Variable Parameter Nonlinear Control for Maximum Power Point Tracking Considering Mitigation of Drive-train Load

Zaiyu Chen, Minghui Yin, *Member, IEEE,* Lianjun Zhou, Yaping Xia, Jiankun Liu, and Yun Zou, *Member, IEEE*

***Abstract*—Since mechanical loads exert a significant influence on the life span of wind turbines, the reduction of transient load on drive-train shaft has received more attention when implementing a maximum power point tracking (MPPT) controller. Moreover, a trade-off between the efficiency of wind energy extraction and the load level of drive-train shaft becomes a key issue. However, for the existing control strategies based on nonlinear model of wind turbines, the MPPT efficiencies are improved at the cost of the intensive fluctuation of generator torque and significant increase of transient load on drive train shaft. Hence, in this paper, a nonlinear controller with variable parameter is proposed for improving MPPT efficiency and mitigating transient load on drive-train simultaneously. Then, simulations on FAST (Fatigue, Aerodynamics, Structures, and Turbulence) code and experiments on the wind turbine simulator (WTS) based test bench are presented to verify the efficiency improvement of the proposed control strategy with less cost of drive-train load.**

***Index Terms*—Drive-train load, maximum power point tracking (MPPT), nonlinear control, wind turbines (WT).**

I. INTRODUCTION

COMPARED with fixed-speed wind turbines, variable-speed wind turbines (VSWTs) possess higher energy conversion efficiency and lower mechanical stress [1], [2]. At low wind speed, wind turbines focus on maximum power point tracking (MPPT) by modifying the rotor speed according to the varying inflow wind speed. Due to the huge number of load cycles that a VSWT will suffer during its lifetime, fatigue is of particular importance in wind turbine design [3].

With the growing capacity of wind turbines, the large inertia of wind rotor leads to turbines' inability to accelerate or decelerate instantly in response to wind speed fluctuation and the decrease of MPPT efficiency [4]. In the existing MPPT control strategies, the MPPT efficiency is usually improved by the drastic regulation of generator torque and consequently the loads on drive-train are inevitably increased [5]. Therefore, it is necessary to take the trade-off between wind energy capture and drive-train load into account in the improvements of MPPT control strategies.

In the last few years, research efforts on the MPPT controls with consideration of mechanical stress have attracted more attention [1], [2], [5]−[16]. It is pointed out that the system dynamics and transient load acting on the turbine shaft compromise each other, and some suggestions and steps were given out in [6] to optimally choose a proper system dynamics. The Linear-Quadratic-Gaussian (LQG) [7] and Model Predictive Control (MPC) [8], [9] methods are applied for MPPT, in which speed tracking and mechanical load are considered simultaneously by solving the optimization problem. The smoothness of control input is taken into consideration in [10], [11] to reduce the mechanical stresses on the drive-train shaft. An optimization method is proposed in [12] to address the transient load reduction issues. After the nonlinear model based methods are developed, the transient load on drive-train shaft is tested according to the maximum and the standard deviation of the torque on the drive-train shaft [1], [2], [13]−[15]. In addition, the intelligent algorithm based methods are presented in [5], [16], with more factors being considered, such as short-term wind speed forecast [16]. Satisfactory results have been achieved in the above researches, and this paper aims to improve the nonlinear model based methods for increasing MPPT efficiency at a lower cost of load.

In order to capture more wind energy in MPPT stage, the nonlinear model based methods are proposed [1], [2], [13]−[15], whose MPPT efficiencies are better than those of the linear model based methods [1] and other classical methods [13]. However, since the derivative of reference speed is included in the calculation of generator torque, the tracking performance is effectively enhanced at the cost of the intensive fluctuation of generator torque and significant increase of transient load on the drive-train shaft. Although the drive-train load is statistically calculated for verification [1], [2], [13]−[15], the issue of improving MPPT performance at a lower cost of load should be addressed.

In this paper, the transient load on the drive-train shaft during MPPT process is considered. The low-speed shaft

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torque is used to quantitatively describe the load on drive-train shaft [2], [14], [15], which will fluctuate dramatically with the intensive fluctuation of generator torque. Then, a nonlinear controller with variable parameter is proposed, in which the saturation function is introduced to mitigate additional fluctuation of generator torque when accelerating MPPT process. Finally, the proposed controller is validated by the simulations on FAST [17] (fatigue, aerodynamics, structures, and turbulence) code and experiments on wind turbine simulator (WTS) based test bench.

The paper is organized as follows. The nonlinear model of wind turbine is described in Section II. The nonlinear MPPT controller with variable parameter is proposed in Section III. In Section IV, the proposed method is validated by the FAST code and the WTS based test bench. Finally, the conclusions are drawn in Section V.

II. WIND TURBINE MODELING AND PROBLEM STATEMENT

In this section, the dynamic model of VSWT consisting of wind rotor, drive train and generator is presented. Then the nonlinear model based MPPT controllers, which will be improved in this paper, are briefly introduced.

