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Optimal operation mode of wind turbines in distribution grid to minimize energy loss considering power generation probability

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ABSTRACT

This research considers a distribution grid where wind turbines were connected. The aim of this reasearch is to determine the optimal operation mode and setting parameter of wind turbines to minimize the energy loss of this distribution grid. To obtain the above purpose, we proposed an algorithm based on PSO algorithm. The suggested algorithm was coded in MATLAB and it was verified via a sample distribution grid. Results indicated the optimal operation mode and setting data in which the energy loss in the tested grid is minimal. Moreover, this research also compared the testing results with three cases of the generation at wind turbine node including average power, rated power and power probability distribution. Comparing results indicated that we cannot use average power generation or rated power of wind turbine to determine the optimal operation mode and setting data of wind turbines instead of we use the power distribution probability.

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1. INTRODUCTION

Wind energy has been exploited successfully in many countries in the world. According to the report of GWEC in 2021, the wind turbine (WT) capacity is going to be accumulated over 1TW before 2025 [1]. This data is going to be also grown up in near future. Practically, the wind energy can be exploited in the range of several kW to several thousand MW. Depending on the wind potential and available land area, it can be exploited as a large wind farm or sole small WTs. For large or medium wind farms, they are integrated to the transmission grid while small wind turbines are often connected to a distribution grid.

For a distributed grid, power loss or energy loss has been an interested issue by its operator because this grid is often low voltage and high resistance. The integration of WTs into the distribution grid can affect significantly to the power loss on this grid [2]. It can lead to increase the power loss or energy loss if the connecting position of WTs is not reasonable. Many authors [3]-[19] carried out determining the optimal position of distributed generator (DG) in the distributed grid. These researches, authors have not yet considered the optimal operation mode of DG and all DGs are operated in the power factor mode (supplying both active power and reactive power or only active power), either unity power factor [4-16,19] or a given power factor [3, 17-18]. In [5, 9], average wind speed was used to determine the optimal position of WT and its size while in [7] and [10], wind speed probability was used. In the case of DG based on WT, though the connecting position of WT is optimal, if WTs' operation mode (OM) and setting parameter are unreasonable, it can make the power loss or energy loss in the distributed grid become higher. Therefore, determining the optimal operation node of WTs existing in the grid to minimize the energy loss is an important issue.

For WTs, there are two kinds of WT consisting of fixed speed WT and variable speed one [20]. For fixed speed WT, which employs a squirrel-cage-induction generator to directly connect to the grid, it has only one OM in which it is always received reactive power from the grid [21]. Hence, using this WT can increase energy loss in distribution grid and this WT is not taken care in this research. For variable speed WT which use a doubly fed induction generator or a permanent magnetic synchronous generator and a power converter to interface to connected grid, there are two popular OMs including constant voltage control and power factor control [22]. Because wind speed is fluctuation during operation interval, determining a suitable OM and setting parameter for WTs such that the annual energy loss in whole distribution grid becomes minimal is an important issue. Moreover, wind speed is not the same at all WT nodes and wind speed probability distribution at any WT node can be different from other nodes; it means the probability of power output of WT at nodes can be different and the relative power output at WT nodes can be not the same at a time. Hence, whether or not can we use the average power generation or rated power of WTs to determine the optimal OM and setting parameter instead of using the power generation probability?

This research will focus on determining the optimal OM of WTs connected to a distribution grid for the energy loss minimization. Beside, we also determine the optimal setting parameter of WTs. Here, we use Matlab/Simulink to code the proposed algorithm and then, we use IEEE 33-bus distribution grid to verify the proposed algorithm. In this research, we suppose WTs were installed in the grid and the WTs' generation is based on the wind speed or power output probability distribution. Verifying results indicate the optimal OM and setting parameter of WT and it ensures a minimal energy loss. Moreover, we also consider other cases of power output of WT including rated power and average power generation, verifying results are used to compare with that of the case of probability-based generation to determine which case gives the best result.

