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The Active Power and Reactive Power Dispatch Plan of DFIG Based Wind Farm Considering Wind Power Curtailment

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Abstract

In normal operation, doubly-fed induction generator (DFIG) can generate certain range of reactive power and the DFIG based wind farm can participate in reactive power control of grid as a reactive power supply. This paper proposes one multi-objective power dispatch optimization model which considers copper loss minimization of all DFIGs in wind farm and maximization reactive power margin of every DFIG. The active power and reactive power generated by wind farm can meet the power gird requirements of both active power and reactive power. This wind farm power dispatch model will cause more economic benefit and bring more reactive power margin to every DFIG. The advantages and validity of the proposed method have been verified in the case study.

Keywords: wind power curtailment; DFIG; active power allocation; reactive power allocation;

1. Introduction

Recently, wind power industry develops rapidly in China. Now, the wind power capacity of China is greater than that of the United States and has become the largest in the world. The emergence of more large scale wind farms will inevitably affect the safety and stability of operation of the power grid, especially the voltage stability. The reactive power generated by the wind farm is directly related to the stability of power grid voltage, so reactive power compensation problem becomes an important research topic. The squirrel-cage induction generator (SCIG) based wind farm does not have the reactive power adjustment ability. However, the doubly-fed induction generator (DFIG) based wind farm can be used as a reactive power supply to support the voltage level of point of common coupling (PCC) and reactive load nearby. Therefore, the studies of the DFIG based wind farm reactive power generating capacity and reactive power scheduling problem are very meaningful.

Owing to a lot of factors [1], the problem of wind power curtailment in wind farm has been a big challenge to the wind power industry in China. The data from Chinese Wind Energy Association shows that the capacity of wind power curtailment in China is almost 20 billion degrees which causes economic losses at the amount of more than 10 billion RMB in 2012. Therefore, the wind power curtailment has become a common phenomenon in China.

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The wind power curtailment refers to the fact that the active power generated by the wind farm is lower than the maximum output ability of the wind farm. The capacity of wind power curtailment does not include the power losses caused by equipment failures. Usually, the power dispatching center gives an active power order to wind farm according to the current wind speed. When the active power generated by the wind farm is larger than the order, the wind power curtailment happens, and the wind farm must reduce its output power. That is to say, when the wind power curtailment happens, the wind farm must output the ordered amount of active power regardless of the current input wind speed of each DFIG.

Many scholars have studied the reactive power compensation problem about wind farms. There are some studies on the advantage of the Static Var Compensator (SVC) on reactive power compensation [2-4] and the function of the Static Synchronous Compensator (STATCOM) [5, 6]. An improvement to the traditional DVR device was proposed in refs. 7, which greatly enhanced the LVRT ability of wind turbine. Based on the reactive power limitations in stator side and grid side, different reactive power control strategies were proposed in refs. 8-10.

Most of researches focus on the additional reactive power compensation devices, such as their capacities [11] or control strategies. A reactive power dispatch principle according to the reactive power limit of each DFIG in the wind farm was proposed [8, 12]. This paper studies the ability of the DFIG based wind farm inherent reactive power compensation problem and proposes a power dispatch plan based on two objective functions. This plan makes the working condition of all DFIGs stay in the optimum states and makes full use of every DFIG reactive power regulation ability. In the following case study, the advantage of the proposed plan will be verified.

2. The Low Voltage Ride Through Ability of Wind Farm

Reactive power generated by wind farm is directly related to power system stability. In order to prevent voltage collapse and a large number of wind turbines being off line because of grid fault, Low Voltage Ride Through (LVRT) ability is necessary for a newly-built wind farm. LVRT refers to wind farm can continuous operate during a period of time when grid fault happens and generate some reactive power to support grid voltage according to the level of voltage drop. In China, the requirement of LVRT is shown in figure 1.

