Structure and Control Strategy of a New Wind Turbine Concept with Power Split

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Contents

1 Abstract

In this paper, a new wind turbine concept with power split is presented in order to down scale of the power electronic devices of the wind turbine. When compared to the existing wind turbines, the introduced wind turbine concept is suitable to improve the utilization of the wind power for the large scale wind turbine. The power split of the wind turbine is realized by a planetary gearbox. Besides a main synchronous generator, a servo machine with small scale converter is implemented for the optimum wind power extraction. The control scheme including a pitch controller and a speed controller of the planetary gearbox for the wind turbine with power split is proposed. The simulation validates the performance of the proposed structure and control of the wind turbine.

2 Introduction and Motivation

The dominant wind turbines in the wind energy market have either technical or economical difficulties for the large scale wind turbine. The crucial shortage of the Doubly Fed Wind Turbine is the mechanical constraint due to the small air gap of the induction generator. The wind turbine with Permanent Magnet Synchronous Generator needs a full scale power converter to achieve the variable speed operation, which results in large size, high weight and cost [COLL12].

In order to overcome the shortages in the existing wind turbines, a novel wind turbine with power split is proposed in [CASE20] and [RUI08]. The structure of the wind turbine with a standard planetary gearbox, which has a sun gear, a ring gear and a carrier, is utilized. The main shaft of the wind turbine, a synchronous generator and a servo machine are connected to the three terminals of the planetary gear box so that the captured wind power can be split and delivered to the synchronous generator and the servo machine. The synchronous generator, which produces most of the electrical power of the wind turbine, is connected to the power grid directly, without any power electronic devices. A servo machine, which is implemented as the actuator of the planetary gearbox, is connected to the power grid with a small scale converter.

In [Liu13], it is shown that for 6 different variants of the wind turbine with a standard planetary gearbox, the nominal power of the servo machine and the converter can be less than 10% of the nominal power of the wind turbine, which is significantly smaller when compared to the one of the wind turbines with DFIG (25%-30%) and with PMSG (100%). Therefore, the cost and the size of the converter and the grid side filter for the wind turbine with power split can be reduced significantly. It results in less high order harmonics in the power grid and less cooling efforts for the converter. On the other hand, since a voltage or reactive power controller such as Automatic Voltage Regulator (AVR) can be applied to the synchronous generator, the controllability and power quality of the wind turbine with power split can be improved.

In this paper, in order to increase the efficiency of the planetary gearbox and to avoid the fast rotation of the ring gear of the standard planetary gearbox, a specific plus planetary gearbox with two sun gears is developed. A switchable standard planetary gearbox with two gear ratios is embedded into the plus planetary to reduce the torque level of the servo machine for high wind speed. A proper control scheme including a sliding mode speed controller of the servo machine and a pitch controller is implemented to achieve a high performance for the wind turbine. The simulation results validate the feasibility of the proposed wind turbine with power split.

3 Structure and Model of the proposed wind turbine

In [Liu13], it is shown, that when the optimum power split is expected, an excellent field weakening capability of the servo machine is required for the wind turbine with power split. In order to loose the requirement of the torque-speed characteristics of the servo machine, a wind turbine includes a plus planetary gearbox and a switchable Two-Mode gearbox is proposed and shown in Figure 1. With the Two-Mode gearbox, suitable torque-speed characteristics of the servo machine can be obtained for the design.

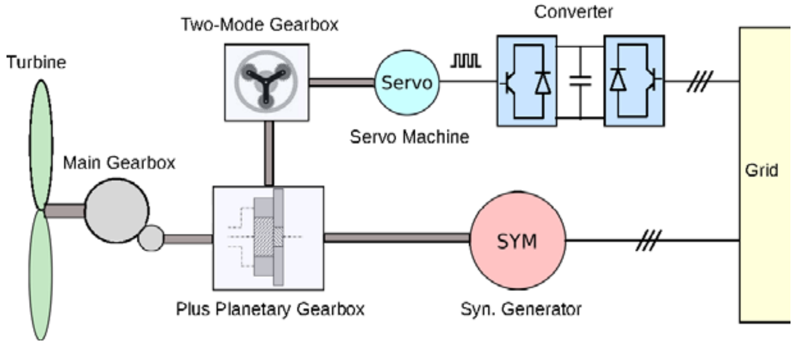

Figure 1: Structure of the wind turbine with a standard planetary gearbox.