A. Wind Turbine Modeling

The energy captured by wind turbine can be expressed as follows [13]:

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

where v is the wind velocity, R is the rotor radius, ρ is the air density. Because this paper is concerned with MPPT, blade pitch angle β remains constant and correspondingly power coefficient C_P is a function of tip speed ratio λ, which is defined as [13]:

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

where ω_r is the rotor speed. The relationship between the aerodynamic power P_a and the aerodynamic torque T_r is given by [13]

$$P_a = T_r\omega_r. \tag{3}$$

And the aerodynamic torque is calculated by [13]

$$T_r = \frac{1}{2}\rho\pi R^3 v^2 C_Q(\lambda) \tag{4}$$

where C_Q is the torque coefficient defined as

$$C_Q(\lambda) = \frac{C_P(\lambda)}{\lambda}. \tag{5}$$

As shown in Fig. 1, a wind turbine can be represented as a two-mass model of shaft dynamics [14]:

$$C_r\omega_r + J_r\dot{\omega}_r = T_r - T_{ls} \tag{6}$$

$$C_g\omega_g + J_g\dot{\omega}_g = T_{hs} - T_g \tag{7}$$

$$T_{ls} = K_{ls}\left(\theta_r - \frac{\theta_g}{n_g}\right) + C_{ls}\left(\omega_r - \frac{\omega_g}{n_g}\right) \tag{8}$$

$$T_{hs} = \frac{T_{ls}}{n_g} \tag{9}$$

where C_r and C_g are the rotor and generator external damping, J_r and J_g are the rotor and generator inertia, T_{ls} and T_{hs} are the low-speed and high-speed shaft torques, K_{ls} and C_{ls} are the stiffness and damping factors of the low-speed shaft, θ_r and θ_g are the rotor-side and generator-side angular deviations, ω_g is the generator speed, n_g is the gearbox ratio, and T_g is the generator torque.

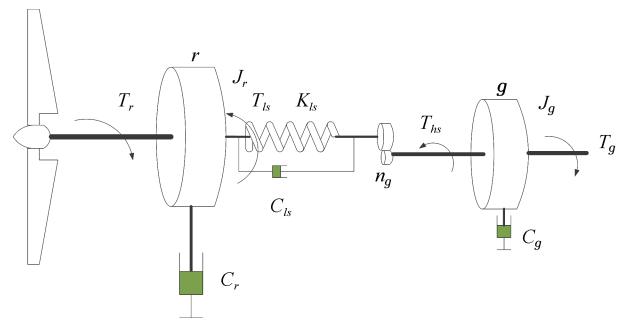

Fig. 1. The two-mass model of wind turbine [14].

With an ideal gearbox, a wind turbine can be further represented as a single lumped mass model [10], [15] by combining the (6)−(9):

$$C_t\omega_r + J_t\dot{\omega}_r = T_r - n_g T_g \tag{10}$$

where

$$C_t = C_r + n_g^2 C_g \tag{11}$$

$$J_t = J_r + n_g^2 J_g \tag{12}$$

$$\omega_r = \frac{\omega_g}{n_g}. \tag{13}$$

Considering that electromagnetic response time is much faster than aero-mechanical response, the designs of MPPT and the generator control can be decoupled [14]. In this paper, the generator torque T_g is assumed to be well controlled by electrical loop and thus can be regarded as the control input of the model (10).

B. Baseline Control Strategies

Because C_P can reach its maximum value $C_{P\max}$ at the optimal tip speed ratio λ_{opt}, the optimal rotor speed can be defined as [13]

$$\omega_{\text{opt}} = \frac{\lambda_{\text{opt}} v}{R}. \tag{14}$$

In order to track the optimal rotor speed, two nonlinear state feedback controllers are proposed in [13]. On this basis, they were extended to the two-mass model in [14]. In addition, these controllers were improved through the sliding mode control (SMC) method in [2], [15].

The nonlinear static state feedback control (NSSFC) [13] is:

$$T_{g.\text{ref}} = \frac{T_r - C_t\omega_t - J_t\dot{\omega}_{\text{ref}} + J_t a_0\varepsilon}{n_g} \tag{15}$$

where $\varepsilon = \omega_t - \omega_{\text{opt}}$ represents the tracking error and $a_0 > 0$. Note that since the wind speed varies over the disc swept by wind rotor, a wind speed estimation [18], [19] (Fig. 2), regarding wind turbine itself as a measurement device [14], is utilized to estimate the effective value of wind speed and obtain $\omega_{\rm opt}$. The nonlinear dynamic state feedback control (NDSFC) [13] is:

$$\dot{T}_{g.\rm ref}=\frac{\dot{T}_r-C_t\dot{\omega}_t-J_t\ddot{\omega}_{\rm ref}+J_tb_1\dot{\varepsilon}+J_tb_0\varepsilon}{n_g}. \quad (16)$$

The coefficients b_0 and b_1 are selected in such a way that the polynomial $s^2+b_1s+b_0$ is Hurwitz [13]. The structure of these two controllers is shown in Fig. 3.

