The research of the power generation performance improvement technologies on fixed-pitch wind turbine

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Keywords: fixed-pitch wind turbine; blade lengthening section; safety assessment; power curve; power generation

Abstract. A fixed-pitch wind turbine power performance improvement technology was studied in order to solve the problem that the actual output of fixed-pitch wind turbines is lower than the rated output in the plateau areas. Considering with the environmental characteristics in plateau areas, one blade-adding technology was proposed, by adding a blade lengthening section to increase the rotor swept area to improve power performance. The software BLADED was used to simulate different length of the blades, economic benefit and safety assessment were conduct and the optimal length of the blade lengthening section was 650mm. The results indicated that a rate of 8.64% increase of power generation was gained after one year performance, the static investment period is about 3 years and the generating gain is about 1.68 million RMB in life period. The blade-adding technology can provide reference of how to improve the output of the fixed-pitch wind turbine.

Introduction

With the rapid development of China's wind power industry, the wind turbine capacity has been increasing, which leads to the running fixed-pitch wind turbines product at early years are neglected [1-2]. While there are still ten thousand units of fixed-pitch wind turbines running in China, most of them are in the plateau areas. Because the air density in the plateau areas is far below the standard air density of 1.225 kg/m^3, combined with the blade surface aging, the actual output is lower than the rated power, i.e. can't reaching the design requirements[3-4]. To make full use of wind resources and improve the efficiency of generating units, put forward a technology research of the improvements in fixed pitch wind turbine generator performance to improve the efficiency of economic benefits.

Well-known manufacturers of wind turbines like Gamesa、Vestas、Suzlon、Siemens and Clipper have studied the technologies to improve power performance such as blade with lengthening section, adding vortex generator[5-6]. The domestic research status is the feasibility study of the blade with lengthening section in Harbin Industrial University [7] and the study on adding vortex generator carried by Cao Rui [8].

At present, the domestic and foreign technology of how to improve the fixed pitch wind turbine generation performance only stays in the theoretical calculation and the test stage, and technical verification results are still unavailable.

Performance improvement technology

Adding the blade lengthening section, increasing the rotor area can effectively improve the wind power generation since the wind energy absorption is proportional to the rotor swept area. By adding the blade lengthening section to increase the rotor swept area, improving power performance. The technology is feasible and has advantages of energy efficiency and economical.

The key of adding the blade lengthening section is to select reasonable blade length. In theory, the longer the blade, the greater the wind energy absorption will be. The lengthen blade unit will inevitably lead to the load increasing, thus safety assessment is needed to meet the design requirements, and to obtain the optimal extension length.

The technology principle of using a longer blade is similar to adding the blade lengthening section, by increasing the rotor swept area to improve the power performance. The technology is operative, but the load increment of main components is bigger, can cause the phenomenon of excess load easily. The assessment of the safety margin of the structure is needed, and one-time investment cost is very high, the original blade replaced except has no other purpose except to be a spare part, which results in resource waste.

Adding the vortex generator in the blade surface, when the wind turbines in operation, with the angle of attack increasing, the flow separation of blade surface is occurred leading to the phenomenon of air eddy stripping, which leads to a significant loss in lift force and an increase in drag, as well as the blade stall ahead of time. Besides, with the blade aging, a dramatic loss of power generation performance is intensified. Through adding vortex generator in the blade surface, can defer the air vortex stripping blade surface early to improve power performance.

The technology has the advantages such as low cost of implement, short cycle, security risk is small and convenient , while there are also shortcomings just like aging, falling off of the vortex generator.

The technology of adding the blade lengthening section

The design of the blade lengthening section, a wind turbine unit in the Yunnan plateau area is picked as the research object. The wind farm is between 2420-2820 m above sea level, the average wind speed is 8.1 m/s, the air density is 0.894 kg/m^3, belongs to high altitude wind farm. The rated power of the units is 750 kw, while the maximum of the actual operating power is 670 kw, can't arrive a rated power for a long time. The basic parameters of wind turbines are as shown in Table 1.

