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Reactive Power Allocation Method in a Wind Farm for Improved Voltage Profile and Loss Reduction

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ABSTRACT:
Recently, the reactive power control for wind farm is required with the rapidly increasing integration of wind energy. In general, the two main objectives of the reactive power control are the power loss reduction and offering rapid reactive power support to power grid during fault. This paper focuses on the steady-steady reactive power control of wind turbine generators to achieve the economical operation of a wind farm. It aims to improve the voltage profile within a wind farm to reduce the action of voltage regulation equipment, thereby reduces operation costs. Meanwhile, the conventional control objective, like power loss reduction, is also taken into consideration. To achieve the above goals, four optimal reactive power allocation methods are proposed and formulated as a quadratic programming problem using the linearized relationship between the voltage and reactive power. To verify the performance, a comprehensive wind farm model with 40 WTGs is developed for simulation. The effectiveness of the proposed reactive power allocation method is verified compared with the conventional even allocation method. Moreover, the simulations with 100 different scenarios considering the reactive power reference and wind speed are conducted to demonstrate the feasibility and reliability.

Keywords – Wind farm operation, Reactive power allocation, OLTC, Loess reduction, Voltage profile improvement

I. INTRODUCTION

Wind energy is one of the major renewable energy sources and more and more wind farms have been constructed. According to the world wind farm database, approximately 19,000 wind farms are constructed in the world with total capacity of 675.6 GW [1]. As the wind power capacity has been increasing, power system also faces with a lot of challenges, such as power quality, voltage variation, voltage dip, harmonics and flickers and so on [2]. Benefitting from the modern wind turbines and power electronic technologies, reactive power control is the major solution to fulfill the requirements of dynamic voltage stability described in grid codes. Reference [3] described reactive power management of wind farm in most technical and economical way considering the wind turbine technology. The significance of reactive power control in the wind farm has been reported in many literatures. For example, wind turbine generators (WTGs) are generally required to have the ability to subject to high voltage ride through and low voltage ride through during grid fault [4-5]. From the viewpoint of system operation, reactive power control of wind farm is also used to reduce the power losses and improve the voltage profile [6].

From the perspective of means to implement reactive power control of wind farm, static synchronous compensators (STATCOM), static VAR compensator (SVC) and other devices are showing excellent control performance. For example, STATCOM provides better damping characteristics, which is the best suited for dynamic stability [7]. Moreover, SVC is able to regulate the voltage and stabilize the system and it can bring the system closer to unity power factor. However, it is not suitable for the case of high wind power generation [8]. In addition, these devices greatly increase the wind farm costs. Therefore, it is a highly feasible and economical solution to utilize fully the inherent reactive power control capability of WTGs. However, distributed and local control of wind farm can make configuration complex, and has a big difficulty in following the grid code requirements. Thus, many researcher proposed centralized control strategy [9-10]. In the centralized control strategy, the principle to allocate the reactive power requirement at the point of common coupling (PCC) and designate the reference signal to each single WTG in the wind farm is very important. In fact, optimal reactive power allocation is not only mentioned for wind farm control, but also for the conventional distribution system. For example, a novel allocation method of reactive power, which takes the production cost and transmission cost into consideration at the same time, is proposed in [11]. Similarly, several reactive power allocation methods for wind farm are also proposed in [12-15]. In [12], even allocation is proposed where each wind turbine generator will be controlled with the average reactive power reference value. It is very simple to implement. However, every WTG in the wind farm may not has the same operation state, thus even allocation cannot fully take into account the capability of individual WTGs and hardly achieve economical operation of wind farm. The proportional allocation, where each WTG will be designated the reactive power reference value by proportion principle referring to the capacity limit of each WTG, has been proposed in [13]. By this method, the voltage profile of wind farm has not been taken into consideration, thus the burden of voltage regulating devices is increasing. There are also several allocation methods with the objective of minimizing the power loss, but the lifetime cost of devices is not considered [14-15].

The economical operation of wind farms is undoubtedly a key factor. Generally, the OLTC is an appropriate means to achieve the goal of regulating the voltage of wind farm. As it is a mechanical device, its lifetime directly affects economic efficiency. The rational and improved voltage profile in wind farm can reduce the burden on these devices. Therefore, improvement of voltage profile is imperative. Benefitting from the close relationship between the terminal voltage and reactive power flow of WTG, an appropriate reactive power allocation and control means is enough to achieve the goal of improvement of voltage profile. Herein, the primary focus is reducing the number of tap changer operation through improving voltage profile within wind farm by using a novel reactive power allocation method. Meanwhile, the power loss is also considered. This is formulated as a quadratic programming problem, where the goals of OLTC operation times reduction and power loss reduction is not formulated into objective function directly. Instead, the relationship between voltage and reactive power is linearized and fully utilized.

The remaining part of this paper is organized as follows: a developed offshore wind farm model with 40 WTGs is descripted in detail in section 2 and it may provide some parameter reference for other researchers, and section 3 discusses and analyzes the proposed reactive power allocation methods and their formulations. In section 4, the simulation results illustrate the feasibility and effectiveness of proposed reactive power allocation method. Moreover, different wind directions' wake effects are also considered and analyzed. Finally, section 5 will draw the conclusion for the research.

