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Optimization Control for Flapping Load Mitigation and Output Power Levelling of Wind Turbine

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Abstract: Fatigue load affects the secure and stability of wind turbine operation. Flapping load is the main source of fatigue load endured by wind turbine operating above the rated wind speed. In this paper, a novel optimization control method for wind turbine flapping load mitigation and output power leveling is proposed. At first, wind turbine flapping load is analyzed and its calculation model is presented. Secondly, principle of the proposed control method is presented. Considering on coupling between flapping load and output power, a multi-objective optimization model and differential evolution based flapping load optimization controller are then designed. Additional PID-based output power leveling controller is employed to keep the output power leveling around the rated power. Finally, the effectiveness of the proposed control method is demonstrated by NREL 5MW wind turbine simulations.

Keywords: wind turbine, pitch angle, flapping load calculation model, output power leveling, differential evolution algorithm.

1. INTRODUCTION

With rapid development of wind energy industry and wind turbine technology, more and more MW-class wind turbines with large size and capacity are installed all over the world. The blades and mechanical components of large-scale wind turbine would endure large load under operating in variable and random wind speed environment. This would lead to mechanical vibration and fatigue loading of blades and components of wind turbine, even more serious fatigue damage (N. Beganovic, 2016). In the worst case, these will lead to serious accidents, such as tearing of blades, tower collapse, generator burning due to overspeed and so on (B. Fitzgerald, 2018). Long time fatigue loading also will reduce operating life of wind turbine and increase maintenance costs.

Wind turbine mainly is composed of blades, wheels, tower, transmission system, gearbox and generator (F. P. G. Marquez, 2016). Mechanical loads suffered by wind turbine include the load on blade, load on hub, load on tower, load on gear transmission and so on. Wind turbine converts the aerodynamic energy into mechanical energy of rotor by blades, and then convert mechanical energy into electricity by transmission system, gear box and generator. Thus, blade is the most important component of wind turbine and its load is the main load on wind turbine. In recent years, to guarantee secure and stable operation of wind turbine, more and more research focus on control approach for mitigating and optimizing the load on blade of wind turbine.

Wind turbine blade would endure large load when it is operating above the rated wind speed. Most existing control approach for the load on blade mitigating and optimizing are studied in this situation. The existing control approach can be categorized into Collective Pitch Control (CPC) and Individual Pitch Control (IPC). CPC mainly reduce oscillations and fluctuation of the over-all aerodynamic load on blade (which includes flapping load, shimmy bending load, edgewise bending load and so on) by a collective pitch control system. Many CPC methods have been proposed to reduce fatigue load on wind turbine blade, such as Recursive Least Square filter based feedforward control method (N. Wang, 2012), nonlinear dynamic inversion control(M. J. Reiner, 2015), robust control (H. Geng, 2009). IPC mainly reduce or suppress oscillation of structure load, which is derived from flapping load by Park transformation or d-q transformation (V. Petrovic, 2015), by using each individual pitch controller and installed load sensors. In recent years, many control algorithms are utilized in IPC for load reduction or mitigation, such as Linear-Quadratic-Gaussian based control (K. Selvam, 2009), proportional–integral controller and resonant (PIR) compensator based control method (Y. Zhang, 2013), Proportional resonant control(S. Xiao, 2014), fuzzy logic control (Z. Civelek, 2017) and so on.

Most existing CPC methods only consider the aerodynamic load on the blade but neglect the coupling between the output power and the fatigue load. Meanwhile, most IPC methods are designed based on the common agreement that its individual pitch angle change would not affect the output power of wind turbine. However, when wind speed change rapidly, the interaction cannot be ignored. Previous studies also neglect the coupling of structure load and other loads on the blade. Since the flapping load is the main fatigue load on the blade in above rating wind speed region. Thus, a novel optimization control method for flapping load mitigation considering the above coupling is proposed in this paper.

