Assessment of System Frequency Support Effect of PMSG-WTG Using Torque-Limit-Based Inertial Control

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***Abstract*—To release the "hidden inertia" of variable-speed wind turbines for temporary frequency support, a method of torque-limit based inertial control is proposed in this paper. This method aims to improve the frequency support capability considering the maximum torque restriction of a permanent magnet synchronous generator. The advantages of the proposed method are improved frequency nadir (FN) in the event of an under-frequency disturbance; and avoidance of over-deceleration and a second frequency dip during the inertial response. The system frequency response is different, with different slope values in the power-speed plane when the inertial response is performed. The proposed method is evaluated in a modified three-machine, nine-bus system. The simulation results show that there is a trade-off between the recovery time and FN, such that a gradual slope tends to improve the FN and restrict the rate of change of frequency aggressively while causing an extension of the recovery time. These results provide insight into how to properly design such kinds of inertial control strategies for practical applications.**

Keywords—Inertial control; PMSG-WTG; torque limit

I. INTRODUCTION

Frequency stability indicates an active power balance in a power system. In case the active power generated cannot fulfill the power consumed by the loads, the frequency will decrease and deviate from the nominal value. Generally, a sudden increase in loads or a trip event of synchronous generators may lead to a frequency drop. Three mechanisms exist to coordinate control as the power system reacts to such a frequency excursion: inertial response, primary frequency control and secondary frequency control (also called automatic generation control, AGC) [1]. The inertial response of the synchronous generators contributes mainly to restrict the rate of change of frequency (ROCOF). Later, the primary frequency response increases the active power of the synchronous generators to maintain the frequency nadir (FN) above the secure level; otherwise, under-frequency load-shedding (UFLS) relays and generation protection relays may be triggered, which may even result in a cascading blackout in a power system [1]. The secondary frequency control or AGC, will assign the power set point of each synchronous generator and the frequency is brought back to the nominal value.

Today, the total inertia of a power system tends to deteriorate with increasing penetrations of inverter-based renewable energy sources. A variable-speed wind turbine generator (WTG) cannot respond to a change in system frequency because of the application of its power electronics; these include doubly-fed induction generators (Type 3) and permanent magnet synchronous generators with full converters (Type 4). However, the available equivalent inertia constant of a variable-speed WTG is no less than that of conventional generators, and the operational range of the rotor speed is much wider. This implies that there is a great potential for variable-speed WTGs to participate in system frequency regulation by using synthetic inertial response. Various strategies have been developed by academia and industry to employ this "hidden inertia." These methods can be categorized into two types: (1) step-wise inertial control (SIC), wherein a variable-speed WTG is controlled to release a constant active power for a limited duration of time, [2], [3]; and (2) frequency-based inertial control (FBIC), wherein the active power boost of a variable-speed WTG is dependent on the ROCOF (or frequency deviation) in a way that is similar to that of synchronous generators [4], [5], and it can be realized by additional control loops that relates the variable-speed WTG's rotor speed to the system frequency.

This paper proposes an improved SIC method considering the torque limit. A Type 4 wind energy conversion system, consisting of a permanent magnet synchronous generator (PMSG) and fully-rated power converters is adopted to test the proposed inertial control method due to its high flexibility. The electrical power reference of the PMSG-WTG is defined in two stages during the inertial response: deceleration and acceleration. In the first stage, the reference power is set to be proportional to the pre-disturbance rotor speed with respect to

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the torque limit. Then the reference power decreases along a straight line with a pre-defined slope value in the power-speed plane. When the electrical power becomes equal to the mechanical power, the PMSG-WTG is operated in a quasi-steady state. During the period of acceleration, a certain amount of stepwise power decrease is required at the start, which accelerates the rotor and prevents a severe second frequency dip. At last, the WTG operation recovers to the maximum power point tracking (MPPT) mode when the constant reference electric power meets the MPPT power curve in the acceleration stage.

Case studies and results in MATLAB/Simulink are presented at the end of this paper. The frequency support effect of the proposed method is verified in a modified Western System Coordination Council (WSCC) nine-bus test system. The frequency stability of the simulated power system is enhanced compared to the case without inertial response. In addition, the power references in the deceleration period with different slope values are evaluated in terms of the FN, ROCOF and recovery time as metrics. The result indicates a trade-off between the improvement in the FN and the fast rotor speed recovery. It is observed that a gradual slope value improves the FN more than the steep slope case, whereas the recovery process is delayed due to the excessive kinetic energy extraction in the case with the gradual slope.