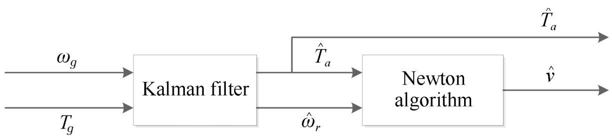

Fig. 2. Wind speed estimation [14].

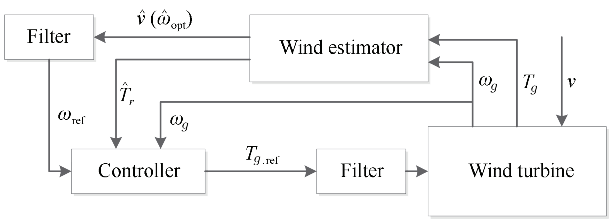

Fig. 3. The structure of NSSFC and NDSFC.

C. Problem Statement

In order to accelerate the MPPT process, as shown in (15) and (16), the reference generator torque $T_{g.\rm ref}$ is directly related to the dynamics of $\omega_{\rm ref}$, which is determined by the random fluctuation of wind speed. It is implied that the fluctuation of generator torque is easy to be induced by the irregular change of wind speed.

On the other hand, the standard deviation of low-speed shaft torque [2], [14], [15] is used to reflect the level of drive-train load in this paper. Combining (6)−(13), the low-speed shaft torque can be expressed by

$$T_{ls}=\frac{n_g^2J_g}{J_t}T_r+\frac{n_gJ_r}{J_t}T_g+\frac{n_g^2}{J_t}\left(J_rC_g-J_gC_r\right)\omega_r. \quad (17)$$

Note that the low-speed shaft torque is directly affected by the generator torque T_g, and its variation will be enlarged with the additional fluctuation of generator torque. To illustrate the transient load that is characterized by the intensive fluctuation of low-speed torque and caused by the aforementioned nonlinear methods, the generator torque and low-speed shaft torque of the wind turbine controlled by NDSFC and the classical indirect speed control (ISC) [15] are compared in Fig. 4. It can be observed that although the NDSFC has a perfect performance of speed tracking when the wind speed increases from 8 m/s to 8.3 m/s, the generator torque outputted from NDSFC varies more strongly than ISC, especially an additional fluctuation occurs in the early stage of MPPT. As a result, intensive fluctuation of low-speed shaft torque is caused when using the controller of NDSFC.

Obviously, it is impractical to pursue the tracking performance at cost of excessively increased transient load. And as discussed above, the mitigation of drive-train load can be realized by optimizing the generator torque. Although the magnitude of the above generator torque fluctuation can be reduced to some extent by filtering the reference speed $\omega_{\rm ref}$ and the reference generator torque $T_{g.\rm ref}$ [13]−[15] (as illustrated in Fig. 3, the additional fluctuation cannot be actually avoided. Hence, the current nonlinear MPPT controllers need to be improved for mitigating the transient load on the drive-train shaft.

III. Nonlinear Control Considering Mitigation of Transient Loads

In this section, a nonlinear controller with variable parameter is developed. Initially, the basic form of the controller is presented with which the rotor speed can track its reference value. Then a parameter adjustment strategy is designed for mitigating the transient load on drive-train shafts by avoiding additional fluctuation of generator torque.

A. Nonlinear State Feedback Control

The tracking error is defined as follows:

$$\varepsilon=\omega_r-\omega_{\rm ref}. \quad (18)$$

Without considering the dynamics of $\omega_{\rm ref}$, the variation rate of tracking error can be expressed as $\dot{\varepsilon}=\dot{\omega}_r$. Then, by combining it with (10), (19) is obtained as

$$\dot{\varepsilon}=\frac{T_r-n_gT_g-C_t\omega_r}{J_t}. \quad (19)$$

Remark 1: In order to prevent tracking the wind speed with high frequency, $\omega_{\rm opt}$ is not directly used as the reference speed $\omega_{\rm ref}$ [13]−[15]. Considering that, as described in Section II-C, the term of $\dot{\omega}_{\rm ref}$ results in intensive fluctuation of generator torque, it is ignored in this paper.

If the tracking error can be limited as [13]

$$\dot{\varepsilon}+a\varepsilon=0,\quad a>0 \quad (20)$$

the rotor speed converges to its reference value. Combining (19) and (20), the generator reference torque is determined by the following equation:

$$T_{g.\rm ref}=\frac{T_r-C_t\omega_r+aJ_t\varepsilon}{n_g}. \quad (21)$$

It can be seen that MPPT of wind turbines can be realized by the controller (21). Moreover, based on the above analysis, a nonlinear controller with variable parameter is proposed in the following section. The control parameter a is adjusted online so as to achieve more wind energy extraction and avoid the additional generator torque fluctuation.