2. WIND TURBINE FLAPPING LOAD AND ITS CALCULATION MODEL

The aerodynamic load suffered by wind turbine blade is mainly composed by shimmy bending moment and flapping bending moment, which cause blade mechanical vibration as source of the fatigue load on blade. The mechanical vibration of wind turbine blade is shown in Fig.1.The vibration includes vibration parallel and perpendicular to rotation plane of wind wheel. Shimmy bending moment is the source of mechanical energy of wind turbine, also lead to the vibration parallel to rotation plane of wind wheel. Flapping bending moment lead to the vibration perpendicular to rotation plane of wind wheel, which is the main source of fatigue load on blade.

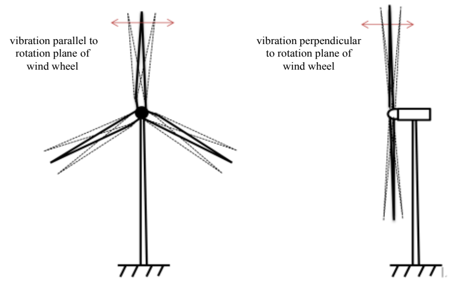

Fig. 1. Mechanical vibration of wind turbine blade

According to Blade Element Momentum theory (G. Richmond-Navarro, 2017), blade could be divided into many elements and the axial force and torque of blade calculated at each element. The force surfed by each element is shown in Fig.2.

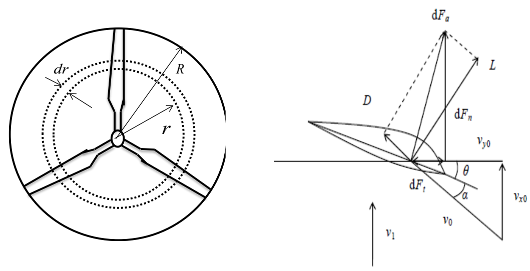

Fig. 2. The force suffered by blade element.

In Fig.2, R is the blade radius of wind turbine, r is the distance from blade element to center of wind rotor, dr is width of the blade element. At each dr, α is the angle of wind attack, θ is the pitch angle, v_1 is the inflow wind speed in front of blade, dF_a is aerodynamic force, dF_n is normal force and dF_t is tangential force.

As seen in Fig.2, airflow speed v_0 could be divided into v_{x0} perpendicular to rotation plane of wind wheel and v_{y0} parallel to rotation plane of wind wheel.

$$v_{x0} = (1-a)v_1 \, , \quad v_{y0} = (1+b)\Omega r \tag{1}$$

where a is axial induction factor, b is tangent induction factor, Ω is rotational speed of wind turbine rotor, r is the radius of the circular ring.

According to the geometric relationship, the inflow angle of blade elemental ϕ could be written as follow.

$$\phi = \arctan\frac{v_{x0}}{v_{y0}} = \arctan\frac{(1-a)v_1}{(1+b)\Omega r} \tag{2}$$

Meanwhile, angle of wind attack α could written as,

$$\alpha = \phi - \theta \tag{3}$$

Airflow speed v_0 could be written as follow.

$$v_0 = \sqrt{v_{x0}^2 + v_{y0}^2} = \sqrt{(1-a)^2 v_1^2 + (1+b)^2 \Omega^2 r^2} \tag{4}$$

By using angle of wind attack α, lift force coefficient C_l and drag force coefficient C_d could be obtained. Normal force coefficient and tangential force coefficient can be given.

$$C_n = C_l \cos\phi + C_d \sin\phi \, , \; C_t = C_l \sin\phi - C_d \cos\phi \tag{5}$$

The aerodynamic force suffered by blade element dr under airflow speed v_0, dF_a could be divided into normal force and tangential force as follows.

$$dF_n = 0.5\rho c v_0^2 C_n dr, \; dF_t = 0.5\rho c v_0^2 C_t dr \tag{6}$$

where ρ is density of airflow, c is Chord length of the blade element.

Now, the axial force suffered by rotation ring at blade element dr in wind wheel plane could be written as follow.

$$dF = 0.5B\rho c v_0^2 C_n dr \tag{7}$$

where B is the number of wind turbine blade.

The axial force suffered by wind wheel could be obtained.

$$F = 0.5B\rho \int c v_0^2 C_n dr = 0.5B\rho \sum_{i=1}^{N} c_i v_{0i}^2 C_{ni} dr_i \tag{8}$$

where i is the i th blade element at r_i, N is the number of wind turbine element.

