Blade-Pitch Control for Structural Load Mitigation of Large-scale Wind Turbines

Manh Hung Do – School of Heat Engineering and Refrigeration, Hanoi University of Science and Technology
E-mail: hung.domanh@hust.edu.vn

Abstract: *Wind energy is one of the fastest-growing sources of electricity nowadays. Modern wind turbines are becoming larger to improve energy efficiency and to harvest more power from the wind. The larger size and more flexible structure of wind turbines lead to higher mechanical stresses on the wind turbine's components. These stresses known as structural load might cause early failures reducing the turbine's service lifetime and limit the size of the turbines. Over the past decade, advanced control algorithms have been developed to reduce structural load allowing to build larger turbines as well as extend the turbine's service lifetime. This article introduces and summaries the results of a novel advanced control algorithm for structural load reduction and power output maximization for large-scale wind turbines developed by the author in the related doctoral dissertation.*

Key Words: *Wind energy, Pitch control, Structral load reduction*

I. INTRODUCTION

Wind turbines (WTs) are devices converting the kinetic energy of the wind into electricity. Most of the large-scale wind turbines have horizontal axis (HAWT) and variable-speed configuration due to the higher efficiency and the ability to maximize the energy havested over a wide range of wind speed. The amount of extractable wind power is strongly related to the turbine operating point defined by wind speed, rotor rotational speed, and blade pitch angle. The wind speed varies stochastically in nature, so to make wind turbines operate at the optimal point, the rotor speed and blade pitch angles need to be controlled accordingly by maximum power point tracking (MPPT) control methods.

The wind turbine operation can be divided into three main regions with distinct objectives: below-rated wind speed region (region 2), above-rated speed region (region 3), and a transition region (region 2.5). More than 50 % of the annual energy production of a modern wind turbine is obtained from region 2 operation. In region 2, the main objective is to maximize the energy harvested from the wind, however, with the scale-up of wind turbines, structural load reduction also need to be considered to extend the lifetime of the turbines and reduced failure rate.

This article introduces a multi-objective control strategy to maintain optimum power coefficient and mitigate undesirable structural loads at the same time. A robust DAC controller (RDAC) [2] is applied in combination with a conventional MPPT controller. Unlike traditional approaches such as LQG and pole-placement, the proposed approach determines the optimal observer and controller simultaneously considering model errors and uncertainties to ensure system robustness to varying wind speed. The structural loads are mitigated by perturbing the blade pitch angles about the optimum value avoiding strong effects on power production. The proposed method successfully reduces the structural load (tower bending moment) without a significant reduction inharvested energy. It can be shown that the method also has high robustness against varying wind speed as unknown input.

II. BACKGROUND

2.1 Maximum Power Point Tracking Control (MPPT)

The power available in the wind P_{wind} is proportional to the cube of wind velocity as

$$P_{wind} = \frac{1}{2}\rho\pi R^2 v^3 \qquad (2.1)$$

where ρ denotes the air density, R the rotor radius, and v the wind velocity. Wind turbines are able to convert a part of the wind power into mechanical energy. The maximum extractable energy is limited to a theoretical value 59.3% of available wind power (Betz limit).

The performance of wind turbines is defined by the power coefficient C_p as

$$C_p(\lambda,\beta)=\frac{P}{P_{wind}} \tag{2.2}$$

where P denotes the wind turbine power. Wind turbine power coefficient C_p is a nonlinear function of tip-speed-ratio λ and blade pitch angle β. Tip-speed-ratio λ is defined as the ratio between rotor speed ω_r and active wind speed v as