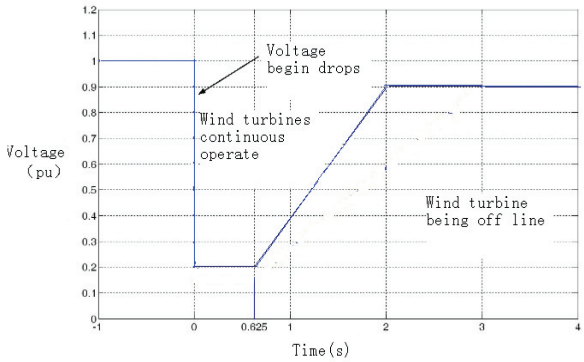

Fig.1. The regulation of wind farm LVRT ability in China

3. The Basic Strategy of Active power and Reactive Power Control

At the normal operation state of wind farm, every DFIG output the maximum active power according to the current input wind speed, so there is not an active power scheduling problem. When wind power curtailment happens, we should take active power scheduling problem into consideration. For the same active power order value from power system dispatch center, the cost of different active power dispatch plans among units is almost equal because wind energy is almost at no cost. Therefore, this paper mainly focuses on different reactive power dispatch plans.

DFIG can output a certain range of reactive power to grid. The paper holds that inductive reactive power is positive.

Generally, reactive power optimization objective of DFIG is: 1. Make the grid optimal operation, such as minimum voltage excursion and power losses [13].2. Minimize DFIG losses.

Take the reactive power limit of DFIG into account, in order to avoid reactive power generated by DFIG over the reactive power limit, refs. 8, 12 proposed the reactive power allocation plan according to its reactive power limit.

To sum up, this paper takes reactive power value which makes grid optimal operation as Q_N , the main work is to find a reactive power dispatch plan which will minimize the losses of all DFIGs in wind farm and keep every DFIG enough reactive power margin.

Wind farm reactive power control diagrammatic drawing is shown in figure 2.

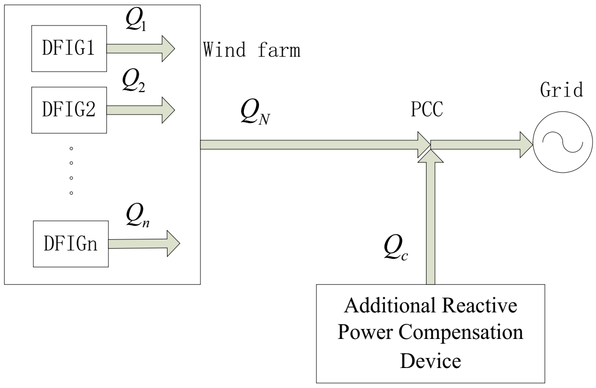

Fig.2. Wind farm reactive power diagrammatic drawing

4. Mathematic Model of Wind Turbine

When input wind speed is between the cut-in wind speed and cut-out wind speed, DFIG i in wind farm outputs the maximum active power $P_{i\max}$

$$P_{i\max} = \begin{cases} 0, V_i < V_{cut-in} \; or \; V_i \ge V_{cut-out} \\ \frac{1}{2} C_{p\max} \rho R^2 r_{air} V_i^3, V_{cut-in} \le V_i < V_{rated} \\ P_N, V_{rated} \le V_i < V_{cut-out} \end{cases} \quad (1)$$

Where $C_{p\max}$ is the maximum power coefficient, V_{cut-in}, V_{rated}, $V_{cut-out}$ are cut-in wind speed, rated wind speed and cut-out wind speed respectively, P_N is rated power of DFIG, $P_{i\max}$ is the maximum active power generated by DFIG i, R is blade radius, ρ_{air} is the air density, V_i is input wind speed of DFIG i.

When wind power curtailment happens, the active power generated by DFIG i is definitely less than $P_{i\max}$.

Considering rather low temperature in "three-north" area winter in China, to protect the wind turbine, as long as input wind speed is over cut-in wind speed, the wind turbine needs to keep working. In other words, the output active power range of DFIG i is $(0, P_{i\max}]$.

5. Active Power and Reactive Power Delivered to grid of DFIG

DFIG stator directly connects to grid, so in the normal situation, the voltage and frequency of the stator are constant. The power flow is unidirectional, and it can only flow from stator to grid. DFIG rotor connects grid by rotor-side converter and grid-side converter, and the power flow in rotor is bidirectional, then it can flow from rotor to grid or in reverse direction. The simple structure chart of DFIG is shown in figure 3.

