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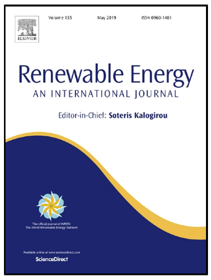

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Optimal Reactive Power Dispatch of a Full-Scale Converter Based Wind Farm Considering Loss Minimization

Ni Wang[1], Jian Li[1], Weihao Hu[1,*], Baohua Zhang[2], Qi Huang[1], Zhe Chen[3]

[1]School of Mechanical and Electrical Engineering, University of Electronic Science and Technology of China, Chengdu, China
[2]Envision, Shanghai, China
[3]Department of Energy Technology, Aalborg University, Aalborg, Denmark
wangni@std.uestc.edu.cn, leejian@uestc.edu.cn, whu@uestc.edu.cn, lordzbh@163.com, hwong@uestc.edu.cn, zch@et.aau.dk

*Author to whom correspondence should be addressed; E-Mail: whu@uestc.edu.cn; Tel.: +86-183-0280-9968

Abstract: With the development of wind power, wind farms are required to provide reactive power to the power system. For permanent magnet synchronous generator (PMSG) based large wind farms (WF), it may be an economical way to generate reactive power using the power electronic devices inside each wind turbine (WT). In this paper, an optimal reactive power dispatch of PMSG WF is proposed to minimize the power loss. Both the losses inside WTs and the losses of transmission system are all considered. Particle swarm optimization (PSO) algorithm is adopted to find the reactive power references of each WT which makes the total loss of WF minimal. A WF with 25 5MW PMSG WTs arranged in 5 rows and 5 columns is used in the case study. And two traditional reactive power dispatch strategies are compared comprehensively with the proposed strategy at different scenarios, the results have shown that that the proposed strategy obtains lower power loss than the other two traditional strategies in all the studied cases.

***Index Terms*—Reactive power dispatch, permanent magnet synchronous generator (PMSG), loss minimization, particle swarm optimization (PSO) algorithm.**

1. Introduction

With the development of wind power technology, the global cumulative and annual installed wind power capacity rises sharply in recent years. The 2016 market was more than 54.6 GW, bringing total global installed capacity to nearly 487 GW [1]. And the International Energy Association's World Energy Outlook predicts that wind power is going to be the leading source of electricity generation in 2040 [2]. With the expansion of the scale of wind farms, wind power capacity occupies an important proportion in the power system. The power system operators have developed the guidance of wind power grid technology [3], which requires the wind farm to have the ability to provide reactive power to support the Point of Common Coupling (PCC) voltage.

To meet the requirements of grid, it is a common method for wind farms to add reactive power sources at the PCC, like capacitor banks, Static Synchronous Compensators (STATCOMs), and Static Var Compensators (SVCs) [4]-[6]. Those methods are suitable for small wind farms of the wind farms with no power electronic devices equipped. The scale of wind farm is increasing. And the doubly fed induction generators (DFIG) and permanent magnet synchronous generators (PMSG) are widely adopted in wind farms recently. This makes that the wind farm (WF) could be a reactive power source because of the power electronic devices inside each wind turbines (WTs) [7]-[9]. In this way, the investment of a wind farm can be reduced by not using extra reactive power sources. Then, the reactive power dispatch between WTs needs to be solved. .

When the power system operator gives a reactive power reference to a WF at PCC, the WF controller gives reactive power references to each WT according to some reactive power dispatch strategy. The traditional strategy is proportional dispatch. Literature [10]-[13] use this strategy to distribute the reactive power reference of each WT according to their available reactive power capacities. It is easy to calculate and it can be ensured that the reactive power of each WT doesn't exceed the limit. Except the simplest strategy mentioned above, some optimization algorithms with different objective functions are used to make the reactive power dispatch meet various operation requirements, like minimizing losses [14] and maintaining voltage stability [15]. Literature [16] uses a Particle Swarm Optimization (PSO) algorithm combined with a feasible solution search (FSS) algorithm to meet the reactive power reference at PCC, while active power losses in a WF are minimized. Considering voltage stability, literature [17] presents a seeker optimization algorithm (SOA), simulating the act of human searching, updating the searching direction by the empirical gradient. Literature [18] adopts an evolutionary-based approach, and its simulation results prove that this method can minimize the power loss, improve the voltage profile, and enhance the voltage stability.

The losses of WF mainly come from the devices in the WF containing the transmission system within wind farm and WTs. The reactive power dispatch will change active power and reactive power flow, which will result in different active power losses of transmission system [19]. So literature [20] [21] adopt the optimal reactive power dispatch strategy aiming at minimizing the loss of transmission system, the objective function is the sum of the active power loss of cables and transformers, and then the optimal reactive power reference of each WT is found by using an optimization algorithm. Literature [22] introduces a reactive power assignment strategy to minimize the system loss caused by the power flow in the inner-grid of the wind farm, but only the loss of cables is considered in this paper. However, the losses inside the WTs are not considered in these articles, which is also a part of the total loss of WF. What's worse, the minimization of the loss of transmission system may cause the increasing of the losses inside WTs. So every part of WF should be taken into account to make the total loss of WF minimal.

In this paper, an optimal reactive power dispatch strategy of PMSG wind farm is proposed, aiming at loss minimization. The losses inside WTs and the losses of transmission system are both taken into account, including the loss of converters, filters, transformers and cables. And a PSO algorithm is adopt to assign the reactive power reference of WF to each WT, while ensure the objective function, the total loss of WF, minimal. And the proposed strategy is compared with other strategies in different scenarios to prove its superiority.

This paper is organized as follows. Section II gives the loss model of the WF. Section III introduces three kinds of reactive power dispatch strategies, concluding the proposed strategy. Section IV is the case study, the three strategies mentioned in Section III are compared in five different cases. Section V is the conclusion.