3.1 Structure of the plus planetary gearbox

The mechanical structure of the plus planetary gearbox is shown in Figure 2. When compared to the standard planetary gearbox, the ring gear is removed from the plus planetary gearbox. Instead, the planet gears which have two parts with different radius are actuated by the carrier. Two sun gears are coupled with the planet gears at different radius, which realizes the power split of the plus planetary gearbox.

The plus planetary gearbox has two advantages when compared to the standard planetary gearbox. In the standard planetary gearbox, the free running ring gear results in relatively high friction losses due to friction between the ring gear and the lubricating oil, which also burdens the cooling system. In the plus planetary gear box, the contact area between the rotational part and the lubricating oil is significantly reduced so that the efficiency of the gearbox can be improved. The other advantage of the plus planetary gearbox is the mountability of the sun gears and the planet gears.

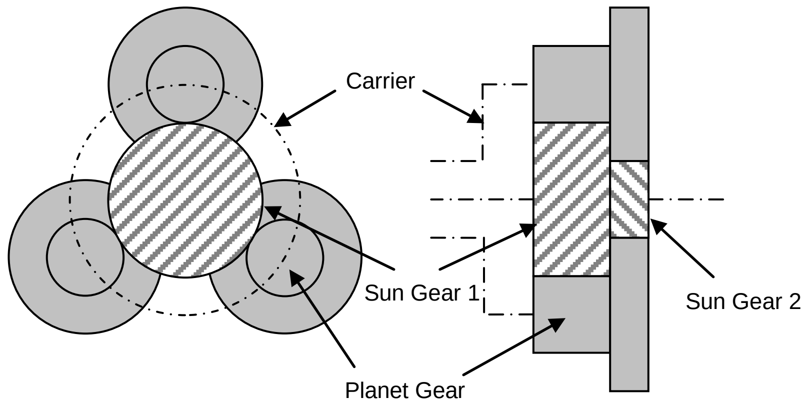

Figure 2: Structure of the plus planetary gearbox.

The mathematical model of a standard planetary gearbox is shown in [LEE12]. For the plus planetary gearbox, the second sun gear achieves the same functionality as the ring gear in the standard planetary gearbox. Therefore, similar differential equations can be utilized to describe the transient behavior of the plus planetary gearbox:

$$\frac{d\omega_{sun1}}{dt} = -k_{11}\omega_{sun1} - k_{12}\omega_{sun2} + a_{11}T_{sun1} + a_{12}T_{sun2} + a_{13}T_{carrier}$$
$$\frac{d\omega_{sun2}}{dt} = -k_{21}\omega_{sun1} - k_{22}\omega_{sun2} + a_{21}T_{sun1} + a_{22}T_{sun2} + a_{23}T_{carrier} \quad \textbf{Eq. 1}$$

$$(1 - g_0)\omega_{sun1} = \omega_{sun2} - g_0\omega_{carrier} \quad \textbf{Eq. 2}$$

where the parameter $k_{ij} \geq 0$ denotes the friction coefficient of the gears; the parameter a_{ij} denotes the inertia coefficient of the plus planetary gearbox; g_0 is a parameter containing the information of the gear ratio, which fulfills $g_0 < -1$. The steady state torque of the plus planetary gearbox can be described by the simplified algebraic equations:

$$T_{carrier} = \frac{g_0}{1-g_0}T_{sun1}, \ T_{sun2} = -\frac{1}{1-g_0}T_{sun1} \quad \textbf{Eq. 3}$$

Eq.2 and eq.3 show that the steady state model of the plus planetary gearbox has the same form as the standard planetary gearbox, which is shown in [LIU13]. The sun gear 1, sun gear 2 and the carrier of the plus planetary gearbox are equivalent to the carrier, sun gear and the ring gear of the standard planetary gearbox respectively. Therefore, the conclusions of the optimal power split in [LIU13] still holds for the wind turbine with a plus planetary gearbox. With the optimum power split, the nominal power of the servo machine and the converter is less than 10% of the nominal power of the turbine.