$$\lambda = R\frac{\omega_r}{v} \tag{2.3}$$

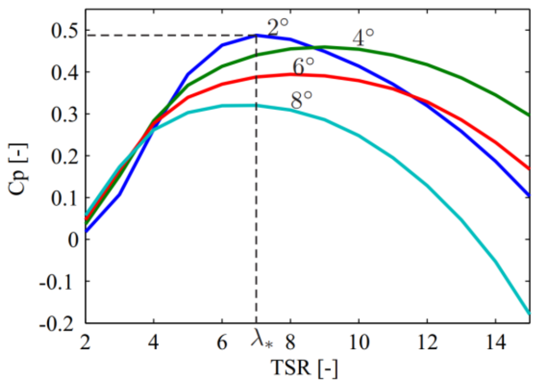

Fig. 2.1. WT power coefficient curve

In fig. 2.1., the power coefficient curves of a WT are shown. The maximum power output of the WT is achieved at the peak of power coefficient curves where the blade pitch angle and TSR are optimal. Typically, blade pitch angle β is held at a constant value that yields the maximum aerodynamic lift such that the power coefficient depends on TSR only. MPPT algorithms aim to keep wind turbines operate at optimal λ maximizing C_p. From eq. 2.3 we can observe that to keep λ constant at the optimal value, the rotor speed ω_r needs to be varied following the change of the wind speed v.

The wind speed affecting the rotor area is difficult to have in general, so the standard method for optimal tip-speed-ratio tracking is to control generator torque T_g using rotor speed feedback as

$$T_g=\frac{1}{2N_g}\rho\pi R^5\frac{C_p(\lambda_{opt},\beta_{opt})_{max}}{(\lambda_{opt})^3}\omega_r^2=K_g\omega_r^2 \tag{2.4}$$

where N_g denotes the gearbox ratio between generator and rotor speed, K_g the gain of the torque controller.

2.2 Robust Disturbance Accommodating Control (RDAC)

In the theory of DAC, external disturbance structures are assumed as known, a predefined internal disturbance model is used to estimate the true value of the disturbance x_d.

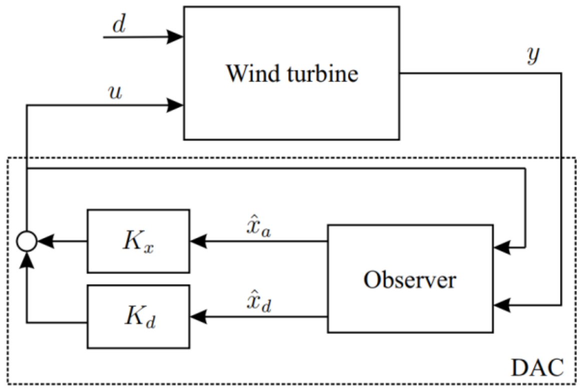

Fig. 2.2. Disturbance accommodating control

The effect of the disturbance, here is the varying wind speed, to the WT is accommodated using the disturbance controller K_d. The state feedback controller K_x realizes primary control objectives such as power regulation and structural load mitigation. The DAC method effectively handles the problem of wind disturbance; however, this method required a precise linear model of the WT and wind which are typically not available.

In wind turbine applications, the disturbance model may not accurate due to uncertainties and stochastic variation of wind disturbance. Also, the use of linearized reduced-order models leads to inaccurate turbine models, especially when the turbine operates outside the given operating conditions. So it is necessary to develop a method to define robust DAC for wind turbines with respect to model and measurement uncertainties.

In [2], a robust method to design the optimal DAC controller is proposed namely robust DAC (RDAC). The idea is using the mixed-sensitivity H_∞ norm of the closed-loop transfer function as the cost function to optimize the DAC parameters. The mixed-sensitivity H_∞ norm of the closedloop transfer function is a good indicator for both system performance and robustness. The norm is used as the cost function to find the optimal robust DAC (RDAC). Unlike the standard H_∞ control finding the full order controller, the proposed RDAC approach finds parameters of a "structured controller" having the DAC structure. Non-smooth H∞ synthesis is used to define the controller parameters with structural constraints. As a novelty, an additional disturbance observer and disturbance rejection controller are introduced to improve the disturbance accommodating performance.

