Optimal placement of wind turbine to minimize voltage variance in distributed grid considering harmonic distortion

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ABSTRACT

This paper suggested an algorithm to choose the optimal location of wind turbines (WT) in a distribution grid. The optimal position is calculated so that the maximal voltage variance in the distribution grid is minimized. This paper considers the harmonic current emitted by WT and the limitation of total harmonic distortion of voltage waves at nodes in the distribution grid. This proposed approach is written in MATLAB software and validated through a sample distribution grid, IEEE 33-bus. The verifying results demonstrated that by applying the suggested algorithm, the maximal voltage variance due to the variation of the power output of WT is minimized, the total harmonic distortion value at all buses remains within the operating range, and the electrical loss in the grid is reduced. Moreover, by considering the limitation of total harmonic distortion, the number of WT allowed to be installed in the grid is able to limited.

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1. INTRODUCTION

Wind turbines (WT) have been used for electrical generation in numerous countries. This energy source contributed a significant electricity yield to the electricity production industry. Many large and medium wind parks were installed and connected to the transmission grid. For areas with low potential wind speed, small WTs, several hundred KW, are interested and they will be connected to a distribution grid.

For a distribution grid, connecting WTs can lead to the variation of voltage in the grid because of the variation of wind speed [1]. Many research focused on finding the optimal distributed generation (DG) position [2]-[24]. The researchers [2]-[10], focused on the minimization of power loss or energy loss. The researchers [11]-[13], are interested in the voltage stability or the voltage deviation. In many research, authors have considered multi-objective functions in which power loss and voltage stability are the most interesting [14]-[21]. Some researchers also considered the harmonic problem in the grid [22]-[24]. The researchers [22], the harmonic source comes from a non-linear load while DG is sinusoidal, and hence, DG installation can support the reduction of the total harmonic distortion value of voltage wave (THD_v). This research is only suitable with DG without an inverter. The researchers [23], [24], inverter-based DG was used but the objective function in [23] is a multi-objective with both voltage deviation and THD_v while in [24] the authors focus on minimizing the power loss.

For WTs, the natural variation of wind speed brings an impact on both energy loss and voltage quality at nodes in the connected grid. The energy loss often concerns the economic operation issues of the distribution grid while the voltage quality effects directly on customers. The economic issue is important but the voltage quality is also no less important. Atwa and El-Saadany [5] states, the wind speed probability was considered to determine the position of WT; however, in this research, the objective function is to minimize energy loss or power loss; authors have not yet considered the maximal voltage variance in the grid and the negative impact of harmonic current injected from WTs. Therefore, the integration of WT to the distribution grid such that the voltage variance is minimized while the THD_v value, node voltage, and load of lines are in the allowance range and the energy loss is reduced still need to be researched.

This paper focuses on determining the best location of WT in a distribution grid to minimize the maximal voltage variance at nodes in the grid. To obtain this objective, we propose an algorithm to select the WT number at nodes so that the maximal variance value of the voltage at nodes becomes minimal; the energy loss is reduced; the limitation of maximal THD_v value, voltage magnitude at nodes, and line load are in the operation range. In this research, all loads are supposed to be linear loads while WTs inject the harmonic current to the grid. The algorithm is verified via a sample distribution grid IEEE-33 bus. Verifying results are analyzed and compared to the case without THD_v consideration.

2. VOLTAGE VARIANCE AND OPTIMAL PROBLEM

2.1. Voltage variance caused by wind turbine

As we know, the amount of power produced by WT is strongly affected by the wind velocity [25].

$$P_w = \frac{1}{2}\rho\pi R^2 C_p V_w^3 \tag{1}$$

where, ρ is the air density, R is the length of the blade, C_p is the coefficient of WT. We suppose that WT is equipped with maximum power point tracking control and active pitch control [26]. Hence, the power output of WT at V_{wi} wind speed is,

$$P_{wi} = \begin{cases} P_{rated} & V_{wr} \le V_{wi} \le V_{wco} \\ \frac{1}{2}\rho\pi R^2 C_{pmax} V_{wi}^3 & V_{wci} \le V_{wi} \le V_{wr} \\ 0 & V_{wi} \le V_{wci}\ or\ V_{wi} \ge V_{wco} \end{cases} \tag{2}$$

where, P_{rated} is the rated power of WT; C_{pmax} is the maximal value of C_p; V_{wci}, V_{wr}, and V_{wco} are cut-in, rated, and cut-out wind speed. The wind speed is always varied naturally, and hence the power produced by WT is always variation. The variation of the power output of WT leads to the variation of voltage at nodes on the connected grid [1] because of the relationship between the voltage drop and the power flow. We suppose that in a day, there are w state of wind speed and the wind speed of V_{wi} occurs in h_i(hours). We can define the probability of V_{wi} in a day is $\wp_i$.