2. Wind Farm Loss Model

The total electrical power loss of a wind farm mainly comes from the losses inside WT and the losses of transmission system. Fig.1 shows the main components of a WF, which contains PMSG, converter, filter, transformer and the cables. In this section, the detail loss model of each part is specified. Actually, the loss of the generator is independent of the reactive power of the wind farm, so the loss model of PMSG is not considered in this paper.

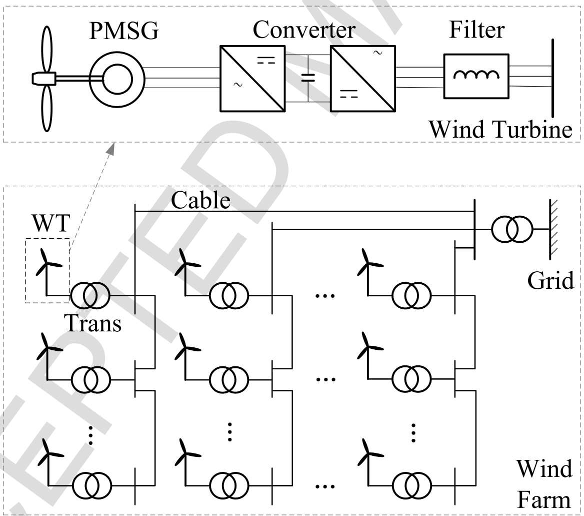


Fig.1. *The wind farm structure*

2.1. Loss Model of Converter

The power loss of converter mainly comes from the IGBT s and revers diodes, and the loss contains switching loss and conducting loss. So the loss model of converter can be expressed as [23]:

$$P_{con} = a_l I_{rms} + b_l I_{rms}^2 \tag{1}$$

$$\begin{cases} a_l = \frac{6\sqrt{2}}{\pi}\left(V_{IGBT} + \frac{E_{ON}+E_{OFF}}{I_{C,nom}} f_{sw} + \frac{E_{rr}}{I_{C,nom}} f_{sw}\right) \\ b_l = 3r_{IGBT} \end{cases} \quad (2)$$

Where I_{rms} is the RMS value of the sinusoidal current at the converter ac terminal, a_l and b_l are the power module constants, V_{IGBT} is the voltage across the collector and emitter of the IGBT, E_{ON} and E_{OFF} are the turn-on and turn-off losses of the IGBT, $I_{C,nom}$ is the nominal collector current of the IGBT, f_{sw} is the switching frequency, E_{rr} is the turn-off loss of the diodes, r_{IGBT} is the lead resistance of the IGBT.

In this paper, two IGBT modules (ABB 5SNA 2000K451300) are series connected on each bridge in the converter. According to the data sheet of IGBT module, the constants is known as $a_l = 7.0252$, $b_l = 0.0087$ and $f_{sw} = 800$ Hz [24].

2.2. Loss Model of Filter

The loss model of filter can be expressed as [8]:

$$P_{filter} = R_{filter}(I_{gd}^2 + I_{gq}^2) \quad (3)$$

Where R_{filter} is the resistance of the filter, I_{gd} and I_{gq} are the d-axis and q-axis current of the grid side converter.

2.3. Loss Model of Transformer

The loss model of transformer can be expressed as [25]:

$$P_{trans} = P_0 + \beta^2 P_k \quad (4)$$

Where P_0 is the no-load loss, P_k is the load loss, β is the load ratio. This paper chooses the Siemens GEAFOL cast-resin transformer rated at 8000kVA as the transformer of WT. According to [26], the no-load loss P_0 is 13.5 kW, and the load loss P_k is 36 kW.

2.4. Loss Model of Cable

The equivalent model of the cable between bus *i* and bus *j* is shown in Fig.2.

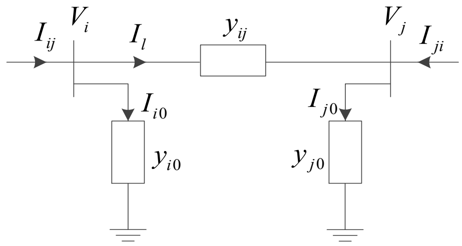


Fig.2. *Equivalent model of the cable [27]*

Define the direction form bus *i* to bus *j* is the positive direction, so the cable current can be expressed as [27]:

$$\begin{cases} I_{ij} = I_l + I_{i0} = y_{ij}(V_i - V_j) + y_{i0}V_i \\ I_{ji} = -I_l + I_{j0} = y_{ij}(V_j - V_i) + y_{i0}V_j \end{cases} \tag{5}$$

And the complex power S_{ij} from bus *i* to bus *j* and S_{ji} from bus *j* to bus *i* can be given by:

$$\begin{cases} S_{ij} = V_i I_{ij}^* \\ S_{ji} = V_j I_{ji}^* \end{cases} \tag{6}$$

The power loss of the cable between bus *i* and bus *j* is the algebraic sum of S_{ij} and S_{ji}:

$$P_{cable,ij} = S_{ij} + S_{ji} \tag{7}$$

3. Reactive Power Dispatch Strategies

The proportional dispatch is a common traditional reactive power dispatch strategy [10], and later some improved optimal reactive power dispatch strategies came out [16]. This section introduces two kinds of existing reactive power dispatch strategies and the proposed reactive power dispatch strategy.

3.1. Strategy A: Proportional Dispatch Strategy

In this strategy, the reference reactive power required by the grid is distributed among all the WTs according to their available reactive power [10]-[13], like the formula shows bellow:

$$Q_{WT,k}^{ref} = \frac{Q_{WT,k}^{avail}}{\sum_{k=1}^{n} Q_{WT,k}^{avail}} Q_{WF}^{ref} \tag{8}$$

Where $Q_{WT,k}^{ref}$ and Q_{WF}^{ref} are the reference reactive power of wind turbine *k* and the whole wind farm respectively, $Q_{WT,k}^{avail}$ is the available reactive power of wind turbine *k*, *n* is the number of WTs.

