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Control Algorithm of Static Loading Test for Wind Turbine Blades Based on Fuzzy Theory

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Abstract

In the process of full-scale static loading test of wind turbine blades, the loading forces all had relatively strong coupling effect, which seriously affected the accuracy of the test result. In order to eliminate this effect, firstly, a vertical static loading device for 10MW wind turbine blades was established and the coupling rule of loading force was obtained. Then, a control algorithm was put forward based on fuzzy theory. This algorithm took the error of loading force, error's change rate as the input variables and the opening degree of proportional valve as the output variable. A control strategy based on this algorithm was constructed. In the end, the static device took the max flapwise of aeroblade5.0-62 wind turbine blade as example to conduct loading test. The result suggested the algorithm in this paper could ensure that the loading forces on five nodes always kept uniform changing and the control errors were respectively less than±2KN, ±2KN,± 2KN,± 2KN and±1KN. When in the 100% phase, the loading force could be finely maintained at the set value. The statistical results showed that the error rates of loading force with control algorithm were smaller than those without control algorithm. The test results verified the feasibility of control strategy applying to full-scale static loading test for wind turbine blades.

Keywords: *Wind turbine blade, Static Loading test, Loading force, Fuzzy control algorithm*

1. Introduction

Wind power is becoming a focus of national new energy industry. As blade is one of the core components of wind generating set, its quality decide the sound development of the wind power industry. Once the blade damaged, manufacturers will suffer great economic losses. So researching on full-scale structural test of wind turbine blades becomes very significant. Static test is the most important step of blade authentication. It aims to verify whether the blade can sustain the ultimate load (such as 50 years return period hurricane). According to the world third-party authorized certification body, Germanischer Loyed's testing standards: Guideline for the Certification of Wind Turbine [1] and IEC61400-23 Full-scale Structural Testing of Wind Turbine Blades [2], the static load assessment is the essential step in the test of blades' structure property. Newly-developed and after-greatly-craft-changing blades all require full-scale static loading test to verify the static strength reserved in blades. However, the in-site test suggested a coupling effect existed among the loading forces inherently in the process of static test. The change of loading force on any node caused irregular fluctuations of loading forces

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on others, and further led to discordant and non-uniform changes among the loading forces. The test data obtained ultimately was serious distorted. So decoupling control among the loading forces becomes greatly important.

Several scholars have conducted studies on coordination control. Csnale M, *et al.,* [3-5] applied sliding-mode control algorithm to drive permanent magnet motors and obtained a good control effect. Arie L, *et al.,* [6-8] put the discrete control rate that produces buffeting on the r-order derivative of selected sliding mode surface. This method ensured algorithm's convergence in limit time and effectively eliminated the buffeting phenomenon. Huang Pu Y G, *et al.,* [9] used high-order sliding control algorithm that had buffet-eliminating effect and put forward a high-order sliding-mode control strategy. This control realized feedback-linearization coordination control. Benitro F R, *et al.,* [10] constructed a self-adaptive sliding-mode control algorithm and applied it to the control system of swing table with three axes and got a good control effect. Ming Hua, a researcher of Nanjing University of Aeronautics and Astronautics, put forward a distributed control method of parallel- operation inverters and it was proved feasible by the theoretical analysis and experimental verification.

A vertical loading system for static test of 10MW wind turbine blades was established. A decoupling control algorithm based on fuzzy theory was constructed as well. Then the algorithm was applied to the full-scale static test of wind turbine blades. The accurate control result was obtained finally.

2. Vertical Full-scale Static Loading System of Wind Turbine Blades

Static loading mode adopted vertical pulling-down method, as shown in Figure 1. Loading mode usually applied horizontal pulling method. However, as the capacity of wind turbines increases, the size of the blade must increase accordingly. Vertical pulling-down method can utilize the weight of the blade and save space because of warp shape of the blade. Every loading node mainly consisted of loading stand, hydraulic drive system and electronic control system. The wind turbine blade was fixed on the cylindrical base by high strength bolts. The clamps on the blade were connected to the loading nodes through wire ropes (in-site test picture see section 4).