$$\wp_i = \frac{h_i}{\sum_{i=1}^{w} h_i} = \frac{h_i}{24} \tag{3}$$

The power output of WT of P_{wi} also occurs in h_i(hours) and this power state causes the voltage at the j^{th} node is U_i^j. The number of hours occurring U_i^j is also h_i(hours).

In a day, suppose that we have w state of wind speed and hence, the voltage at the j^{th} node also has w state. The median value of the j^{th} node voltage in a day is,

$$\bar{U}^j = \frac{1}{\sum_{i=1}^{w} h_i}\sum_{i=1}^{w} U_i^j h_i = \sum_{i=1}^{w} U_i^j \frac{h_i}{\sum_{i=1}^{w} h_i} = \sum_{i=1}^{w} U_i^j \wp_i \tag{4}$$

and hence, the variance of voltage is defined,

$$\delta_j^{\ 2} = \frac{\sum_{i=1}^{w} h_i (U_i^j - \bar{U}^j)^2}{\sum_{i=1}^{w} h_i} = \sum_{i=1}^{w} \frac{h_i}{\sum_{i=1}^{w} h_i}(U_i^j - \bar{U}^j)^2 = \sum_{i=1}^{w} \wp_i (U_i^j - \bar{U}^j)^2 \tag{5}$$

2.2. Optimal problem

To choose the position of WT such that the voltage variance is minimized, we state the optimal problem as,

$$\delta_{max}^2 = \max\left\{\delta_1^{t_{max}\,2},\ \delta_2^{t_{max}\,2}, \dots, \delta_{j_{max}}^{t_{max}\,2}\right\} = f(v^{t_{max}}) \to min \tag{6}$$

subject to,

$$n^h \leq n_{max}^h \quad (7)$$

$$U_{min}^j \leq U^j \leq U_{max}^j \quad (8)$$

$$I^{lj} \leq I_{max}^{lj} \quad (9)$$

$$TDH_v \leq 5\% \quad (10)$$

$$\Delta E \leq \Delta E_{based} \quad (11)$$

where, j_{max} is the number of nodes in the grid; t_{max} is the maximum WT number needing to install; $v^{t_{max}}$ is the position of t_{max} WTs in the set ℵ; $n^i$and n_{max}^h are respectively the WT number and its maximum value at the h^{th} node in the set ℵ; U^j is the voltage at the j^{th} node in the grid and it must be between U_{min} and U_{max}; I^{lj} is the current flowing from the l^{th} node to the j^{th} node and it must be below I_{max}^{lj}; ΔE and ΔE_{based} are respectively the energy loss in the grid after installing WTs and that in the case of without WT. Here, the objective function, $f(v^{t_{max}})$, is a function of WT position, which effects on the voltage variance at nodes. To obtain the cost function, we choose the WT position step-by-step. To select the best location of the t^{th} WT, we use the sub-optimal problem as,

$${\delta_{max}^t}^2 = \max\left\{{\delta_{max,1}^t}^2,\ {\delta_{max,2}^t}^2, \dots, {\delta_{max,h_{max}}^t}^2\right\} = g(v^t) \to min \quad (12)$$

such that (7)-(10) and (13) are satisfied,

$$\Delta E_t \leq \Delta E_{t-1} \quad (13)$$

where, ${\delta_{max,h}^t}^2$ and ΔE_t are the voltage variances at the j^{th} node, the maximum voltage variance in the grid, and the grid's electrical loss as the t^{th} WT occurs at the position v^t in the set ℵ, respectively. The maximum voltage variance value in the grid when the t^{th} WT occurs at the h^{th} node in the set ℵ is calculated from the variance at the j^{th} nodes, ${\delta_{j,h}^t}^2$, as (14).

$${\delta_{max,h}^t}^2 = \max\left\{{\delta_{1,h}^t}^2,\ {\delta_{2,h}^t}^2, \dots, {\delta_{j_{max},h}^t}^2\right\} \quad (14)$$

3. ALGORITHM PROPOSAL

The primary goal of this proposal is to calculate the best location of WT so that the maximal variance of voltage in the grid is minimal. In this algorithm, WTs are only installed in the set of WT node ℵ where the wind energy is exploitability, the WT number at each node is limited, and the invested WT number in total, t_{max}, is fore-given. Here, we consider the limit of THD_v in the grid. This algorithm is shown in Figure 1 in which Figure 1(a) is the main algorithm, Figure 1(b) is to select the best location of WT, and Figure 1(c) is to calculate the maximum voltage variance in the grid.