II. Wind Farm Model

II.I Wind Farm Configuration

Wind farm can be modelled differently according to the objective of the research. When the effect of wind farms on the transmission system is the main concern, wind farm is usually represented by one aggregated generator driven by a single equivalent wind turbine [16-17]. On the contrary, a complete wind farm model with an exact number of WTGs is preferred for wind farm controller design studies [12]. In this paper, a detailed wind farm model composed of 40 GE 3.6MW wind turbines is used. The configuration and the parameters, including bus numbers, are shown in Fig 1. The wind farm consists of five radials, where eight WTGs are installed in each radial. The 33kV cables are used to connect each radial to the offshore platform bus. The offshore transformer installed at offshore platform is used to step up the voltage from the 33kV of wind farm to 150kV of the submarine cable for high voltage transmission. The data for the offshore transformer are summarized in Table 1.

II.II Offshore Transmission System

Many large scale offshore wind farms have been built in the last decade, such as Horns Rev of Denmark, North Hoyle of the UK and so on [18]. For large wind farms, offshore substations are required for stepping up the voltage level and for converting the power to HVDC. The choice of appropriate design and technology for the transmission system can be a crucial factor of the offshore wind farm projects [19]. In this paper, a 20 km HVAC transmission is assumed which is based on the report from the real wind farm projects [18]. The HVAC cable adopts 150 kV XLPE and its technical data are summarized in Table 2.

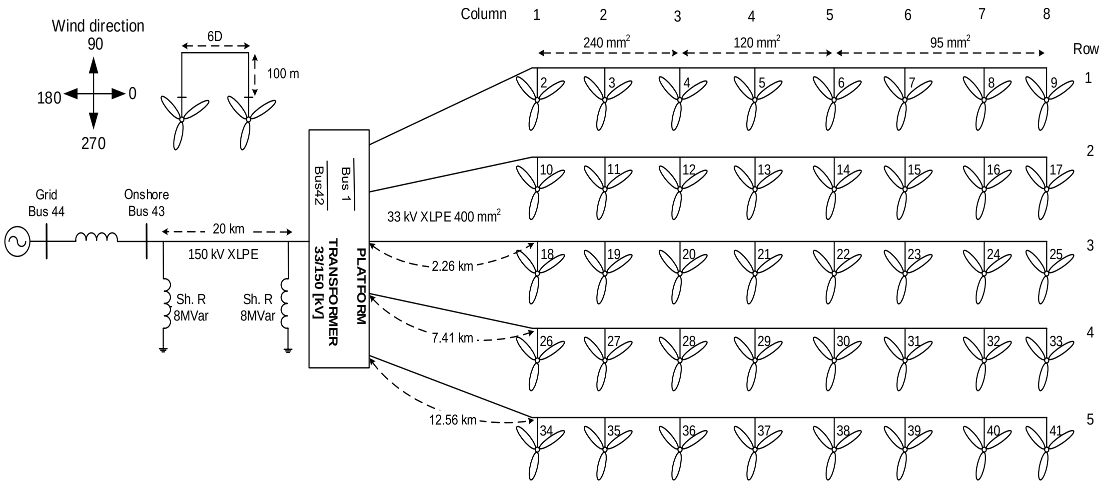

Fig. 1. Wind farm configuration

The generation of large amounts of reactive power is a major limiting factor in the use of HVAC cables in long distance transmission systems [19-20]. Therefore, consideration of the effect of reactive power generation induced by HVAC is necessary. An estimation of the reactive power generation by the 150 kV HVAC can be calculated based on equation (1) [20]

$$Q = \omega \times C \times l \times V^2 \tag{1}$$

where ω is the angular frequency, C is the capacitance, l is the length and V is the voltage. In fact, compensation only at the onshore end is possible, but adding compensation both sides can greatly improve the current profile along the HVAC link, consequently transmission loss can be reduced. Therefore, two 8 MVar shunt reactors are installed at both ends to compensate for the 60% of the estimated reactive power generated in the cable.

II.III Wind Farm Cable Selection

Larger conductor cross-section gives less loss and higher power rating, but it is more expensive. When sizing cables, it is often preferred to size the largest cable first and choose the size for the intermediate and small cables in sequence. In this wind farm model, the largest cables are connected between the offshore platform and the first wind turbine of each radial by using 400 mm^2 cables. The length of the cables from the offshore platform to each radial is shown in Fig 1, and technical data are shown in Table 3. Based on the power rating, the cable in each radial is divided into three different sizes [21]. The first two cables from column 1 to 3 adopt a cross section of 240 mm^2, and 120 mm^2 cables are adopted for the cables from column 3 to 5. The last three cables were selected to support three wind turbines with the 95 mm^2 cross section.

The distance between each wind turbine is assumed to be six rotor diameters, where the rotor diameter is 104 m. The distance from seabed to the wind turbine is 100 m and the cable length at seabed should include 3% slack of the distance at seabed [21]. Thus, the length of the cables between any two wind turbines is 0.8427 km. The impedance data for the cables in each radial are given in Table 4.

