Control Design for the Ward–Leonard System in Wind Turbines

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ABSTRACT

A robust optimal controller for the Ward-Leonard system in a wind turbine is used to meet the performance and stability requirements when the system parameters change. However, designing according to the robust optimal method often leads to a high-order controller. This study investigated the application of order reduction algorithms to simplify the controller and help it better meet the real control problem. Comparative evaluation of the order reduction controller methods showed that the second-order reduction controller according to Moore's balanced truncation algorithm was the most suitable to replace the higher-order controller. The step response quality of the system was better when using a second-order reduction controller than a higher-order controller.

Keywords-model order reduction; Ward–Leonard system; wind tube system; robust optimal control

I. INTRODUCTION

Wind energy is a natural form of energy produced by the movement of air in the atmosphere. Also, it is an indirect form of solar energy. Wind energy is the process where wind uses its movement to generate mechanical energy. The research on the potential application of wind energy is quite diverse [1-9], but most researchers believe that the prospect of wind energy development is an inevitable future trend, as clean energy sources will gradually replace current fossil energy sources. This share is determined based on the countries' energy policies and the roadmap to reduce adverse environmental impact. Wind turbines convert the kinetic energy of the air into mechanical energy. For maximum efficiency, the wind turbine blades must direct the wind with an optimum angle, must be flexible and strong to withstand disturbances and high-speed rapid oscillations, and require a suitable control system [10].

The Ward-Leonard DC motor speed control system is used when the speed control requirements are very wide and very sensitive. It is a suitable system for wind turbine control and antenna tracking systems [11]. The system contains a DC generator that serves as a power amplifier for the DC control signal. The generator is rotated at a constant speed from the main motor and an output voltage is generated and supplied to the DC motor, while an external DC power source powers the motor's inductor. The wind turbine control problem requires the controller to have good performance and strong stability when the parameters of the model change. A robust optimal controller is the most suitable to control the Ward–Leonard system in a wind turbine system. However, the design method of the robust optimal controller H∞ [12] often leads to a high-order controller. A high-order controller has many disadvantages, such as complicated programming and long computation time, resulting in slow system responses. Reducing the order of a high-order robust controller while ensuring quality has a high practical significance. Two basic methods are used to obtain a low-order robust optimal controller. The first method designs a high-order controller according to a stable optimal control algorithm and then applies model order reduction algorithms to obtain a lower-order stable optimal controller [13-14], while the second method uses optimization algorithms to design a low-order controller that satisfies the requirements of sustainable optimal control [15].

II. THE WARD-LEONARD SYSTEM IN WIND TURBINES AND HIGH-ORDER ROBUST CONTROLLER

The Ward-Leonard system contains a DC generator that serves as a power amplifier of the control signal. The DC generator is rotated at a constant speed by the main motor, and its output voltage powers the DC motor, while the field winding of the motor is supplied by a separate DC source. In [10], the Ward-Leonard system was used to control a wind turbine system, and its modeling gave the following results:

$$G(s) = \frac{300}{s(s^3+184s^2+760.5s+162)} \qquad (1)$$

The wind turbine control problem requires the controller to have good performance and strong stability when the parameters of the model change. A robust optimal controller with the following results was designed in [10]:

$$R(s) = \frac{8.967s^5+1663s^4+9154s^3+1.159.10^4s^2+4096s+436.2}{s^6+189.9s^5+1852s^4+6969s^3+1.302.10^4s^2+9566s+1664} \qquad (2)$$

The 6th-order robust controller has many disadvantages when used in practice, such as slow response time and complex programming. Therefore, it is necessary to reduce the order of this 6th-order robust controller to increase the response speed of the system and better meet the requirements of robust control.

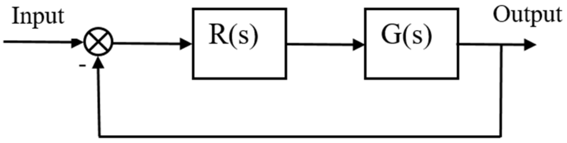

Fig. 1. Block diagram of the control system.

