Active Power Dispatch Strategy of Wind Farms under Generator Faults

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Active power dispatch strategy of wind farms under generator faults

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ABSTRACT: Generator is a critical component of the wind turbine. It transforms the mechanical energy to the electric energy and transmits electricity to the grid. Based on the previous experience, the fault rate of the generator is fairly high which increases the downtime of the turbine. It has a significant effect on the performance and the economic benefit of the wind farm. The traditional wind farm controller adopts the proportional dispatch strategy and does not consider the fault severity. In this paper, a power dispatch strategy of wind farm focusing on the fault condition of the generator is proposed. The main faults are divided into three levels according to their severities. The wind farm controller dispatches power references to wind turbines onthe basis of fault level, wind condition and power demand from the grid. When the fault level is high, the strategy gives priority to protect the generator. If the fault level is not high, the wind farm should follow the power demand. In addition, the wake effect is also an important factor that must be taken into account in the wind farm control. Because it can affect the power production directly. To verify the advantage of this strategy, it is compared with the proportional dispatch strategy in the simulation. The result shows that the proposed strategy can make a good trade-off between component protection and power production.

1 INTRODUCTION

Wind energy is one of the most widely used renewable energies. With the rapid development of technology and industry application, it plays an important role in the energy market of the world. By 2016, wind energy overtook coal and became the second largest form of power generation capacity in Europe (Europe 2016). Wind Farm (WF) is seen as a mature and effective form to utilize wind energy for commercial operation. The large-scale offshore WF is the development trend of wind energy. This also implies that the wind energy penetration in the grid is larger and larger. However, wind energy has its congenital defects. One of them is the high failure rate of the Wind Turbine (WT) due to the harsh operating environment and the highly turbulent wind speed. Therefore, the stability and reliability of WF are more and more important to the grid. The fault of WT should not be neglect in the operation of WF as well.

In recent years, wind farm control draws more and more attention of the researchers. Previous Wind Turbine Control (WTC) can no longer guarantee the good performance of WF during operation, no matter from the aspects of power production, fatigue loads, etc. For the coordination, control and management of all WTs in the entire WF, it is apparent that Wind Farm Control (WFC) is more direct and effective. The research on WFC can be divided into two categories depending on whether participating in the individual turbine control. One is to achieve the control objectives of WF through adjusting WTC from the WF level (Ebrahimi et al. 2016, Tian et al. 2017, Gonzalez et al. 2013). While the other is opposite, it only coordinates and distributes the variables that are not involved in WTC such as start/stop and power reference (Soleimanzadeh and Wisniewski 2011, Soleimanzadeh et al. 2012, Zhang et al. 2015). The former method seems to be able to get better results due to more controllable variables. However, the latter method does not need to change the original controller from the manufacturer, it is easier to apply in the practice. Normally, the objectives of WFC includes power maximization, fatigue and wake reduction, frequency response, voltage control, following some specific requirements from TSO, etc.

The generator faults will influence the power output of WT directly and even result in the emergency stop. Although the failure rate of the generator is not the highest in all components, the average fault-removal time is quite long and the maintenance cost is high as well. Most research on generator faults focuses on Fault Detection and Diagnosis (FDD). The common methods need to detect some physical quantities such as voltage, current, power and then analyze the signals based on the model or signal-processing (Balasubramanian and Muthu 2017, Qiao and Lu 2015). However,

there are few articles considered generator faults in WFC. Some similar research on the fault of blade and drive-train can be found in (Badihi et al. 2015, Odgaard et al. 2009).

The analysis of generator faults shows that some faults can be mitigated by reducing load, such as turn-to-turn short circuit (Lešić et al. 2013). The down-regulation of WT can not only prevent the faulty generator from further damage but also reduce the downtime.

The contribution of this paper is to distribute power demand to the individual WTs reasonably when the generator fault occurs. According to the severity and mechanism, we divided the faults of Doubly-Fed Induction Generator (DFIG) into three levels. The proposed power dispatch strategy will take different distribution type depending on the fault level and try to fulfil the power demand under the premise of ensuring WT's safety, assuming that all faults can be detected.

This paper is organized as follows. Section 2 describes DFIG faults briefly and the fault classification. The WF model with wake effect is presented in section 3. Section 4 gives the active power dispatch strategy of WF. Section 5 provides the simulation results of different cases.