3.1. Main algorithm

- Step 1. We load the grid data, which consists of line data, load data, and the capacity limitation of lines; the set of WT nodes and the harmonic spectrum of WT; the power output probability of each node. We begin the first WT $t = 1$
- Step 2. We select the best location for the t^{th} WT, v^t. This step is going to be described by a sub-algorithm in subsection 3.2.
- Step 3. We verify the stopping criterion that the last WT was considered. If $t \geq t_{max}$, we move to the next WT in step 4, otherwise, this algorithm terminates.
- Step 4. We proceed to the next WT by incrementing t to $t + 1$ and then step 2 is turn back.

3.2. Algorithm to select the position of the t^{th} wind turbine

This algorithm allocates the position of the t^{th} WT such that the cost function (12) is achieved and constraints of (7)-(10) and (13) are satisfied. Here, we install the t^{th} WT at each node in the set ℵ step-by-step and the best location is the bus where the maximal voltage variance is minimized and constraints (7)-(10) and (13) are satisfied. It is noted that the WT number at each node cannot be over its capability. Figure 1(b) illustrates this algorithm and it is detailed as follows:

- Step 2.1. We begin the first element in $\aleph$, $h = 1$. It means the t^{th} WT is considered to install at the h^{th} node.
- Step 2.2. We check the constrain of the WT number limitation at the h^{th} node. If the existing WT number at the h^{th} node, n^h, is over its capability, n^h_{max}, step 2.3 is continued, otherwise, we proceed to step 2.4.
- Step 2.3. We set the maximum variance of node voltage in the grid when the t^{th} WT is installed at the h^{th} bus is the infinity, ${\delta^t_{max,h}}^2 = inf$.
- Step 2.4. We attach the t^{th} WT to the h^{th} bus.
- Step 2.5. We calculate the maximum variance of node voltage in the grid when we install the t^{th} WT at the h^{th} bus, ${\delta^t_{max,h}}^2$. To calculate ${\delta^t_{max,h}}^2$, we use the algorithm in Figure 1c and it is mentioned in subsection 3.3.
- Step 2.6. We verify whether or not all nodes in the set $\aleph$ is considered, $h \geq h_{max}$. If $h < h_{max}$, step 2.7 is proceeded, otherwise, step 2.8 is continued.
- Step 2.7. We continue the next element in $\aleph$ by setting $h = h + 1$ and after that, we loop back to step 2.2.
- Step 2.8. We identify the minimal value of the maximal voltage variance, ${\delta^t_{max}}^2$. We suppose that the minimal value of the maximal voltage variance occurs as WT is installed at the h^{th} bus, as (15). Hence, we set (16).

$$\min\left\{{\delta^t_{max,1}}^2, \ldots, {\delta^t_{max.hmax}}^2\right\} = {\delta^t_{max,h}}^2 \tag{15}$$

$${\delta^t_{max}}^2 = {\delta^t_{max,h}}^2 \tag{16}$$

- Step 2.9. We check ${\delta^t_{max}}^2$ comparing to the infinity value. If ${\delta^t_{max}}^2 \neq inf$, this implies that the best location for the t^{th} WT is the h^{th} bus and then step 2.10 is executed, otherwise, step 2.11 is continued.
- Step 2.10. We set the optimal position of the t^{th} WT is the h^{th} node in the set $\aleph$, $v^t = \aleph\{h\}$, and hence, the WT number in total at this node is set n^h= n^h+1.
- Step 2.11. We cannot choose a optimal position of this WT. The reason is that constraints are violated when this WT is connected to any node in the set $\aleph$. Hence, the optimal position of this WT, v^t, is empty, $v^t = \emptyset$, and we set $t = t_{max}$ to finish the main algorithm.