III. REDUCING THE HIGH-ORDER ROBUST CONTROLLER

All the poles of the 6th-order controller have negative real parts, so the 6th-order controller is a stable model. Different order reduction algorithms were used to reduce the order of the 6th-order controller, and the different resulting controllers were compared to choose the most suitable low-order controller. This study used Moore's balanced truncation algorithm [16], LQG balancing algorithm [17], and Singular Perturbation Approximation (SPA) [18] to reduce the order of the controller. The results of the step reduction are shown in Tables I-III.

TABLE I. ORDER REDUCTION OF THE 6TH-ORDER CONTROLLER ACCORDING TO MOORE'S BALANCED TRUNCATION ALGORITHM [16]

Order	R_r(s)	$\|R - R_c\|_\infty$
3	$\frac{8.968s^2+45.54s+10.7}{s^3+9.531s^2+29.82s+40.12}$	0.0047
2	$\frac{8.881s+1.978}{s^2+4.501s+7.927}$	0.017
1	$\frac{8.895}{s+4.493}$	1.1718

TABLE II. ORDER REDUCTION OF THE 6TH-ORDER CONTROLLER ACCORDING TO LQG BALANCING ALGORITHM [17]

Order	R_r(s)	$\|R - R_c\|_\infty$
3	$\frac{8.967s^2+46.1s+10.71}{s^3+9.596s^2+30.11s+40.47}$	0.0043
2	$\frac{8.831s+2.052}{s^2+4.565s+7.992}$	0.0324
1	$\frac{8.945}{s+4.552}$	1.707

TABLE III. ORDER REDUCTION RESULTS OF THE 6TH-ORDER CONTROLLER ACCORDING TO SINGULAR PERTURBATION APPROXIMATION [18]

Order	R_r(s)	$\|R - R_c\|_\infty$
3	$\frac{8.967s^2+45.79s+10.62}{s^3+9.561s^2+29.95s+40.2}$	0.0044
2	$\frac{8.953s+2.051}{s^2+4.574s+7.978}$	0.0335
1	$\frac{8.956}{s+4.548}$	1.7029

To evaluate the reduced-order controllers, their step and bode responses were compared with the original. Figures 2-7 show the results.

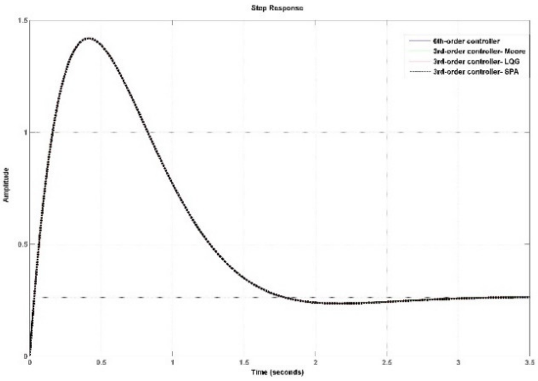

Fig. 2. The step response of the 3rd and the 6th-order controllers.

The step response of the 3rd-order controller is exactly the same as that of the 6th-order.

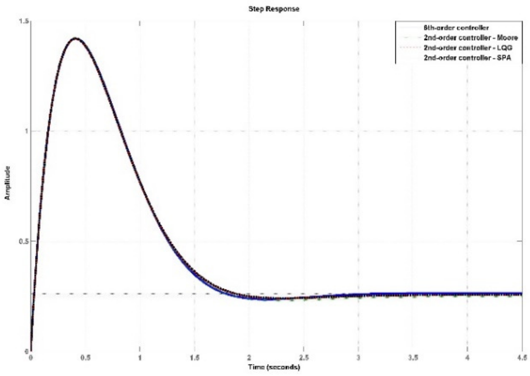

Fig. 3. The step response of the 2nd and the 6th-order controllers.

The step responses of the 3rd and the 2nd-order controllers are exactly the same as that of the 6th-order.