Similarly, the torque on rotation ring at blade element dr and whole wind wheel could be given as follows.

$$T = 0.5B\rho\int cv_0^2 C_t r dr = 0.5B\rho\sum_{i=1}^{N} c_i v_{0i}^2 C_{ti} r_i dr_i \qquad (9)$$

Obviously, torque will cause blade vibration parallel to rotation plane of wind wheel. Axial force will cause blade vibration perpendicular to rotation plane of wind wheel, i.e., flapping vibration. Thus, flapping load could be given as follow,

$$M = 0.5B\rho\int cv_0^2 C_n r dr = 0.5B\rho\sum_{i=1}^{N} c_i v_{0i}^2 C_{ni} r_i dr_i \qquad (10)$$

The flapping load coefficient C_M can be defined as follow,

$$C_M = \frac{M}{0.5\rho v_1^2 AR} \qquad (11)$$

By using wind turbine blade parameters and above aerodynamic parameters at each blade element and non-linear fitting algorithm, C_M could be derived as follow (C. Peng, 2017),

$$C_M(\lambda,\ \theta) = (h_1 - h_2\theta)\sin\left[\frac{\pi(\lambda - h_3)}{h_4 - h_5\theta}\right] - h_6(\lambda - h_3)\theta \qquad (12)$$

where λ is tip speed ratio, h_i $(i = 1,2,\cdots,6)$ are the fitted parameters. Now, the flapping load could be calculated by following equation.

$$M = 0.5\rho\pi v_1^2 R^3 C_M(\lambda,\theta) \qquad (13)$$

3. THE SIMPLIFIED WIND TURBINE MODEL

Wind turbine system model is mainly composed by aerodynamic to rotation mechanic energy transmission model, drive train system model, electric power control system model and pitch angle control system model. Their simplified mathematical models are given as following equations respectively.

$$\begin{cases} T_r = P_r / \omega_r = 0.5\rho\pi R^2 v^3 C_p(\lambda,\beta) / \omega_r \\ \left(J_g + J_r / n^2\right) d\omega_g / dt = T / n - T_g \\ P_e = \omega_g T_g \\ \dot{T}_g = (P_{ref} / \omega_g - T_g) / \tau_g \\ \dot{\theta} = (\theta_{ref} - \theta) / \tau_\theta \end{cases} \qquad (14)$$

where T_r is aerodynamic torque, ω_r is rotation speed of wind turbine rotor, R is diameter of wind blades, v is wind speed, λ is tip velocity ratio, C_p is wind power coefficient, P_r is rotation mechanical power, J_r and J_g are rotation inertia of wind turbine rotor and generator respectively; n is the increased speed ratio, ω_g is the speed of power generator, T_g is electromagnetic torque, τ_g is the time constant of power generator, P_{ref} is the reference output power, θ_{ref} βref is the reference pitch angle and τ_θ is time constant of pitch system.

4. THE PROPOSED CONTROL METHOD

In this section, the principle of the proposed control method and its design will be presented in detail.

4.1 The Principle and Control Scheme

The control scheme of the proposed control method is shown in Fig.3. In Fig.3, V is actual wind speed, P_{rated} and P_e are reference power , i.e., the rated power and actual power output of wind turbine respectively, e_1 is the power error between P_{rated} and P_e , θ_{ref} and θ are the reference pitch angle and actual pitch respectively.

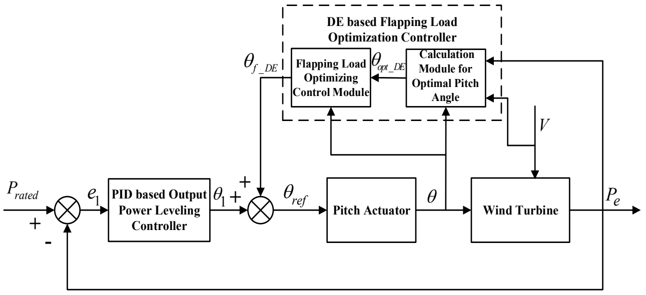

Fig. 3. The control scheme of the proposed control method.