3.2 The Two-Mode Gearbox

For the wind turbine discussed in this paper, it is designed that the main shaft is connected to the sun gear 1. The synchronous generator is connected to the sun gear 2 and the servo machine is connected to the carrier. According to eq.3, the torque of the servo machine is larger than half of the torque of the main shaft. High torque level of the servo machine results in large size and high cost. To reduce the torque level and adjust the operating range of the servo machine, a switchable two-mode gearbox is introduced. Figure 3 shows the topology for two possible structures of a two-mode gearbox, which are realized by the standard planetary gearbox. In the figure, z_H and z_S stand for the number of teeth for the ring gear and sun gear respectively. The topology shown by Figure 3 (a) has a simpler structure. However, in the case of small gear ratio, the planet gears in the gear box have small radius. Large shafts are required to sustain the torque on the planet gears, which increases the cost and complexity. In this paper, the structure shown by Figure 3 (b) is utilized.

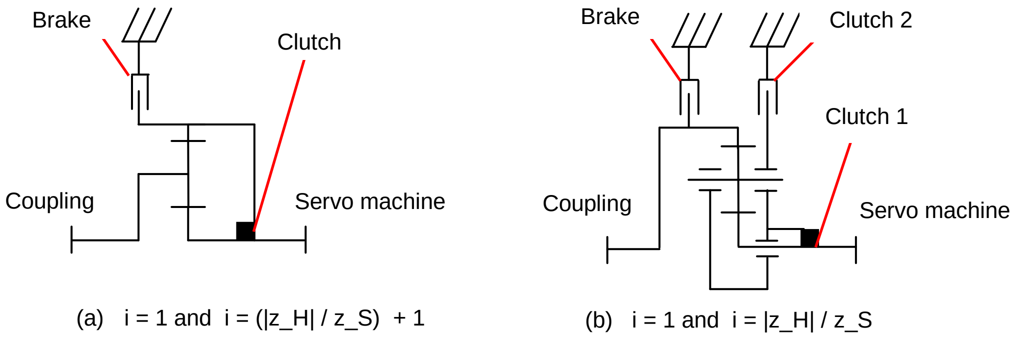

Figure 3: Structure of the switchable Two-Mode gearbox: (a) for large gear ratio; (b) for small gear ratio

The switching of the Two-Mode gearbox takes place when the rotational speed of the servo machine is crossing zero. For the Two-Mode gearbox shown by Figure 3 (b), in normal operation, when clutch 1 is open and clutch 2 is closed, the gear ratio of the Two-Mode gear box is i = 1. On the other hand, when clutch 1 is closed and clutch 2 is open, the gear ratio is i = z_H/z_S.

4 Control strategy of the proposed wind turbine

As shown in Figure 2 and Figure 3, the mechanical structure of the proposed wind turbine is more complicated when compared to existing wind turbines. For a proper operation, a control strategy is needed to ensure the performance of the wind turbine. The controllers for the proposed wind turbine include the pitch controller, the speed controller of the main shaft and the grid side controller of the back-to-back converter. The pitch controller and the speed controller are designed to guarantee the performance of the wind turbine with power split and will be shown in this section. The grid side controller of the converter is utilized in the same way as the one of the conventional wind turbine, which can be found in several literatures [GHE09] [TRE06]. The functionality of the pitch controller and the speed controller is to capture the optimum power from the wind and to protect the turbine from overspeed. For the conventional wind turbines, the optimum wind power extraction can be achieved by two different methods. One is the speed controller of the main shaft to keep the turbine at the optimum tip speed ratio [PER08]. The other is the torque or power controller by using the pre-calculated torque curve for the generator [YUA14] [SLO01]. For the wind turbine with power split, the control is realized by the servo machine. Due to the complexity of the plus planetary gearbox and the Two-Mode planetary gearbox, it is costly to pre-define the optimum operating curve of the servo machine. Therefore, a speed controller for the main shaft and the synchronous generator is chosen for the servo machine. The pitch controller is a combined controller to limit the maximum torque of the turbine.

4.1 Pitch controller

Basically, two categories of pitch controllers can be found in the literature: one is the speed controlled pitch controller [SLO01] [LEI08]; the other is the power controlled pitch controller [SEN06]. For the proposed wind turbine, a speed controller for the main shaft is implemented on the servo machine. Therefore, the speed controlled pitch controller has redundancy with the speed controller of the servo machine in the high wind speed range. With this redundancy, it is possible that the pitch angle converges to a wrong value, which results in the displacement between the optimum and real active power. Therefore, the power based pitch controller is implemented in this paper.