3.3. Algorithm to calculate the maximum variance of node voltage in the grid

This algorithm primarily aims to calculate the maximal voltage variance in the grid. To obtain this objective, for each combinatory of power generation, we must use the load follow algorithm for fundamental component and harmonic component to calculate the current on-line segments, the voltage and THD_v at nodes in the grid. From these data, we calculate the variance of node voltage. The algorithm is shown in Figure 1(c).

- Step 2.5.1. We generate the group of power state combinators from m WT buses and the probability of each combinator can be calculated from the power state of WTs. The 1st combinator is started, $k = 1$.
- Step 2.5.2. We compute the power output of each WT bus from the generation state in the k^{th}combinator.
- Step 2.5.3. For the k^{th}combinator, the power flow algorithm is executed for the fundamental component and harmonic component [27], [28] to calculate the current on-line segments, the voltage $U^t_{j,h,k}$ and THD_v at nodes in the grid, the power loss on the grid, $\Delta P^t_{h,k}$.
- Step 2.5.4. We check all constraints (7)-(10). If all constraints are satisfied, we move to step 2.5.5, otherwise, we move to step 2.5.11.
- Step 2.5.5. We calculate the electrical energy loss in the grid,

$$\Delta E_k = \Delta E_{k-1} +, \Delta P^t_{h,k} \wp_k \tag{17}$$

- Step 2.5.6. Whether or not all combinators are considered ($k \geq c^m$), where $c^m$is the number of combinators. If $k < c^m$, step 2.5.7 is executed, otherwise, step 2.5.8 is continued.
- Step 2.5.7. We set $k = k + 1$ to continue the next combinator and after that, we proceed back to step 2.5.2.
- Step 2.5.8. We set $\Delta E_t = \Delta E_k$

- Step 2.5.9. We check the condition $\Delta E_t \leq \Delta E_{t-1}$. If it is satisfied, step 2.5.10 is proceeded, alternatively, Step 2.5.11 is carried out.
- Step 2.5.10. We calculate the mean voltage at all buses and then, the maximal voltage variance in the grid is achieved. From the voltage variance of all nodes, we can determine the maximum value of the voltage variance.
- Step 2.5.11. We set ${\delta^t_{max,h}}^2 = inf$ such that we cannot install the t^{th} WT to the h^{th} node.