This research has two contributions. The first contribution is the determining the optimal operation mode of WTs, which have been existing in a distribution grid in a distribution grid, to obtain minimal energy loss. The second one is that to determine this optimal operation mode, whether or not we can use the rated power or the average power instead of the probability of WT output.

2. WIND TURBINE POWER OUTPUT

The power output of a WT, P_{wt}, depends on the wind speed, V_w, as [23]

$$P_{wt} = \frac{1}{2}\eta\rho\pi R^2 C_p V_w^3, \tag{1}$$

where, $\rho, R, C_p,$ and η stand for the air density, blade length, power coefficient, and efficiency of WT system, respectively. It means the power output of WT is heavily reliant on the wind speed. The wind speed at the different WT nodes can be different. Hence, the power output of WTs in the distribution grid may be different at any time. Suppose that wind speed at the j^{th} node has v state, $V_j = \{ V_{w,1}, \dots, V_{w,a}, \dots, V_{w,v}\}$, and the number of WT nodes, where the WTs are connected, is n_{DG}. It means we have $\mathrm{v}^{\mathrm{n_{DG}}}$set of wind speed. We suppose that at a WT, the probability to occur the set of wind speed, $k = \{V_1, \dots, V_j, \dots, V_{n_{DG}}\}$ where V_j is one of v states, is $\wp_{\mathrm{n_{DG}},\mathrm{k}}$ and the probability to occur $V_{w,a}$ at the j^{th} node in the k^{th} set is $\wp_{j,V_{w,a}}$.

$$\wp_{n_{DG},k} = \prod_{j=1}^{n_{DG}} \wp_{j,V_{w,a}} \tag{2}$$

Noted that according to (1), in the case of WT controlled to obtain MPPT, $\wp_{n_{DG},k}$is also the probability to occur the combination of WT's power output $p = \{P_1, \dots, P_j, \dots, P_{n_{DG}}\}$ where P_j is calculated from (1) and it is one of wind speed states in V_j. It means

$$\wp_p = \wp_{n_{DG},k} \ . \tag{3}$$

For example, we have two WT nodes and the probability to occur wind speed $V_{w,1}, V_{w,2}, V_{w,3}, V_{w,4}$ at each WT node as Table 1.

Table 1. Probability of wind speeds at 2 WT nodes

Wind speed probability	$V_{w,1}$	$V_{w,2}$	$V_{w,3}$	$V_{w,4}$
At *1st* node $\wp_{1,V_{w,a}}$	0.1	0.25	0.4	0.25
At *2nd* node $\wp_{2,V_{w,a}}$	0.15	0.3	0.45	0.1

From data in Table 1, with 4 velocities and 2 WT nodes, we have 16 sets of wind speed. Moreover, the probability to occur the wind speed $\mathrm{V_{w,1}}$ at the *1st* node ($\wp_{1,V_{w,l}} = 0.1$) and $V_{w,3}$at the *2nd* node ($\wp_{1,V_{w,3}} = 0.45$) at the same time is 0.045. It means the probability of set $k = \{V_{w,1}, V_{w,3}\}$ is 0.045. Likely, the probability to occur the set $k = \{V_{w,3}, V_{w,1}\}$ is 0.06.

3. ENERGY LOSS MINIMIZATION AND PROPOSED ALGORITHM.

3.1. Energy loss minimization

Energy loss in a distribution grid depends on both active and reactive power flowing on the lines. The active power on the lines is reliant on the generation at WT nodes and the demand at vicinity nodes while reactive power on lines depends on OM of WTs and their setting parameters. Each WT can be operated in one of two OMs either constant voltage or constant power factor. We suppose that the grid has $\boldsymbol{n_{DG}}$ WT nodes. It means we have $\boldsymbol{2^{n_{DG}}}$ combination of OM. Here, the power loss in the distribution grid when the combination of OM is **the** $\boldsymbol{m^{th}}$ combination and the WTs' power output is $\boldsymbol{p} = \{\boldsymbol{P_1}, \dots, \boldsymbol{P_j}, \dots, \boldsymbol{P_{n_{DG}}}\}$ is denoted $\Delta \boldsymbol{P_{m,p}}$. Annual energy loss when WTs operate in the $\boldsymbol{m^{th}}$ OM combination is computed as [7], [10]

$$\Delta E_m = \tau \Delta P_m = \tau \sum_p^{v^{n_{DG}}} (\Delta P_{m,p} \prod_{j=1}^{n_{DG}} \wp_{j,V_{w,a}}). \tag{4}$$