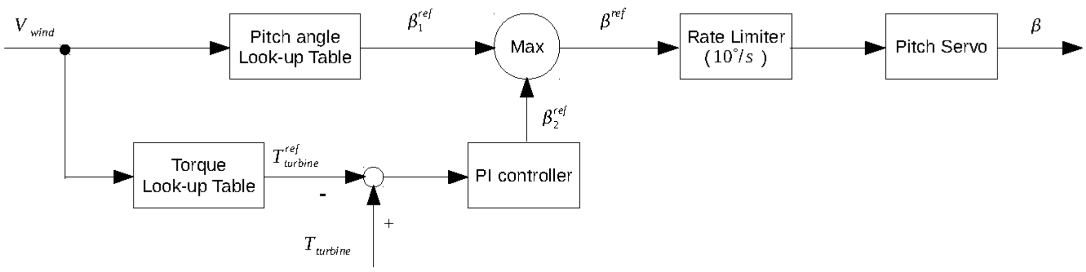

Figure 4: Pitch controller for the wind turbine with power split.

The structure of the pitch controller is shown by Figure 4, which includes a pitch angle look-up table and a torque control. The reference pitch angle β_1^{ref} is obtained by the corresponding power coefficient c_p^{ref} for the pre-defined power curve. The look-up table for the reference pitch angle β_1^{ref} is to guarantee the performance of the wind turbine when the wind speed varies smoothly. The reference pitch angle β_2^{ref} is obtained by a PI controller operating the error of the reference and real torque of the turbine. The reference torque $T_{turbine}^{ref}$ of the turbine is calculated from the pre-defined power curve of the turbine. During the wind gust, particularly in the high power region of the wind turbine, the sudden increment of the captured wind power results in high torque and unexpected acceleration for the turbine. If the pitch angle does not react fast enough, it is possible that the torque of the turbine runs beyond the controllable range of the servo machine, which leads to failure or destruction of the wind turbine. Therefore, a PI controller for β_2^{ref} is designed with fast dynamic to prevent the turbine from sudden massive torque increment during the wind gust.

4.2 Controller implemented on the servo machine

The servo machine is the unique control unit of the active power besides the pitch controller in the wind turbine with power split. Two objectives have to be achieved by the controller of the wind turbine. One is the synchronization of the synchronous generator since it is connected to the power grid directly. The other is to ensure that the turbine follows the pre-defined power curve. For the proposed wind turbine, according to the mathematical model of the plus planetary gearbox (1), the model for the controller design of the servo machine can be described by the following equations:

$$\frac{d\omega_s}{dt} = -k_{11}\omega_s - k_{12}\omega_{syn} + a_{11}T_s + a_{12}T_{syn} + g(\omega_{servo})a_{13}T_{servo}$$
$$\frac{d\omega_{syn}}{dt} = -k_{21}\omega_s - k_{22}\omega_{syn} + a_{21}T_s + a_{22}T_{syn} + g(\omega_{servo})a_{23}T_{servo} \qquad \textbf{Eq. 4}$$

The subscripts *t*, *syn* and *servo* present the quantities of the shaft, synchronous generator and the servo machine respectively. $g(\omega_{servo})$ is a function denoting the switching of the Two-Mode gearbox: $g(\omega_{servo}) = 1$ for $\omega_{servo} < 0$ and $g(\omega_{servo}) = Z_H/Z_S$ otherwise.

The synchronous generator itself is stable for the transient operation and can recover synchronism when the mechanical power does not exceed its maximum pull down power of the synchronous generator [MAC11]. In the proposed wind turbine, the massive increment of the mechanical power is prevented by the pitch controller, which ensures the transient power within the recovery region for the synchronism of the synchronous generator. On the other hand, the tracking of the pre-defined power curve for the turbine is achieved by the servo machine, which guarantees that the mechanical power delivered to the synchronous generator within its stable region. Therefore, only the tracking of the pre-defined power curve for the turbine has to be considered for the controller design of the servo machine.

The tracking of the pre-defined reference power for the turbine is realized by the speed control for the main shaft since the captured wind power is determined by the speed of the turbine as well as the speed of the main shaft. In order to obtain the control law, the first equation in eq.4 is considered. In the real system, it is difficult to obtain the precise parameters such as the inertia and friction coefficient for the plus planetary and Two-Mode gearboxes. Besides, the switching of the Two-Mode gearbox is not ideal but with unexpected delay or nonlinear procedure. Therefore, the first equation in eq.4 is transformed into the following form:

$$\frac{d\omega_s}{dt} = -k_{11}^*\omega_s + g(\omega_{servo})a_{13}^*T_{servo} + T_d \qquad \textbf{Eq. 5}$$

