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A study of a novel wind turbine concept with power split gearbox

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Abstract — This paper focuses on the design and control of a new concept for wind turbines with a planetary gearbox to realize a power split. This concept, where the generated wind power is split into two parts, is to increase the utilization of the wind power and may be particularly suitable for large scale off-shore wind turbines. In order to reduce the cost of the power electronic devices, a synchronous generator, which is driven by the ring gear, is directly connected to the power grid without electronic converter. A servo drive, which functions as the control actuator is connected to the power grid by a power electronic converter. The speed of the main shaft is controlled to track the optimal tip speed ratio. Meanwhile the speed of the synchronous generator is controlled to stay at the synchronous speed. The minimum rated power of the servo motor, which is also the rated power of the converter, is studied and discussed in this paper. The controller for optimal tip speed ratio and synchronous speed tracking is given.

I. INTRODUCTION

To improve the utilization of the wind energy, in the last several years the size and capacity of a single wind turbine grow rapidly (5MW to 10MW) for off-shore application. Currently in the wind energy market, the wind turbines with doubly fed induction generator (DFIG) and with direct drive synchronous generator are the most popular small and mid scale wind turbines. However, both of them have technical or economical difficulties for the application on large scale wind turbines. The crucial aspect of the DFIG wind turbines is the small air gap of the DFIG due to mechanical considerations [2]. Meanwhile, the required power level of the converter for the DFIG wind turbine is about 25% to 30% of the rated power of the wind turbine. On the other hand, the direct drive wind turbines require full scale power electronics, which results in large size, high weight and cost [2].

Besides the machine types, to reduce the cost and the weight of the wind turbine, different gearboxes are studied and implemented. The planetary gearbox is recommended due to its high torque to weight ratio, low backlash, improved efficiency and high resistance to shock [4]. Another advantage of the planetary gearbox is its degree of freedom between the speed of the sun, ring and carrier compared to the standard gearbox. The power splitting of the planetary gearbox and its freedom of speed have been widely used in vehicles and robotics [5-7]. It is possible that one of the terminals can rotate with a constant speed while the other two are well controlled.

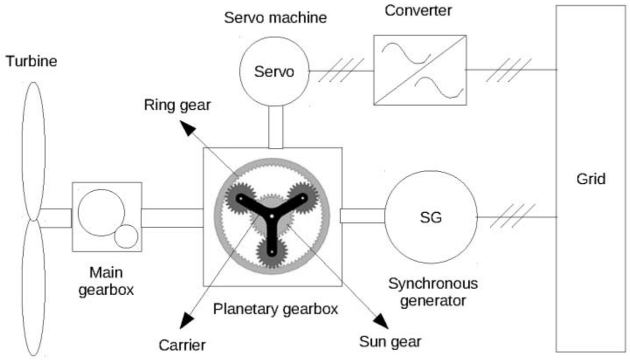

Fig. 1: An example structure of a wind turbine with planetary gearbox.

With this idea, a new concept of the wind turbine with a planetary gearbox is proposed in [1] [3]. Fig.1 shows the structure of the wind turbine. The turbine is connected to a main gearbox. A synchronous generator is connected to the planetary gear box and directly to the power grid without any power electronic devices; a servo machine is working as the control actuator of the planetary gearbox, which is connected to the power grid with a converter. The main benefit of this structure is the requirement of a small scale converter for the servo machine. Another aspect is that the avoidance of the slip-ring reduces the failure rates of the wind turbine when compared to DFIG wind turbines. The optimal tip speed ratio of the turbine and the synchronous speed of the synchronous generator can be achieved by the controlling of the servo machine. In [1], the general operation of the wind turbine with power splitting device and the model of the planetary gear box are shown. However, the control of this wind turbine and the validation of the feasibility are not discussed. Some analysis of this wind turbine and an example controller are described in [3]. However, the configuration of the wind turbine is not considered for the operation. Moreover, the transient behavior of the synchronous generator is not shown and discussed there.

In this paper, the minimum rated power of the servo machine and the configuration of the gearboxes to achieve the functionality of the optimal tip speed ratio and the synchronous speed tracking are discussed. Due to the producibility limitation of the gear ratio of the gearboxes, three parameters are considered for the variation of the wind turbine: the gear ratio of the main and planetary gearboxes and

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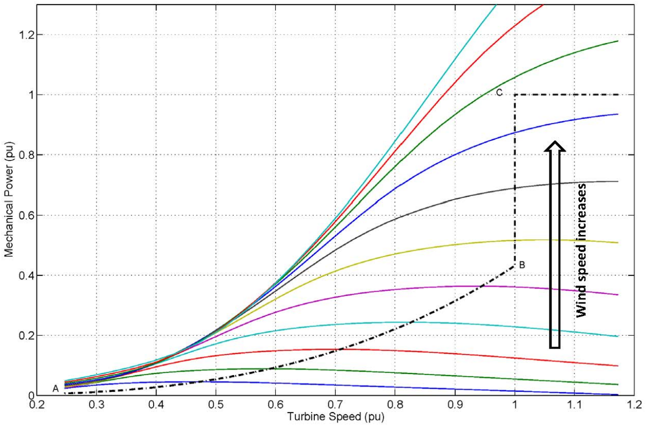

Fig. 2: Power curve of an example variable speed wind turbine.

the speed range of the main shaft. The simulation structure and the controller of the servo machine are also presented to verify the optimal wind power extraction and the frequency variation of the synchronous generator.