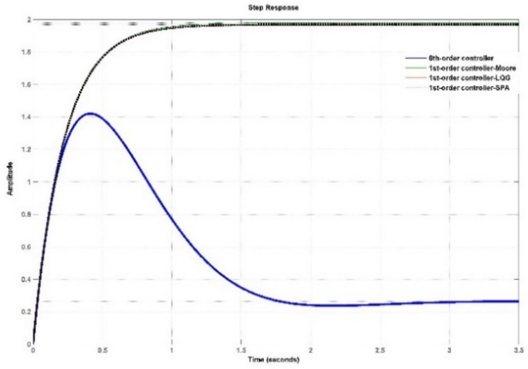

Fig. 4. The step response of the 1st and the 6th-order controllers.

The step response of the 1st-order controller is different from that of the 6th-order controller. The step response of the 1st-order controllers, according to the different order reduction algorithms, is completely coincident.

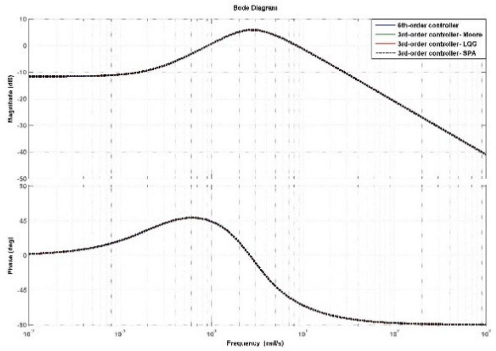

Fig. 5. Bode response of the 3rd and 6th-order controllers

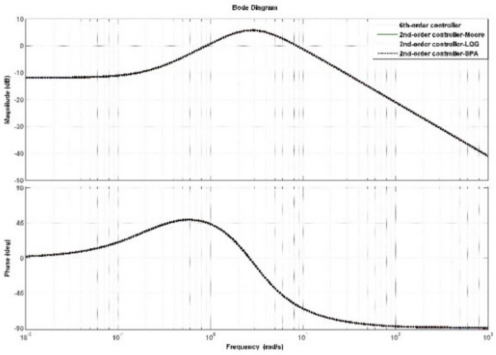

Fig. 6. Bode response of the 2nd and 6th-order controllers.

The bode response of the 3rd and the 2nd-order controllers completely coincides with the frequency response of the 6th-order controller.

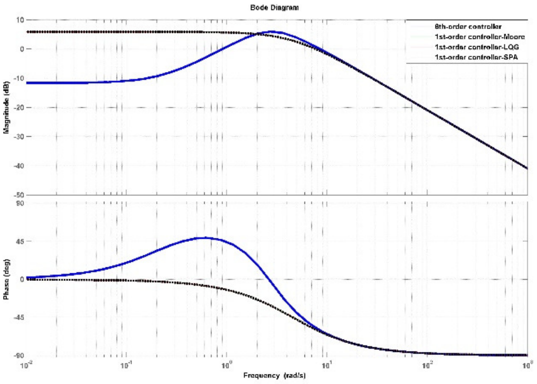

Fig. 7. Bode response of the 1st and 6th-order controllers.

The frequency response of the 1st-order controller, according to the algorithms, is coincident. In the frequency range *ω* < 29.8rad/s, the frequency response of the 1st-order controller is different from that of the 6th-order. In the frequency range over 29.8rad/s, the frequency response of the 1st-order controller coincides with that of the 6th-order. The 2nd-order controllers can all replace the 6th-order, where the 2nd-order controller according to Moore's balanced truncation algorithm is the most suitable controller to replace the 6th-order (due to the smallest order reduction error). The 1st-order controllers can not substitute the 6th-order controllers.

IV. USING A REDUCED ORDER CONTROLLER TO CONTROL THE WARD - LEONARD SYSTEM IN A WIND TURBINE SYSTEM

The results of using the 2nd-order controllers in Tables I, II, and III and the 6th-order controller for the Ward-Leonard system in a wind turbine are shown in Figures 8-10 and Table IV.

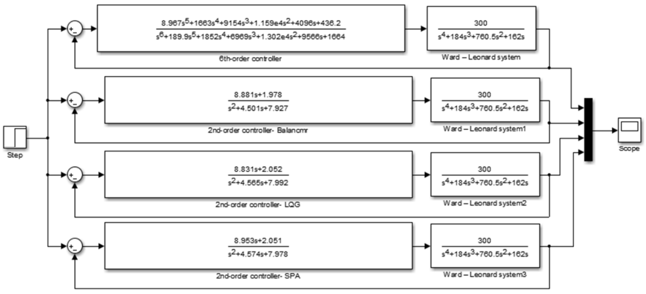

Fig. 8. Simulink diagram of the control system for the Ward-Leonard system in a wind turbine using 6th-order and 2nd-order controllers.