Static loading test is usually divided into four phases, that is, the loading and unloading were conducted at 40percent, 60 percent, 80 percent and 100 percent of the max loading and the time of 100 percent phase was required to no less than ten seconds. When loading phases were finished, unloading was conducted at the reversed order of the loading process. The whole process is shown in Figure 2.

The throttle speed control mode was used in this hydraulic system. Loading force was produced by the hydraulic winch rotating and the speed of each loading node was controlled by hydraulic valve. Control system adopted distributed network architecture mode. The main controller and every sub-controller transmitted date through CAN bus. The main controller communicated with the HMI through RS485 bus. HMI was developed by Delphi software and it was used for monitoring the static loading process. A tension sensor fixed on the wire rope to collect the present loading force for every node (Figure 1). The loading force data were recorded by Excel. The control algorithm was realized in main controller and the sub-controller was used only for terminal. The whole control diagram is shown in Figure 3.

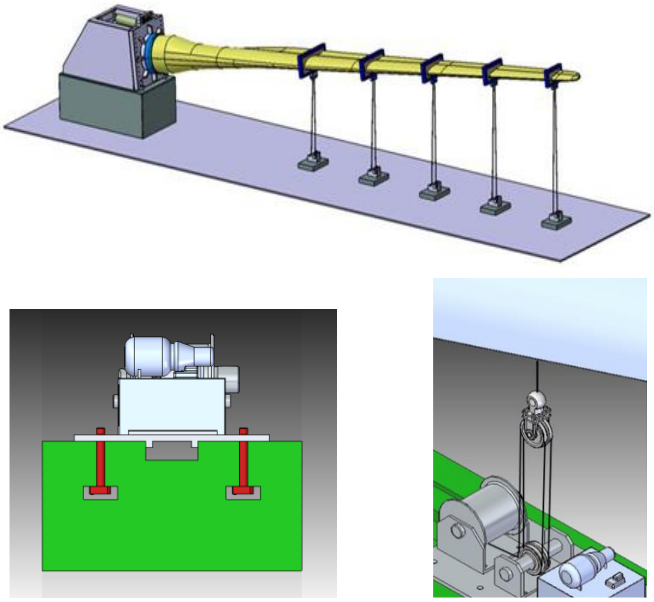

Figure 1. Static Loading Test of Wind Turbine Blades

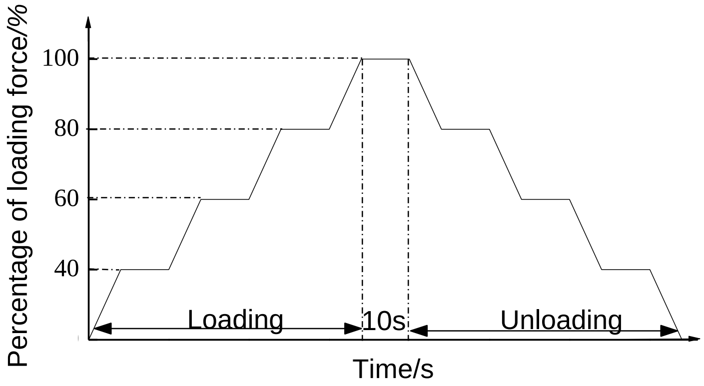

Figure 2. Static Loading and Unloading Phases

3. Loading Control Algorithm based on Fuzzy Theory

3.1. Coupling Rules of Loading Force

First, the coupling rules of loading force needed to be obtained. The set value of loading force for every phase was made as target value. Assuming that the loading forces on five nodes were F[i], the control of every node was independent. Then, loading forces approached to target values in the process respectively. The first loading force reaching the set value would be forced to stop and the value of other loading forces would keep pace with each other. In the whole process of the test, the loading forces and their errors of the five nodes are separately showed in Figure 4 and Figure 5.