Table 1. Offshore transformer data

Bus From	Bus To	Rated voltage [kV]	Power rating [MVA]	Rated impedance [%]
1	42	33/150	160	13.8

Table 2. 150 kV HVAC XLPE cable data

Bus number	Length [km]	R [Ω]	L [ohm]	C [uF]
42-43	20	0.78	2.40	3.80

Table 3. Data for the cables between the offshore platform and the radials

Bus number	Length [km]	R [ohm]	L [ohm]	C [uF]
1-2/1-34	12.56	0.7536	1.3810	3.5168
1-10/1-26	7.41	0.4460	0.8148	2.0748
1-18	2.26	0.1356	0.2485	0.6328

Table 4. Data for the cables between wind turbines

Cross-Section [mm^2]	Power rating [MVA]	R [ohm]	L [ohm]	C [uF]
95	15.8	0.2023	0.11643	0.13483
120	18.6	0.1685	0.10857	0.15169
240	29.3	0.0843	0.09796	0.19383

III. Reactive Power Allocation Methods

Fig 2 illustrates the reactive power allocation scheme based on the centralized control strategy for a wind farm. First, the reactive power requirement at the PCC (Q_{WF}^*) is determined by the transmission system operator (TSO). After that, the wind farm controller allocates the reactive power requirement and dispatches it to each WTG. Herein, the simplest and conventional allocation method, even allocation method, will be used as benchmark [12], which are further elaborated based on equation (2)

$$Q_{ref,WT_i} = \frac{1}{N_{WT}} Q_{WF}^* \tag{2}$$

where, Q_{ref,WT_i} is the reactive power reference value of each WTG received from wind farm controller and N_{WT} is the total number of WTGs in a wind farm. As mentioned in section 1, the voltage profiles of WTG buses are mainly dependent on the active and reactive power flow of each WTG. Therefore, the steady state voltage profiles of WTGs can be improved by proper reactive power allocation. With improved voltage profiles, the number of switching operation of tap changing transformer and/or capacitors and reactors can be reduced and the power loss in the wind farm can also be decreased. Considering the above mentioned purposes, four reactive power allocation methods are proposed and analyzed.

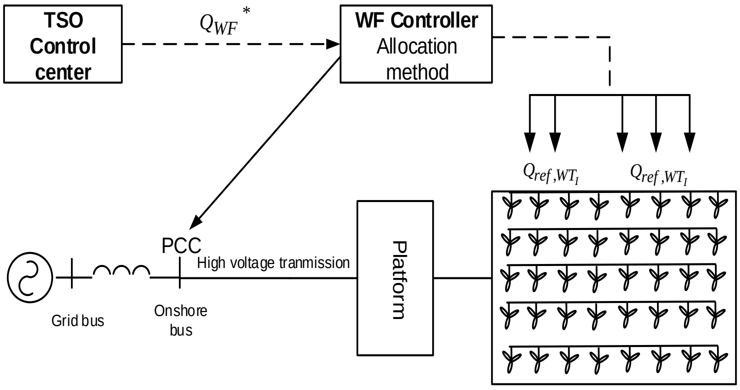

Fig. 2. Schematic of centralized wind farm reactive power allocation

III.I Reactive Power Allocation Method 1

The objective of the method 1 is to make the terminal voltage of each WTG as close to the wind farm average voltage value (V_{avg}) as possible. Because of the impedance of the transmission line in wind farm, the terminal voltage of WTGs along any radial line will show a monotonically increasing profile. The objective of method 1 is to make the voltage profile in each radial as flat as possible. The OLTC installed at offshore platform is used to regulate the voltages of wind farm. If the voltage of any point violates, the OLTC will change its tap position to pull it back to allowable range. Therefore, an improved voltage profile can reduce the number of OLTC operation, which can lengthen its lifetime, thus economic effectiveness can be achieved. The process of reactive power allocation to each WTG can be formulated as follows. The objective function is presented as equation (3)

$$\min \ \sum_{i=1}^{N_{WT}} \left(V_i - V_{avg}\right)^2 \tag{3}$$

where, V_i is the terminal voltage of the i^{th} WTG.

The constraints are given in equations (4) – (6).

$$\sum_{i=1}^{N_{WT}} Q_j = Q_{WF}^* \tag{4}$$

$$Q_j^{min} \le Q_j \le Q_j^{max} \tag{5}$$

$$V_{i,min} \le V_i \le V_{i,max} \tag{6}$$

The sum of reactive power reference signal (Q_j) allocated to each WTG should be equal to the reactive power requirement (Q_{WF}^*) at PCC to meet the grid requirements. The voltages of WTGs should be maintained within the upper ($V_{i,max}$) and lower ($V_{i,min}$) limits, and the reactive power reference signal for each WTG should be within the capacity limits (Q_j^{max} and Q_j^{min}).