2 FAULT CLASSIFICATION

DFIG is a widely used generator in WT because of its low capital cost and good energy yield (Hansen and Hansen 2007). The components with high fault rate include slip ring/brush, bearing, cooling system, winding insulation, encoder, etc (Shipurkar 2015). Although DFIG has many different types of fault modes, the only control variable in this paper is the power reference which can adjust the electrical load of WT. So we focus more on the fault modes that can be mitigated by reducing the load. The characteristic of the fault according to Fault Tree Analysis (FTA) and Failure Modes Effect Analysis (FMEA) is used for reference. In addition, the safety of WT is always the most important. Fault severity is another factor need to be considered. The fault classification is as follows:

Fault level 1 (FL1): this fault level includes the faults that are not serious or cannot be mitigated by down-regulation. For example, some fault of the redundant sensor, minor rotor misalignment and bearing vibration.

Fault level 2 (FL2): this fault level includes the early inter-turn short-circuit faults of the stator and rotor, as well as the initial fault of the cooling system. The characteristic of this level is that the overheating caused by fault can have a more serious effect on the generator. However, down-regulation operation can reduce generator heating by decreasing the current. For protecting generator, there is a limit value of power $P_{limit,f}$. This value depends on the specific fault mode and means that the load of WT should not exceed it. The specific value of $P_{limit,f}$ can be estimated according to the fault mechanism and lifetime estimation.

Fault level 3 (FL3): this level has the highest severity, such as the phase to phase short-circuit of stator and rotor. It will result in the generator failure directly. Therefore, WT must be shut down when the fault of this level is detected for protecting WT.

3 WIND FARM MODEL

WF consists of several WTs. However, simply taking the ambient wind speed as the wind speed of all the WTs, then adding all power output of WTs as the power output of WF is not accurate due to the aerodynamic interaction. To show the results of power dispatch strategy, a WF model that taking wake effect into account is used. WF model includes three parts: WT model, wake model and WF layout.

3.1 *Wind turbine model*

A 5MW DFIG WT model is adopted here. According to the Betz theory, the mechanical power extracted by the turbine from wind energy can be calculated by the following equations:

$$P_m = \frac{1}{2}\rho\pi R^2 v^3 C_p(\lambda,\beta) \tag{1}$$

$$\lambda = \frac{\omega_r R}{v} \tag{2}$$

$$F_t = \frac{1}{2}\rho\pi R^2 v^2 C_t(\lambda,\beta) \tag{3}$$

where, P_m is the mechanical power extracted by turbine; ρ is the air density; R is the radius of rotor; v is the wind speed; C_p is the power coefficient, which depends on λ and β; λ is the tip speed radio; β is the pitch angle; ω_r is the rotor speed; F_t is the thrust force; C_t is the thrust coefficient, which depends on λ and β as well. The surfaces of C_p and C_t are shown in in Figure 1.

Pitch system adjusts the aerodynamic characteristic of blades by controlling the pitch angle. It can change the efficiency of energy capture and offer aerodynamic brake. Gearbox supports the necessary speed conversion for DFIG. Generation system includes a DFIG and a partial scale power electronic converter.

These subsystems are the major parts of DFIG WT and will be simplified as an inertial system.

The control strategies of normal operation are Maximum Power Point Tracking (MPPT) and Constant Power in low and high wind speed region respectively. The down-regulation strategy should be emphasized here because it can affect the wake.

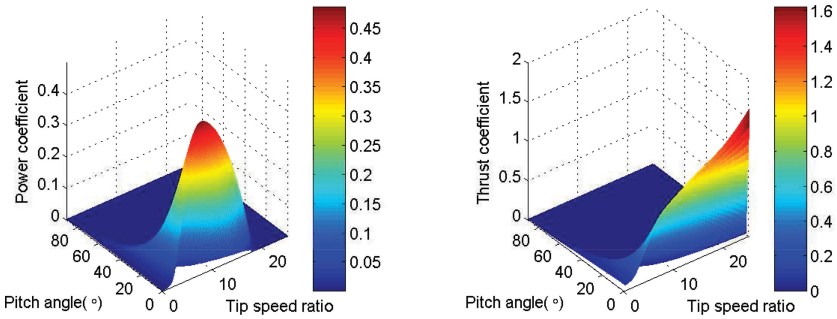

Figure 1. Surfaces of C_p and C_t.

The strategy adopted here is Max ω, which is the most widely used in the industry (Mirzaei et al. 2014).