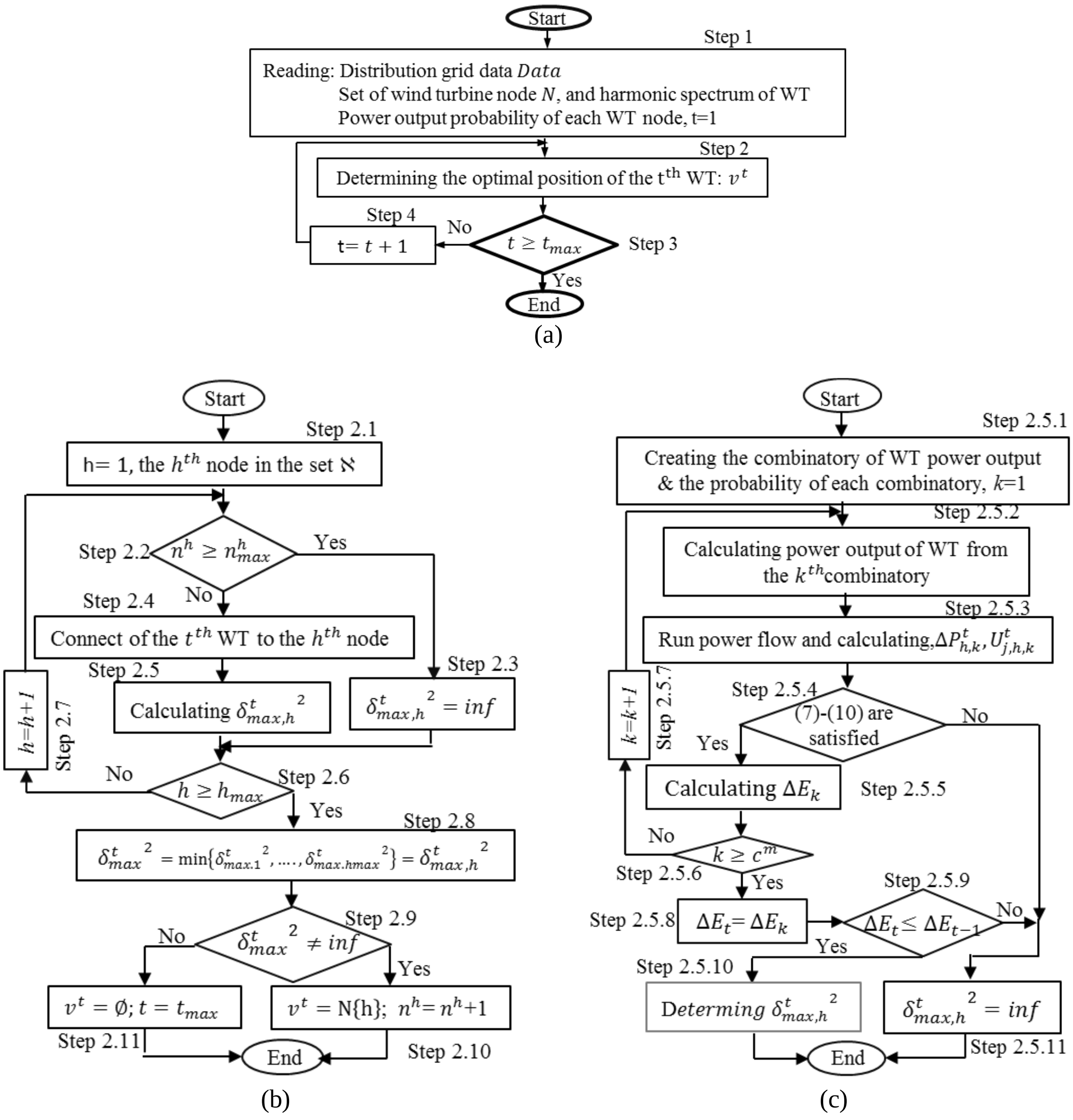


Figure 1. Algorithm to calculate the optimal WT position: (a) main algorithm, (b) algorithm to calculate the optimal position, and (c) algorithm to calculate maximum voltage variance in the grid

4. VERIFICATION AND DISCUSION

To validate the algorithm, we use a distribution grid sample, IEEE 33 bus, as Figure 2. Details of the grid data are available in [6]. We suppose that all loads in this grid are linear loads; wind energy exploitability at node in the set ℵ and the maximal WT number at each node are shown in Table 1; the power output probability at nodes is listed in Table 2 [29]. We suppose that the investigated WT number in total in the grid is 10, the full power converter-based WT is used, each WT's rating is 200 kW, and it operates at unity power factor. The harmonic spectrum of WT is shown in Table 3.

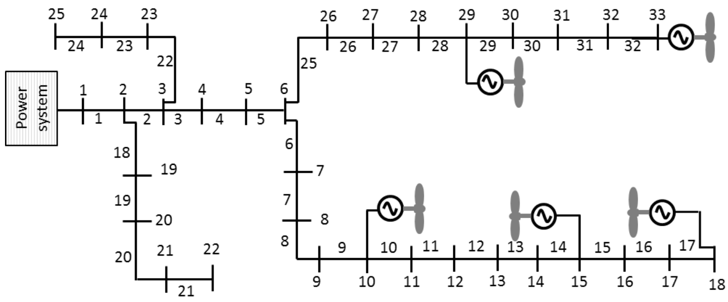


Figure 2. IEEE distribution grid with WT position

Table 1. Allowance WT number at nodes

Node	10th node	15th node	18nd node	29th node	33rd node
Maximum WT number	3	5	6	4	7

Table 2. Probability of generation state at nodes [29]

Generation state	10th node	15th node	18nd node	29th 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%

Table 3. Harmonic spectrum of WT

Harmonic order	Magnitude (%)	Phase(deg.)	Harmonic order	Magnitude (%)	Phase(deg.)
3	20	-15.29	11	5	140.6
5	15	-20.74	13	3	65.54
7	10	-80.35	15	2	153.28
9	8	140.36			

4.1. With THD_v consideration

In this subsection, we consider the limitation of THD_v at nodes. With the allowance THD_v value of 5% [30], the results are shown in Table 4. Obviously, only 8 WTs are suggested to be installed in this grid. The 29th node is suggested to install 4 WTs while the 18th node is not allowed to install. With eight WTs recommended in this table, the maximum voltage variance is 74.85×10^{-6}pu and the voltage at nodes is shown in Figure 3; the maximum THD_v value is approximate to the limitation value, 4.9563%; the electrical energy loss is 10,722 MWh which is reduced 5,097 MWh comparing to the case of without WT installation. Figure 3 shows the maximum voltage, median voltage, and minimum voltage at nodes in the grid. Obviously, the voltage at nodes remains within the operating range of 0.95 pu to 1.05 pu; the median voltage at nodes from the 10th node to 18th node and from the 29th node to the 33rd node is below 1 pu while that of other nodes is over 1 pu.