In order to solve the above optimization problem, the linearized relationship between the reactive power and the voltage, given in equation (7), is used

$$\Delta V_i = V_i - V_{i,0} = \sum_{j=1}^{N_{WT}} \mathrm{Z}(i,j)\Delta Q_j \tag{7}$$

where, $\mathrm{Z}(i,j)$ is the element of the sensitivity matrix, and represents the sensitivity between the voltage at bus *i* and the reactive power value of the WTG *j*. ΔV_i represents the voltage change from the initial voltage ($V_{i,0}$) after the reactive power control. The constraints (4) – (6) can be transformed into equations (8) – (10)

$$\sum_{j=1}^{N_{WT}} \Delta Q_j = \Delta Q_{WF}^{*} \tag{8}$$

$$\Delta \mathrm{Q}_{\mathrm{j}}^{\min} \leq \Delta \mathrm{Q}_{\mathrm{j}} \leq \Delta \mathrm{Q}_{\mathrm{j}}^{\max} \tag{9}$$

$$V_{i,min} - V_{i,0} \leq \sum_{j=1}^{N_{WT}} \mathbf{Z}(i,j)\Delta Q_j \leq V_{i,max} - V_{i,0} \tag{10}$$

where, ΔQ_{WF}^{*} is the variation of the reactive power requirement at PCC for the wind farm. ΔQ_j is the reactive power variation of WTG *j*.

The problem is formulated as a quadratic programming problem whose general form is given in (11) – (14).

$$\min \ \frac{1}{2} x^T H x + f^T x \tag{11}$$

$$A \cdot x \leq b \tag{12}$$

$$A_{eq} \cdot x = b_{eq} \tag{13}$$

$$l_b \leq x \leq u_b \tag{14}$$

Reactive power reference values designated to each WTG are defined as *x* in equation (15) and the matrix *H* and vector *f* of the objective function are given by equations (16) and (17).

$$x = \left[\Delta Q_1, \Delta Q_2, \cdots, \Delta Q_{N_{WT}}\right]^T \tag{15}$$

$$H(m,n) = \sum_{K=1}^{N_{BUS}} K(k,m) * K(k,n) \tag{16}$$

$$f(m) = \sum_{k=1}^{N_{BUS}} K(k,m) * \left(V_{k,0} - V_{avg,0}\right) \tag{17}$$

Where, $V_{avg,0}$ is the initial average voltage. *K* is the modified sensitivity matrix, and it is used to represent the sensitivity between the voltage at bus i and the reactive power value of the WTG *j* whose elements are calculated form the matrix *Z* as follows.

$$K(i,j) = Z(i,j) - \frac{1}{N_{WT}} \sum_{i=1}^{N_{WT}} Z(i,j) \tag{18}$$

The inequality constrains are given as follows.

$$A(i,j) = \begin{cases} Z(i,j) & 1 \leq i \leq N_{WT} \\ -Z(i - N_{WT}, j) & N_{WT} + 1 \leq i \leq 2N_{WT} \end{cases} \tag{19}$$

$$b(i) = \begin{cases} V_{max} - V_{i,0} & 1 \leq i \leq N_{WT} \\ V_{(i-N_{WT}),0} - V_{min} & N_{WT} + 1 \leq i \leq 2N_{WT} \end{cases} \tag{20}$$

Finally, the equality constrains are represented as follows.

$$A_{eq} = [1,1,\cdots,1] \tag{21}$$

$$b_{eq} = \Delta Q_{WF}^{*} \tag{22}$$

III.II Reactive Power Allocation Method 2

The objective function of the proposed allocation method 2 is the same as that of the method 1, which makes the terminal voltages of WTGs as close to the average voltage of wind farm as possible. However, in this method, the reactive power limit of each WTG is set according to the sign of the wind farm reactive power reference. If the wind farm is required to supply the reactive power to the grid, i.e. $Q_{WF}^{*} > 0$, each WTG is required not to absorb the reactive power. In the opposite case, all WTGs are required not to supply the reactive power. This is because that the improvement of the voltage profile by using allocating reactive power may induce unnecessary reactive power current along the cable. Without this restriction, unnecessary reactive current flowing between WTGs can increase power loss. The formulations are the same as those mentioned in the method 1, except the constraint (5) is changed to (23).

$$\begin{cases} 0 \le Q_j \le Q_j^{max} & Q_{WF}^{*} \ge 0 \\ Q_j^{min} \le Q_j \le 0 & Q_{WF}^{*} < 0 \end{cases} \tag{23}$$

III.III Reactive Power Allocation Method 3

Allocation method 3 is proposed to try to make the terminal voltages of WTGs closer to the upper limit (V_{max}). As well known, the power loss in a wind farm has a close relationship with the impedance and current of the cable. Due to the inverse relationship between voltage and current, higher terminal voltage decreases the cable current, thereby reducing the power loss [22]. The objective function can be formulated as equation (24), while the constraints are the same as equations (4), (6), and (23)

$$\min \sum_{i=1}^{N_{WT}} (V_i - V_{max})^2 \tag{24}$$

where, V_{max} is the maximum limit of the voltage in a wind farm. The equality and inequality constraints are identical to the equations (19) - (22). The matrix H and vector f of the objective function for this allocation method are given as follows.