II. REVIEW OF BASIC CONTROL FOR PMSG-WTG

Wind energy conversion system can be categorized into four types: Type 1 to Type 4 [1]. Type 1 wind energy conversion systems are fixed-speed WTGs, whereas Type 3 and Type 4 are variable-speed WTGs. Fixed-speed WTGs connect to the grid directly, so their rotating speed must be synchronized to the grid frequency. Because the rotor speed is controlled to match the wind speed in order to maintain the optimal efficiency, it is proven that, on average, variable-speed WTGs will collect up to 10% more annual energy than fixed-speed WTGs that have the same capacity [6], and the power quality is improved significantly. Further, the variable speed operation reduces the structural loads on the turbine's mechanical components, and the lifetime of a variable-speed WTG is expected to be longer than that of a fixed-speed WTG.

The Majority of new wind turbines installed in wind power plants are variable-speed WTGs. A doubly-fed induction generator (DFIG) equipped with a partially scaled power converter is defined as Type 3. Because the power converter is interfaced only through the rotor circuits, the capacity of the power converter can be sized as a part of the WTG's capacity, which reduces the expense of a DFIG-WTG. A Type 4 wind energy conversion system consists of a full-converter system with a PMSG. Compared to a DFIG-WTG, a PMSG-WTG is completely decoupled from the grid, and it is able to be driven directly by a wind turbine because of the multi-poles structure; thus, the gearbox of a wind energy conversion system, which is regarded as the most vulnerable part, can be removed from a PMSG-WTG. These features contribute to the higher efficiency and reliability of a PMSG-WTG; however, most of the variable-speed WTGs in service are Type 3, and the market share of PMSG-WTGs is relatively smaller than that DFIG-WTGs because of the high cost of full converters. In addition, the size of a direct-drive system is expected to be very large because of the multi-pole structures. Even so, the market share of Type 4 wind energy conversion system is increasing because of the reduced price of the power electronics and technology transformation, especially in the off-shore wind market.

A. Basic Control Concept for variable-speed WTGs

Two control units work coordinately in a variable-speed WTG system. A pitch controller regulates the pitch angle, and it is clamped to the optimal value (around zero degrees) when the rotor speed is below the maximum limit allowable. The most important function of the pitch controller is to restrict the rotor speed above the rotor speed limit and thus help reduce the loads on the mechanical components and avoids a run-away condition.

The electromagnetic power or torque is controlled by the power converter system. The rotor speed of the turbine is regulated to maintain the optimal tip-speed ratio (TSR) to maximize the mechanical power extraction from the wind. The mechanical power is formulated in (1) [7], as:

$$P_m = \frac{1}{2}\rho\pi R^2 V_w{}^3 C_p\left(\lambda,\beta\right) \tag{1}$$

The available mechanical power is related to the power coefficient, C_p, which is determined by the TSR, λ, only when the pith angle, β, is held constant. The TSR is defined as:

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

The maximum power coefficient, $C_{p\_\max}$, corresponds to the optimal TSR, λ_{opt}, and the optimal pitch angle. Obviously, the rotor speed should be regulated proportionally to the wind speed in order to maximize the power extraction; however, the WTG is usually operated based on the power or torque reference, according to (3), because it is difficult to measure the wind speed accurately. As $C_{p\_\max}$ and λ_{opt} are known in advance, the electromagnetic power reference is deduced as:

$$P_e = K\omega_r{}^3 \tag{3}$$

where:

$$K = \frac{1}{2}\rho\pi R^5 \frac{C_{p\_\max}}{\lambda_{opt}{}^3} \tag{4}$$

The WTG operates under MPPT mode with the power converter regulating the power according to the reference, which is updated in a cubic relation to the rotor speed as the rotor speed changes. Note that only the power and rotor speed sensors are required to achieve the MPPT control objective.

B. *Power Converter Control Topology for PMSG-WTGs*

The topology of a Type 4 PMSG-WTG is shown in Fig. 1. The power generated is injected into the grid through the fully-rated power converter. The control strategies introduced in [7] are adopted.