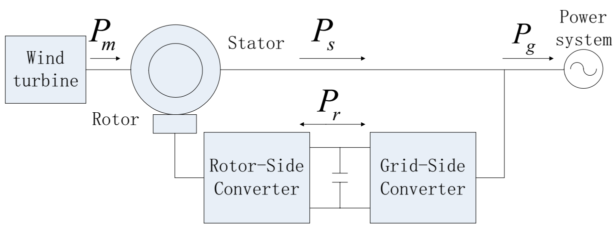

Fig.3. Simple structure chart of DFIG

Because the stator voltage is constant, Stator Voltage Orientated Control (SVOC) is convenient, namely align the synchronous reference frame d-axis at stator voltage vector $\vec{v}_s$, then d-axis stator voltage v_{ds} and q-axis stator voltage v_{qs} are

$$v_{ds} = v_s \text{ and } v_{qs} = 0 \quad (2)$$

Where v_s is the voltage of power grid.

Synchronous reference frame angular speed is

$$w_s = 2\pi f_s \quad (3)$$

Where f_s is power grid frequency, $f_s = 50Hz$ in China.

Stator active power and stator reactive power are

$$\begin{cases} P_s = 1.5(v_{ds} i_{ds} + v_{qs} i_{qs}) \\ Q_s = 1.5(v_{qs} i_{ds} - v_{ds} i_{qs}) \end{cases} \quad (4)$$

Where P_s and Q_s are stator active power and stator reactive power of DFIG, i_{ds} and i_{qs} are d-axis stator current and q-axis stator current.

Substitute (2) into (4), we can get

$$\begin{cases} P_s = 1.5 v_s i_{ds} \\ Q_s = -1.5 v_s i_{qs} \end{cases} \quad (5)$$

Cancelled stator current, we can get [14]

$$\begin{cases} P_s = -1.5 \dfrac{v_s L_m i_{dr}}{L_s} \\ Q_s = 1.5 \dfrac{v_s L_m}{L_s} (i_{qr} + \dfrac{v_s}{w_s L_m}) \end{cases} \quad (6)$$

Where L_m is magnetizing inductance, L_s is stator self-inductance, i_{dr} and i_{qr} are d-axis rotor current and q-axis rotor current. From (6) we can see that P_s and Q_s are independently controlled by regulation of i_{dr} and i_{qr} respectively.

Grid-side converter (GSC) capacity is small, so its reactive power regulation ability is very limited and in order to reduce the losses of converter switch device, DFIG should make the stator participate in reactive power regulation first. Accordingly, this paper does not consider the GSC reactive power regulation, namely:

$$Q_g = Q_s \tag{7}$$

Where Q_g is reactive power delivered to the grid of DFIG.

The relationship of stator active power and active power delivered to the grid of DFIG is as follows

$$P_g = P_s(1-\mathrm{s}) \tag{8}$$

Where P_g is active power delivered to the grid of DFIG, s is slip.

Substitute (7) and (8) into (6), we can get

$$\begin{cases} P_g = -1.5\dfrac{v_s L_m i_{dr}}{L_s}(1-\mathrm{s}) \\ Q_g = 1.5\dfrac{v_s L_m}{L_s}(i_{qr} + \dfrac{v_s}{w_s L_m}) \end{cases} \tag{9}$$

6. Calculation of Single DFIG Reactive Power Reference Value Q_s^*

For single DFIG, the calculation principle of reactive power reference value is within the scope of the DFIG reactive power limit, selecting a reactive power value which can make a certain performance evaluation function optimally. Different performance evaluation function will cause different calculation principle of reactive power reference value. Usually there are two principles: 1. the goal of performance evaluation function is to enhance power system stability and optimize the operation condition of power system; 2. the goal of performance evaluation function is to reduce the loss of DFIG itself and optimize the DFIG operation efficiency.

