Electrical Power and Energy Systems 105 (2019) 660–670

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Adaptive active fault-tolerant MPPT control for wind power generation system under partial loss of actuator effectiveness

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ARTICLE INFO

Keywords:
Wind power generation system
Maximum power point tracking
Actuators fault
Active fault-tolerant control
Adaptive control

ABSTRACT

In order to improve the dynamic performance and reliability of the maximum power point tracking (MPPT), this paper proposes an adaptive active fault-tolerant control (AFTC) strategy of the wind power generation system to overcome uncertain problems, including potential partial loss of actuator effectiveness, unknown modeling errors and external disturbances. The AFTC method is designed according to a new dynamic model of angular speed tracking for wind power generation system based on generalized perturbation. It neither requires the actuator fault information detection, nor relies on the system model parameters and external disturbance identification. In terms of the on-line estimation of the disturbance boundary amplitude and the nonlinear state feedback based on MPPT tracking error, the gain of the switching control is adaptively adjusted to speed up the convergence of the system and reduce the delay of the fault compensation. A first-order integral process is involved in the AFTC law to further weaken the chattering of output signal amplitude, hence smooth the torque and improve the tracking accuracy during generation. In addition, the global stability of the closed-loop control system based on AFTC is proved by the Lyapunov approach. By comparing with the conventional linear PID control and the nonlinear dynamic state feedback control (NDSFC), the case studies simulation results validate the great MPPT fault-tolerant capability even subject to partial loss of actuator effectiveness, and separately show the strong robustness and self-adaptation of the proposed adaptive AFTC method.

1. Introduction

Investigations on wind power generation have gained substantial attention in the last three decades. As one of the main focus areas, the maximum power point tracking (MPPT) controller plays an important role in the wind power capture operation, because its control performance is directly related to the operation characteristics, generation economic efficiency, and safety stability of the equipment. Meanwhile, low reliability inherently exists in the MPPT strategies, due to the complex multi-variable nonlinear characteristics in the wind power generation system [1–3]. Thus, research on the nonlinear control method have been successively investigated, including nonlinear PID control [4,5], state feedback control [6,7], nonlinear predictive control [8,9], robust control [10,11], sliding mode control [12,13], fuzzy neural network control [14,15], particle swarm optimization [16,17], etc.

However, as sustained growth in size and capacity of wind power generation system, it is difficult to design the control structure well. In particular, partial failure of electromechanical components such as drive train, motor, generator and power converter, are unavoidable during the long-time running in remote and harsh environment [18–21]. The occurrences of these partial faults may lead to partial loss of actuator effectiveness. Although the system can continue to work, this directly lead to changes in the description of the dynamic model and parameters of the wind power generation system. In this case, if the generation controller is still carried out according to the conventional nominal MPPT control strategy, it will inevitably reduce generation performance, induce safe production accidents, and even lead to unexpected heavy losses. Therefore, in the face of the special work requirements of long life, high reliability and safety for the wind power generation system, it is of great practical significance to research corresponding fault-tolerant control method to ensure the system is able to maintain good operation state in the case of the system subjects to partial failure.

Fault-tolerant control is a control technique that ensures the controlled system is able to maintain stable operation and achieve

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https://doi.org/10.1016/j.ijepes.2018.09.015
Received 3 June 2018; Received in revised form 2 August 2018; Accepted 8 September 2018

particular performance not only under nominal operation condition but also in case of fault. Generally, it is divided into passive fault-tolerant control (PFTC) and active fault tolerant control (AFTC). The PFTC method is based on robust control ideas. It attributes the fault to the model parameter perturbation issue, and compensates the fault by the kind of fixed gain controller with strong robustness to ensure the system is insensitive to certain faults. In the wind power generation system control applications, the literature [22] presents a novel PFTC scheme to against turbine power capture loss caused by the blade erosion/ debris build-up fault. The turbine benchmark model is modified with a generic fault scenario representing occurrence of 3% power loss, and a fuzzy model reference adaptive control approach is designed to improve the reliability and availability of wind farms. In the literature [23], the wind power generation system is decomposed into two loops with low frequency and high frequency, and the PI static optimal controller and robust fault-tolerant controller are designed respectively to guarantee the system's ability to suppress the fault.

It can be found that the PFTC method require designers to predict as many faults as possible before the controller design. According to the changing characteristics of the dynamic system model parameters in the fault states, a robust controller with fixed structure and gain are worked out, which it does not need to be adjusted on-line for the particular predicted fault modes. Its advantage is that the control law is fixed and easy to implement, and it can guarantee the system stability and achieve the preset performance whether or not a fault. However, the controller must calculate the parameters for the most serious fault condition that the system can take. It often lead to the control law too conservative, and with the increase of the system fault complexity, the controller design process will become more difficult.