3.2. Strategy B: Optimal Dispatch Strategy with WF Transmission Loss Minimization

This dispatch uses optimization algorithm to get the reference reactive power of each WT. And the target of the optimization algorithm is to minimize the loss of WF transmission including the transformers and cables [16] [20]. Its objective function is given as:

$$\min\left\{\sum_{k=1}^{n} P_{trans,k} + \sum_{l=1}^{m} P_{cable,l}\right\} \tag{9}$$

Where $P_{trans,k}$ is the loss of transformer k, $P_{cable,l}$ is the loss of cable l, n is the total number of transformers, m is the total number of cables.

3.3. Strategy C: Proposed Optimal Dispatch Strategy with WF Total Loss Minimization

This strategy uses optimization algorithm to get the reference reactive power of each WT, aiming to minimize the total loss of the WF. The objective function of strategy C contains not only the loss of WF transmission system but also the loss inside each WT, which is given as:

$$\min\left\{\sum_{k=1}^{n}(P_{con,k} + P_{filter,k} + P_{trans,k}) + \sum_{l=1}^{m} P_{calbe,l}\right\} \tag{10}$$

The constraints are given as:

$$P_j = \left|V_j\right|\sum_{i=1}^{N_B}\left|V_i\right|\left|V_{ji}\right|\cos\left(\theta_{ji} - \delta_j + \delta_i\right) \tag{11}$$

$$Q_j = -\left|V_j\right|\sum_{i=1}^{N_B}\left|V_i\right|\left|V_{ji}\right|\sin\left(\theta_{ji} - \delta_j + \delta_i\right) \tag{12}$$

$$Q_{PCC} = Q_{WF}^{ref} \tag{13}$$

$$V_j^{\min} \le V_j \le V_j^{\max} \tag{14}$$

$$I_{GSC,k}^{rms} \le I_{GSC}^{rated} \tag{15}$$

Where P_j and Q_j are the active and reactive power injected at bus j, and formula (11) and (12) are the power flow balance limits. Q_{PCC} is the reactive power at the point of common coupling, and formula (13) is the WF reference reactive power constraint. V_j is the voltage of bus j, and formula (14) is the bus voltage constraint. $I_{GSC,k}^{rms}$ is the RMS value of grid side converter current, and formula (15) is the GSC current constraint.

3.4. Optimization Method

To solve such nonlinear and non-convex problems like Strategy C and Strategy B, Particle Swarm Optimization (PSO) algorithm is rather suitable. Particle Swarm Optimization was introduced by Eberhart and Kennedy originally according to swarm intelligence [28]. In PSO, each d-dimensional particle x_i is a possible solution. The particles collaborate as a population to reach a collective goal, usually to minimize a function *f*.

In PSO, a group of particles is randomly generated as initialization firstly. And then every particle is evaluated by calculating its fitness value using function *f*, thus the personal best position (*pbest*) and global best position (*gbest*) will be found. The velocity and position of each particle is updated according to *pbest* and *gbest*, like the formula shows below [29]:

$$v_i^{k+1} = v_i^k + c_1 r_1 (pbest_i^k - x_i^k) + c_2 r_2 (gbest^k - x_i^k) \quad (16)$$

$$x_i^{k+1} = v_i^{k+1} + x_i^k \quad (17)$$

Where v_i^k and x_i^k are the velocity and position of particle *i* at *k*-iteration, c_1 and c_2 are acceleration coefficients, r_1 and r_2 are random numbers between 0 and 1, $pbest_i^k$ is the personal best position of particle *i* at *k*-iteration, $gbest^k$ is the global best position at *k*-iteration. After the updating of velocity and position, a new generation of particles is generated. Repeat the work until the number of iterations reaches the set value or the change of *gbest* in N iterations is less than *M* (the value of *N* and *M* is set by users).

Fig.3 is the PSO algorithm flow chart with the objective function and constraints of Strategy C shown inside it. Formula (10) is set as the objective function, and formula (11)-(15) are the constraints. The reactive power reference given by power system Q_{WF}^{ref} is the input of the entire program, more specifically, Q_{WF}^{ref} is put in as a part of the WF reactive power constraint as formula (13) shows. After times of iterations, the reactive power reference of each WT $Q_{WT,k}^{ref}$ is found out at the end of PSO program.