Table 1: Basic parameters of 750KW wind turbine

Item	Parameter
Rated power	750kW
Type of wind wheel	three blades, upwind, fixed pitch
Impeller diameter	50m
Wheel hub height	50m
Power control	stall control
Rotor speed	21.7rpm
Rated wind speed	14m/s
Cut-in wind speed	3.5-4m/s
Cut-out wind speed	25 m/s
Extreme wind speed	60 m/s

Considering the operation of the wind turbine can’t reach the rated power for long-term, in combination with characteristic of three technologies, the technology of adding the blade lengthening section is chosen as the research direction. The design of the length of blade lengthening section is according to the forecast of the capacity gain requirements (8.5%AEP), The software Bladed was used to calculate the boost of power generation in theory and design the blade lengthening section, obtain the optimal length and structure of the blade lengthening section by continuous iterative design[9-11]. Then load simulation calculation and intensity analysis had been done in order to meet the requirements of the design and safe operation, finally get the best length of 650 mm, and adopt the cylinder type blade lengthening section and fixed with the long bolts. As shown in Fig.1 is the power curve after adding blade lengthening section compared with the actual power curve. Fig.2 is the design model of the blade lengthening section.

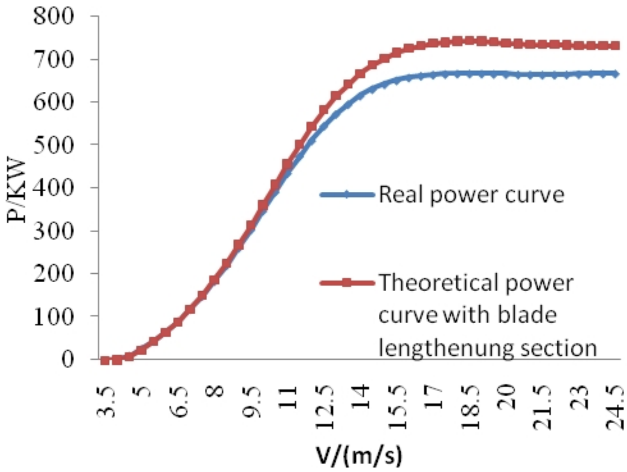

Fig.1.Power comparison between wind turbines with and without blade lengthening section

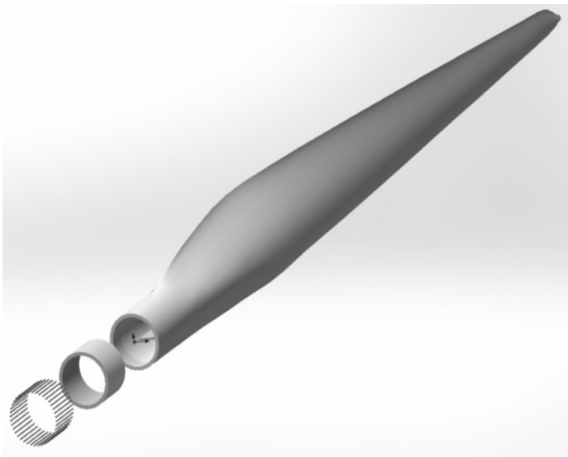

Fig.2. Design model of the blade lengthening section

Load calculation and strength analysis, according to the design of the blade lengthening section, the software Bladed was introduced to calculate the load, as shown in Table 2 is the limit load comparison between major components with and without 650 mm blade lengthening section.