B. Parameter Adjustment Strategy for Torque Limitation

The principles that the proposed MPPT controller should follow are:

1) The MPPT of wind turbines should be realized;

2) The additional fluctuations of generator torque caused by controller should be avoided;

3) The convergence rate of speed error should be improved under the premise of 1) and 2).

By solving (20), it can be obtained that

$$\varepsilon\left(t\right)=e^{-at}\varepsilon_0. \quad (22)$$

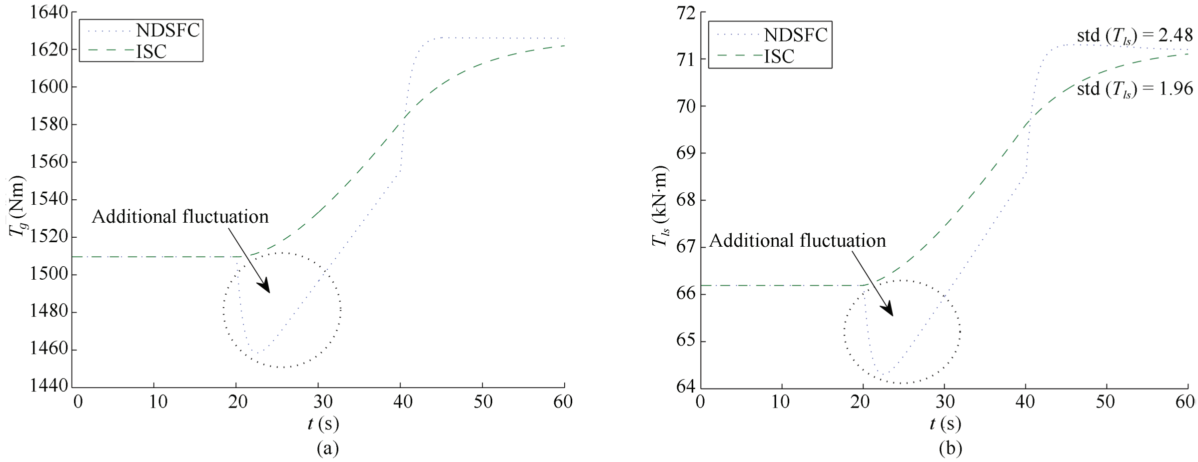

Fig. 4 Generator torque and low-speed shaft torque of two controllers (wind speed increases from 8 m/s to 8.3 m/s). (a) Generator torque. (b) Low-speed shaft torque.

According to (21) and (22), the value of the control parameter a affects the MPPT performance as well as the variation of generator torque. Specifically, the larger is the value of a, the more quickly the tracking error $\varepsilon(t)$ converges to zero and the larger is the variation of generator torque, and vice versa.

Consider the following equation

$$u = \dot{\varepsilon} = -a\varepsilon \tag{23}$$

where u is the effective control input that affects the convergence speed of ε. Here, the controller parameter a is defined as

$$a(\varepsilon) = \frac{u_{\max}}{|\varepsilon| + \frac{u_{\max}}{a_{\max}}} \tag{24}$$

where $u_{\max} > 0$ and $a_{\max} > 0$. $a_{\max}$ is the maximum of a.

It can be observed from (24) that

$$0 < a(\varepsilon) \leq a_{\max} \tag{25}$$

$u_{\max}$ is the upper bound of $u = -a(\varepsilon)\varepsilon$, i.e.,

$$|u| = |-a(\varepsilon)\varepsilon| = a(\varepsilon)|\varepsilon| = \frac{u_{\max}}{|\varepsilon| + \frac{u_{\max}}{a_{\max}}}|\varepsilon| < u_{\max}. \tag{26}$$

Remark 2: The parameter a is given by (24), in which both a and u have its upper bound. $a_{\max}$ is introduced to limit the value of a. $u_{\max}$ is the boundary of control input (i.e., reference generator torque). As will be discussed below, the additional fluctuation of generator torque can be avoided by appropriately setting the value of $u_{\max}$.

The optimal value of generator torque can be expressed by

$$T_{g.\text{opt}} = \frac{1}{n_g}(T_r - C_t\omega_{\text{ref}}). \tag{27}$$

When the wind turbine steadily operates at the reference speed, the generator torque reaches $T_{g.\text{opt}}$.

Define s as

$$s = T_g - T_{g.\text{opt}} = T_g - \frac{T_r}{n_g} + \frac{C_t\omega_{\text{ref}}}{n_g}. \tag{28}$$

To avoid the additional fluctuation of generator torque, the following inequalities should be satisfied

$$(T_{g.\text{ref}} - T_g)\,\text{sgn}(s) \leq 0 \tag{29}$$

$$(T_{g.\text{ref}} - T_{g.\text{opt}})\,\text{sgn}(s) \geq 0. \tag{30}$$

Remark 3: If the inequalities (29) and (30) are satisfied, the reference value of the generator torque varies between the current value and the optimal value, and accordingly the additional fluctuation of generator torque is mitigated.