Hence, the optimization problem is defined as

$$\Delta E_m = \tau \sum_p^{v^{n_{DG}}} (\Delta P_{m,p} \prod_{j=1}^{n_{DG}} \wp_{j,V_{w,a}}) \rightarrow \min \tag{5}$$

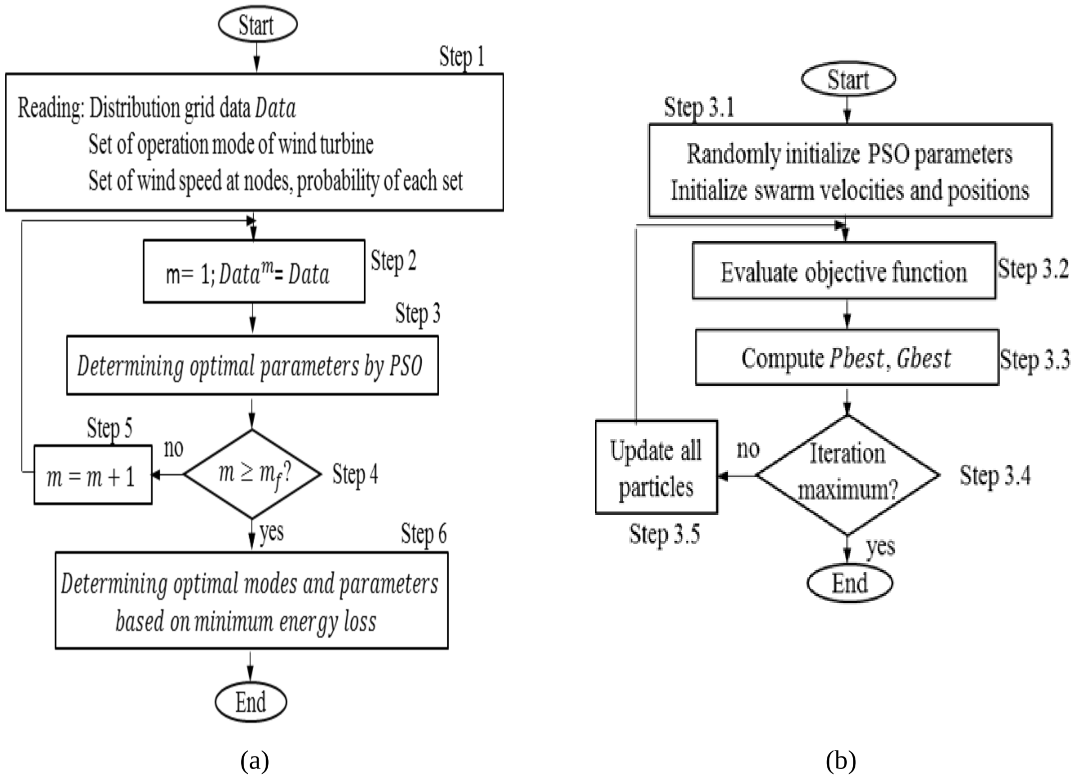
subject to

$$U_{min} \leq U_i \leq U_{max} \tag{6}$$

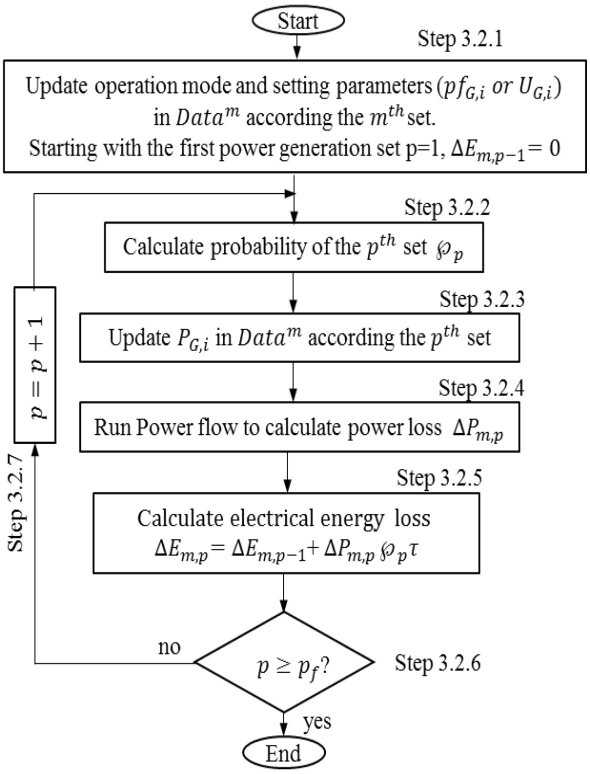
$$I_{ij} \leq I_{ijmax} \tag{7}$$

$$Q_{i,min} \leq Q_i \leq Q_{i,max}, \tag{8}$$

where, U_i, U_{max}, and U_{min} are voltage at the i^{th} node, maximum and minimum allowable voltage at nodes, respectively; I_{ij} and I_{ijmax} are current and its limitation of the line connecting from the i^{th} node to the j^{th} node; Q_i, is the reactive power generating of WT at the i^{th}node and its limitations are $Q_{i,max}$and $Q_{i,min}$.



(a) (b)



(c)

Figure 1. Algorithm determining optimal OMs and setting parameter of WT: (a) main algorithm, (b) algorithm to determine setting parameter, and (c) Algorithm evaluating the cost function

3.2. Algorithm proposal

The main idea of the proposed algorithm is to determine the best OM of WTs by solving the optimization problem in (5). To obtain this objective, here, we create the sets of OM of WTs. For each OM set, we determine the optimal setting parameters by using the particle swarm optimization (PSO) algorithm such that the energy loss in the grid becomes minimal. The optimal set of OM is determined from the minimal energy loss value in all OM sets. This algorithm is shown in Figure 1.

3.2.1. Main algorithm