Selection function f is the sum of various losses of DFIG, there is

$$f = \sum P_{lossi} \tag{10}$$

If the iron loss and mechanical loss of the generator are ignored, losses of DFIG operation are mainly the stator and rotor copper loss, namely

$$f = P_{cus} + P_{cur} \tag{11}$$

Where, P_{cus} is stator copper loss, P_{cur} is rotor copper loss.

$$\begin{cases} P_{cus} = 3 I_s^2 R_s \\ P_{cur} = 3 I_r^2 R_r \end{cases} \tag{12}$$

Where, I_s is stator current, I_r is rotor current, R_s is stator resistance, R_r is rotor resistance.

Under SVOC, there is

$$\begin{cases} I_s = \sqrt{i_{ds}^2 + i_{qs}^2} \\ I_r = \sqrt{i_{dr}^2 + i_{qr}^2} \end{cases} \tag{13}$$

Substitute (5), (6), (12), (13) into (11), we can get a quadratic expression about Q_s , the expression is as follows:

$$f = aQ_s^2 + bQ_s + c \tag{14}$$

Where, coefficient a , b , c are

$$\begin{cases} a = \dfrac{4}{3}\dfrac{R_s L_m^2 + L_s^2 R_r}{v_s^2 L_m^2} \\ b = -\dfrac{4 L_s R_r}{L_m^2 \omega_s} \\ c = \dfrac{4 P_s^2 R_s}{3 v_s^2} + \dfrac{4 L_s^2 P_s^2 R_r}{3 v_s^2 L_m^2} + \dfrac{3 v_s^2 R_r}{\omega_s^2 L_m^2} \end{cases} \tag{15}$$

When $Q_s^* = -\dfrac{b}{2a}$, function f can achieve the minimum value $f_{\min}$.

$$f_{\min} = \frac{4ac - b^2}{4a} \tag{16}$$

Substitute a and b into $Q_s^* = -\dfrac{b}{2a}$, we can get

$$Q_s^* = \frac{3 L_s R_r v_s^2}{2\omega_s (R_s L_m^2 + R_r L_s^2)} \tag{17}$$

From (17) we can see that Q_s^* is only related to DFIG parameters and angular frequency of power system. Q_s^* has nothing to do with DFIG operation status. That is to say, for a given parameters of DFIG, when it generates reactive power Q_s^* , the loss of DFIG is the minimum. But in the actual cases, reactive power generated by wind farm must meet power system demand first. Therefore, in actual operation, DFIG is not running in the state of minimum loss.

7. Optimization Model of Power Dispatch among DFIGs

7.1. *Objective function*

(1) Copper loss of DFIG

If the iron loss of DFIG is ignored, only the copper loss of DFIG is considered, the copper loss of DFIG is as follows:

$$\begin{aligned} P_{cu} &= P_{cus} + P_{cur} = 3r_s i_s^{\,2} + 3r_r i_r^{\,2} \\ &= 3r_s\left(\frac{P_s^2 + Q_s^{\,2}}{9v_s^{\,2}}\right) + 3r_r\left(i_{dr}^{\,2} + i_{qr}^{\,2}\right) \end{aligned} \tag{18}$$

Where P_{cu} is the copper loss of DFIG, P_{cus} and P_{cur} are stator copper loss and rotor copper loss respectively, i_s and i_r are stator current and rotor current respectively.

Substitute (7), (8), (9) into (18), we can get

$$P_{cu} = f(P_g, Q_g) \tag{19}$$

We can see that the copper loss of DFIG is the function of P_g and Q_g from (19).

In order to minimize all copper loss of DFIGs in wind farm, if there is N DFIGs, the objective function is

$$F_1 = \sum_{i=1}^{N} P_{cui} = \sum_{i=1}^{N} f(P_{gi}, Q_{gi}) \tag{20}$$

Where P_{cui} is the copper loss of DFIG i, P_{gi} is active power delivered to the grid of DFIG i, Q_{gi} is reactive power delivered to the grid of DFIG i.