Table 2:The limit load comparison between major components with and without 650 mm blade lengthening section

Component	Direction	Unit	FD51.3-750	FD50-750(original)
B-Root	Mxy	kNm	1301.3	1927.6
	Mz	kNm	77.6	109.4
	Fxy	kN	108.1	141.8
	Fz	kN	336.2	313.5
R-Hub	Mx	kNm	869.1	843.8
	Myz	kNm	917.5	1648.1
	Fx	kN	300	470.9
	Fyz	kN	254.7	263.1
S-Hub	Mx	kNm	869.1	843.8
	Myz	kNm	917.5	1648.1
	Fx	kN	300	470.9
	Fyz	kN	254.7	263.1
T-top	Mxy	kNm	1335.3	1748.1
	Mz	kNm	530.4	813.7
	Fxy	kN	344.7	452.8
	Fz	kN	603.2	362.4

From Table 2, the design limit loads of the main parts with 650 mm blade lengthening section are barely greater than the originals', and so are the fatigue loads. Mxy is mainly used for the hub strength analysis, Mx, Myz of the R- hub and the S- hub are mainly used for the strength analysis of the main shaft, frame, the main bearing and the bolts fixed in the wind turbine; The Mxy of the

T-top is mainly used for the strength analysis of the yaw system and the top flange.

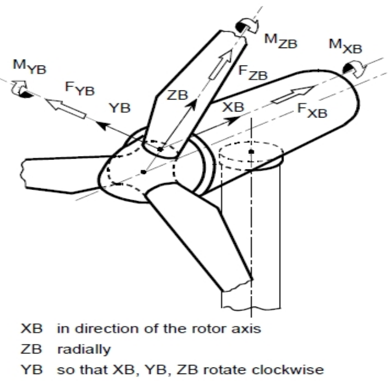

Fig.3. Coordinate frame of the blade

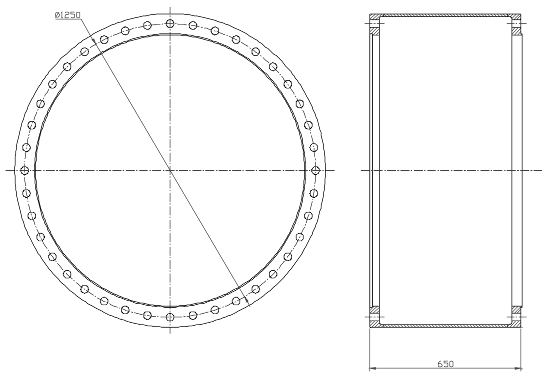

Fig.4. Structure of the blade lengthening section

The Coordinate frame of the blade and Structure of the blade lengthening section are shown in Fig.3 and Fig.4 respectively. The bottom loads of the blade lengthening section are calculated.

$$Mx = \mathrm{M}x' - Fy \cdot h - Fy'' \cdot \frac{h}{2} \quad My = \mathrm{M}y' + Fx \cdot h + Fx'' \cdot \frac{h}{2}$$
$$Mz = Mz' \quad Fx = Fx' + Fx'' \quad Fy = Fy' + Fy'' \quad Fz = F'z + Fz'' \tag{1}$$

The definition of each symbol in the formula is as shown below: *Mx, My, Mz, Fx, Fy, Fz* : the bottom load of the blade lengthening section; *Mx', My', Mz', Fx', Fy', Fz'* : the top load of the blade lengthening section, namely the bottom load of the blade; *Fx'', Fy'', Fz''* : wind load and gravity load beard by the blade lengthening section, and $Fx'' = 0.5P \cdot A, Fy'' = -mg \cdot \sin\theta$, $Fz'' = -mg \cdot \cos\theta$ .Wind pressure: $P = V^2 / 1.6$, A: the wind load area, m: quality of blade lengthening section, θ: wind turbines azimuth, h: the length of blade lengthening section.