By combining (19) and (23),

$$u = \frac{T_r - n_g T_{g.\text{ref}} - C_t\omega_r}{J_t}. \tag{31}$$

Hence, it follows from (29)−(31) that:

Case 1: When $\text{sgn}(s)\,\text{sgn}(\varepsilon) > 0$ is satisfied, then it comes (32);

Case 2: When $\text{sgn}(s)\,\text{sgn}(\varepsilon) < 0$ is satisfied, it yields (33).

$$u_{\max} = \frac{n_g T_g - T_r + C_t\omega_r}{J_t\ \text{sgn}(\varepsilon)} \tag{32}$$

$$u_{\max} = \frac{C_t\varepsilon}{J_t\,\text{sgn}(\varepsilon)}. \tag{33}$$

The reference generator torque $T_{g.\text{ref}}$, with which (29) and (30) are satisfied, will not result in the additional generator torque fluctuations. In addition, $u_{\max} > 0$ should be satisfied to ensure the speed tracking ($a(\varepsilon) > 0$). Here, let $u_{\max} \geq u_0$ with $u_0 > 0$. Then $u_{\max}$ can be calculated as (34), shown at the bottom of this page.

$$u_{\max} = \begin{cases} \dfrac{n_g T_g - T_r + C_t\omega_r}{J_t\,\text{sgn}(\varepsilon)}, & \text{sgn}(s)\,\text{sgn}(\varepsilon) > 0 \text{ and } \dfrac{n_g T_g - T_r + C_t\omega_r}{J_t\,\text{sgn}(\varepsilon)} \geq u_0 \\ \dfrac{C_t\varepsilon}{J_t\,\text{sgn}(\varepsilon)}, & \text{sgn}(s)\,\text{sgn}(\varepsilon) < 0 \text{ and } \dfrac{C_t\varepsilon}{J_t\,\text{sgn}(\varepsilon)} \geq u_0 \\ u_0, & \text{others.} \end{cases} \tag{34}$$

Finally, the controller can be defined as

$$T_{g.\mathrm{ref}} = \frac{T_r - C_t\omega_r + a(\varepsilon) J_t\varepsilon}{n_g} \tag{35}$$

where $a(\varepsilon)$ can be derived online from (24) and (34).

To sum up, the calculation procedure of the generator reference torque is shown in Fig. 5.

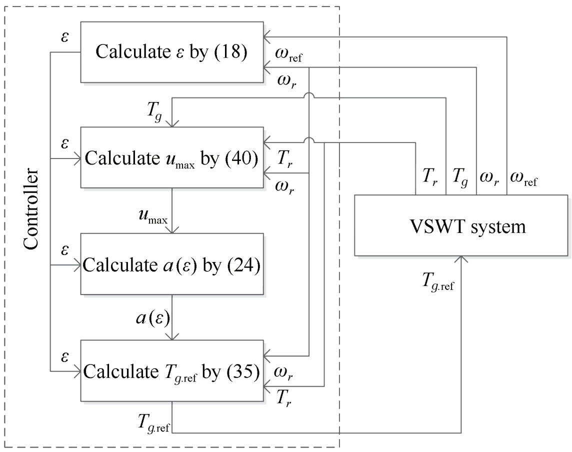

Fig. 5. Calculation procedure of $T_{g.\mathrm{ref}}$.

IV. Simulations and Experiments

In this section, in order to verify the performance of the proposed controller, it is compared with the other nonlinear controllers by the FAST-based simulations and WTS-based experiments on the NREL (National Renewable Energy Laboratory) CART3 [20] wind turbine.

A. Preparation of Comparisons

The FAST [17] code is a comprehensive aeroelastic simulator developed by NREL. The FAST model of the CART three-blade wind turbine built by NREL is selected, whose parameters are listed in Table I.

TABLE I
CART3 Wind Turbine Parameters

Parameter	Value
Number of blades	3
Rotor radius	20 m
Hub height	36.6 m
Gearbox ratio	43.165
Rated power	600 kW
λ_{opt}	5.8
$C_{P\max}$	0.467

The TURBSIM [21] software developed by NREL is used to generate a 600-second wind profile with the mean value of 6 m/s according to Class A Kaimal turbulence spectra [22]. The wind speed profile is plotted in Fig. 6.

The proposed nonlinear controller with variable parameter (VPNC) is compared with ISC [15], NSSFC and NDSFC under the same wind profile. ISC, also known as the Optimal Torque (OT) method, is a classical MPPT control algorithm and commonly applied in practical VSWTs [23]. The parameters of these MPPT controllers are listed in Table II. In addition, the reference generator torque $T_{g.\mathrm{ref}}$ is filtered using a low-pass filter in order to smooth the control action, and the reference speed ω_{ref} and its time derivatives are filtered to obtain a less turbulent signal[13], [14], [23].