II. WIND ENERGY AND POWER CURVE

One of the key points of the wind turbines is to obtain more kinetic energy from the wind. The extracted wind power can be presented by the following equation [8]:

$$P_{mech} = \frac{\rho}{2} C_p(\lambda,\beta) A_t V_w^3 \tag{1}$$

where ρ is the air density; A_t is the area covered by the turbine rotor; V_w is the wind speed; C_p is the power coefficient which is a function of the tip speed ratio λ and the pitch angle β. The description of the power coefficient is discussed in several literatures [8] [10]. The optimal value $C_p^{\max}$ of the power coefficient is reached when the tip speed ratio is a constant. In order to generate the optimal energy from the wind, the turbine speed has to be controlled to keep the tip speed ratio a constant (optimal value).

To extract more power out of the wind, it is preferred that the wind turbine stays at the optimal tip speed ratio in a wide speed range. The mechanical power curve of a wind turbine is shown in [9] [10]. An example power curve of a variable speed wind turbine is shown in fig.2. The curves with wind speed 4m/s to 14m/s show the power which can be obtained from the wind at different wind speed and turbine speed. The slashed curve shows the actual wind power delivered to the wind turbine. When the turbine speed is below its maximum speed (curve A to B in fig.2), the wind turbine is operating in the optimal power region where the tip speed ratio is controlled to its optimal value. When the turbine speed reaches its maximum value and the wind speed still increases, the turbine speed is controlled to stay at its maximum value and the extracted wind power increases until the rated power is reached (curve B to C in fig.2).

III. POWER SPLITTING OF THE WIND TURBINE

The power splitting of the wind turbine is achieved by the planetary gearbox, which has three terminals: sun, ring and carrier. For the novel concept of power split wind turbine, the turbine, synchronous generator and servo machine can be connected to each of these three terminals respectively. Therefore, there are 6 different variants. Since the analysis for these 6 variants are similar, without loss of generality, we take the variant shown in fig.1 as an example: the main shaft is connected to the carrier; the synchronous generator is connected to the ring gear and the servo machine is connected to the sun gear.

To analyze the power level of the servo machine, the stationary model is chosen in this section, which can be found in literature [1] [3]. The constraints of the speed and torque for a planetary gearbox are shown below:

$$(1-i_0)\omega_c = \omega_s - i_0\omega_r \tag{2}$$

$$T_s = -\frac{1}{1-i_0} T_c \tag{3}$$

$$T_r = \frac{i_0}{1-i_0} T_c \tag{4}$$

where ω and T are the rotational speed and torque and the subscript s, r and c present the sun, ring and carrier respectively. i_0 is the gear ratio between the ring gear and sun gear, which is defined as:

$$i_0 = -\frac{Z_r}{Z_s} \tag{5}$$

where Z_r and Z_s are the radius of the ring and sun gear respectively. Therefore, the value of $i_0 < -1$.

In order to investigate the minimum rated power of the servo machine, in this paper the losses of the gearboxes are neglected and the steady state characteristics are considered. First, some parameters are defined:

- Synchronous speed ω_1, which is the synchronous speed of the synchronous generator.
- The gear ratio of the main gearbox xG_0. Here G_0 is a constant so that the maximum speed of the turbine can be transformed to the synchronous speed ω_1 at the main shaft. x is a variable scale to be determined.
- $\Delta\omega$ is the normalized speed variation of the main shaft, where the base value is the synchronous speed.

With the parameters, the main shaft speed, which is also the carrier speed, can be rewritten as:

$$\omega_c = x\omega_1(1+\Delta\omega) \tag{6}$$

with $\Delta\omega \in (-1,0]$. Therefore, the extracted wind power from equation (1) can be rewritten as:

$$P_c = K(\lambda,C_p)(\frac{\omega_c}{x})^3 = K(\lambda,C_p)[\omega_1(1+\Delta\omega)]^3 \tag{7}$$

here $K(\lambda,C_p)$ is a function of the tip speed ratio λ and power coefficient C_p. As shown in the previous section, due to the operated power curve of the wind turbine, the optimal power coefficient and tip speed ratio can be realized when the turbine speed is less than its maximum value (curve A to B in fig.2). Therefore, the coefficient $K(\lambda,C_p)$ is a constant K_0 in this situation. Using (7), it is easily to know that the mechanical power delivered to carrier is:

$$P_c = K_0\left[\omega_1(1+\Delta\omega)\right]^3 \tag{8}$$

The ring gear is always controlled to rotate at synchronous speed ω_1 under the requirement of the synchronous generator. Using (2) (3) and (8), the mechanical power delivered to the sun gear can be calculated:

$$P_s = -K_0\omega_1^3(1+\Delta\omega)^2\left[(1+\Delta\omega)+\frac{i_0}{x(1-i_0)}\right] \tag{9}$$