3.2 *Wake model*

Wake effect can decrease the power production of WF and increase the fatigue load of downwind WT. Therefore, it should be considered in WFC. There are several research focus on how to describe wake effect accurately (Göçmen et al. 2016). Among engineering applications, Jensen wake model is widely used because its practicality and simplicity. In this paper, we adopt Jensen wake model for the single wake and quadratic summation method for the multiple wakes (Katic, Højstrup, & Jensen 1986). The velocity deficit can be expressed as:

$$1-\frac{v}{u}=\frac{1-\sqrt{1-C_t(\lambda,\beta)}}{(1-2\alpha X/D)^2} \tag{4}$$

where, v is the downwind wind speed at position X; u is the ambient free wind speed; X is the distance between upwind and downwind WT; D is the diameter of rotor; α is decay constant, choosing 0.05 for offshore WF.

To calculate the velocity deficit of the jth WT in multiple wakes, the following equation can be used.

$$\left(1-\frac{v_j}{u}\right)=\sum_{i=1}^{n}(1-\frac{v_{ij}}{u})^2 \tag{5}$$

where, v_j is the wind speed of the jth WT; n is the number of wakes that the jth WT is in; v_{ij} is the wind speed of the jth WT under the influence of the wake of the ith WT.

3.3 *Wind farm layout*

In order to reflect the wake effect to WF and to simplify the calculation, five WTs are arranged in a straight line. The selected wind direction makes the downwind WTs are in the full wake of the upwind

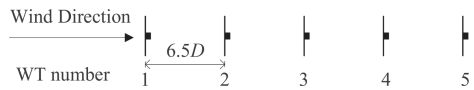

Figure 2. Wind farm layout.

WTs. This layout allows the study of the worst-casewake effect. The distance between two WTs is 6.5 times the diameter of the rotor. The layout is shown in Figure 2.

4 ACTIVE POWER DISPATCH STRATEGY WITH FAULT ACCOMMODATION

The traditional active power dispatch strategy is proportional dispatch strategy (Grunnet, Soltani, Knudsen, Kragelund, & Bak 2010). Power demand is distributed to WTs proportionally to the available power of each WT by the WF controller as follows:

$$P_{a,i}=\frac{1}{2}\rho\pi R^2 v^3 C_{p,max} \tag{6}$$

$$P_{r,i}=\frac{P_{a,i}}{\sum P_{a,i}}P_{dem} \tag{7}$$

where, $P_{a,i}$ is the available power of the ith WT; $C_{p,max}$ is the maximum coefficient of power of WT; $P_{r,i}$ is the power reference of the ith WT; P_{dem} is the power demand of WF from TSO.

The traditional proportional strategy neither considers the impact of the wake effect on power production, nor does it consider the fault of WT. The proposed strategy is also based on the proportional dispatch strategy. But it takes generator fault classification and wake effect into consideration, and tries to follow the power demand ensuring WT's safety as the precondition.

The whole strategy according to the fault level is also divided into three parts:

1. Strategy for FL1: The fault in FL1 is not severe and cannot be remitted by down-regulating

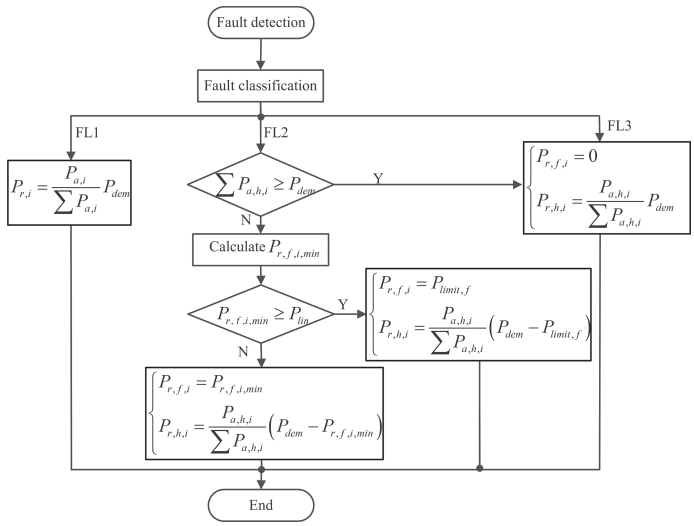

Figure 3. Flowchart of the proposed active power dispatch strategy.

WT. Therefore, the active power dispatch will maintain the original proportional strategy for both healthy WT and faulty WT.

2. Strategy for FL2: This strategy is the focus of this paper as it relates to the trade-offs between fault protection and following power demand. The general idea includes three steps.