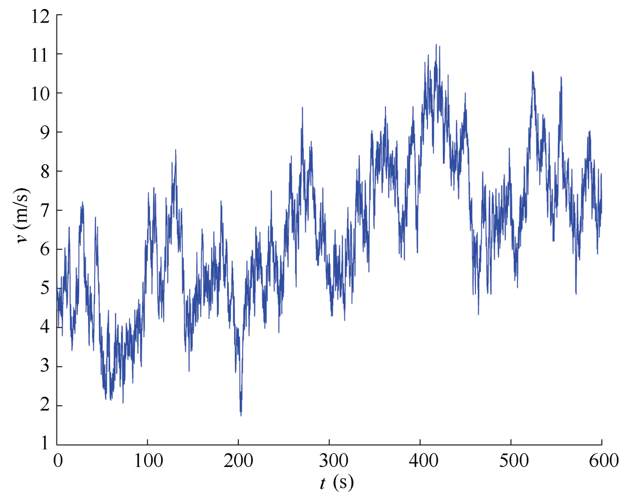

Fig. 6. Wind speed profile.

TABLE II
Parameters of MPPT Controllers

Control algorithm	Parameter [13]
ISC	$k_{\mathrm{opt}} = 5.38 \times 10^3$
NSSFC	$a_0 = 0.1$
NDSFC	$b_0 = 0.01$, $b_1 = 0.2$
VPNC	$a_{\max} = 1$,$u_0 = 0.001$

In order to provide a quantitative comparison among the aforementioned controllers, three indicators [2], [14], [15], which are the MPPT efficiency, the standard deviation of T_g, and the standard deviation of T_{ls}, respectively, are employed. The MPPT efficiency η is defined as [13]

$$\eta\,(\%) = \frac{\int_{t_{\mathrm{ini}}}^{t_{\mathrm{fin}}} P_{\mathrm{out}}dt}{\int_{t_{\mathrm{ini}}}^{t_{\mathrm{fin}}} P_{\mathrm{opt}}dt} = \frac{\int_{t_{\mathrm{ini}}}^{t_{\mathrm{fin}}} T_g\omega_g\,dt}{\int_{t_{\mathrm{ini}}}^{t_{\mathrm{fin}}} \frac{1}{2}\rho\pi R^2 C_{P.\max} v^3\,dt} \tag{36}$$

where P_{out} is the output power of generator and P_{opt} is the optimal aerodynamic power.

B. Simulation Results

According to the dynamic simulations of wind turbines, the MPPT performance, generator torque and low-speed shaft torque are respectively compared among the above MPPT controllers.

The trajectories of rotor speed corresponding to the different controllers are depicted in Fig. 7. And, as shown in Fig. 8, the rotor speed from 200 s to 300 s is magnified for clear comparison. It can be observed from Fig. 9 that the rotor speed regulated by the nonlinear controllers can track the optimal speed more rapidly than ISC. Especially, when the wind speed varies quickly, the nonlinear controllers can improve the tracking performance significantly. Moreover, the MPPT efficiencies η of the different controllers are summarized in Table III. On the other hand, the variations of generator torque are plotted in Fig. 9. It is shown in Fig. 9 that the generator

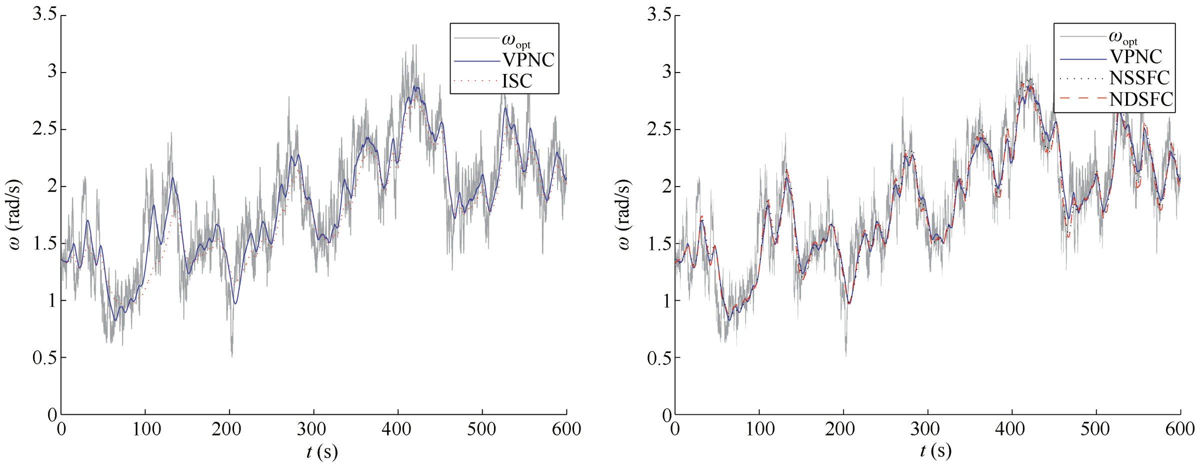

Fig. 7. Rotor speed of wind turbine (FAST simulation). (a) VPNC and ISC. (b) VPNC, NSSFC, and NDSFC.