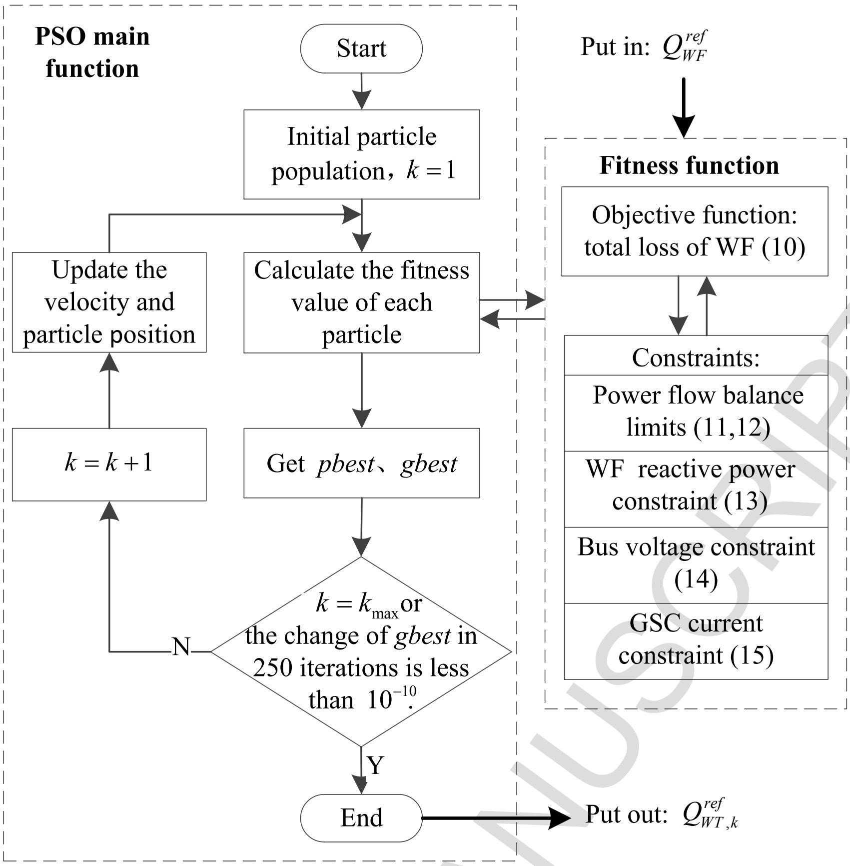


Fig.3. *PSO algorithm flow chart*

4. Case Study

In this section, a wind farm with 25 PMSG WTs is chosen for the case studies. The WTs are arranged in 5 rows and 5 columns like Fig.4 shows. The 5 MW NREL WT is chosen as the WT in the simulation wind farm, its parameters are shown in Table 1. The distance between each WT is 882 m, and the parameters of the cables is given by Table 2. Considering the different load of each cable, the cables between row 1 and row 3 use the 95 mm2 XLPE-Cu, the cables between row 3 and row 5 use the 150 mm2 XLPE-Cu, the cables between row 5 and PCC use the 240 mm2 XLPE-Cu.

This paper mainly focus on the dispatch of reactive power, so the traditional MPPT control strategy for each WT is chosen as the active power dispatch. Considering the wake effect of WF, the active power of each WT is calculated by the Jensen Model.

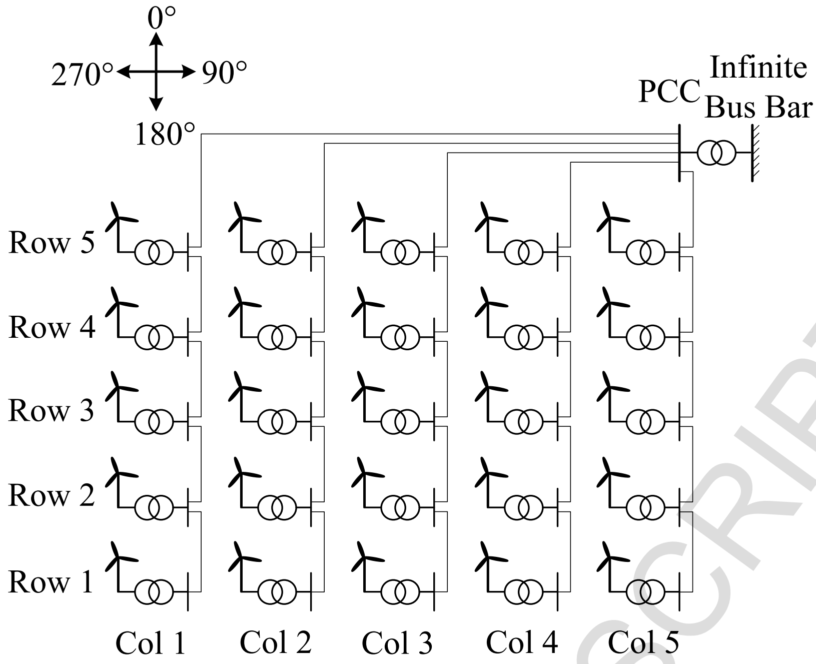


Fig.4. *The layout of the wind farm*

Table 1 Parameters of Wind Turbine [30]

Parameter	5 MW NREL Wind Turbine
Cut-in, Rated, Cut-out Wind Speed	4 m/s, 11.4 m/s, 25m/s
Rotor, Hub Diameter	126 m, 3m
Rated Power	5 MW
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm

Table 2 Parameters of Cable [31]

Cables' position	Cross section (mm^2)	Resistance (Ω/km)	Capacitance (μF/km)	Inductance (mH/km)
row 1 - 3	95	0.1842	0.18	0.44
row 3 - 5	150	0.1167	0.21	0.41
row 5 - PCC	240	0.0729	0.24	0.38

4.1. Scenario 1: Simulation at different Q_{WF}^{ref} with wind velocity=10 m/s, wind direction=270°

In this scenario, the velocity and direction of wind are set to 10 m/s and 270° . The active power of each WT captured from wind is show in Fig.5.

