes is still in the normal operation range. The power factor of wind turbines has an impact on the optimal number of wind turbines at nodes and efficiency of wind turbine installation. In this research, we recommended that the 0.95 power factor should be used to obtain the lowest annual energy loss.

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