Table 4. Verifying results

Node	10	15	18	29	33
WT number	2	1	0	4	1
Maximal voltage variance $\delta^2_{max}(10^{-6}pu)$			74.85		
Maximum THD_v(%)			4.9563		
Energy loss (10^3 MWh)			1.0722		

The priority order to install WTs is shown in Table 5. The first WT should be installed at the 29th node and with this WT, the maximal value of voltage variance and maximal THD_v in the grid is insignificant. The next WT is suggested at the 10th node and the occurrence of the next WTs makes the maximal voltage variance value and the maximal THD_v value in the grid increases significantly. This indicates that the higher the WT number, the worse the voltage quality at nodes becomes. However, the grid's electrical loss is improved when the WT number increases.

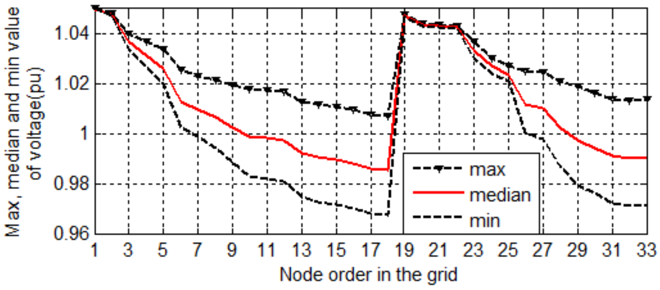


Figure 3. Maximum, median, and minimum voltage values in the grid

Table 5. Priority order to install WT

Order	Node	$\delta^2_{max,t}$ (10^{-6} pu)	TDH_v (%)	ΔE_t (10^3 MWh)	Order	Node	$\delta^2_{max,t}$ (10^{-6} pu)	TDH_v (%)	ΔE_t (10^3 MWh)
1	29	0.40	0.7694	1.5126	5	29	25.56	3.3194	1.2680
2	10	5.53	1.1954	1.4353	6	10	36.05	4.0074	1.2147
3	33	12.74	2.3103	1.3456	7	29	47.68	4.2903	1.1563
4	15	19.70	2.9256	1.2680	8	29	74.85	4.9563	1.1113

4.2. Impact of harmonic distortion on determining the optimal position of wind turbine

To evaluate the impact of harmonic current injected by WT on selecting the best location of WT in the grid, we compare the verifying results of two cases. The first case is with THD_v consideration and the second one is without THD_v consideration. Comparison results are shown in Table 6, Table 7, and Figure 4.

Table 6. Comparing results

Case	With THD_v consideration					Without THD_v consideration				
Node	10	15	18	29	33	10	15	18	29	33
WT number	2	1	0	4	1	3	1	1	3	2
Maximal voltage variance δ^2_{max}(10^{-6} pu)	74.85					86.45				
Maximum THD_v(%)	4.9563					7.1410				
Energy loss (10^3 MWh)	1.0722					0.9512				