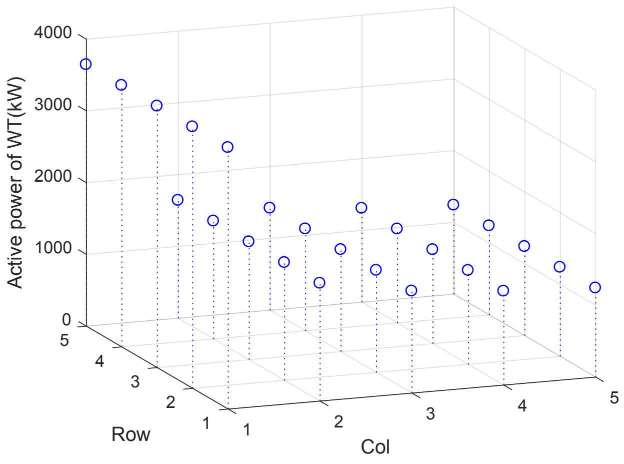


Fig.5. The active power of WTs captured from wind

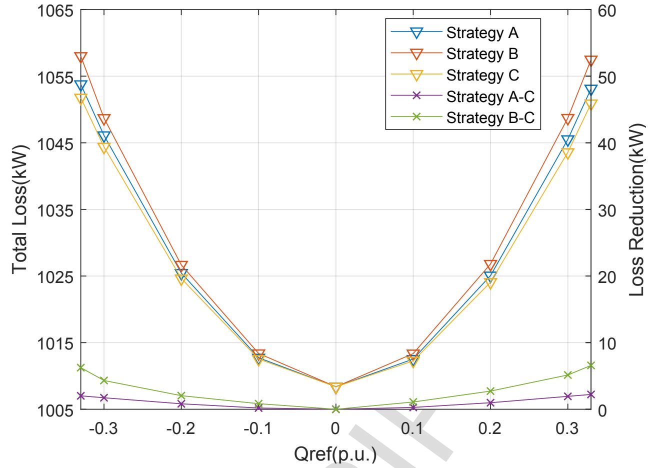


Fig.6. The total power loss of WF using each strategy at different Q_{WF}^{ref}

Fig.6. shows the total power loss of WF using each strategy at different Q_{WF}^{ref}. It is obvious that Strategy C always gets the lowest total loss, while Strategy B gets the highest. The reason is that the target of Strategy B is minimizing the loss of cables and transformers, which may cause the rising of the loss inside WTs, so the total loss of WF will be bigger. As the figure shows, the bigger the absolute value of Q_{WF}^{ref}, the higher difference between each Strategy. Because when $Q_{WF}^{ref}=0$, the $Q_{WT,k}^{ref}(k=1,...,25)$ tends to 0, while the absolute value of Q_{WF}^{ref} rising, the difference of $Q_{WT,k}^{ref}$ becomes obvious, so the difference of total power loss of WF also becomes significant.

4.2. Scenario 2: Simulation at different wind velocity with $Q_{WF}^{ref}=0.2$, wind direction=270°

In this scenario, the wind direction is set to 270° , and $Q_{WF}^{ref}=0.2$. At this direction, the wind speed at each column is equal, and Fig.7 shows the active power captured by WTs at each column.

When the wind velocity is lower than 4m/s, every WT's active power generation is 0, because 4m/s is the cut-in wind speed of WT. when the wind velocity is higher than 14m/s, every WT's active power generation is 5 MW, because the rate active power of WT is 5 MW. Therefore, the strategies are compared at different Wind Velocities within the range of 4 m/s to 14 m/s. And the total power loss of wind farm using each strategy under Scenario 2 is show in Fig.8.

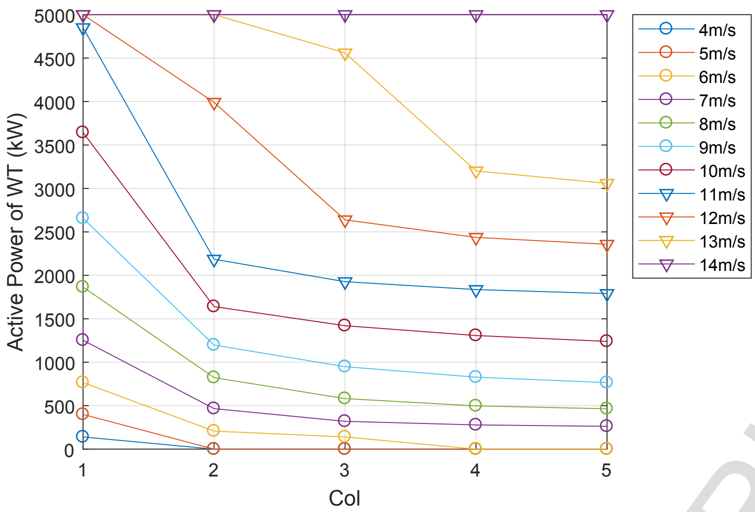


Fig.7. *Active power of WTs in each column at 270°*

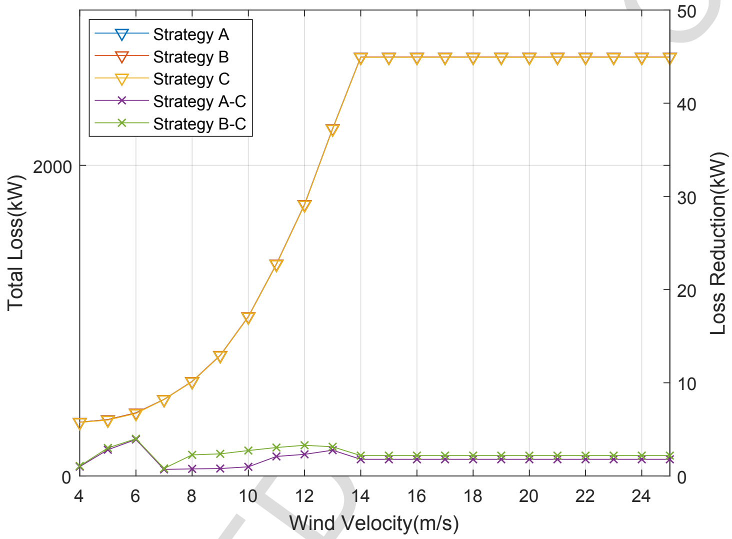


Fig.8. *The total power loss of WF using each strategy and the loss reduction at different wind velocity*

In Fig.8, it is hard to identify the difference of these strategies, so the reduction of the total power loss of WF is made. Strategy A-C means the result of the total loss got by Strategy A minus that got by Strategy C, and Strategy B-C has the similar meaning. As shown in Fig. 8, the loss reductions after 14 m/s remains unchanged. Because when the wind speed is higher than 14 m / s, the active power generation of each WT is 5 MW, so the results given by each strategy no longer change with the wind velocity. And the loss reduction is always positive, which means that strategy C gets lower total power loss than the other two strategies at each wind velocity.