We got the bottom load of the blade lengthening section by using the load calculation method formula (1) combined with the Bladed, and the ultimate load (including earthquake condition) was obtained, the maximum bending moment of junctions between the blade lengthening section and the hub was 1366.6kNm, Fz = 258.8kN. The section modulus of the blade lengthening section can be calculated as follows:

$$Wz = \frac{\pi(1335^2 - 1315^2)}{32 \times 1335} + \frac{\pi(1175^2 - 1155^2)}{32 \times 1175} = 24255819\, mm^2$$

Sectional area of the blade lengthening section is:

$$S = \frac{\pi(1335^2 - 1315^2)}{4} + \frac{\pi(1175^2 - 1155^2)}{4} = 78226\, mm^2$$

The roots maximum stress of the blade lengthening section is:

$$\sigma_{\max} = \frac{M}{Wz} + \frac{Fz}{S} = \frac{1366.6 \times 10^6}{24255819} + \frac{258.8 \times 10^3}{78226} = 59.6 N / mm^2$$

The material of the blade lengthening section is Q345E, Q345E's yield strength is 335MPa. The safety coefficient is chosen as 1.1, so the allowable stress is 304.5MPa, So $\sigma_{\max}{}^2 < [\sigma]$, that is, the strength of the blade lengthening section can meet the design requirements.

The calculation of the blade lengthening section was chosen the engineering algorithm, Assuming that the working load is all beard by bolts, calculation method is as follows:

$$F_O = F_M + 2Mxy / R \cdot n + Fz / n \tag{2}$$

$s_{bolt}^{2} = F_O / As$ (3)

F_O in the formula (3) is the axial force of the bolt beard the largest stress, F_M: bolt pre-tightening force; *R: distribution* radius of bolt; *n:* the number of bolts in the single blade lengthening section; σbolt: section stress of bolt; *As*: areas of dangerous section.

The bolt used is M30, the diameter of thin rod is 27mm, the torque is 1350Nm and the torque coefficient is 0.12-0.14.Combined with the maximum bending moment of junctions between the blade lengthening section and the hub 1366.6kNm and Fz = 258.8kN, the value of section stress of bolt is $s_{bolt}^{2} = 874.86MPa$, and the allowable stress is 940MPa, so the strength of the bolt also comply with the design requirements [12-15].

Strength analysis of wind turbines' main components, for the intensity of hub, the overturning moment of the hub is crucial, so the Mxy 1301.3kNm in Table 2 is used as the input load value in the strength analysis of the hub.

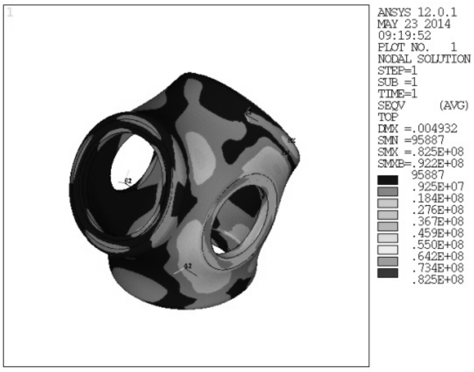

Fig.5. Extreme stress of the hub

As shown in Fig.5 is the stress under the ultimate load through the finite element simulation software. We can see that the structural strength of the hub meets the design requirements from Fig.5. Due to the blade lengthening section does not increase the power rating of the wind turbine, so has little impact on the structural strength of the transmission chain.

And for other major structures inside the unit, the input load is from the hub, namely for the structural strength of the main shaft, frame, the main bearing and connecting bolts in different position and so on, the overturning moment, thrust, torque and shearing force of the hub play the main roles. Compare the load value of the hub with the blade lengthening section with the original design value in the Table 2, we can get Table 3.

Table 3: Limit load of the hub with the blade lengthening section compared with the original design

Load	Load increment of the hub with the blade lengthening section
Mx	3%
Mxy	-44%
Fx	-36%
Fyz	-3%

By comparison, we can find that except the Mx, other limit load values are less than the original design. So the value of Mx 869.1kNm is used to take the strength analysis on each component in the wind turbine, Fig.6 and Fig.7 are the cloud images of the strength analysis of the main shaft and the frame respectively.