The control scheme mainly consists of a DE based flapping load optimization controller and a PID based output power levelling controller. PID based output power leveling controller regulates the output power to the rated power of wind turbine by pitch angle control. Cooperating with power controller, DE based flapping load optimization controller utilizes flapping load calculation model and differential evolution algorithm to adjusts the pitch angle to achieve optimization of flapping load and output power leveling above the rated wind speed.

4.2 The Design of DE based Flapping Load Optimization Controller

As seen in Fig.3, DE based flapping load optimization controller is composed by a calculation module for optimal pitch angle and flapping load optimizing control module. The calculation module for optimal pitch angle takes wind speed, actual pitch angle, actual output power and wind turbine blade parameters as input, utilizes flapping load calculation model and differential evolution algorithm to obtain the optimal blade which could reduce flapping load and regulating output power around the rated power in same time. By using differential evolution algorithm, it not only could search the optimal pitch angle according to wind speed change, but also could consider on the coupling relationship between output power and flapping load. The flapping load optimizing control module takes optimal pitch angle and actual pitch angle as input, outputs the adjusting angle to output power controller.

1) Optimization Objective function

The optimization objective of wind turbine operating above the rated wind speed, is search an optimal pitch angle to minimize flapping load and output power error between actual output power and the rated power as much as possible.

The output power leveling optimization objective function could be given as follow,

$$\min \Delta P_e = \left| P_e - P_{rated} \right| \tag{15}$$

The flapping load optimization function could be calculated as follows,

$$\min M = \frac{1}{2} \rho \pi R^3 v_r{}^2 C_M(\lambda, \beta) \tag{16}$$

Thus, the multi-optimization objective function of flapping load optimization control could be given as follows.

$$F = \min\left[\sqrt{w_p \Delta P_e^2 + w_m M^2} \right] \tag{17}$$

where w_p and w_m are the weighting factor of output power and flapping load respectively, $w_p \in [0,1]$, $w_m \in [0,1]$ and $w_p + w_m = 1$.

2) DE based Calculation Module for Optimal Pitch Angle

Differential Evolution (DE) is utilized to solve above multi-optimization objective function. DE is a type of intelligent search method that by generating data groups through cooperation and competition among individuals in a data group (L. Tang, 2015; J. Zhang, 2016). It is based on differential simple mutation operation and one-on-one competitive survival strategy, use real coding to reduce the complexity of genetic operations. DE algorithm can consider on the correlation between multi-variables, has advantages of being suitable in solving problem of variable coupling, fast solution and good robustness.

The basic algorithm procedure of DE is composed of initialization, mutation, recombination and selection. The algorithm procedures for DE based calculation module for optimal pitch angle is given as follows.

Step 1: Initialization. Takes Equ.(17) as optimization objective function, initializes size of population N_{p} , pitch angle vectors Θ_G to be searched.

$$\Theta_G = \left[\theta_{1,G}, \theta_{2,G}, \theta_{3,G}, \cdots, \cdots, \theta_{N_p,G} \right] \tag{18}$$

where G is the generation number.

Defines lower and upper bounds for each parameter: $\theta_{i,G,\min} \le \theta_{i,G} \le \theta_{i,G,\max}$.

Initializes the pitch angel vector of first generation ($G = 0$) with random initial value in the bounds, which could be written as follow,

$$\theta_{i,G} = \theta_{i,G,\min} + \xi_{G,1}(\theta_{i,G,\max} - \theta_{i,G,\min}) \tag{19}$$

where $\xi_{0,1}$ is a random value in range of $[0,1]$.

Step 2: Mutation. Expands the search space. Mutation variable $v_{i,G+1}$ could be obtained by following mutation strategy.

$$v_{i,G+1} = \theta_{i,G} + F\left(\theta_{\mathrm{best},G} - \theta_{i,G}\right) + F\left(\theta_{r_1,G} - \theta_{r_2,G}\right) \tag{20}$$

where r_1 , r_2 are selected randomly in $\{1,2,3,\cdots,N_p\}$ and $r_1 \ne r_2$, F is mutation factor with constant value in $[0,2]$, $\theta_{\mathrm{best},G}$ is the best solution of optimization objective function in G th generation pitch angle vector.