(2) Reactive power margin of DFIG

For keep every DFIG enough reactive power margin, so based on the reactive power limit of DFIG, the unit which has a large reactive power limit should take more reactive power regulation task, the principle [8, 12] is as follows:

$$Q_{bi} = \left(\frac{Q_{s\max i}}{\sum_{i=1}^{N} Q_{s\max i}}\right) Q_N \tag{21}$$

Where, Q_{bi} is reactive power generated by DFIG i, Q_N is reactive power order from power system dispatch center, $Q_{s\max i}$ is the reactive power limit of DFIG i, $Q_{s\max i} = -\dfrac{3v_s^2}{2X_s} + \sqrt{\left(\dfrac{3}{2}\dfrac{X_m}{X_s} v_s I_{r\max}\right)^2 - P_{si}^2}$, X_s is stator reactance, X_m is magnetizing reactance, $I_{r\max}$ is the maximum current passing through rotor converter, P_{si} is stator active power of DFIG i. From (21) we can see that Q_{bi} is decided by reactive power limit of DFIG i, therefore, if we follow this principle [8, 12], there is definitely enough reactive power margin between Q_{bi} and $Q_{s\max i}$. The difference between Q_{bi} and Q_{gi} can reflect this principle implementation well. So, if there is N DFIGs, in order to follow this principle, F_2 is another objective function,

$$F_2 = \sum_{i=1}^{N} \left(Q_{gi} - \frac{Q_{s\max i}}{\sum_{i=1}^{N} Q_{g\max i}} Q_N\right)^2 \tag{22}$$

Our objective is to find an active power and reactive power dispatch plan which can minimize F_1, F_2 at the same time.

7.2. *Constraint condition*

(1) Equality constraints

Assuming there are N DFIGs in wind farm, equality constraints are as follows:

$$\begin{cases} \sum_{i=1}^{N} P_{gi} = P_t \\ \sum_{i=1}^{N} Q_{gi} = Q_N \end{cases} \tag{23}$$

Where P_t and Q_N are active power order and reactive power order respectively. When wind power curtailment happens, P_t is less than the maximum active power delivered to grid by wind farm.

(2) Inequality constraints

This paper holds that inductive reactive power generated by wind farm is positive, takes no account of the capacitive reactive power generated by wind farm. According to the reactive power limit of DFIG i, the reactive power range delivered to the grid of DFIG i is

$$0 \le Q_{gi} \le Q_{s\max i} \tag{24}$$

The range of active power delivered to the grid of DFIG i is stated in section 4, that is

$$0 < P_{gi} \le P_{i\max} \tag{25}$$

The range of PCC voltage is

$$U_{B\min} \le U_B \le U_{B\max} \quad (26)$$

Where, U_B is PCC voltage, $U_{B\min}$ is PCC voltage lower limit, $U_{B\max}$ is PCC voltage upper limit.

In conclusion, we can get bi-objective constrained optimization dispatch model (BOCDM), the model is as follows:

$$(\text{BOCDM})\begin{cases} F_1 = \min\sum_{i=1}^{N} P_{cui} = \sum_{i=1}^{N} f(P_{gi}, Q_{gi}) \\ F_2 = \min\sum_{i=1}^{N} (Q_{gi} - Q_{bi})^2 \end{cases}$$

subject to constraint conditions (23)-(26).

The power dispatch model of DFIG based wind farm is shown as figure 4.

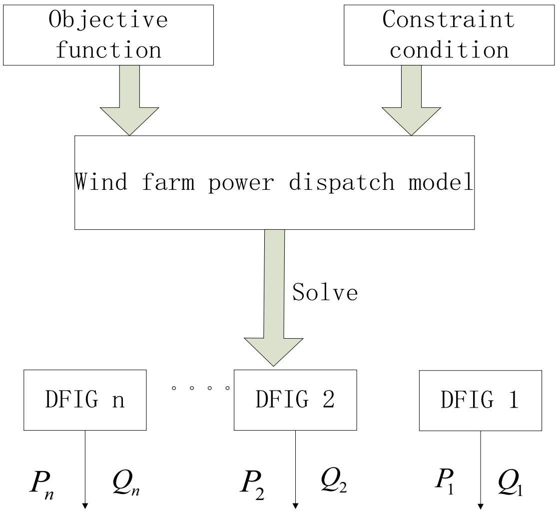

Fig.4. Optimization model of wind turbines power dispatch in wind farm

BOCDM is a bi-objective optimization problem. There is not an absolute optimal solution generally, but there is a Pareto solution usually. Linear weighting model is one of the most common used methods for this problem. This method is simple and the meaning is clear. Weight coefficient can reflect the importance of the objective. In this paper, Linear weighting model was used, then the BOCDM turns to single objective constrained optimization dispatch model (SOCDM). SOCDM is as follows:

$$F = \min(\lambda F_1 + (1-\lambda)F_2)$$

subject to the same constraint conditions with BOCDM.