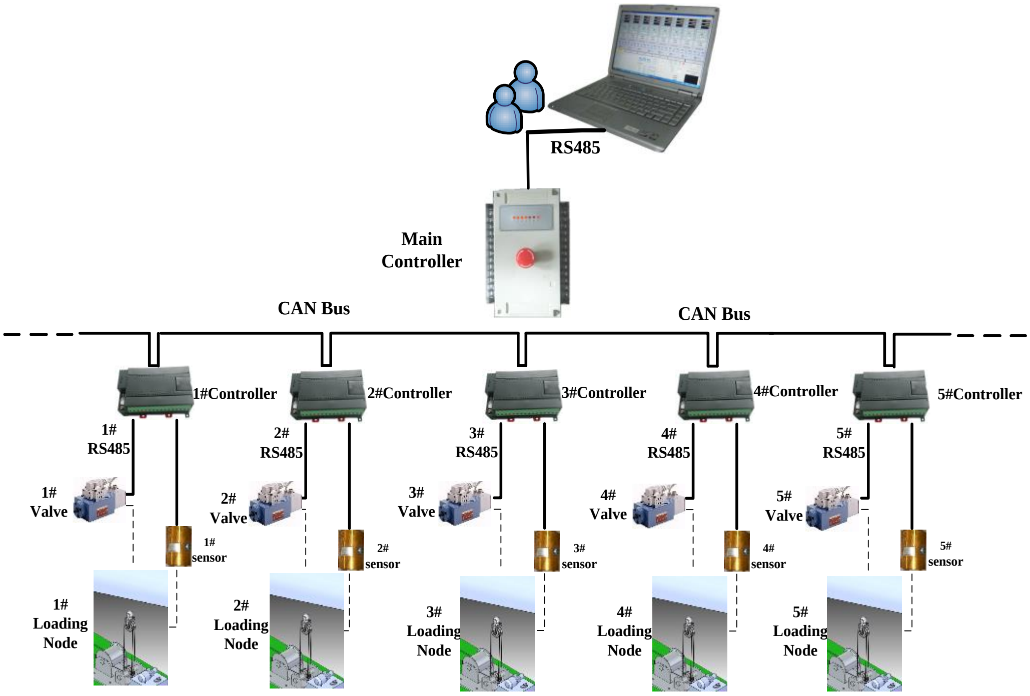

Figure 3. Control Diagram

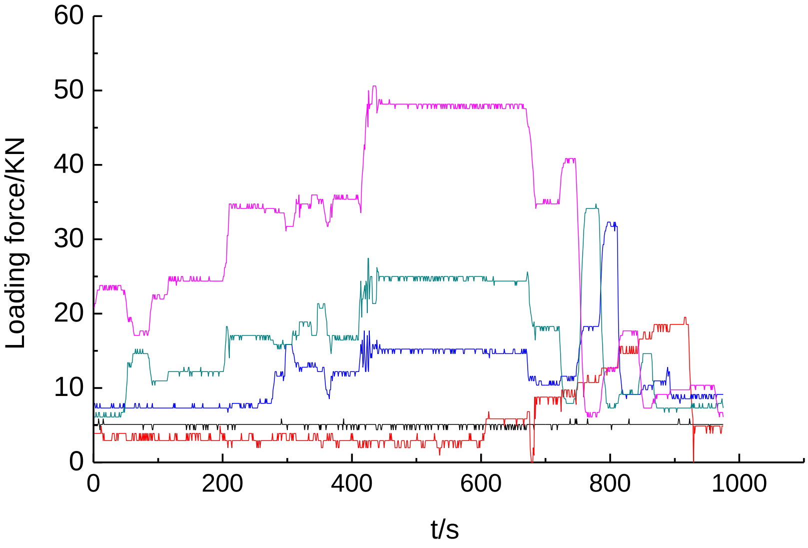

Figure 4. Change Curves of Loading Force

From the curves of loading change in Figure 4, we could conclude that in the whole process of the test, the coupling effect was seriously among the loading forces. The change of loading force for any node would cause changes of loading forces for others. According to the curves of loading force error in Figure 5, the loading force would have great error within a short time when the hydraulic winch just started or the load changed drastically. Then, with the wire rope being tensioned, the loading error would decrease relatively. If the loading force was bigger; the coupling degree was more serious. In the whole test process, the max errors of the four nodes' loading forces approximately were: 15KN, 15KN, 10KN, 3KN and 3KN, respectively.

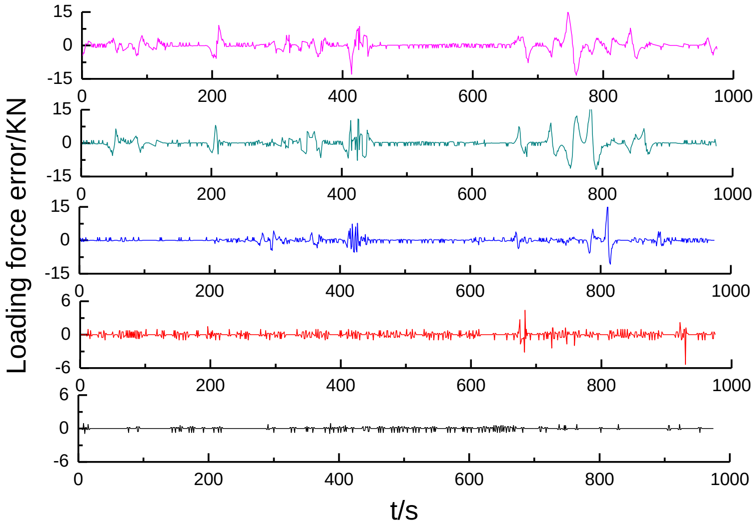

Figure 5. Change Curve of Loading Force Error

3.2. Coordination Control Algorithm of Loading Force

From the section 2.1, we can conclude the full-scale static test of wind turbine blade is a nonlinear and strong-coupling process. The faster the loading speed was the higher coupling degree it caused. In order to get fine control accuracy, firstly dynamic command method was adopted to determine the slowest loading node. Then, other loading nodes were compared with the slowest one and were adjusted dynamically. This method can be described as:

The loading forces of every sampling period were expressed as F[i], then, the array F[i] was composed of a group of sequences {F[0], F[1], F[2]……}. The loading force F[n] of the slowest node was taken as the base in every cycle period. Other nodes' loading forces F[m] were compared with this one in real time. If $k_{m,n} \times F[m] < F[n]$, The F[m] was taken as the slowest node in the next period ($k_{m,n}$ is a preset value). In this way, the dynamic errors of the loading nodes expect the standard can be expressed as:

$$E(m)=R(m)- k_{m,n} \times F[m] \qquad (1)$$

In this formula, E(m) was the dynamic error of loading force , and R(m) was the set value of loading force.

It's difficult to develop an accurate mathematical model of loading control. However, fuzzy theory doesn't rely on mathematical model. So, this theory is finely applied to coordination control of loading force in static test. The control algorithm takes loading error as controlled object. According to the approximately linear corresponding relation between the loading velocity and the change of loading force, the regulating of the loading force could be converted to the opening degree of proportional velocity regulating valve. Two-dimensional fuzzy controller was adopted. The input variable were loading error E (KN) and its changing rate DE, the output variable was the opening degree of proportional velocity regulating valve. The process of fuzzy control for loading force is shown in Figure 6.