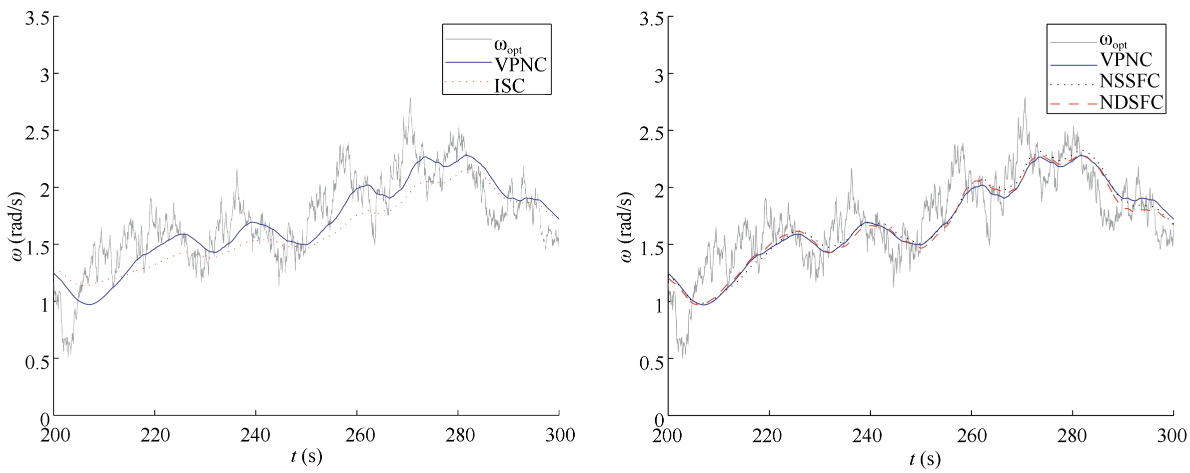

Fig. 8. Rotor speed during 200 s to 300 s (FAST simulation). (a) VPNC and ISC. (b) VPNC, NSSFC, and NDSFC.

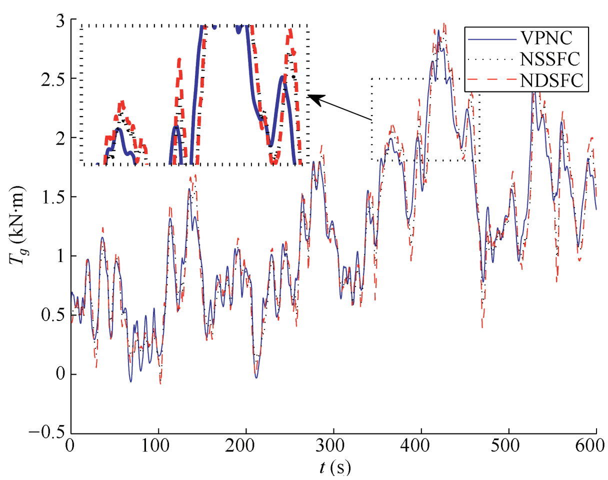

Fig. 9. Generator torque of wind turbine (FAST simulation).

torque outputted from VPNC changes more smoothly than NSSFC and NDSFC. As a result, according to Table III, when applying VPNC, both the standard deviations of T_g and T_{ls} decrease.

It can be summarized that, as compared to NSSFC and NDSFC, VPNC can capture more energy from the available wind energy with the least cost of load on drive-train.

TABLE III
COMPARISON OF CONTROLLER PERFORMANCE
(FAST SIMULATION)

	η/%	std (T_g)/(kN·m)	std (T_{ls})/(kN·m)
ISC	88.85	0.6095	26.53
VPNC	91.39	0.6323	26.91
NSSFC	91.36	0.6513	27.35
NDSFC	91.39	0.6853	28.61

C. Experimental Results

Furthermore, a 10 kW WTS-based wind power generation system (WPGS) test bench [24], shown in Fig. 10, is built to verify the performance of the proposed controller. As illustrated in Fig. 11 the test bench mainly consists of three parts:

1) The WTS including a direct current motor (DCM) and a motor drive is to simulate the wind turbulence, the aerodynamic [25] and the large rotor inertia of turbine. Note that large rotor inertia is compensated by a flywheel [26] and the inertia compensation scheme [24].

2) The electrical part, which is identical with that of real W-PGS, comprises the permanent-magnet synchronous generator (PMSG) and its full-power convertor for grid connection.

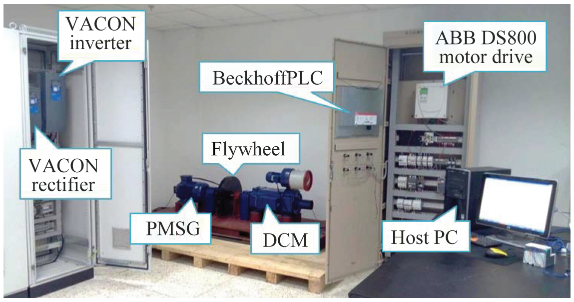

Fig. 10. 10 kW WTS-based WPGS test bench.