Where, λ is weight coefficient, $\lambda \in [0,1]$.

8. Case Study

A wind farm consists of 10 wind turbines with double fed induction generators, each wind turbine is equipped with a 0.69 KV / 20 KV box transformer, and air density in wind farm being 1.225Kg/m3. Simple layout of wind farm is shown in figure 5. The parameters of DFIG are shown in table 1, the input wind speed of every unit is shown in table 2. The active power order from power dispatching center is 4.5MW, the reactive power demand of power grid is 4.5Mvar.

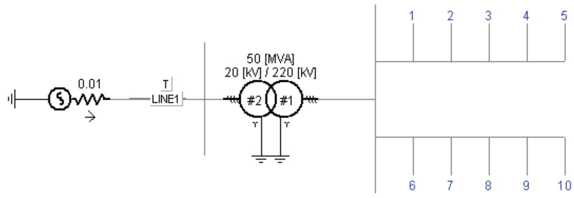

Fig.5. Simple layout of wind farm

Table 1. The parameters of one DFIG

Parameter	DFIG
Rated power	1.5MW
Stator self-inductance	5.6436mH
Stator leakage inductance	0.1687mH
Rotor leakage inductance	0.1337mH
Mgnetizing inductance	5.4749mH
Maximum rotor current	1200A

Table 2. Wind speed of every wind turbine (m/s)

1# turbine	11.1	6# turbine	7.8
2# turbine	11.2	7# turbine	7.6
3# turbine	10.6	8# turbine	7.5
4# turbine	8.1	9# turbine	7.7
5# turbine	8.0	10# turbine	7.6

In this case, $N = 10$, $P_T = 4.5MW$, $Q_N = 4.5M\text{var}$. In this paper, we use "fmincon" to solve this nonlinear minimization problem in Matlab. When $\lambda = 1$ or 0, the model becomes the single objective optimization problem. The active power and reactive power allocation results are shown in table 3-7, value of F_1 and F_2 are shown in table 8.

Table 3. Active power and reactive power allocation results (MW/Mvar) ($\lambda = 1$)

Units	P_g	Q_g	Units	P_g	Q_g
1# turbine	0.514	0.415	6# turbine	0.432	0.463
2# turbine	0.514	0.421	7# turbine	0.399	0.465
3# turbine	0.513	0.426	8# turbine	0.384	0.466
4# turbine	0.483	0.450	9# turbine	0.415	0.468
5# turbine	0.446	0.457	10# turbine	0.399	0.466

Table 4. Active power and reactive power allocation results (MW/Mvar) ($\lambda = 0.7$)

Units	P_g	Q_g	Units	P_g	Q_g
1# turbine	0.514	0.415	6# turbine	0.432	0.460
2# turbine	0.514	0.415	7# turbine	0.399	0.476
3# turbine	0.513	0.415	8# turbine	0.384	0.484
4# turbine	0.483	0.433	9# turbine	0.415	0.468
5# turbine	0.446	0.453	10# turbine	0.399	0.476

Table 5. Active power and reactive power allocation results (MW/Mvar) ($\lambda = 0.5$)

Units	P_g	Q_g	Units	P_g	Q_g
1# turbine	0.517	0.413	6# turbine	0.432	0.460
2# turbine	0.517	0.413	7# turbine	0.399	0.476
3# turbine	0.513	0.415	8# turbine	0.384	0.484
4# turbine	0.476	0.436	9# turbine	0.415	0.468
5# turbine	0.446	0.453	10# turbine	0.399	0.476

Table 6. Active power and reactive power allocation results (MW/Mvar) ($\lambda = 0.3$)