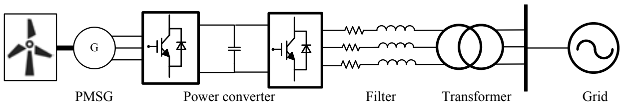


Fig.1 Topology of PMSG-WTG

Because the generator is a PMSG, the air gap flux is maintained by the permanent magnet; thus, the generator-side converter (GSC) employs the zero d-axis current control, and the electrical torque is determined only by the q-axis current only when the rotating coordinate is aligned to the permanent flux. Voltage-oriented control is applied at the line-side converter (LSC) by combining the feed-forward method to achieve decoupled active power and reactive power control. The conservation of energy within the DC bus dictates that the real power generated by the GSC (PGSC) must be transferred directly to the LSC (PLSC), or PGSC = PLSC. Otherwise, if PGSC > PLSC, the DC bus voltage will increase; or if PGSC < PLSC, the DC bus voltage will decrease. Based on the conservation of energy in the DC bus, the active power control of the LSC is often replaced by controlling the DC-link voltage at a constant value because the total power generated by the generator is delivered to the line side continuously with a balancing voltage across the capacitor [7], [8].

III. PROPOSED TORQUE-LIMIT BASED INERTIAL CONTROL

To provide energy to the main grid and protect the whole wind power system from damage, some restrictions must be respected. A wind turbine has a maximum rotor speed limit to protect the mechanical components and to avoid a run-away condition. In addition, the minimum rotor speed limit ensures the stable operation of a WTG. In this paper, the rotor speed ranges from 0.5 p.u. to 1.1 p.u.. The power limit should be checked considering the power converter and generator capacity. As mentioned above, the q-axis current relates to the electromagnetic torque directly, so the torque limit should be respected to prevent permanent damage to the IGBT [10]. In addition, the torque limit ensures that the gearbox stress stays within its limit and that the mechanical components are not damaged.

The proposed inertial control method aims to improve the PMSG-WTG's frequency support capability based on the torque limit. The defined two-stage power reference in the process of inertial response is illustrated in the rotor-speed domain, as shown in Fig. 2. Prior to a frequency event, a PMSG-WTG is operated in a stable MPPT mode; this corresponds to ω_{MPPT} and P_{MPPT} at Point A. At the moment a frequency dip is detected, the PMSG-WTG increases its active power output stepwise to Point B, which corresponds to the torque limit at the current rotor speed, namely:

$$P_B = T_{\text{limit}} \cdot \omega_{MPPT} \tag{5}$$

The torque limit is set to be 1.2 p.u. to prevent damage caused by an excessive transient torque. Then the reference power for the deceleration period is regulated along BC (three possible C points are shown: C1, C2, or C3). Note that the slopes for the decelerations impact the performance of the inertial response provided by the PMSG-WTG. Line BC1 corresponds to the gradual slope, and Line BC3 corresponds to the steep slope. The values of the slope are selected from the range between BC1 and BC3. The most gradual slope is determined such that C1 corresponds to the minimum allowable rotor speed (0.5 p.u.), and the rotor speed at C3 is 0.1 p.u. less than ω_{MPPT}. The PMSG-WTG begins to accelerate after the turbine is stabilized at Point C (C1, C2 or C3). In the stage of acceleration (C-D-E-A), the electromagnetic power reference decreases stepwise at first, then it remains constant below the mechanical power to restore the kinetic energy. Note that it is significant for the turbine to operate in the quasi-stable state at Point C because even a relatively small amount of de-loaded power is enough to accelerate the PMSG-WTG while not causing a severe second frequency dip. Finally, when the constant power reference intersects the MPPT curve, the turbine recovers to MPPT mode along E-A.

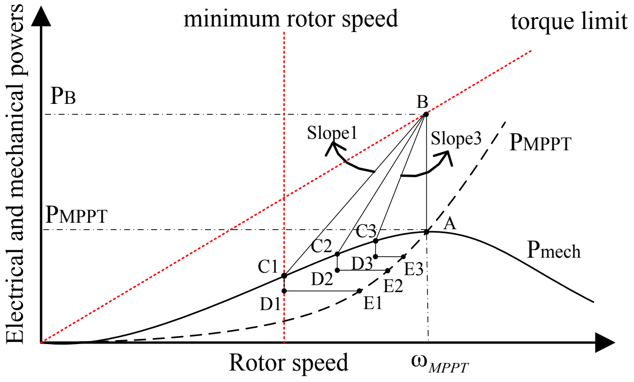


Fig.2 Illustration of proposed inertial response in rotor speed domain

The proposed torque-limit-based inertial control for a PMSG-WTG maximizes the active power injection to temporarily support the power system frequency during the frequency event. As a result, the frequency nadir is raised significantly compared to that without inertial control. Further, no severe second frequency dip happens at the beginning of rotor-accelerating process due to and the small amount of de-loaded power after the stable operating point of the turbine. Also, over-deceleration can be avoided.