In the static loading system of wind turbine blades, the loading force ranged from 0 to F_{max}. So, the basic domain of loading error was set to$[-F_{max}, F_{max}]$and its discrete domain was defined E={-5,-4,-3,-2,-1,0,1,2,3,4,5}. The linguistic variables of loading force error E were five fuzzy subsets: NB, NS, Z, PS, PB. The basic domain of changing rate for loading error was set to [-50,50] and its discrete domain was defined E={-5,-4,-3,-2,-1,0,1,2,3,4,5}. The linguistic variables of changing rate for loading force error DE were five fuzzy subsets: NB, NS, Z, PS, PB. The output variable of fuzzy controller was the motor speed V and the basic domain of proportional velocity regulating valve was[0,100] and its discrete domain was defined to V={-5,-4,-3,-2,-1,0,1,2,3,4,5}. The linguistic variables of valve opening degree were also five fuzzy subsets: NB, NS, Z, PS, PB (The negative value represented the inverting of reversing valve).

Figure 6. Principle of Fuzzy Control System

According to the basic domain and the quantization level, the scale factors of inputs and output were:

$$k_{\mathrm{E}} = 5/F_{\max};\ k_{\mathrm{DE}} = 5/50 = 0.1;\ k_{\mathrm{V}} = 100/5 = 20;$$

Two-input-single-output fuzzy controller was adopted, and trigonometric function was used for the membership function of inputs and the output. Control rules were expressed in conditional statements. Mamdani method was applied to fuzzy decision-making, and accurate value could be obtained by using gravity method. The fuzzy control rule of loading force is shown in Table1.

4. Test Process

The max flapwise of aeroblade5.0-62 wind turbine blade was taken as controlled object. The blade was fixed on the loading support by 120 high strength bolts. Five nodes placed on the guide rail were adopted to finish the loading test. Test site was shown in Figure 7 and test parameters are shown in Table 2. Static loading test was usually divided into four phases, as we mentioned in section 2. The 100 percent of the max loading force and its loading location were shown in Figure 8.

Table 1. Fuzzy Control Rules

		Error of loading force E				
		NB	NS	Z	PS	PB
Change rate of error DE	NB	PB	PS	PS	NS	NB
	NS	PB	PS	Z	NS	NB
	Z	PS	PS	Z	NS	NS
	PS	PS	Z	NS	NS	NB
	PB	PS	Z	NS	NS	NB

Figure 7. In-site Test of Static Loading

Figure 8. Loading Force and Location Diagram

Decoupling control algorithm mentioned above was adopted to conduct static loading test. The control algorithm was written through 16bit Infineon XC164CS Single chip. Variations of loading forces and their errors of five loading nodes in the whole test were obtained, as shown in Figure 9 and Figure 10.

As we can see from the loading test curves in Figure 9 and Figure 10, loading forces of the five nodes basically kept the uniform and stable change in the whole process of the test. When in the 100 percent phase, loading forces of five nodes could be finely maintained at 90kN, 35kN, 20kN, 6kN and 5kN. Errors of loading forces of five nodes could be finely controlled at±2KN, ±2KN, ±2KN, ±2KN and±1KN.

Table 2. Test Parameters

parameters	Values
Rated power of the blade	5MW
Length of the blades	60m
Number of loading point	5
Type of the tension sensor	DBSL-50T
Max force of loading point	500KN
Temperature	16℃
Humidity	35RH