$$H(m,n) = \sum_{K=1}^{N_{BUS}} Z(k,m) * Z(k,n) \tag{25}$$

$$f(m) = \sum_{k=1}^{N_{BUS}} Z(k,m) * (V_{k,0} - V_{max}) \tag{26}$$

III.IV Reactive Power Allocation Method 4

Allocation method 4 aims to coordinate the two concerned goals: to reduce the number of OLTC tap operation and to reduce the power loss. To further investigate the voltage profile and power loss in a wind farm, Fig. 3 illustrates five representative voltage profiles in a radial according to the reactive power control of WTGs. Line (a) represents a voltage profile when all WTGs operate in a unity power factor, where the voltage rise along the line is due to the active power of the WTGs. When the foremost WTG supplies or absorbs reactive power, the voltage rise/drop at each WTG terminal will be almost the same. Therefore, the lines (b) and (d) are parallel to line (a). On the contrary, when the hindmost WTG supplies or absorbs reactive power, the voltage rise/drop at each WTG terminal will be proportional to the length from the platform transformer, as presented in lines (c) and (e).

If the WTGs installed at the end of the radial supply or absorb the reactive power, the reactive current in the line will increase the power loss. Therefore, by allocating the required reactive power to the upstream WTGs, power loss due to the reactive current can be reduced. When $Q_{WF}^* > 0$, and the upstream WTGs supply the required reactive power, the voltage profile will be similar to line (b). On the contrary, the desired voltage profile will be like line (b) if $Q_{WF}^* < 0$. From the above analysis, a coordinated rule for combining the methods 2 and 3 according to the sing of Q_{WF}^* is proposed as follows:

$$\begin{cases} Proposed\ method\ 2 & Q_{WF}^* > 0 \\ Proposed\ method\ 3 & Q_{WF}^* < 0 \end{cases} \tag{27}$$

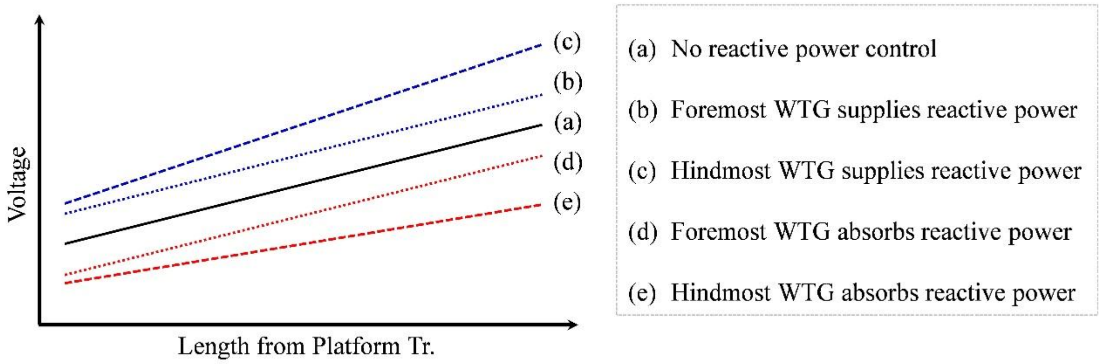

Fig. 3. Voltage profiles in a radial according to the reactive power control of WTGs

IV. Simulation Results and Discussion

In order to compare the performance of the proposed methods, simulations were conducted using the wind farm model presented in section 2. The wind speed and the wind farm reactive power reference are assumed to be changed every 15 min during 24 hours as shown in Fig 4. To take the wake effect into consideration, three different wind direction scenarios are included in the simulation. The wind direction is defined according to [23] and displayed in Fig 1. The minimum and maximum voltage limits of each WTG are set as 0.95 p.u. and 1.05 p.u., respectively. A simple rule is applied for the OLTC operation. The OLTC tap is adjusted step by step if there is no feasible solution due to the voltage limits. The simulation process is summarized in the flow chart of Fig 5. Five allocation methods, i.e. conventional even allocation method and the proposed methods 1–4, are applied for each simulation scenario. The power loss and the number of tap changer operation are analyzed.

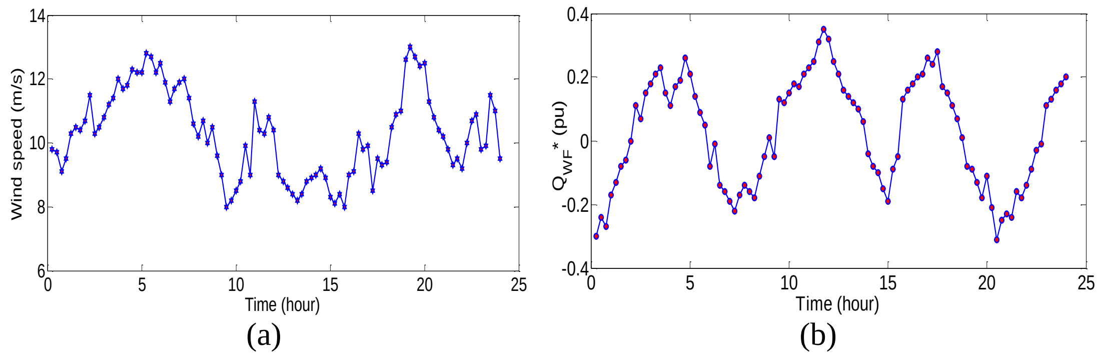

Fig. 4. Simulation scenarios: (a) wind speed, (b) wind farm reactive power reference