Step 1. If the sum of the power of healthy WTs can follow the Power demand enough, it is allowed to shut down the faulty turbine. Then the power demand will be distributed as follows:

$$\begin{cases} P_{r,f,i} & = 0; \\ P_{r,h,i} & = \dfrac{P_{a,h,i}}{\sum P_{a,h,i}} P_{dem}. \end{cases} \tag{8}$$

where, $P_{r,f,i}$ is the power reference of the ith faulty WT; $P_{r,h,i}$ is the power reference of the ith healthy WT; $P_{a,h,i}$ is the available power of the ith healthy WT.

Step 2. If the sum of the power of healthy WTs cannot follow the Power demand. The minimum power reference of the faulty WT that can fulfil the power demand should be found by the exhaustive method. There are two possible reasons why the power demand can still be followed by reducing the power of a particular WT. One is that the available power of WF is higher than power demand. The other reason is that, due to the wake effect, the down-regulation of upwind WT will increase the wind speed of the downwind WTs, and the power loss because of down-regulation will be compensated by the downwind WTs. The wind speeds of WTs are highly coupled due to wake effect and are related to the power references of all the WTs. Therefore, the exhaustive method is the simplest and quickest way.

Step 3. If $P_{r,f,i,min}$ is higher than $P_{limit,f}$, the power reference of faulty WT will be set as $P_{limit,f}$. So the power output of WF must be less than the power demand. This power deviation is ineluctable for protecting WT. The power distribution will be as follows:

$$\begin{cases} P_{r,f,i} & = P_{limit,f}; \\ P_{r,h,i} & = \dfrac{P_{a,h,i}}{\sum P_{a,h,i}} \left(P_{dem} - P_{limit,f}\right). \end{cases} \tag{9}$$

If $P_{r,f,i,min}$ is smaller than $P_{limit,f}$, the power reference of faulty WT will be set as $P_{r,f,i,min}$. In this way, the strategy can follow power demand and reduce the load of faulty WT as much as possible. The power distribution will be as follows:

$$\begin{cases} P_{r,f,i} & = P_{r,f,i,min}; \\ P_{r,h,i} & = \dfrac{P_{a,h,i}}{\sum P_{a,h,i}} \left(P_{dem} - P_{r,f,i,min}\right). \end{cases} \tag{10}$$

3. Strategy for FL3: The generator fault with high severity is a serious threat to WT's safety. Therefore, the WT with FL3 must be shut down as soon as possible. The power distribution is the same with equation 8. The whole strategy is shown in the flowchart in Figure 3.

5 SIMULATION

To verify the advantage of the proposed active power dispatch strategy, the WF model mentioned in Section 3 is used. The parameters of a 5MW DFIG WT are shown in Table 1. Figure 2 shows the

distribution of wind speed under wake effect in this WF. The ambient wind speed of WT1 is 10 m/s. All power references are set to 5MW as MPPT strategy. The distribution shows that the wind speed of the downwind WT drops due to the wake effect. The following simulation will also use this WF model.

The strategies for FL1 and FL3 will not be simulated here. Because these two parts can be understood easily and there is no difference with the existing protection measure. To illustrate the fault protection, the phase current of faulty WT, $I_{N,f}$ is used in the comparison. Because all of these faults has the relationship with the current. With respect to the simulation of strategy for FL2, $P_{limit,f}$ is set to 2 MW. Three cases will be studied here to show the simulation results in different situations.

In Case 1, wind speed is 12 m/s, and power demand is 15MW. An FL2 fault occurs on WT3. The sum of power of healthy WTs can follow the Power demand enough, so the faulty WT can be shut down. It will not affect the power demand tracking. The power output of each WT is shown in Fig. 4. The red and blue bars represent the power output in Traditional Proportional Strategy (TPS) and Proposed Proportional Strategy (PPS) respectively. The power references, Power output of WF and the phase current of faulty WT are shown in Table 2. The result shows that the faulty WT is shut down, but WF can still produce enough power to follow the power demand. The faulty WT is also protected from further deterioration.

In Case 2, wind speed is 12 m/s, and power demand is 17.5MW. An FL2 fault occurs on WT5. The healthy WTs cannot supply enough power. Through the exhaustive method, the value of $P_{r,f,i,min}$ is 2.28MW in this case. It is higher than $P_{limit,f}$. According to the proposed strategy, although WF power cannot follow the power demand, in the consideration of protecting generator, the faulty WT has to be limited to 2MW. The result is shown in Table 3. The phase current of faulty WT has been decreased from 2.70kA to 1.71kA.