IV. SYSTEM MODELING AND CASE STUDY

The performance of the proposed torque-limit based inertial control is tested in a modified WSCC nine-bus system using MATLAB/Simulink. The configuration of the system is presented in Fig. 3.

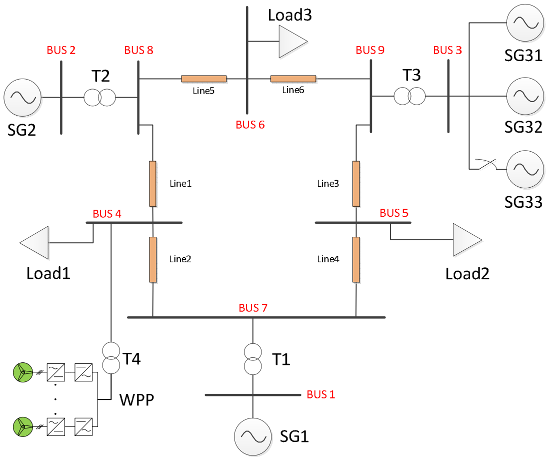
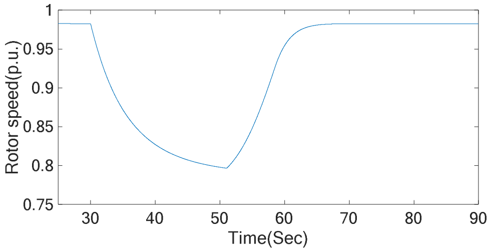
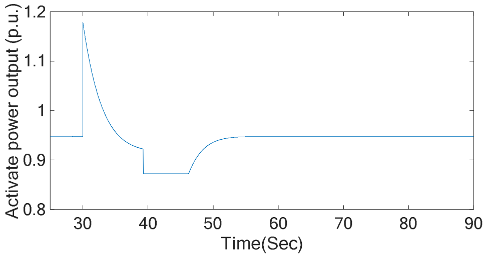


Fig.3 Configuration of the modified nine-bus grid

Each generator is equipped with an excitation and governor to control the terminal voltage and rotating speed, respectively. Two modifications are made to the original 9-bus system to facilitate the test: (1) Synchronous Generator 3 is divided into three small generators, and the wind power plant (WPP) is connected to Bus 4 where Load 1 is located; (2) the capacity of the entire power system is reduced to accommodate the capacity of the WPP to illustrate the frequency regulation effects. The capacity of a single PMSG-WTG is 2 MW and the WPP consists of 20 identical PMSG-WTGs, so the total capacity of the WPP is 40 MW. The droop coefficient for all of the synchronous generators is set to be 5%, and the inertia constant ranges from 4 s to 6s. The parameters for the test grid, PMSG, and wind turbine can be found in the appendix and references [7], [9].