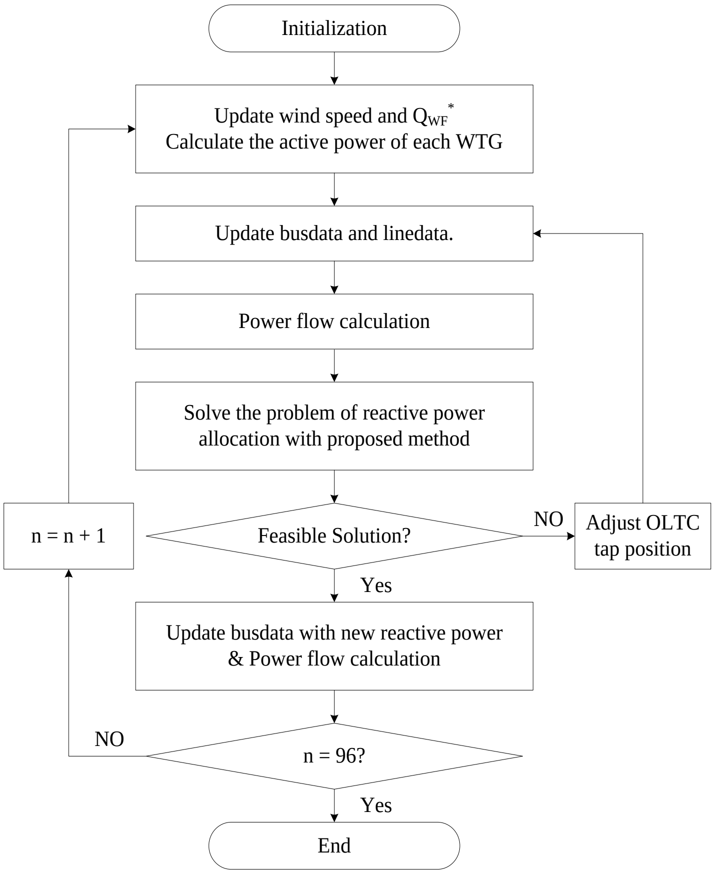

Fig. 5. Simulation flow chart

Fig 6 compares the voltage profiles of the wind farm when the even allocation method and proposed method 1 are applied. It obviously displays that the voltage profiles along each redial line under proposed method 1 is flatter than that of even allocation method. Moreover, the voltage difference among the radials is also decreased significantly. It means that the OLTC can more easily control the voltages of wind farm within the limit with less tap change. Table 5 summarizes the tap operation number (N_{Tap}) and the power loss in MWh of five allocation methods considering the effect of wind wake. The tap operation number of the proposed allocation method 1 was much smaller than that of the even allocation method, as desired. However, at price of it, loss was increased by 53.9% in average. With the proposed method 1, it was observed that some WTGs supply reactive power while some WTGs in the same radial absorb reactive power to make the voltage profile flattened. It means that the excessive reactive power transmission through the cable is the reason for the increased loss of the proposed method 1.

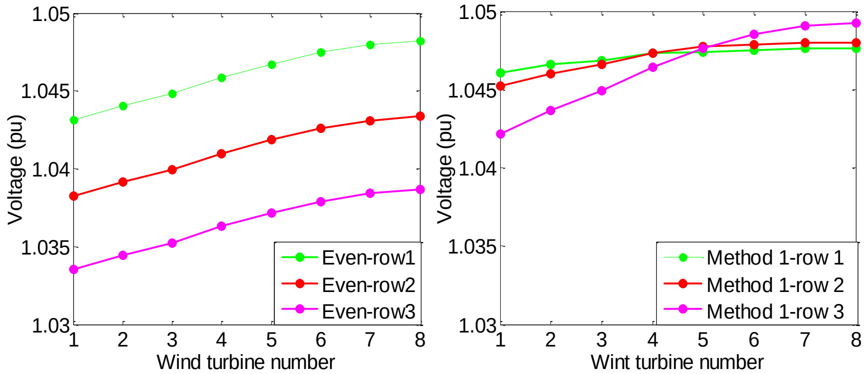

Fig. 6. Voltage profile under even method and proposed allocation method 1

Table 5. Tap changes and loss under various methods

Wind direction	Parameter	Even method	Proposed methods			
			method 1	method 2	method 3	method 4
w/o wake	N_{Tap}	19	14	15	17	15
	Loss (MWh)	5.13	7.45	5.67	5.47	5.18
0^o	N_{Tap}	15	10	10	14	12
	Loss (MWh)	3.39	5.29	3.79	3.68	3.34
90^o	N_{Tap}	19	10	11	15	13
	Loss (MWh)	3.16	4.98	3.66	3.59	3.21
180^o	N_{Tap}	13	10	10	12	10
	Loss (MWh)	1.85	3.10	2.16	2.15	1.84

The proposed method 2 showed a great improvement in reducing loss, while the tap operation number were the same or increased slightly compared to the proposed method 1. It is obvious that, by setting the reactive power limit of WTGs according to the value of Q_{WF}^*, unnecessary reactive current, and thus the loss, can be reduced. With the proposed method 3, more reduction was observed in loss compared to the method 2, but not as much as expected, whereas the increase of N_{Tap} was noticeable in every wind direction scenario. The additional tap changing operations were observed between hours 5 and 15, when Q_{WF}^*, changes in relatively low wind speed condition, as shown in Fig. 7.