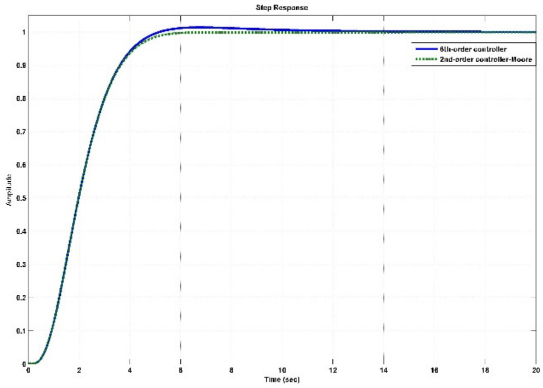

Fig. 9. Response of the control system for the Ward-Leonard system in a wind turbine using 6th-order and 2nd-order controllers according to Moore's balanced truncation algorithm.

TABLE IV. RESPONSE RESULTS OF CONTROL SYSTEM USING 6TH AND 2ND-ORDER REDUCTION CONTROLLERS

Response	**6th-order controller**	**2nd-order controller - Moore**	**2nd-order controller - LQG**	**2nd-order controller – SPA**
Respone time	3.61	3.633	3.62	5.75
Settling time (0.5%)	11	5.25	9.08	7.7
Overshoot	1.4%	0%	0.87%	0.67%

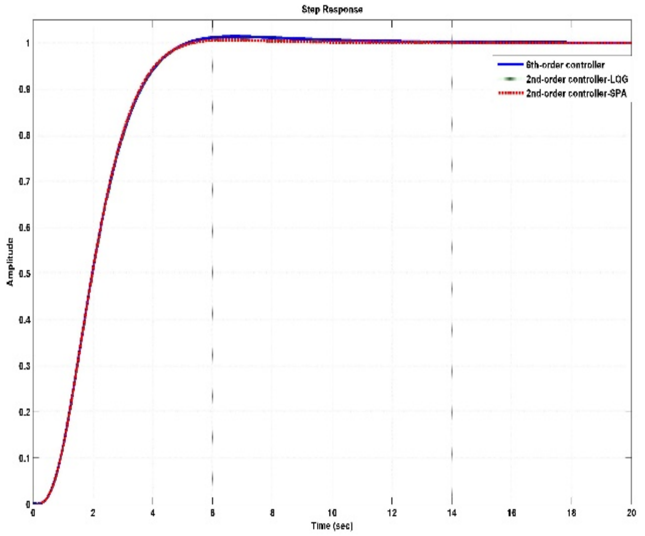

Fig. 10. Response of the control system for a Ward-Leonard system in a wind turbine using 6th and 2nd-order controllers according to LQG truncation algorithm and SPA.

Compared to the 6th-order controller, the Ward-Leonard system in the wind turbine gives better response quality (smaller settling time and overshoot) when using reduced 2nd-order controllers. Using a 2nd-order controller according to Moore's balanced truncation algorithm gives the best response quality (minimum settling time and overshoot -0%). These results show that the 2nd-order controller according to Moore's balanced truncation algorithm is the most suitable controller to replace the 6th-order controller.

V. CONCLUSIONS

Controlling the Ward-Leonard system in a wind turbine according to a sustainable optimization method helps the system to perform well and maintain strong stability when the parameters of the model change. The disadvantage of the controller design, according to the robust optimization method, is that the order of the controller is high (6th-order). Three different order reduction algorithms were used in this paper to simplify high-order controllers. Comparison and evaluation of the step-down controllers showed that 2nd-order controllers are the most suitable to replace the 6th-order controller. Among the 2nd-order controllers, Moore's balanced truncation algorithm provided the controller with the best response quality. Future work could investigate other order reduction algorithms to reduce the order of the 6th-order controller of the Ward-Leonard system in a wind turbine.

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