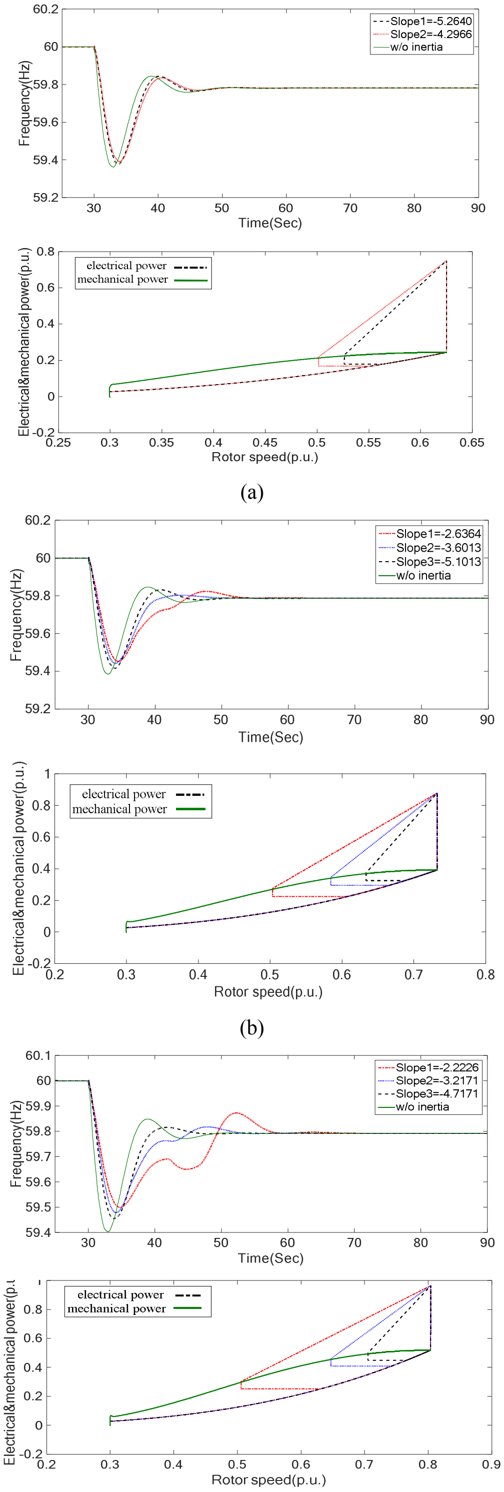
(a). Rotor speed



(b). Active power output

Fig.4 Rotor speed and active power dynamic of a single PMSG-WTG

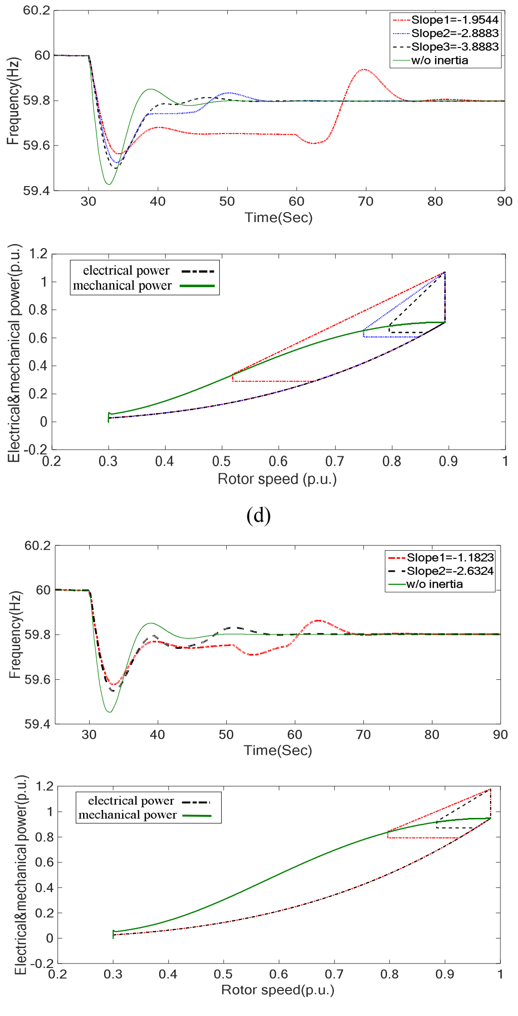
SG33 is tripped off at 30 s, then the system frequency drops, and the inertial response of the WPP is activated when the frequency excursion exceeds the dead-band (0.05 Hz). Assume that the wind speed remains constant for each case study, with different wind speed conditions for each case study. Figs. 4 (a) and 4 (b) show the rotor speed and active power output of a single PMSG-WTG when the wind speed is 11 m/s. As shown, the rotor speed and active power output are regulated according to the proposed control method.



(a)

(b)

(c)



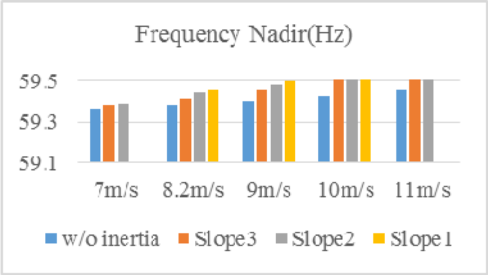
(d)

(e)

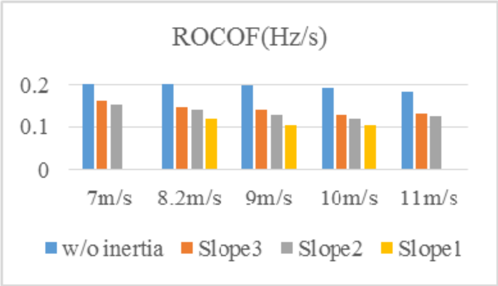
Fig. 5. Frequency profile and power-speed characteristics under different wind conditions (a: 7 m/s, b: 8.2 m/s, c: 9 m/s, d: 10 m/s, e: 11m/s)

The slope values in the power-speed trajectory of the deceleration process impacts the performance of the inertial response. This phenomenon is testified under different wind speed conditions: 7 m/s, 8.2 m/s, 9 m/s, 10 m/s, and 11 m/s. The frequency dynamics and power-speed characters under different wind speed conditions are presented in Fig.5. Note that the red dotted-dashed line corresponds to the gradual slope, and the black dashed line corresponds to the steep slope. The blue dotted line refers to the slope in the middle.