Figure 8 displays the comparison of loss between the proposed methods 2 and 3. It was observed that the loss of method 2 was smaller than that of method 3 when the value of Q_{WF}^* is positive, while the situation was reversed for the negative Q_{WF}^* condition. The result provides the idea of method 4, which utilizes the methods 2 or 3 according to the sign of Q_{WF}^{*}. In the viewpoint of tap operation number, the performance of method 4 lies between those of method 2 and 3. However, the proposed method showed significant advantage in terms of loss reduction. The loss of method 4 was reduced by 11.2% and 8.9% compared to method 2 and method 3, respectively. Comparing to the even allocation method, the tap operation number of method 4 was decreased by between 20% and 31%, depending on the wind direction, while the loss was almost the same or even smaller.

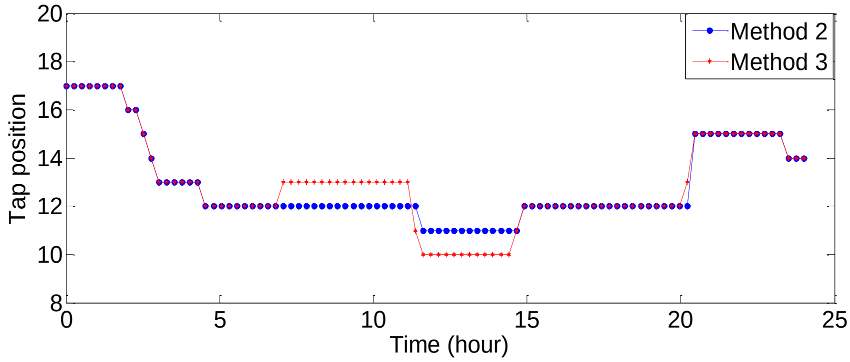

Fig. 7. Comparison of tap changing operation between the method 2 and method 3

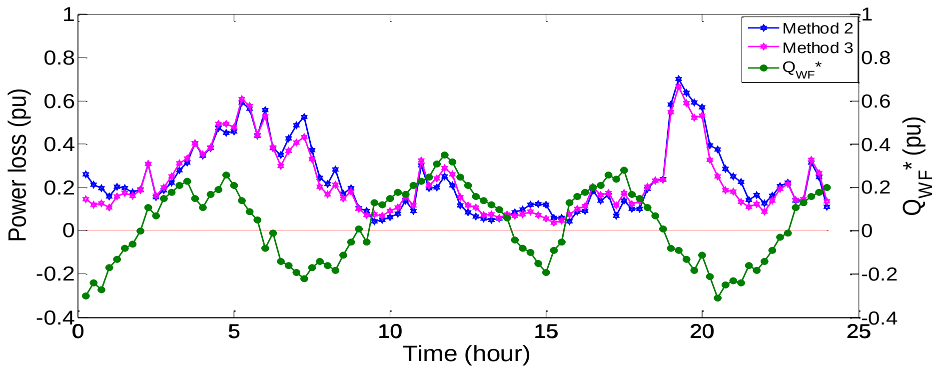

Fig. 8. Comparison of loss between the method 2 and method 3

To further verify the feasibility and reliability, 100 simulation cases with different wind farm reactive reference scenarios and wind speed scenarios are conducted. The 10 wind speed scenarios and 10 reactive power scenarios are shown in Figs 9 and 10, respectively. The simulation process was the same as shown in Fig 5, but only the wake effect of wind direction 0 is considered in this simulation. In accordance with the 100 experiment results, the average value of tap operation times and loss of the five allocation methods are summarized in Table 6. The result shows that the conclusion is the same as the case presented in Table 5. In other words, the proposed method 4 shows more advantages on coordinating the two goal of the tap operation reduction and power loss reduction at the same time.