Step 3: Recombination. The trial variables $u_{i,G+1}$ are developed by combing $\theta_{i,G}$ and $v_{i,G+1}$.

$$u_{i,G+1} = \begin{cases} v_{i,G+1} & \xi_{0,1} \le C_r \quad or\ i = i_{\mathrm{rand}} \\ \theta_{i,G} & \xi_{0,1} > C_r \quad and\ i \ne i_{\mathrm{rand}} \end{cases} \tag{21}$$

where i_{rand} is a random integer in $\{1,2,3,\cdots,N_p\}$, which is used to ensure $u_{i,G+1} \ne \theta_{i,G}$, C_r is a recombination probability which is a random value in $[0,1]$.

Step 4: Selection. Compares trial variables $u_{i,G+1}$ and current generation variables $\theta_{i,G}$, by calculating the results of optimization objective function. The variables with lower results of function are admitted into next generation as follow,

$$\theta_{i,G+1} = \begin{cases} v_{i,G+1} & f\left(v_{i,G+1}\right) < f\left(\theta_{i,G}\right) \\ \theta_{i,G} & otherwise \end{cases} \tag{22}$$

where $f\left(\square\right) = \sqrt{w_p \Delta P_e^2 + w_m M\left(\square\right)^2}$.

Step 5: If $f\left(\theta_{i,G+1}\right)$ is less than minimum of objective function f_m or number of generation G is larger than max generation $G_{\max}$, stop, else $G = G + 1$, goto Step 2.

3) Flapping Load Optimizing Control Module

Flapping load optimizing control module calculates the adjustment of pitch angle according to the optimal pitch angle obtained from above DE based calculation module and actual pitch angle. Its calculation is presented as follows,

$$\theta_{f\_DE} = \theta_{opt\_DE} - \theta \qquad (23)$$

Thus,

$$\theta_{ref} = \theta_1 + \theta_{f\_DE} \qquad (24)$$

where θ_1 is the output of PID based output power leveling controller, θ_{f_DE} is output of flapping load optimizing control module.

4.3 *The Design of PID based Output Power Leveling Controller*

Above the rated wind speed, PID based output power leveling controller regulates the pitch angle according to the error between the rated power and actual output power. The control algorithm is presented as follows,

$$e_1(t) = P_{rated} - P_e(t) \qquad (25)$$

$$\theta_1(t) = k_P e(t) + k_I \int_0^t e(\tau) d\tau + k_D de(t)/dt \qquad (26)$$

where k_P , k_I , k_D are proportional gain, integral gain and derivative gain of controller.

5. SIMULATION EXPERIMENT AND RESULTS ANALYSIS

In this section, the proposed control method is illustrated by NREL 5MW wind turbine control simulation experiment and experiment results will be analysed.

5.1 Simulation Experiment Parameters

The parameters of NREL 5MW wind turbine used in simulation experiment are shown in Table 1.

Table 1. Parameters of NREL 5MW Wind Turbine

Blade radius R	63 m
Rotation inertia of wind turbine rotor J_r	35444067kgm^2
Rotation inertia of Generator J_g	534.116kgm^2
Time constant of generator τ_g	0.05s
Time constant of generator τ_g	0.12s
Rated wind speed	11.4m/s
Rated power	5Mw

The flapping load coefficient $C_M(\lambda,\theta)$ of NREL 5MW wind turbine could be used by the non-linear fitting result (C. Peng, 2017). The parameters h_i $(i = 1,2,\cdots,6)$ in Equ. (12) are set as 0.66, 0.03, 0.51, 25.64, 1.26, 0.005 respectively. Considering on optimization flappimg load mitigation and output power leveling simultaneously, the weighting factor of output power and flapping load in optimization objective function are selected as 0.5 and 0.5 respectively. The parameters of DE algorithm in flapping load optimization controller are used in experiments are shown in TABLE III.