where the coefficients with superscript * denote the nominal values of the corresponding inertia and friction coefficients. T_d is a general disturbance which includes the torques from the main shaft and synchronous generator, the dynamics caused by the parameter error and the unmodeled transient dynamics. In order to achieve a fast dynamic and robust performance for the wind turbine, the well known sliding mode control [SLO91] [ZHA00] is introduced for the speed control. The sliding plane is defined by the following equation:

$$s = (\omega_s^* - \omega_s) + c\int(\omega_s^* - \omega_s)\,dt \qquad \textbf{Eq. 6}$$

where ω_s^* is the reference speed of the main shaft and *c* is a positive settable constant. Since T_d is the disturbance from the mechanical system, it should be bounded by a maximum value T_d^{max} so that $|T_d| < T_d^{max}$. To obtain the control law, the Lyapunov function $V = 0.5s^2$ is considered. If the torque of the servo machine is controlled to:

$$T_{servo} = sign(s)\frac{T_d^{max}}{g(\omega_{servo})a_{13}^*} + \frac{k_{11}^*\omega_s}{g(\omega_{servo})a_{13}^*} + \frac{c(\omega_s^* - \omega_s)}{g(\omega_{servo})a_{13}^*}$$ **Eq. 7**

the derivative of the Lyapunov function can be described as:

$$\frac{dV}{dt} = s(-sign(s)T_d^{max} - T_d) \leq 0$$ **Eq. 8**

Therefore, the plane s converges asymptotically to 0. On the other hand, according to eq.6, $s = 0$ indicates $\omega_s^* = \omega_s$. The speed of the main shaft converges asymptotically to its reference value. For the continuous operation, the torque of the servo machine is limited by its maximum torque. In order to reach the full utilization of the servo machine to obtain the fastest dynamic of the speed control and to avoid the chattering effect of the sliding mode control, a continuous approximation is applied to the discrete describing function $sign(s)$ [SLO91], which is described by the following equation:

$$T_{servo} = \begin{cases} sign(s)\frac{|s|}{\sigma}T_{servo}^{max} & for\ |s| < \sigma \\ sign(s)T_{servo}^{max} & for\ |s| \geq \sigma \end{cases}$$ **Eq. 9**

5 Simulation results

The simulation of the wind turbine with a rated power of $P_t^{rated} = 2.2$ MW is used to validate the proposed structure and control. The cut-in and cut-off wind speeds are 4 m/s and 20 m/s, respectively. The rated wind speed is 12 m/s. The synchronous speed of the synchronous generator is 1500 rpm. The servo machine has a rated torque of 1800 Nm and a maximum speed of 2500 rpm. The simulation of the proposed wind turbine with the mentioned control strategy is implemented in Matlab/Simulink.

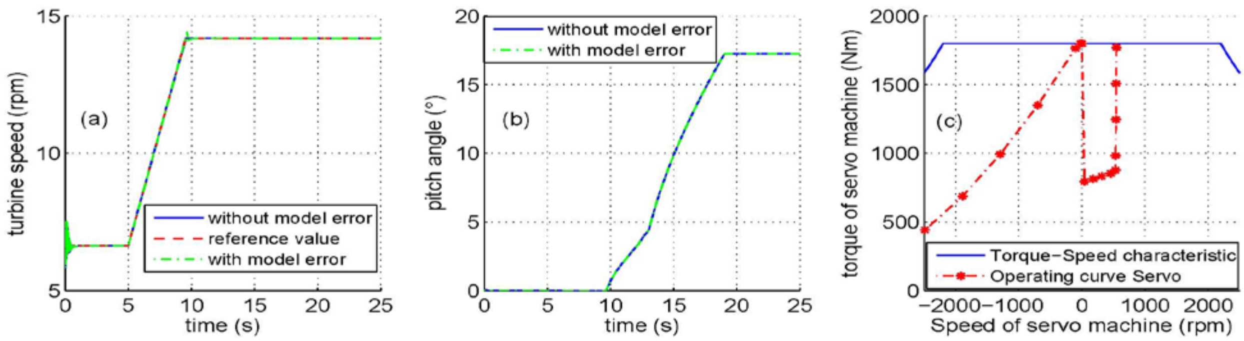

Figure 5: Simulation results: (a) turbine speed (b) pitch angle (c) operating curve of the servo machine.