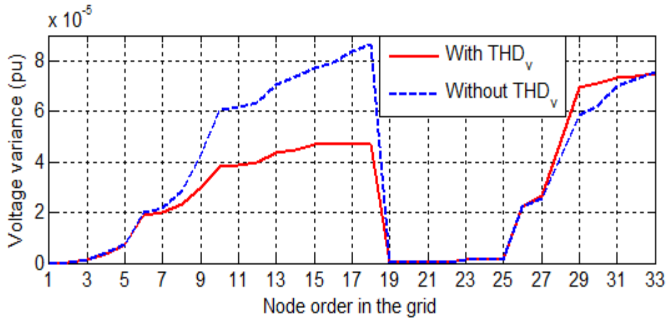
Table 7. Installing order of WT

Order	With THD_v consideration				Without THD_v consideration			
	Node	$\delta^2_{max,t}$ (10^{-6} pu)	TDH_v (%)	ΔE_t (10^3 MWh)	Node	$\delta^2_{max,t}$ (10^{-6} pu)	TDH_v (%)	ΔE_t (10^3 MWh)
1	29	0.40	0.7694	1.5126	29	0.40	0.7694	1.5126
2	10	5.53	1.1954	1.4353	10	5.53	1.1954	1.4353
3	33	12.74	2.3103	1.3456	33	12.74	2.3103	1.3456
4	15	19.70	2.9256	1.2680	15	19.70	2.9256	1.2680
5	29	25.56	3.3194	1.2147	29	25.56	3.3194	1.2147
6	10	36.05	4.0074	1.1563	10	36.05	4.0074	1.1563
7	29	47.68	4.2903	1.1113	29	47.68	4.2903	1.1113
8	29	74.85	4.9563	1.0722	18	61.69	6.1668	1.0511
9					33	71.48	6.4292	0.9921
10					10	86.45	7.1410	0.9512

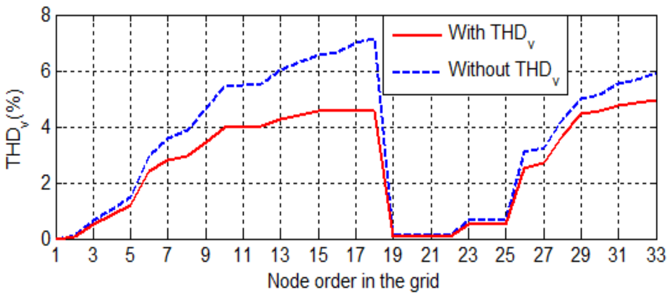
Considering to the THD_v limitation affects the optimal position of WTs, WT number in total, and the grid performance. Firstly, in the first case, the suggested WT number is lower than in the second case. For the first case, we only install 8 WTs while in the second case, the data is equal to the available WT number, 10 WTs. Secondly, the WT number at nodes is different. For the second case, it is able to install WT at the 18th node while for the first case, it is impossible because this WT contributes to increasing the THD_v value. Finally, the electrical loss reduction in the grid is worse. In the second case, the energy loss is 951.2 MWh while in the first case, this data is up to 1072.2 MWh. This is because the WT number in the two cases is different. However, the voltage quality in the first case is better than that in the second case. Obviously, in the second case, TDH_v value is over allowance value 5% and the maximum voltage variance in the grid is up to 86.45× 10^{-6} pu while the data is only 4.9563% and 74.85× 10^{-6} pu, respectively.

Considering to the THD_v limitation also affects the priority order of WT installation, as shown in Table 7. There is a difference in the priority order of WT installation between the two cases, especially from the 8th WT. For the first case, the 29th node is recommended to install while for the second case, the 18th node is prioritized. Because WT installed at the 18th node contributes to the THD_v value high while the voltage variance and energy loss are lower than that installed the 29th node. Hence, two last WTs cannot be allowed to install in the grid if the THD_v value is limited at 5%.

With the WT number suggested in Table 6, the voltage variance and THD_v at nodes in the grid is shown in Figure 4. Considering to THD_v limitation has an impact on the performance of the voltage variance and THD_v value at nodes. Obviously, with the second case, the voltage variance is significantly different from that with the first case, especially nodes on the branches where WTs are suggested to be installed, Figure 4(a). The higher the WT number, the higher the voltage variance is. Take, for instance, the branch from the 28th node to the 32nd node. In the first case, the voltage variance is higher than that of the second case because of the higher WT number at the 29th node. In the second case, the maximum voltage variance is observed at the 18th node, whereas in the first case, it occurs at the 33rd node. Unlikely, in the first case, the THD_v value at almost nodes is lower compared to the second case. The 33rd node is the highest value of THD_v in the first case while in the second case, the 18th node owns the highest THD_v value, Figure 4(b).



(a)



(b)

Figure 4. Comparing result of (a) voltage variance and (b) THD_vvalue at nodes

5. CONCLUSION

This research suggested a flowchart to allocate the optimal position of WTs in a distribution grid such that the maximum voltage variance in the grid is minimized. In this research, we consider the harmonic current injected by WTs and the limitation of THD_v at nodes in the grid. We verified this algorithm via IEEE 33 bus distribution grid. The verifying results indicated that the optimal position of WT such that the cost function is archived, the grid is operated in allowance condition, and the energy loss is reduced significantly. We also indicated that the consideration of THD_v limitation impacts on calculating the optimal position of WT and the grid performance after WTs are connected.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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Dinh Truc Ha		✓	✓	✓				✓	✓	✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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