As above-mentioned, the objective of this algorithm is to determine the optimal set of OM of WTs based on the minimal energy loss. This algorithm is shown in Figure 1a as following

Step 1: reading the grid's data, $Data$, including loads' power, generators' parameter at nodes, node types, lines' parameters, wind speed or available power of WTs and its probability $\wp_{j,V_{w,a}}$. The probability of generation coincidence of WTs is $\wp_p$. Creating the sets of OM, the sets of power generation, and we can calculate the probability of generation coincidence of WTs $\wp_p$ by using the production of probability of power generation at each node, $\wp_p = \prod_{j=1}^{n_{DG}} \wp_{j,V_{w,a}}$. We start the first set of OM and we set $m = 1$

Step 2: setting $Data^m = Data$

Step 3: running PSO algorithm to determine the optimal setting parameter of the m^{th} set of OM. This step's output is the optimal setting parameter for each WT and energy loss. It is described in sub-section 3.2.2.

Step 4: checking whether the last set of OM is considered. If the last set has not yet checked, $m < m_f$, we move to Step 5, otherwise, we move to Step 6.

Step 5: moving to next set by increasing m to $m + 1$ and then, we return to Step 2.

Step 6: determining the optimal set of OM based on the minimum energy loss, $min\left\{\Delta E_1, \dots, \Delta E_{m_f}\right\}$. It is supposed that the m^{th} set gives us $\Delta E_m = min\left\{\Delta E_1, \dots, \Delta E_{m_f}\right\}$, the optimal setting parameter of WT are determined based on the m^{th} set.