The first simulation is made when the wind speed increases from 4 m/s to 18 m/s. The solid blue curves in Figure 5 (a) and (b) show the main shaft speed and the pitch angle. The dashed green curves show the results under model error that the switching of the Two-Mode gearbox has 0.5s delay and the nominal inertia is only half of the real one ($a_{13}^* = 0.5a_{13}$). It can be noticed, the simulation results for with and without model error behave almost in the same way. The speed of the main shaft tracks its reference value very well so that the tracking of the reference power curve of the turbine is realized. The simulation result for the operating curve of the servo machine is shown in Figure 5 (c). It can be noticed that the torque level of the servo machine is reduced to a proper range due to the switching of the Two-Mode gearbox. The maximum power delivered to the servo machine is approximately 5% of the rated power of the turbine.

Figure 6 shows the simulation results for the time variant wind speed. The wind speed for the simulation varies from 4 m/s to 16 m/s with wind gust. It can be noticed that the power and the speed of the turbine can be limited within their rated values. The speed of the turbine tracks its reference value well so that the capture of optimum wind power is realized. The frequency of the synchronous generator oscillates slightly around 50 Hz, so that the synchronization is also guaranteed. The torque and the speed of the servo machine are within their designed limitations. During the transient process, the servo machine is operating with the continuous operating mode.

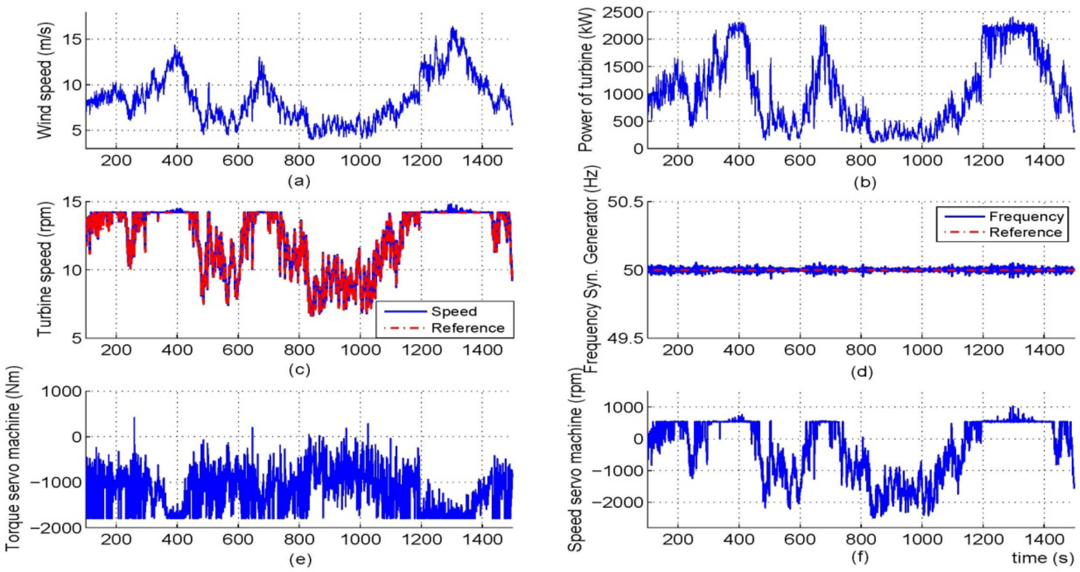

Figure 6: Simulation results for time variant wind speed: (a) wind speed; (b) power of turbine; (c) turbine speed; (d) frequency of syn. generator; (e) torque of servo machine; (f) speed of servo machine.

6 Conclusions

In this paper, a structure and the control strategy of a novel wind turbine with power split is proposed to reduce the size of the power electronic converter. To improve the efficiency of the wind turbine, a plus planetary gearbox is introduced instead of the standard planetary gearbox. To reduce the operating torque and to loose the requirement of the field weakening capability for the servo machine, a switchable Two-Mode gearbox is introduced. The control strategy is designed to fit for the structure of the proposed wind turbine. A sliding mode controller for the speed of the main shaft is implemented on the servo machine. With the sliding mode controller, the system disturbance such as inaccurate inertia and switching delay of the Two-Mode gearbox can be tolerated and the fast dynamic performance can be achieved for the proposed wind turbine. The pitch controller is designed to guarantee the wind power extraction for both smooth wind speed and wind gust. The simulation results show a good performance of the wind turbine with proposed structure and control strategy.

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