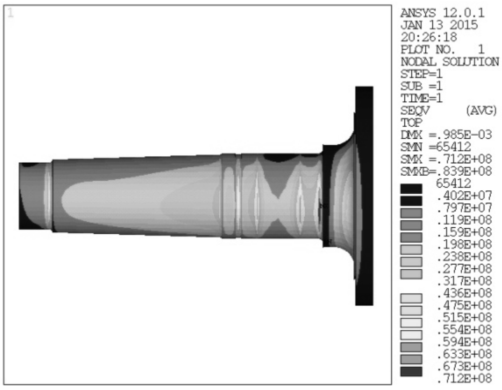

Fig.6. The cloud images of finite element analysis of the main shaft

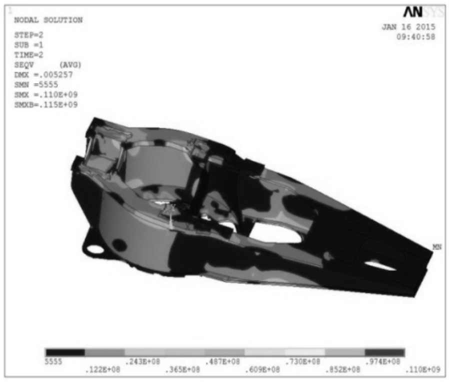

Fig.7. The cloud images of finite element analysis of the frame

The strength analysis result of the main components is shown as Table 4.

Table 4: The strength analysis result of the main components

Component	Maximum stress(Mpa)	Material yield strength (Mpa)	Safety factor
Hub	114	181.8	1.59
Shaft	211	354.5	1.68
Frame	146	295.5	2.02
Top flange	237	250	1.35
Yaw bolt	912.8	940	1.43
Hub-Shaft bolt	879.8	940	1.37

From the Table 4 we know the result can reach the design requirement. Besides, we assessed the strength of the tower, and got the stress and yield strength of various sections as shown in table 5.So we find the most dangerous section is at a height of 29.57 meters, the value of safety margin is 25.4% ,can meet the design requirement.

Table 5: The intensity analysis of various cross section

H(m)	$\sigma_{xs,R,d}$ (Mpa)	$\tau_{s,R,d}$ (Mpa)	$\sigma_{x,n}/\sigma_{xs,R,d}$	$\tau/\tau_{s,R,d}$	Safety margin
0.00	206.6	97.7	0.684	0.051	60.2%
4.17	210.4	99.7	0.665	0.052	65.8%
8.37	233.8	94.3	0.654	0.063	68.8%
27.52	238.8	84.5	0.629	0.110	74.8%
29.57	228.9	73.3	0.818	0.138	25.4%
31.70	231.5	74.7	0.770	0.138	35.1%
34.09	234.8	76.9	0.543	0.154	104.4%
38.75	252.0	93.9	0.472	0.102	149.1%
43.45	239.2	76.4	0.372	0.156	218.0%

We've come to the conclusion: the power gain with the 650mm blade lengthening section is expected to reach 8.5%, structure strength of every part can meet the design requirements, and the wind turbine can run safely.

Test and evaluation in wind farm

To assess the growth of the power generation performance with the 650mm blade lengthening section, the wind turbine 13 # and 15 # were selected as the experimental objects, whose blade equipped with the 650mm blade lengthening section. After a year of power generation continuously, statistical analysis these dates for 13 # and 15 # unit power curve contrast diagram, as shown in Fig.8 and Fig.9.

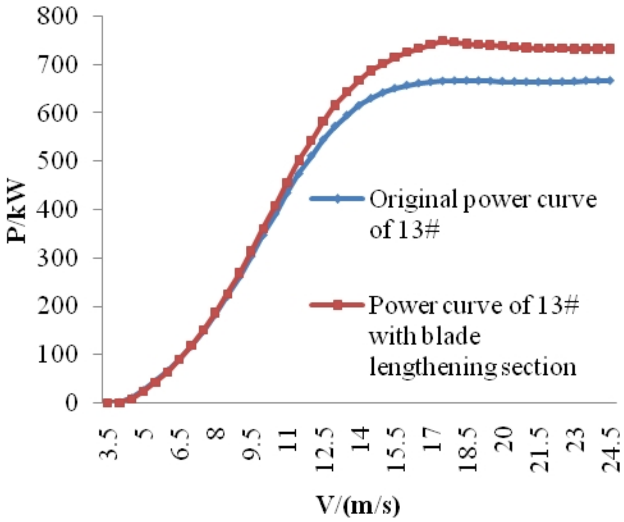

Fig.8.Power comparison between wind turbines with and without blade lengthening section