Table 2. Parameters of DE algorithm

Size of population N_p	10
Lower bound $\theta_{i,G,\min}$	0
mutation factor F	0.6
minimum of objective function f_m	0.001
Maximum of generation $G_{\max}$	200
Upper bound $\theta_{i,G,\max}$	40
Recombination probability C_r	0.4

5.2 Experiments and Results Discussion

The experiments are conducted under random change wind speed. The results of experiments by using the proposed control method and traditional PID control method will be discussed. The random change wind speed, output power and flapping load control results in this experiment are shown in Fig.5-Fig.7 respectively. The wind speed data used in this experiment are collected in Baolige wind farm in inner Mongolia in China (J. Zou, 2015).

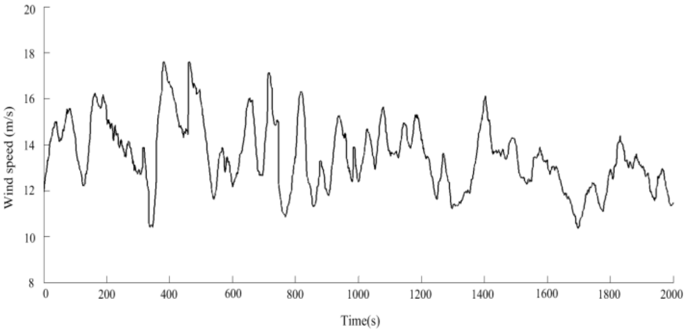

Fig.5. Wind speed data

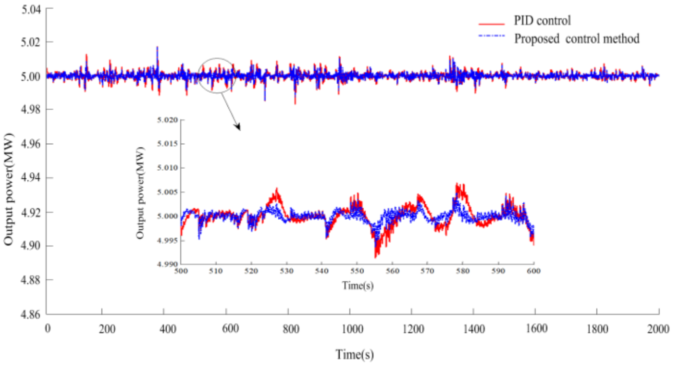

Fig. 6. Experiment result of output power

As seen in Fig.6, the magnitude of oscillation of output power by using the proposed control method is obvious smaller than that by using PID control. During time between 500s and 600s, the maximum magnitude by using the proposed control method is 0.006MW, which is 66.6% of that by using PID control. As seen in Fig.7, During time between

500s and 600s, the minimum and of maximum flapping load by using the proposed control method are 1.26 ×107 Nm and 1.66 ×107 Nm respectively, the minimum and of maximum flapping load by using PID control method are 1.20 ×107 Nm and 1.80×107 Nm. The magnitude of oscillation of flapping load by using the proposed control method is obvious smaller than that by using PID control.

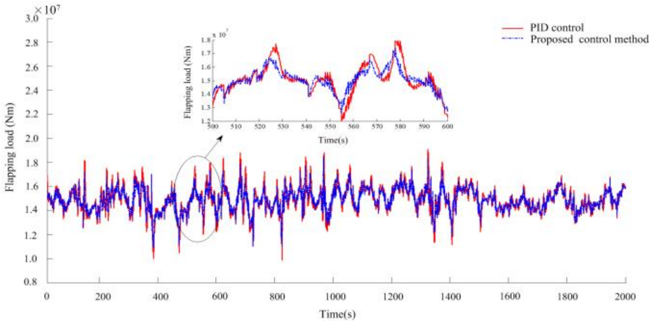

Fig. 7. Experiment result of flapping load

6. CONCLUSIONS

A novel optimization control method for wind turbine flapping load mitigation and output power leveling is proposed in this paper. The proposed control method combines a differential evolution based flapping load optimization controller and a PID based output power leveling controller. The proposed control method is implemented in NREL 5MW wind turbine control simulations and results show that the proposed control method can reduce flapping load and keep output power leveling around the rated power simultaneously when wind turbine operates above the rated wind speed.

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