4.3. Scenario 3: Simulation at different wind directions with wind velocity =10 m/s, $Q_{WF}^{ref} = 0.2$

In this scenario, the wind velocity is set to 10 m/s, and $Q_{WF}^{ref} = 0.2$. Fig.9 shows the total active power of WF at different directions.

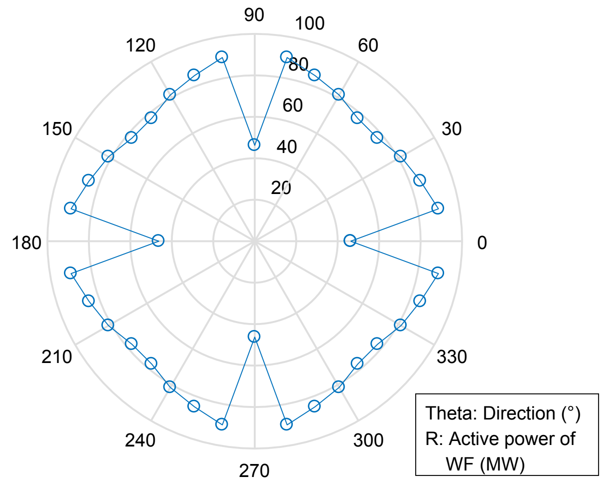


Fig.9. Active power of WF at different wind directions

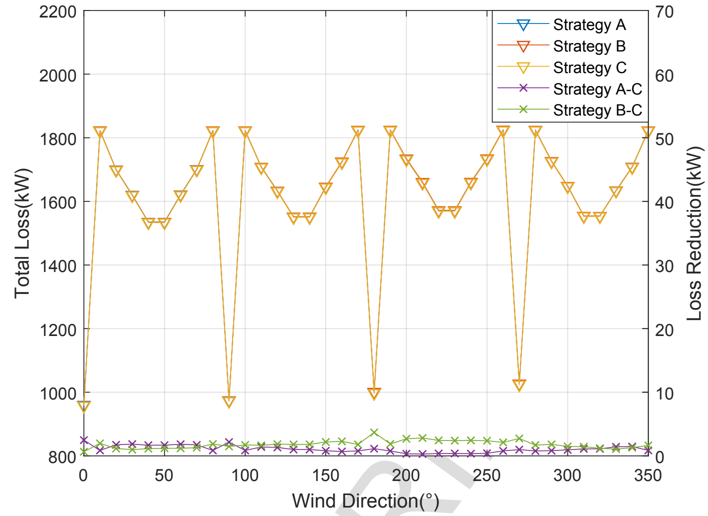


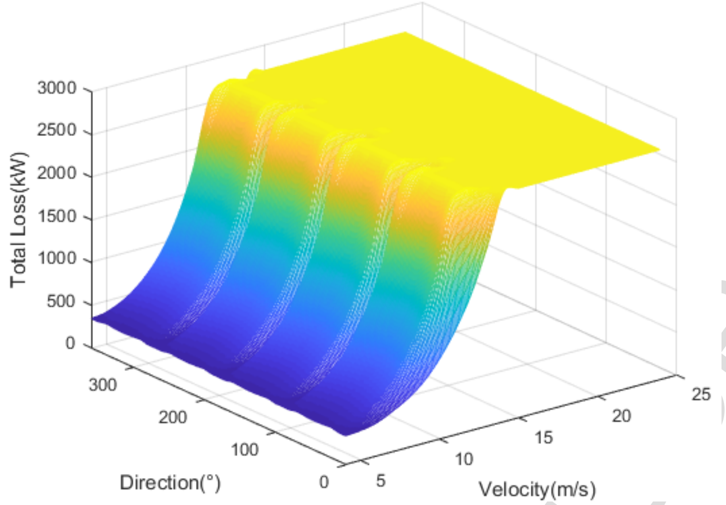
Fig.10. The total power loss of WF using each strategy and the loss reduction at different wind direction

In Fig.9, the active power of WF decreases sharply at four directions of 0° , 90° ,180° and 270° , because at these directions, the wake effect is the strongest, the active power captured from wind is the lowest at these four directions. As the wind farm is square, Fig.9 is similar in quarters. The strategies are compared at different wind direction from 0° to 360° . And the total power loss of wind farm using each strategy under Scenario 3 is show in Fig.10.