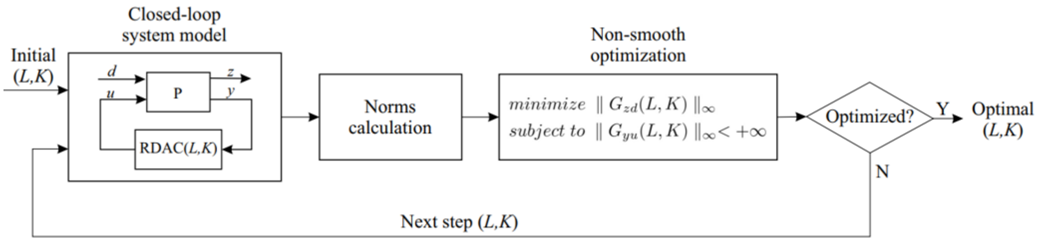

Fig. 2.3. RDAC using non-smooth H∞ synthesis with constrains

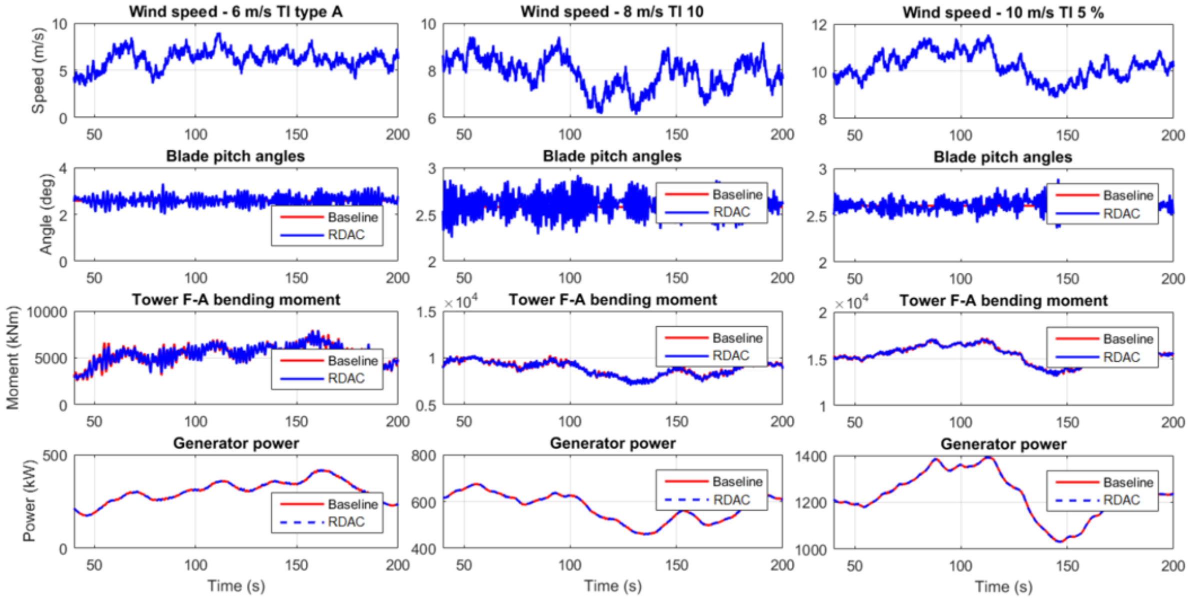

Fig. 3.1. Results of RDAC for WT region 2 control

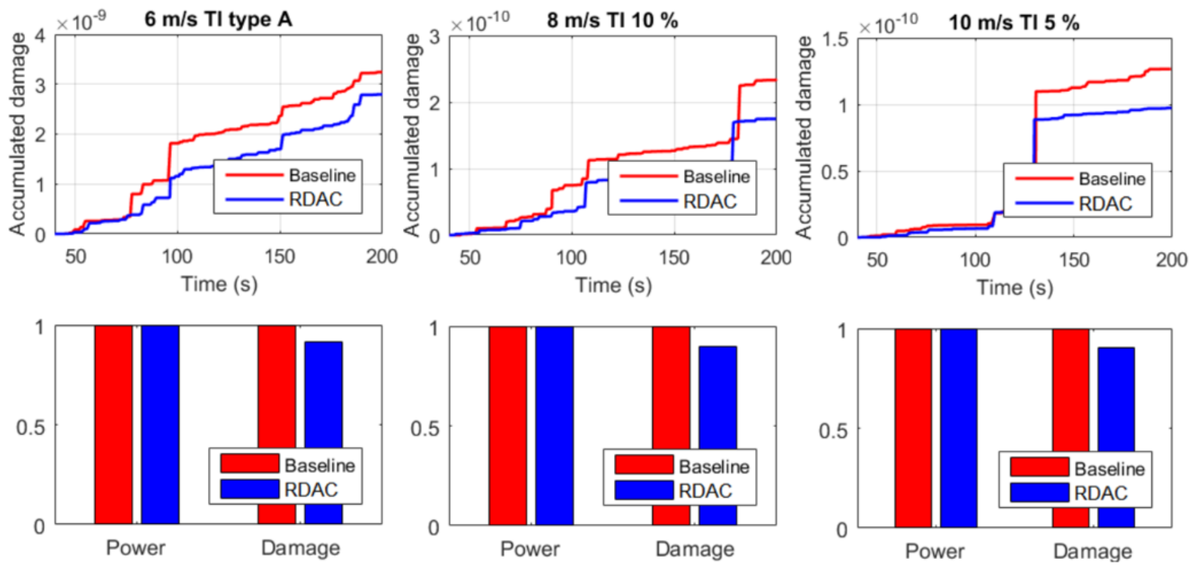

Fig. 3.2. WT region 2 normalized accumulated damage and power production

The problem to find the robust disturbance accommodating controller (RDAC) is formulated as

$$RDAC = DAC^{*} = argmin \parallel G_{zd}(DAC) \parallel_{\infty} \quad s.t. \; \parallel C_a(sI - \mathcal{A}(DAC))^{-1}B_a \parallel_{\infty} < +\infty.$$

The procedure to calculate RDAC controller parameters is shown in fig. 2.3.

III. RESULTS AND DISCUSSIONS

The RDAC approach is applied in combination with a standard torque controller in region 2 (eq. 2.4) to reduce the tower bending moment. The maximization power production objective is realized by the torque controller. Structural load, here is the tower bending moment, is reduced by a blade pitch controller using RDAC algorithm.

The proposed approach is validated using simulation software FAST [3] in combination with MATLAB Simulink. A nonlinear reference WindPACT 1.5 MW onshore wind turbine model is used as the control plant [4]. The load case is based on the IEC 61400-1 DLC 1.2 standard [5] for fatigue in normal power production conditions. To reflect realistic operating conditions, stochastic wind profiles with different mean wind speed and turbulence intensity (TI) is applied. The wind profiles are generated using the IEC von Karman wind turbulence model. The wind profiles are chosen to have the mean speed of 6 m/s, 8 m/s, 10 m/s and the turbulence level of IEC type A of the IEC standard [5], 10 %, and 5 % respectively.