Units	P_g	Q_g	Units	P_g	Q_g
1# turbine	0.553	0.395	6# turbine	0.377	0.491
2# turbine	0.553	0.395	7# turbine	0.398	0.481
3# turbine	0.674	0.311	8# turbine	0.349	0.504
4# turbine	0.471	0.443	9# turbine	0.352	0.502
5# turbine	0.420	0.469	10# turbine	0.347	0.505

Table 7. Active power and reactive power allocation results (MW/Mvar) ($\lambda = 0$)

Units	P_g	Q_g	Units	P_g	Q_g
1# turbine	0.692	0.299	6# turbine	0.376	0.495
2# turbine	0.692	0.299	7# turbine	0.341	0.511
3# turbine	0.527	0.414	8# turbine	0.313	0.524
4# turbine	0.468	0.448	9# turbine	0.356	0.505
5# turbine	0.418	0.475	10# turbine	0.311	0.525

Table 8. Value of F_1 and F_2

	$\lambda = 1$	$\lambda = 0.7$	$\lambda = 0.5$	$\lambda = 0.3$	$\lambda = 0$
F_1	235360w	235410w	235460w	245070w	253810w
F_2	1.021e+009	1.341e+005	3.127	0.198	7.781e-005

λ is determined by the importance of two objective functions, which depends on power system operation situation and decision maker. If two objective functions are of equal importance, λ is 0.5. In this case study, different λ will be used in this optimization model.

In order to verify the validity of the model, a wind farm model on Power Systems Computer Aided Design (PSCAD) platform was built. The active power and reactive power generated by wind farm are shown as figure 6, 7. The results show that the model is effective and the scheme is feasible.

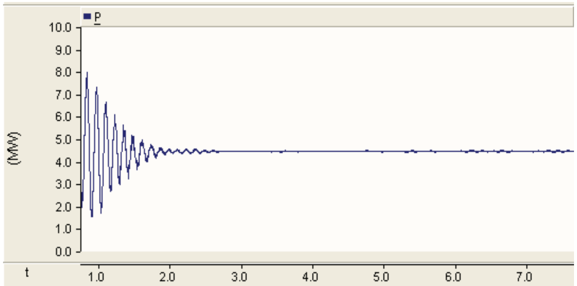

Fig.6. Active power generated by wind farm

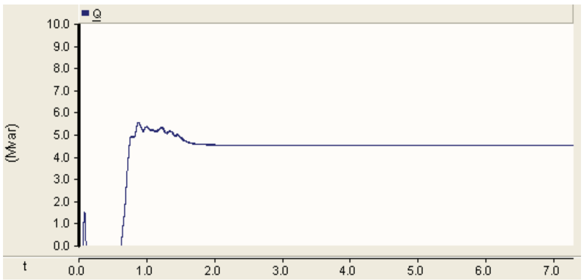

Fig.7. Reactive power generated by wind farm

Actually, table 3 only considers copper loss and table 7 only considers reactive power margin. They are all single object constrained optimization dispatch model.

From table 8 we can see that when $\lambda = 1$, the copper loss is minimum; when $\lambda = 0$, the copper loss is maximum.

BOCDM is used to combine both objectives.

Table 1~7 reflect that with the decrease of weight λ (importance of copper loss decreases), wind farm running will cause more copper loss. With the increase of weight $1-\lambda$ (importance of reactive power margin), value of F_2 decreases gradually, so reactive power generated by DFIG i will be more and more accord with principle [8, 12]. It can help decision makers choose the appropriate weights, give consideration to both objectives, and formulate reasonable scheduling scheme.

In this case, there are only 10 units, if there are more units in wind farm, the advantages of this model will be more obvious.

9. Conclusions

The multi-objective optimization model not only reduces the copper loss of all DFIGs in wind farm, but also provides each unit with enough reactive power margin. Therefore, the wind farm will operate in the most economical state and make full use of adjustment ability of every DFIG reactive power.

In large scale wind farm, there are a great number of units, so the proposed method in this paper can actually perform better. In other words, for the wind farm consists of hundreds units and the area where wind power curtailment happens frequently, this method can cause lesser copper loss and bring more economic benefit.

Acknowledgements

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