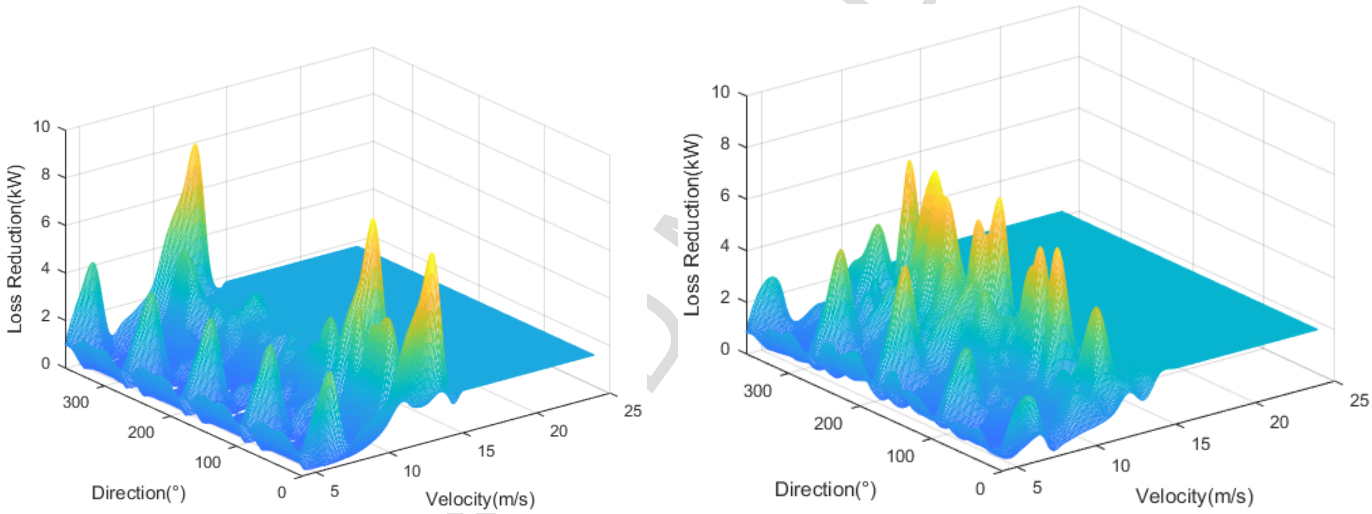
As we can see in Fig.10, the total power loss decreases sharply at four directions of 0° , 90° ,180° and 270° , which is similar the Fig.8, that's because at these directions, the total active power the WF captured from the wind is very low, thus the total power loss is low. And among these four directions, the power loss is the highest at 270° , because at this direction, the WTs far from PCC generate more active power, so the losses on the cables increase. In Fig.10, it is hard to identify the difference of these strategies, so the reduction of the total power loss of WF is made. As Fig.10 shows, the loss reductions are positive, thus Strategy C always gets lower power loss at every wind directions.

4.4. Scenario 4: Simulation at different wind velocities and different wind directions, $Q_{WF}^{ref}=0.2$

In this scenario, set $Q_{WF}^{ref}=0.2$. The strategies are compared at different wind velocities and different wind directions. Fig.11 (a) shows the total loss of WF at $Q_{WF}^{ref}=0.2$ using Strategy A, B and C, and the reduction of Strategy A and C is shown in Fig.11 (b), the reduction of Strategy B and C is shown in Fig.11 (c). In Fig.11 (a), the total loss of WF rises with wind velocity, and then stays the same when the wind velociy exceeds about 14 m/s. But this phenomenon will be earlier when the wind direction is not 0°, 90°, 180° or 270°, the total loss of WF stays the same when the Wind Veloctiy exceeds about 12 m/s. Because in these directions, the wake effect is not that strong, so there are four gaps in the surface. And the four ridges in Fig.11 (b) and (c) can be explained, too. As the reuctions are all positive, it can be ensured that Strategy C will always be the best in any conditions with three datas (wind velocity, wind direction, Q_{WF}^{ref}).



(a) The total power loss of WF using differnt strategies at $Q_{WF}^{ref} = 0.2$



(b) The loss reduction of Strategy A-C *(c) The loss reduction of Strategy B-C*

Fig.11. *The total power loss of WF and loss reductuion using different strategies at different wind velocities and directions*

4.5. Scenario 5: Simulation in a year at different Q_{WF}^{ref}

To prove the superiority of strategy C in practical application, these three strategies are compared in the case of a year's actual wind record at diffennent Q_{WF}^{ref} . The wind velocity and wind direction are sampled every 3 hours, totally 2920 data, and the wind rose of a year is shown in Fig.12. Table 3 shows the total loss of a year using Strategy A, Strategy B, Strategy C, and the loss reductions as Strategy A-C and Strategy B-C are also calculated.

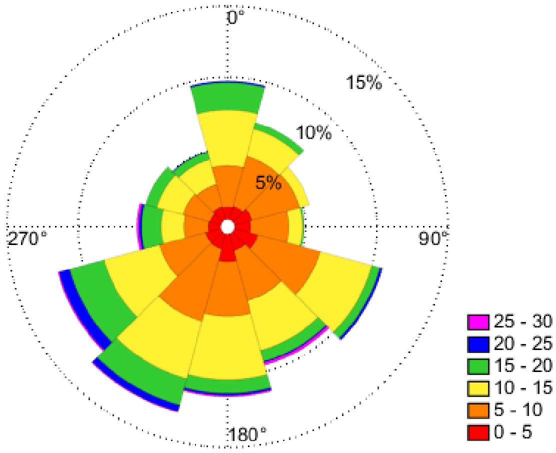


Fig.12. *Wind rose of a year*

Table 3 Total power loss of a year using different strategies at each Q_{WF}^{ref}

Q_{WF}^{ref} (p.u.)	Strategy A (GWh)	Strategy B (GWh)	Strategy C (GWh)	A-C (MWh)	B-C (MWh)
-0.33	13.9015	13.9020	13.8725	29.0014	29.5043
-0.3	13.7639	13.7677	13.7395	24.3834	28.1642
-0.2	13.3964	13.3975	13.3851	11.2283	12.3806
-0.1	13.1723	13.1723	13.1691	3.2110	3.2450
0	13.0942	13.0942	13.0941	0.0821	0.0402
0.1	13.1637	13.1661	13.1616	2.0840	4.5000
0.2	13.3787	13.3845	13.3695	9.1309	14.9987
0.3	13.7361	13.7428	13.7148	21.2349	27.9427
0.33	13.8704	13.8737	13.8443	26.1514	29.4761

It can be seen from Table 3 that the total loss of a year using different strategies always obeys the sequence: Strategy B > Strategy A > Strategy C at every Q_{WF}^{ref} . And the total loss of a year using different strategies are all the lowest at $Q_{WF}^{ref} = 0$, and rise with the increasing of the absolute value of Q_{WF}^{ref} . As the results in Scenario 2 and Scenario 3 show, the total loss of WF using different strategies always obeys the sequence: Strategy B > Strategy A > Strategy C, no matter at which wind velocity or wind direction. The total loss of a year can be seen as a cumulative result of losses of WF at many different wind velocities and wind directions. Therefore, it is not hard to explain the result shows in Table 1 that the total loss of a year using Strategy B is the highest and that of Strategy C is the lowest.