The proposed RDAC approach is able to reduce the fluctuation of the tower compared to the baseline for all cases, as shown in fig.3.1. The generator power of the two approaches has no obvious difference.

For quantitative evaluation, the normalized total power production and accumulated fatigue damage results of the two approaches are shown in fig.3.2. The damage is calculated using the rain-flow counting (RFC) algorithm and Miner's rule. A 14 % reduction in the accumulated damage is obtained using RDAC without affecting the power production.

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Điều khiển cao độ cánh để giảm nhẹ tải kết cấu của tuabin gió cỡ lớn

Đỗ Mạnh Hùng
Viện KH & CN Nhiệt-Lạnh, Trường Đại học Bách Khoa Hà Nội
E-mail:* *hung.domanh@hust.edu.vn

Abstract: *Hiện nay, năng lượng gió là một trong những nguồn điện phát triển nhanh nhất. Các tuabin gió hiện đại ngày càng trở nên lớn hơn để nâng cao hiệu quả sản xuất năng lượng và thu được nhiều năng lượng hơn từ gió. Kích thước lớn hơn và cấu trúc mềm dẻo hơn của tuabin gió dẫn đến ứng suất cơ học cao hơn trên các bộ phận của tuabin gió. Những ứng suất này được gọi là tải trọng kết cấu có thể gây ra hỏng hóc sớm làm giảm tuổi thọ của tuabin và giới hạn kích thước của tuabin. Trong thập kỷ qua, các thuật toán điều khiển tiên tiến đã được phát triển để giảm tải trọng kết cấu cho phép xây dựng các tuabin lớn hơn cũng như kéo dài tuổi thọ của tuabin. Bài báo này giới thiệu và tóm tắt kết quả của một thuật toán điều khiển nâng cao mới để giảm tải kết cấu và tối đa hóa sản lượng điện cho tuabin gió cỡ lớn do tác giả phát triển trong luận án tiến sĩ của mình.*