We finish this algorithm.

3.2.2. Algorithm determining optimal parameter of WT for each OM set.

The aim of this algorithm is to determine the optimal setting parameter of WTs in the m^{th} OM set. To obtain this objective, we use the PSO algorithm [24] and the cost function defined as (9). The PSO algorithm is used in this objective because of its simplicity and acceptable accuracy. Noted that we can use other optimal algorithm instead of the PSO algoritm.

$$\Delta E_m = \tau \sum_p^{v^{n_{DG}}} (\Delta P_{m,p} \prod_{j=1}^{n_{DG}} \wp_{j,V_{w,a}}) \rightarrow \text{min.} \quad (9)$$

This algorithm is shown in Figure 1b and it is described in detail as

Step 3.1: initializing randomly PSO parameter and initializing swam velocities and positions of particles. We start the first iteration.

Step 3.2: calculating the cost function. The cost function is calculated as subsection 3.2.3.

Step 3.3: determining P_{best} and g_{best} from the current and previous value of cost function.

Step 3.4: checking iteration. If it has not yet been maximal, we move to Step 3.5, otherwise, we finish the algorithm and we obtain g_{best}.

Step 3.5: updating particles based on P_{best}, g_{best} and velocities and then, we return Step 3.2.

We finish this algorithm.

3.2.3. Algorithm determining cost function value.

The main objective is to calculate the value of the cost function, which is defined in Step 3.2 in subsection 3.2.2. From the particles, we run Newton Raphson for each set of power generation to calculate the power loss $\Delta P_{m,p}$. The energy loss is the production of $\Delta P_{m,p}$ and the probability to occur the p^{th}set of power generation $\wp_p$. The energy loss is the summation of energy loss from all generation power sets. The algorithm is shown in Figure 1c.

Step 3.2.1: updating generators' setting parameter. We update node voltage if WT at that node operates in the constant voltage mode and power factor if WT operates in the power factor mode from the m^{th} OM set.

The initial energy loss $\Delta E_{m,0}$ is set zero. We start the first set, $p = 1$.

Step 3.2.2: calculating the probability to occur the p^{th}set of power output $p = \{P_1, \dots, P_j, \dots, P_{n_{DG}}\}$, $\wp_{n_{DG},k}$.

Step 3.2.3: updating the active power $P_{G,i}$ of generators at WT nodes from the p^{th} power set

Step 3.2.4: running Newton Raphson to calculate the power loss $\Delta P_{m,p}$. Noted that this step, we must check constraints of nodes' voltage and line's capability.

Step 3.2.5: calculating energy loss accumulated to the p^{th} power set, $\Delta E_{m,p}$, based on $\Delta P_{m,p}$ and probability $\wp_p$, and previous step energy loss as

$$\Delta E_{m,p} = \Delta E_{m,p-1} + \Delta P_{m,p} \wp_p \tau \quad (10)$$

Step 3.2.6: checking the last set $p = p_f$. If $p < p_f$, we move to Step 3.2.7, otherwise, we finish this algorithm.

Step 3.2.7: increasing p to $p + 1$ and then, we return Step 3.2.2.

This algorithm is completed.

4. RESULTS AND DISCUSSION.

To test the proposed algorithm, the IEEE 33 buses [9] is used as an example. We suppose that nodes including the *25th*, *18th* and *33rd* nodes are connected to WT as Figure 2. The rating of WTs in total at each node, the probability of the power output and average power output at each WT node are shown as Table 2. For each WT, there are 4 power states and these states are named *0, 1, 2* and *3* for 0%, 40%, 75% and 100% of the rating power, respectively. Noted that the average power output is calculated from the probability of power output and rating power. With data in Table 2, we can get Table 3 where the set name column is the set of power generation states of WTs. It is noted that the first, second, and last number in any set are respectively WTs at the *18th*, *25th* and *33rd* nodes. For example, the set "213" means that the power output percentage of WTs at the *18th*, *25th* and *33rd* nodes are 75%, 40%, and 100%, respectively. From the power output probability in Table 2, we are easy to obtain the probability to occur any set as the $\wp_p$column.