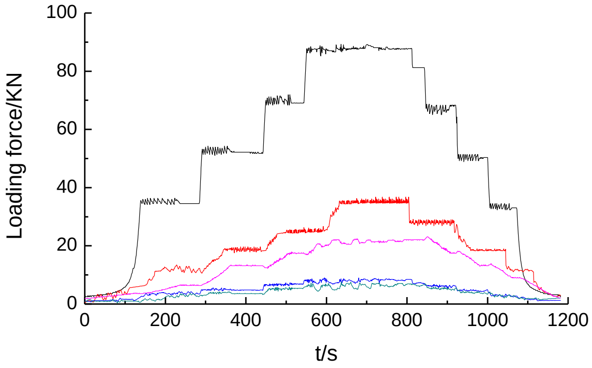

Figure 9. Variation Curve of Loading Force

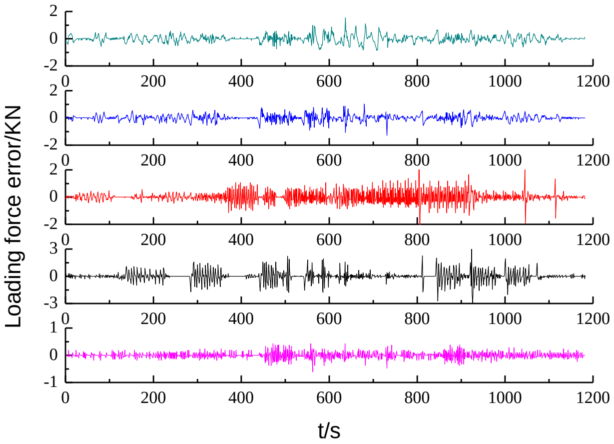

Figure 10. Change Curve of Loading Force Error Applying Fuzzy Control

Compared the control effect based on fuzzy theory to uncontrolled effect, the statistics result of error rate of loading force for five loading nodes is shown as Figure 11. Because the loading force of fourth and fifth loading node was too small, there was no significance change even with control strategy.

The stability of loading force under fuzzy control algorithm was better than before in Figure 11 obviously. The loading force error of the largest node was less than 2%.The control effect could meet the requirement of the wind turbine blade full-scale static loading test fully.

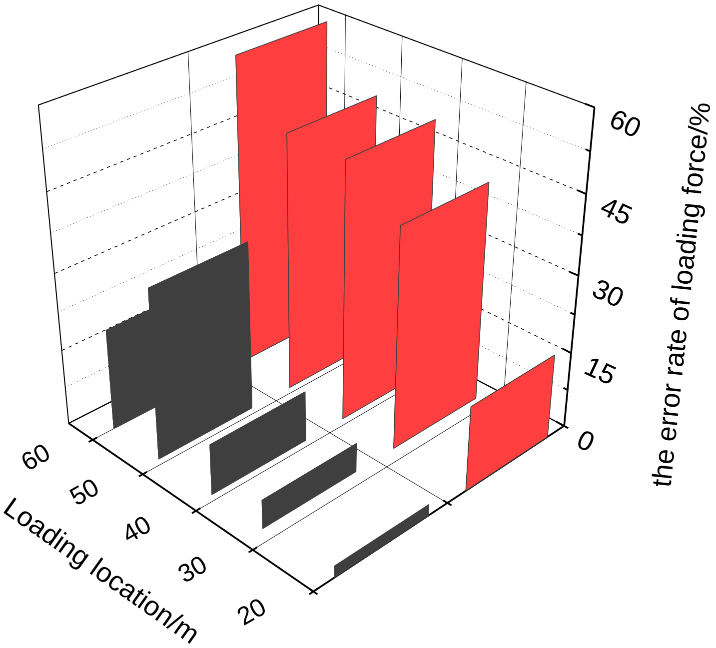

Figure 11. The Error Rate Statistics Result of Loading Force

5. Conclusion

The full-scale static test of wind turbine blade was a complicated nonlinear and strong-coupling process. In this paper, a vertical loading system for full-scale static test of 10 MW wind turbine blade was established firstly. Then a decoupling control algorithm based on fuzzy theory was put forward and applied to five-node full-scale test of jumbo-size wind turbine blade successfully. The test results showed the decoupling control algorithm of this paper could substantially increase the coordination and control precision of loading forces in static test. Also, this algorithm ensured the accuracy of the test results as well as had the advantages of prompt tracking and strong anti-interference ability. The above research provided substantial theoretical basis and detailed test data for the further redesigning of blades.

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