The AFTC method is based on the fact that the controller can reset its parameters or even change its structure, as well as implement rapid dynamic compensation control output to keep system stable after the fault occurs. To overcome this problem, the AFTC method must have the ability to actively acquire the information of the faults or system state changes. Currently, fault diagnosis and isolation (FDI) approach is an important strategy for the design of AFTC. In wind power generation system FDI approach applications, the literatures have adopted such as observer method [24], Kalman filtering method [25], variable parameter method [26], robust fuzzy method [27], support vector machine method [28], data-driven method [29], set-membership model method [30], deep learning network [31], classifier fusion [32], etc. The fault information of wind power generation system is obtained by using these identification techniques, and then, through the online adjustment of control law parameters enables the AFTC has ability to optimally adapt to the operation status after fault. Each identification technique has its respective advantages, and in the principle of control system construction, the AFTC has stronger robustness and adaptability because FDI calculates the accurate value of fault information. But the AFTC is overly dependent on the FDI performance, and it may lead to failure of fault-tolerant control system, due to the mistake detection, omission, long delay or large diagnosis error caused by fault diagnosis mechanism. In order to avoid accurate fault information diagnosis, another AFTC method based on adaptive control output compensation, has become a new focus. The adaptive mechanism may provide fault information required by the controller using only the system state variable changes aroused by the faults. This method has obvious advantage of fast compensation for faults, and has been applied in the fault-tolerant control of wind power generation [33], but the reported research is relatively limited.

In this paper, the adaptive AFTC method is applied to implement MPPT control of wind power generation system subjected to partial fault of actuator. In view of that uncertainty of system model and fundamental characteristic of external disturbance torques, a kind of dynamic model of wind power generation system based on generalized perturbation is established, and a novel MPPT active adaptive fault-tolerance control method is proposed. In this work, adaptive technique is used to dynamically compensate fault, so as to avoid the issue that the control law is too conservative which is caused by the high gain of the nominal control method, and to improve the self-adaptive robustness of the system to fault suppression. In addition, a nonlinear state feedback of the MPPT tracking error is introduced into the control law to speed up the convergence process and reduce the delay of fault compensation. Furthermore, the proposed adaptive AFTC law is performed on a first-order integral operation, whose output takes as the reference input of actual generator power control, so as to ensure the MPPT tracking process more smoothly and without steady state error. Finally, the global stability of the closed-loop control system is proved by the Lyapunov approach. In case studies scheme, the proposed adaptive AFTC method is applied to the fault suppression control of the constant and realistic wind speed of the wind power generation system respectively, and compared with the conventional linear PID control and the nonlinear dynamic state feedback control (NDSFC). The simulation results validate the great MPPT fault-tolerant capability even subject to partial loss of actuator effectiveness, and separately show the strong robustness and self-adaptation of the proposed adaptive AFTC method.

The main contributions of this paper include: (I) establish a novel generalized perturbation and angular speed tracking state function based dynamic model for wind power generation MPPT control under partial loss of actuator effectiveness; (II) propose an adaptive active fault-tolerant control method with good characteristics of adaptive actuator fault compensation and generalized perturbation boundary online estimation; (III) validate the strong robustness and self-adaptation for MPPT tracking and fault suppression performance of the proposed method.

The rest of this paper is organized as follows. The system modeling, actuator faults description and analysis are presented in Section 2. Section 3 focuses on adapted active fault-tolerant MPPT controller design under actuator faults operating condition. Case studies simulation results are provided in Section 4 to verify the effectiveness of the proposed adaptive AFTC method. Finally, conclusions are drawn in Section 5.

2. System modeling and analysis

2.1. Wind turbine aerodynamics model

According to Bates theory, the aerodynamic power captured by wind turbine can be expressed as

$$P_a = \frac{1}{2}\rho\pi R^2 v^3 C_p(\lambda, \beta) \tag{1}$$

where ρ is the air density; v is the wind speed; R is wind turbine blade radius; $C_p(\lambda,\beta)$ is the turbine power coefficient; β is the blade pitch angle; λ is the tip speed ratio, which is defined as follows

$$\lambda = \frac{R\omega_r}{v} \tag{2}$$

where ω_r is the blade angular speed.

The aerodynamic torque T_a can be expressed as

$$T_a = \frac{P_a}{\omega_r} \tag{3}$$

By applying Eq. (1) and Eq. (2) into Eq. (3), it has

$$T_a = K_a \omega_r^2 \tag{4}$$

where K_a is the turbine running state coefficient, which is defined as follows

$$K_a = \frac{1}{2}\rho\pi R^5 \frac{C_p(\lambda, \beta)}{\lambda^3} \tag{5}$$

The turbine power coefficient $C_p(\lambda,\beta)$ is the nonlinear function of