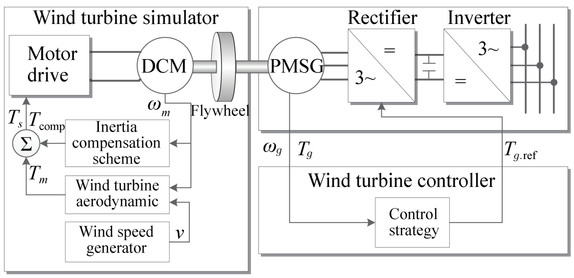

Fig. 11. Main structure of WTS-based WPGS test bench.

3) The programmable logic controller (PLC) based digital controller implements MPPT control algorithm, based on which the electromagnetic torque reference is calculated and sent to the rectifier.

The comparison of the nonlinear controllers with the same parameter setting mentioned in Section IV-A is conducted again through the test bench and summarized in Table IV. Besides, the trajectories of rotor speed and generator torque corresponding to VPNC, NSSFC and NDSFC are plotted in Figs. 12 and 13, respectively. It can be observed that the experimental results similar to the simulation are obtained. That is to say, compared with NSSFC and NDSFC, VPNC not only achieves the similar improvement of MPPT efficiency, but also results in the least standard deviations of T_g and T_{ls}. This indicates that with increase of MPPT efficiency, the load on drive-train shaft is effectively mitigated by VPNC.

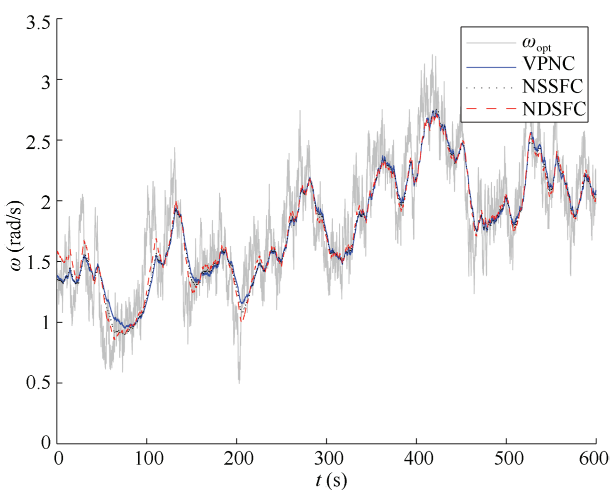

Fig. 12. Rotor speed of wind turbine (WTS-based test bench).

Remark 4: Because only the generator speed and torque can be measured in the test bench, the rotor speed ω_r is calculated by (13). Besides, the low-speed shaft torque T_{ls} is calculated by (17) for analyzing the load on drive-train shaft, in which the aerodynamic torque simulated in WTS is used as T_r. However, in the implementation of the nonlinear controllers, the aerodynamic torque is immeasurable and can only be estimated.

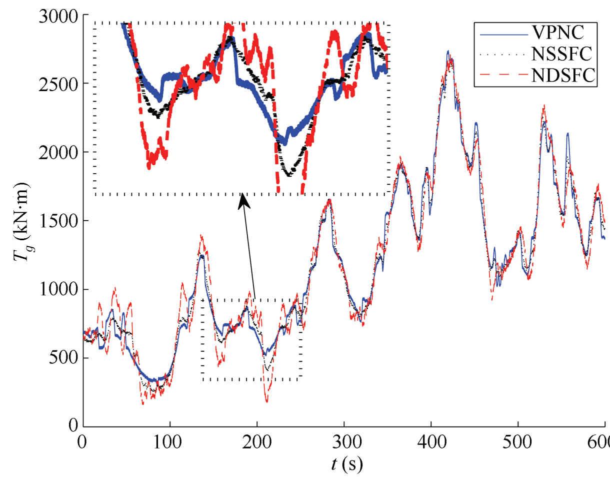

Fig. 13. Generator torque of wind turbine (WTS-based test bench).

TABLE IV
COMPARISON OF CONTROLLER PERFORMANCE (WTS-BASED TEST BENCH)

	η/%	std (T_g)/(kN·m)	std (T_{ls})/(kN·m)
ISC	84.31	0.5442	24.24
VPNC	88.71	0.5564	24.69
NSSFC	88.28	0.5603	24.79
NDSFC	89.01	0.5756	25.13

V. CONCLUSION

In this paper, a nonlinear controller with variable parameter is proposed for MPPT. By analyzing the relationship between transient load on drive-train shaft and generator torque, the MPPT controller is designed for favorable tracking performance under this restriction that no additional fluctuations of generator torque is caused. To validate the proposed controller, simulations and experiments are conducted in comparison with ISC, NSSFC and NDSFC. Results show that the proposed controller can capture more energy from the available wind energy at a lower cost of load on drive-train.

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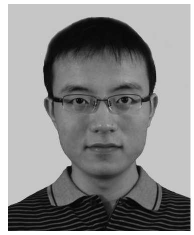

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