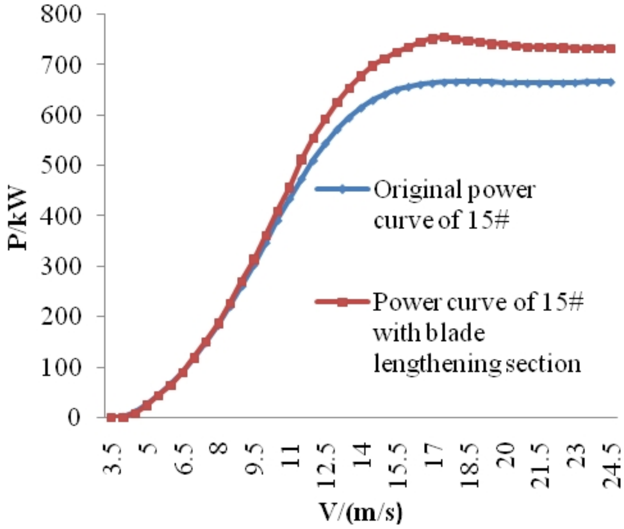

Fig.9.Power comparison between wind turbines with and without blade lengthening section

See from Fig.8 and Fig.9, the power curve of 13 # and 15 # with blade lengthening section is in conformity with the theoretical power curve, and the maximum power is 750 kW, compared to the original power curve the output of the power has an obvious ascension. We can find that the power of the wind turbines with blade lengthening section is more than the original's 90 kW in the region of the rated wind speed by comparing the power curve, the gain rate is about 12.75%.

To assess the growth of the power generation performance with the 650mm blade lengthening section, we had compared the annual energy output of the wind turbines with blade lengthening section with the originals' under the same wind speed conditions, got the data as shown in Table 6.

Table 6: The gain rate of the units with blade lengthening section

Item	FD51.3-750	FD50-750（original）	Gain rate
Average wind speed（m/s）	5.87	5.85	/
Annual energy output（kW.h）	1873585.6	1724581.7	8.64%

The average annual energy output of the wind turbines with blade lengthening section is more than the original's under the same wind speed from Table 6, and the gain rate is about 8.64%, in accordance with the basic theoretical design indexes.

Besides, a single charge of adding the blade lengthening section is 300000 RMB, the cost recovery period is 3 years, the return period of cost is short and the rate of return on investment is large. The gain profit of a single wind turbine with blade lengthening section at the period of life is about 1.68 million RMB. The technology improves the fixed-pitch wind turbine power generation performance has very good economical and technical reference.

Conclusions

Aiming at most of the actual output of fixed-pitch wind turbines is lower than the rated power. To improve the power generation performance, selected the 750kW wind turbine in one plateau region in Yunnan province as a research object, whose rated power is 750kW while the maximum actual operation power is 670kW. According to the project situation, the technology of adding the blade lengthening section was chose. The software Bladed were used to simulate different length of the blade lengthening section, the economic benefit and safety assessment was conduct and the optimal length of the blade lengthening section was selected as 650mm. The monitoring statistics of a year was obtained after the wind turbine adding the blade lengthening section, and the results indicated as the wind speed growing, the power generation performance is more significant. The actual output is 750kW, consistent with the theoretical design value. And the annual energy output gain rate of the wind turbines with blade lengthening section was 8.64%, the static cost recovery period is 3 years and the gain profit of a single wind turbine with blade lengthening section at the period of life is about 1.68 million RMB. The technology is feasible and has an advantage of good economy, provides a reference of how to improve the output performance of the fixed-pitch wind turbine.

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