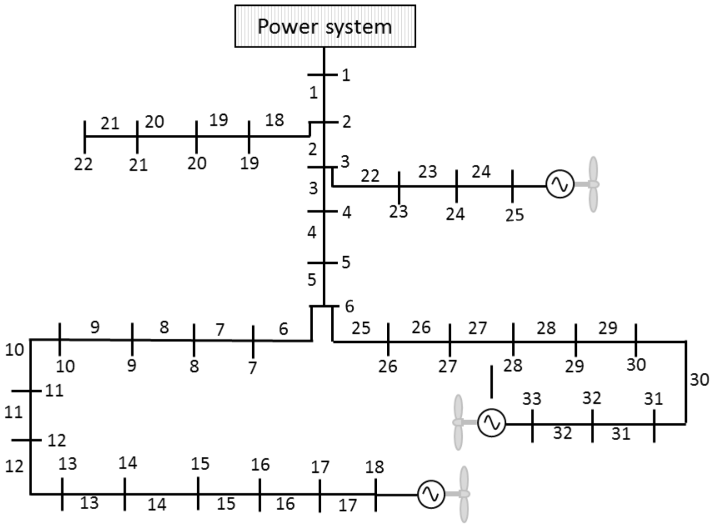


Figure 2. Sample of distribution grid with WT integration

Table 2. Power generation probability

Node	Rating power (kW)	Probability of power output (%)				Average power (kW)
		100% (3)	75% (2)	40% (1)	0% (0)	
18	800	10	50	25	15	460
25	300	13	45	30	12	176.25
33	800	5	60	25	10	480

Here, we consider three cases of generation. The first case, WTs at all nodes always generates the rated power. The next case, WTs always generates the average power. The last one, we consider the power generation probability at each WT node. We will compare these cases to suggest which case should be used.

4.1. Calculation result and annalysis

From above data, by running the proposed algorithm in MATLAB, the optimal setting parameter of each WT and electrical energy loss for each OM set are listed in Table 4 and Figure 3, respectively. From the Figure 3 and Table 4, if we only consider WTs always generating the rated power, the optimal OM of WTs is the *8th* mode set. In this set, all WTs operate in the voltage control mode and their terminal voltage should be set at 1.013pu, 0.992pu, and 0.992pu for WTs at the *18th*, *25th*, and *33rd* nodes, respectively. With this OM and setting data, the energy loss in this grid is minimum, 222.69MWh.

For the case of using the average power generation, that is 460kW, 176.25kW and 480kW for *18th*, *25th* and *33rd* node, respectively, the 8th mode set is also the optimal OM set. By using this set, the energy loss is minimal 387.56 MWh, and setting data are 0.981pu, 0.983pu, 0.964pu corresponding to WTs at the *18th* node, the *25th* node and the *33rd* node. Obviously, by comparing the case of rated power output to that of the average power output, the optimal OM of WTs is similar but the setting data is different.