In Case 3, wind speed is 10 m/s, and power demand is 10MW. An FL2 fault occurs on WT3. The healthy WTs cannot fulfill the power demand either. The value of $P_{r,f,i,min}$ in this case is 0.73MW and much lower than $P_{limit,f}$. Therefore, the faulty WT can be down-regulated to 0.73MW. Meanwhile, the power demand can also be followed. The result

Table 1. Parameters of a 5MW wind turbine.

Parameter	Value
Rated Power	5 MW
Rotor Diameter	126 m
Min. and Max. Rotor Speed	6.9 rpm, 12.1 rpm
Cut-in, Rated, Cut-out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Gearbox Ratio	97:1
Synchronous Frequency	50 Hz
Electrical Generator Efficiency	94.4%
Number of Pole-pairs	3

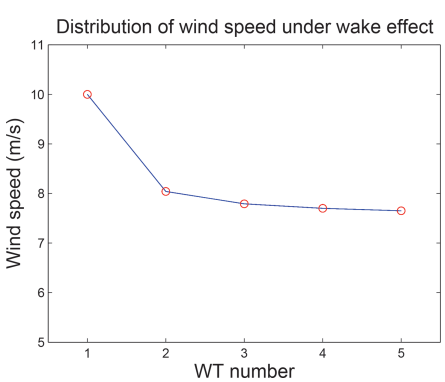

Figure 4. Distribution of wind speed in WF.

Table 2. Comparison of two strategies in Case 1.

	TPS	PPS
$P_{r,1}$ (MW)	3.19	4.01
$P_{r,2}$ (MW)	3.16	3.71
$P_{r,3}$ (MW)	2.93	0
$P_{r,4}$ (MW)	2.87	3.97
$P_{r,5}$ (MW)	2.85	3.31
P_{WF} (MW)	15.06	15.06
$I_{N,3}$ (kA)	2.50	0

Table 3. Comparison of two strategies in Case 2.

	TPS	PPS
$P_{r,1}$ (MW)	4.08	3.49
$P_{r,2}$ (MW)	3.75	1.81
$P_{r,3}$ (MW)	3.31	0.73
$P_{r,4}$ (MW)	3.20	2.26
$P_{r,5}$ (MW)	3.16	1.71
P_{WF} (MW)	17.57	10.00
$I_{N,3}$ (kA)	2.70	1.71

Table 4. Comparison of two strategies in Case 3.

	TPS	PPS
$P_{r,1}$ (MW)	2.77	3.49
$P_{r,2}$ (MW)	1.94	1.81
$P_{r,3}$ (MW)	1.82	0.73
$P_{r,4}$ (MW)	1.77	2.26
$P_{r,5}$ (MW)	1.75	1.71
P_{WF} (MW)	10.04	10.00
$I_{N,3}$ (kA)	1.55	0.62

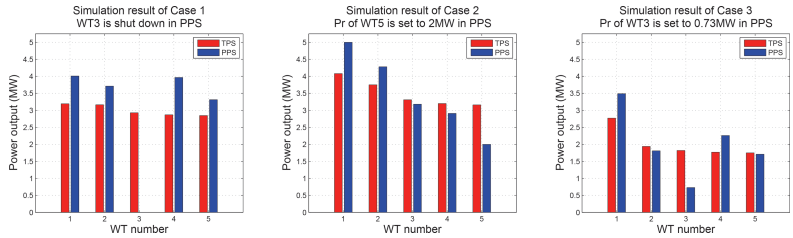

Figure 5. Comparison of power output of WTs in two strategies.

can be found in Table 4. The phase current of faulty WT can be decreased from 1.55kA to 0.62kA.

Figure 5 shows the power output of WTs in these three cases. From the simulation results, it can be seen that the proposed active power dispatch strategy can effectively ensure the safety of WT in the event of a generator fault, and follow the power demand as much as possible.

6 CONCLUSIONS

In this paper, an active power dispatch strategy of WF under generator fault is proposed. It gives the idea of implementing power distribution based on fault level. With the comparison of traditional proportional strategy, the simulation results show that the proposed strategy can make a good balance between generator protection and power production. It not only reduce the downtime caused by non-severe fault, but also follow the power demand as much as possible under the premise of ensuring WT's safety. The general idea can also be extended to some other faults in WT.

However, the shortcoming is lack of detailed research on the specific fault mode and the reliability evaluation. The fault model, lifetime estimation of generator and reliability model should be studied to combine the failure, condition, power production and reliability together in the further research.

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