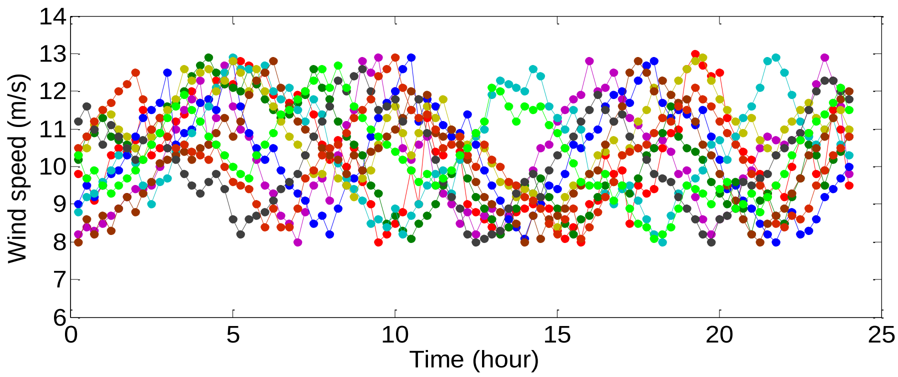

Fig. 9. Ten wind speed scenarios

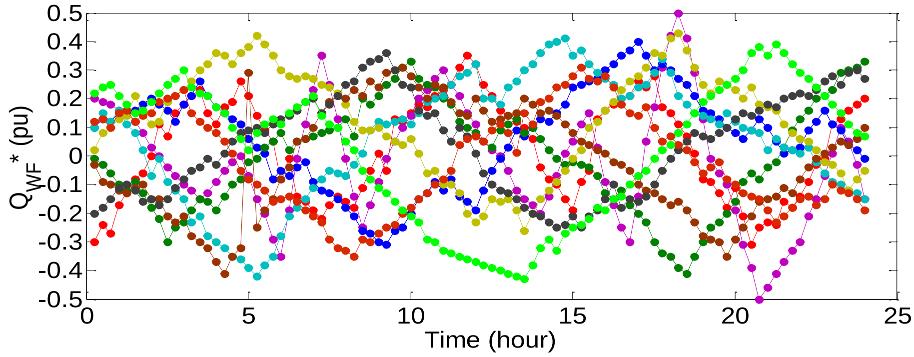

Fig. 10. Ten wind farm reactive power reference scenarios

Table 6. Average value of tap operation number and loss of five allocation methods

Items	Even	Proposed			
		1	2	3	4
N_{Tap}	23.8	18.5	19.2	21.3	19.8
Loss	3.59	5.48	3.99	3.92	3.57

In order to analyze and compare the performance of the proposed methods in more detail, the tap operation number and loss of the proposed methods were normalized to those of even allocation method. In other words, the performance based on even allocation method were regarded as the benchmark value 1.0. The distribution of normalized tap operation number and loss are shown as box-and-whisker plot in Fig. 11 (a) and (b), respectively. According to the result, it is obvious that method 1 shows the greatest advantage of reducing the tap operation number by nearly 21% but the power loss is the worst. Method 2 and method 3 are showing greater advantage of less power loss at the price of increased tap operation number, compared to the method 1. Besides, the upper whisker of proposed method 3 in Fig. 11 (a) is even bigger than 1.0, which means that the tap operation number under part of reactive power and wind speed scenarios were even larger than that of even allocation method. Although the method 4 is not the best one in terms of tap operation reduction, the value is reduced by nearly 16% compared to even allocation. Moreover, it is worth noting that the loss is the least compared to other proposed allocation methods and almost equal or even less than that of even allocation method. The smaller box range also shows that the proposed method 4 has stronger effectiveness.

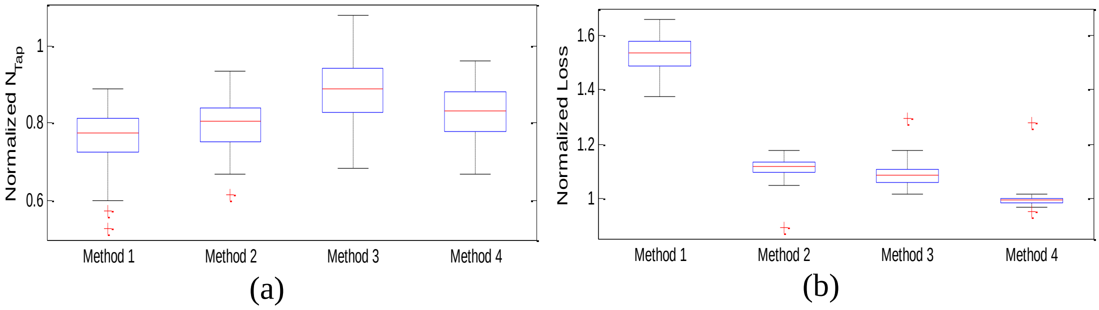

Fig. 11. Summary and comparison of 100 simulation cases: (a) distribution of normalized tap operation number, (b) distribution of normalized loss

V. CONCLUSION

In this paper, reactive power allocation methods of WTGs are developed to improve the economic effectiveness of the wind farm operation. The main objective is to reduce the number of OLTC operation by improving the voltage profile within the wind farm while the loss reduction is also considered. Four methods are developed step by step, and formulated as a quadratic programming problem. In the formulation, the number of tap operation and the power loss are not presented in the objective function directly. Instead, the objectives can be achieved by optimizing the voltage profile of WTGs terminals. Therefore, it is regarded as an optimization-based coordination approach. The proposed reactive power allocation method for wind farm can effectively reduce the operation burden of voltage regulating devices. Moreover, the economic efficiency of wind farm operation can be improved through the coordinated consideration of power loss and wind farm voltage profile improvement. The simulation results with 100 scenarios can fully confirm that the proposed reactive power allocation method for wind farms is effective, feasible, and stable.

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