Table 3. Probability of power generation set of WT

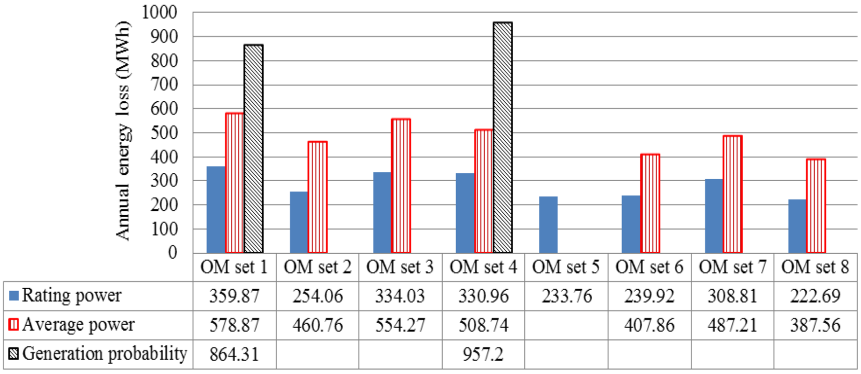
Order of set	Set name	$\wp_p$	Order of set	Set name	$\wp_p$	Order of set	Set name	$\wp_p$	Order of set	Set name	$\wp_p$
1	013	0.4860	17	333	0.72	33	111	0.924	49	131	1.232
2	010	0.513	18	303	0.72	34	012	0.945	50	101	1.232
3	313	0.54	19	011	0.756	35	001	1.008	51	032	1.26
4	310	0.57	20	300	0.76	36	031	1.008	52	002	1.26
5	113	0.594	21	330	0.76	37	312	1.050	53	302	1.4
6	110	0.627	22	133	0.792	38	213	1.08	54	332	1.4
7	003	0.648	23	103	0.792	39	331	1.12	55	233	1.44
8	033	0.648	24	100	0.836	40	301	1.12	56	203	1.44
9	000	0.684	25	130	0.836	41	210	1.14	57	023	1.458
10	030	0.684	26	311	0.84	42	112	1.155	58	200	1.52
11	230	1.52	27	020	1.539	43	132	1.54	59	102	1.54
12	323	1.62	28	311	1.68	44	320	1.71	60	123	1.782
13	120	1.881	29	212	2.1	45	231	2.24	61	201	2.24
14	021	2.268	30	321	2.52	46	121	2.772	62	202	2.8
15	232	2.8	31	022	2.835	47	322	3.15	63	223	3.24
16	220	3.42	32	122	3.465	48	221	5.04	64	222	6.3

Table 4. Verifying results with IEEE 33-bus as WTs connected at the *18th*, *25th*, and *33rd* node

OM set	OM and generation cases	Setting parameter of WTs at nodes (pu)			OM set	OM and generation cases	Setting parameter of WTs at nodes (pu)		
		18th	25th	33rd			18th	25th	33rd
1	Mode	cosφ	cosφ	cosφ	5	Mode	cosφ	V%	V%
	Rated	0.967	0.987	0.967		Rated	0.967	0.991	0.990
	Average	0.967	0.987	0.967		Average	0.971	0.984	0.982
	Probability	0.967	0.987	0.967		Probability	1	0.978	0.955
2	Mode	cosφ	cosφ	V(%)	6	Mode	V(%)	cosφ	V(%)
	Rated	0.967	0.987	0.990		Rated	1.013	0.987	0.991
	Average	0.967	0.995	0.961		Average	0.980	1	0.963
	Probability	0.967	0.987	0.961		Probability	0.962	0.987	0.961
3	Mode	cosφ	V(%)	cosφ	7	Mode	V(%)	V(%)	cosφ
	Rated	0.967	0.991	0.967		Rated	1.013	0.991	0.967
	Average	0.967	0.982	0.967		Average	0.978	0.982	0.967
	Probability	0.967	0.978	1		Probability	0.952	0.977	-0.999
4	Mode	V(%)	cosφ	cosφ	8	Mode	V(%)	V(%)	V(%)
	Rated	1.014	0.987	0.967		Rated	1.013	0.992	0.992
	Average	0.978	0.987	0.967		Average	0.981	0.983	0.964
	Probability	0.952	0.987	-0.998		Probability	0.959	0.978	0.953

When we use the WTs' power output based on the power generation probability, only the *1st* and *4th* mode set do not cause overload on lines. Remaining modes can cause overload on the lines. The main reason is that to obtain the terminal voltage of WTs at the setting value, it requires a high amount of reactive power flowing on the lines and this explains why overload occurs on lines. In the *1st* set, all WTs are operated in the constant power factor while in the *4th* mode set, the WTs at the *18th* node are operated in the voltage control mode and WTs at other nodes are operated in the constant power factor. It is easy to see that with the *1st* set, the energy loss of 864.31 MWh is the lowest in all set, and hence, it is the optimal OM set. In this set, the setting power factor of these WTs should be 0.967pu, 0.987pu, and 0.967pu for WTs at the *18th*, *25th*, and *33rd* nodes, respectively. In the *4th* mode set, by comparing the cases of the rated power to the average power, the energy loss in the case of using the power generation probability is so much higher and the setting data is quite different. The main reason is that the probability of zero power output of WT is quite high, and hence, the contribution of WTs to reduce the energy loss during zero power output is almost zero.