With the calculation and comparison of total power loss using different strategies under different conditions, the highest loss reduction of A-C appears at wind velocity=13m/s, wind direction=90° , $Q_{WF}^{ref} = -0.33$, and the highest loss reduction of B-C appears at wind velocity=12m/s, wind direction=180° , $Q_{WF}^{ref} = 0.33$. Assuming that the wind farm is working for a year under these conditions, the power loss and economic loss of WF using different strategies is calculated in Table 4. And the economic loss is calculated according to the spot price in Denmark in 2017 [32].

Table 4 Max loss reduction conditions

Condition	W=13 m/s , D=90°; $Q_{WF}^{ref}=-0.33$			W=12 m/s , D=180°; $Q_{WF}^{ref}=0.33$		
Strategy	A	C	A-C	B	C	B-C
Loss of WTs (GWh)	9.8532	9.7891	0.0641	7.8679	7.7371	0.1307
Loss of transformers and cables (GWh)	9.7937	9.6665	0.1272	7.7649	7.8016	-0.0366
Total loss of WF (GWh)	19.6469	19.4556	0.1914	15.6328	15.5387	0.0941
Economic loss (MDKK)	14.2202	14.0817	0.1385	11.3148	11.2467	0.0681

It is clear form Table 4 that power loss of WF using Strategy C is the lowest. Comparing with Strategy A, Strategy C saves a large amount of wind power of 0.1914 GWh, equivalent to 0.1385 MDKK. Comparing with Strategy B, Strategy C saves a large amount of wind power of 0.0941 GWh, equivalent to 0.0681 MDKK. Because Strategy A is the traditional proportional strategy, in which the power loss is not considered, so the loss of WT and the loss of transformers and cables are both higher than that of Strategy C. Since Strategy B aims to minimize the loss of transformers and cables, so the loss of transformers and cables is lower than that of Strategy C, but its loss of WT is higher than that of Strategy C.

4.6. Scenario 6: Simulation in a year

To simulate the values of Q_{WF}^{ref} in a year, a normal distribution function is used to generate 2920 data. The values of Q_{WF}^{ref} and the number of times each value appears is corresponded in Fig.13. So the 2920 sample points (each point with three values of wind velocity, wind direction, Q_{WF}^{ref}) are used as the status record of WF in a whole year sampled every 3 hours. And the total power losses and economic loss of WF in a whole year using different strategies are list in Table 5. The economic losses of a year are also calculated according to the spot price in Denmark in 2017 [32].

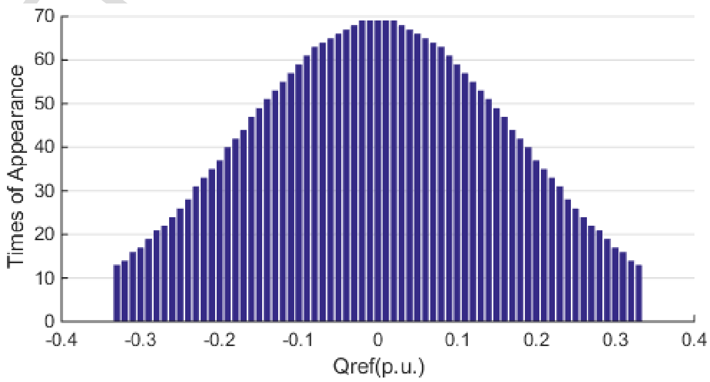


Fig.13. *A year's* Q_{WF}^{ref}

Table 5 Total power loss of a year using different strategies

Strategy	Strategy A	Strategy B	Strategy C	A-C	B-C
Power loss (GWh)	13.2727	13.2743	13.2659	0.0067	0.0083
Economic loss (MDKK)	22.8854	22.8881	22.8738	0.0116	0.0144

It is clear form Table 5 that that the total loss of a year using Strategy C is the lowest. Comparing with Strategy A and Strategy B, Strategy C saves a large amount of wind power of 0.0067 GWh and 0.0083 GWh respectively. And Strategy C saves the money of 0.0116 MDKK and 0.0144 MDKK in a year compared to Strategy A and Strategy B.

5. Conclusions and Future Works

This paper proposed an optimal reactive power dispatch strategy aiming to minimize the total loss of wind farm. With this method, reactive power demand of grid is distributed to each wind turbine, reducing the capital investment of reactive power compensation equipment. The optimized reactive power dispatch strategy reduces the power loss of the wind farm, increasing the income of the wind farm. Compared with the existing literature, the novelty of the paper is that the objective function contains not only the loss of transmission system but also the loss of wind turbines. And PSO algorithm is adopted to get the optimal reactive power reference of each WT, making the total loss smallest. Another two stategies are compared with the proposed strategy at different wind velocities, different wind directions and different WF reactive power references, and the result in the case studies proves that the propose strategy always gets lower power loss than the other two strategies. And the last simulation shows that the proposed strategy can save 0.0116 MDKK and 0.0144 MDKK compared to the other two traditional strategies respectively. The proposed reactive power dispatch strategy can be used in the wind farm control center to make the wind farm more efficiency. In further study, the operating costs of WF will be considered in the reactive power dispatch strategy to make the wind farm operating at a higher output and a lower cost.

6. References

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Highlights:

(1) An optimal reactive power dispatch of a full-scale converter based wind farm is proposed to minimize the power loss of wind farm.

(2) The power losses of wind turbines and transmission system of wind farm are both considered.

(3) Compared to the traditional reactive power dispatch strategy, the proposed strategy can reduce the power loss of 0.98% in the most effective case.