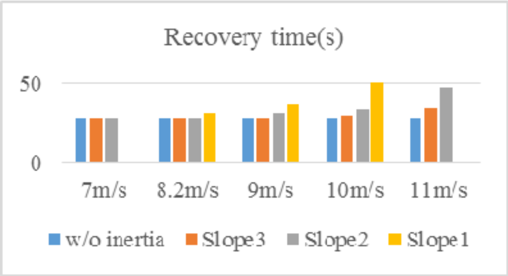
The FN, ROCOF, and recovery time are selected as metrics for different scenarios. Note that the duration from the beginning of the event to the time that the system frequency settles down (rotor speed is stabilized at Point A) is defined as the recovery time. The comparison results are presented in Fig. 6. The inertial response improves the FN and restricts the ROCOF in the meantime. The improvement of the FN reduces the probability of a disconnection from the grid due to tripped under-frequency relay protection. The final frequency is not fully recovered to the pre-fault value because of the linear nature of the droop control of the remaining synchronous generators and because AGC is not implemented in the model system. In addition, the recovery time tends to be longer when the slope changes from steep to gradual. The extension of the recovery time is undesirable because it delays the quasi-stable frequency stage, and AGC takes over even later to eliminate the frequency deviation from the nominal value. This torque-limit-based inertial response exploits the maximum frequency support capability of the PMSG-WTG and the released energy is considerable throughout this duration, especially when the rotor speed reaches the minimum possible value along the gradual slope. However, the recovery time is extended a lot with this gradual slope, which is obvious in high wind conditions, as shown in Figs. 5 (d) and 5 (e). As a result, there is a trade-off between the FN (ROCOF) and recovery time. The selection of slopes should be thoroughly considered with respect to the power system configuration and acceptable ranges of recovery time.



(a). Frequency nadir



(b). ROCOF



(c). Recovery time

Fig. 6. Comparison of FN, ROCOF and recovery time with different slope values

V. CONCLUSION AND FUTURE WORK

This paper presents a novel inertial control method for a PMSG-WTG that improves its frequency support capability by taking into account the torque limit of the WTG. The effectiveness of the proposed scheme is verified in a WSCC nine-bus grid modeled in MATLAB/Simulink. The impact of different slope values in a power-speed trajectory is evaluated in terms of the FN, ROCOF, and recovery time. The results indicate a trade-off among the performance metrics, and they provide insight into designing such kinds of inertial control strategies. However, this paper does not study the quantitative relationship among the slope values and the three metrics; this is a topic for future research. Further, the proposed method will be tested in a power-hardware-in-the-loop (PHIL) platform to validate the performance of real systems. The difference between the simulation and a real turbine’s response will be investigated later on. The ramp-rate capability of the actual turbine may be lower than the expected simulated results; and a communication delay exists between commanded signal and the actual signal received at the turbine, which may influence the control performance in reality.

VI. APPENDIX

A. Parameters of the Nine-Bus System [9]

	Rated Capacity (MVA)	Rated voltage (kV)	Inertial Constant (s)	Tdo’(s)	Tdo”(s)	Tqo’(s)	Tqo”(s)
SG1	200	16.5	6.64	8.96	0.12	-	0.95
SG2	80	18	5.31	8.0	0.03	1.0	0.07
SG31	30	13.8	4.01	8.0	0.03	1.0	0.07
SG32	30	13.8	4.01	8.0	0.03	1.0	0.07
SG33	40	13.8	4.01	8.0	0.03	1.0	0.07

B. Parameters of the WPP [7]

Rated Voltage	690V
Rated Power	2MW
Rated rotor speed (GEN)	22.5 rpm
Np	26
Rated Torque	848.826kN.m
Diameter of Blades	78.52m
Rated Wind Speed	11.2m/s
Rated rotor speed (WT)	2.32rad/s
Air Density	1.225kg/m3
Cp,max	0.48
λ_{opt}	8.1

c1 = 0.5176, c2 = 116, c3 = 0.4, c4 = 5, c5 = 21 and c6 = 0.0068 [11]

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