From above analysis, by using the probability of power generation, the optimal OM of WTs is different from other cases including the rated power generation and the average one. The main reason is that when the wind power output is low, to remain a constant voltage at connected node, it requires a huge amount of reactive power on the lines and this causes overload or high power loss on the lines. If we only use the average power or the rated value to calculate, the overload on the lines can be never occurs because the active power output withdrawing from WTs is quite high. Practically, during the operation interval of WTs, low wind speed can occur and hence, the use of the rated power or average power to determine the optimal OM is not suitable. The use of power output probability distribution is suggested to obtain reasonable results.



	OM set 1	OM set 2	OM set 3	OM set 4	OM set 5	OM set 6	OM set 7	OM set 8
■ Rating power	359.87	254.06	334.03	330.96	233.76	239.92	308.81	222.69
▥ Average power	578.87	460.76	554.27	508.74		407.86	487.21	387.56
▨ Generation probability	864.31			957.2				

Figure 3. Annual energy loss in different OMs

4.2. Comparison of the proposed algorithm with other researches

As we analyzed above, the proposed algorithm determined the optimal operation mode and setting data of WTs. The optimal operation mode is the power factor mode for all WTs while the power factor should set at 0.967, 0.987, and 0.967 for WTs at the 18th node, the 25th node, and the 33rd node, respectively. This section, we compare the annual energy loss in three cases. The first case is the case of without WTs. The second case is WTs operating at the unity factor [4-16]. The last case is the proposed algorithm. The comparing result is shown in Figure 4. As can be seen that with the proposed algorithm, the annual energy loss is always the lowest no matter of using rating power, average power, or generation probability of WTs.

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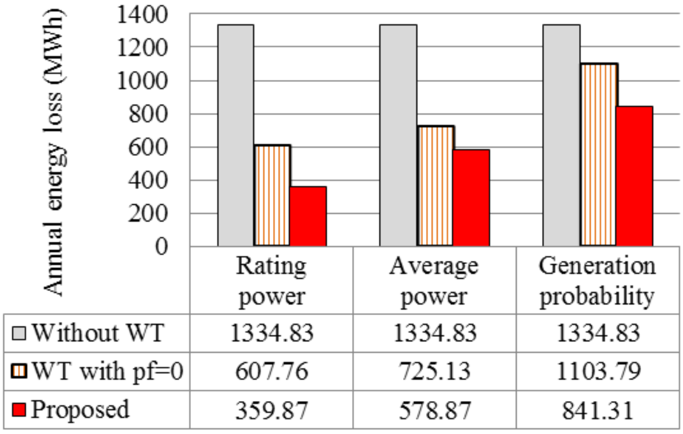

	Rating power	Average power	Generation probability
☐ Without WT	1334.83	1334.83	1334.83
▥ WT with pf=0	607.76	725.13	1103.79
🟥 Proposed	359.87	578.87	841.31

Figure 4. Comparing the annual energy loss of the proposed algorithm and other researches

5. CONCLUSIONS

This research suggested an algorithm to determine the optimal OM of WTs in a distribution grid to reduce the energy loss. Besides, this algorithm also determined the optimal setting parameter of WTs. This algorithm was verified via the IEEE 33-bus distribution grid. The results pointed out both optimal OM and optimal setting parameter of WTs to obtain the minimal energy loss. Verifying results also indicated that the probability distribution of power generation should be used to calculate the optimal OM and the optimal setting parameter of WTs.

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