When the turbine speed reaches its maximum value and the wind speed still increases, the wind turbine is operating at its rated speed (on the power curve B to C in fig.2). Therefore, the mechanical power delivered to the carrier is expressed as:

$$P_c = K(\omega_1,\lambda,C_p)\omega_1^{\,3} \tag{10}$$

where $K(\omega_1,\lambda,C_p)$ is larger than K_0 and is strictly increasing when the wind speed increases. Denote K_{max} as the maximum value of $K(\omega_1,\lambda,C_p)$, which results in the rated power of the wind turbine. Using (2) (3) and (10) the mechanical power delivered to the sun gear is:

$$P_s = -K(\omega_1,\lambda,C_p)\omega_1^3\left(1+\frac{i_0}{x(1-i_0)}\right) \tag{11}$$

The servo drive can be operated in motor and generator modes. From (9) and (11), it can be noticed that the peak value of the mechanical power of the sun gear depends on the gear ratios of the gearboxes (negative power means generator mode and positive power means motor mode). The optimal mechanical power delivered to the servo machine equals to $\min\{\max\{|P_s|\}\}$. The extreme value of equation (11) is:

$$P_{s1}^{ext} = -K_{\max}\omega_1^3\left(1+\frac{i_0}{x(1-i_0)}\right) = -\left(1+\frac{i_0}{x(1-i_0)}\right)P_{rated} \tag{12}$$

where P_{rated} is the rated power of the turbine. The extreme value of equation (9) is:

$$P_{s2}^{ext} = \frac{4}{27}K_0\omega_1^3\left(\frac{-i_0}{x(1-i_0)}\right)^3 = \frac{4}{27}\frac{K_0}{K_{\max}}\left(\frac{-i_0}{x(1-i_0)}\right)^3 P_{rated} \tag{13}$$

when the following relationship holds:

$$a = \frac{-i_0}{x(1-i_0)} < 1.5 \tag{14}$$

Considering the minimum value $P_{opt} = \min\{\max\{|P_s|\}\}$ with different configurations in (9) to (14): $0 < a < 1$, $1 \le a \le 1.5$ and $a > 1.5$. P_{opt} can be reached in the region $0 < a < 1$ with $P_{opt} = |P_{s1}^{ext}| = |P_{s2}^{ext}|$. Therefore, the optimum configuration also depends on the power characteristic of the turbine, which in details is depending on $b = K_0 / K_{max}$.

The parameter b determines the region of the partial load with optimal tip speed ratio. The larger the b is, the region of the partial load with optimal tip speed ratio is also larger. However, the minimum mechanical power delivered to the servo drive is also larger. For example, when b = 1 holds, the minimum power of the servo machine $P_{opt} = 0.106P_{rated}$ with $a = 0.894$. In another case, when $b = 0.432$ (the power curve shown in fig.(2)), $P_{opt} = 0.054P_{rated}$ with $a = 0.946$.

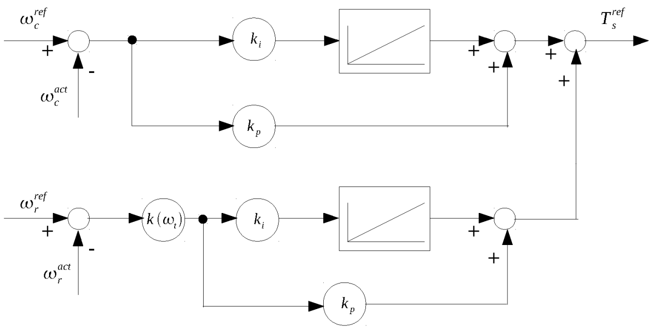

Fig. 3: Time variant parallel controller of the servo machine.

Therefore, a compromise has to be made between the optimal tip speed ratio region and the power level of the servo machine. Since there is still one degree of freedom in the gear ratios of the main and planetary gearboxes to meet the optimum configuration, it is possible that both of the gear ratios lie in the producible range. With the minimum power delivered to the servo machine, the power rating of the converter can be minimized, which results in small size and low cost.

After the parameter a of the gearboxes are determined, from (2) to (6), the speed and torque range of the servo machine can be expressed by the following equations:

$$\omega_s = -i_0\omega_1\left(\frac{1-a}{a}+\frac{1}{a}\Delta\omega\right) \tag{15}$$

$$T_s = -\frac{a}{i_0}T_c^* \tag{16}$$

where T_c^* is the torque when the variable $x = 1$, which is strictly increasing along the power curve. So the rated operating point of the servo machine can be designed at $\Delta\omega=0$. With the determined rated torque, rated speed and speed variation range, a proper machine type can be chosen.

IV. CONTROL OF THE SERVO MACHINE

In the new concept wind turbine, the functionalities of the optimal tip speed ratio tracking and the synchronization of the synchronous generator are realized by the servo machine. A control structure of the servo machine is shown in [3], which is a speed controller of the servo drive. In this paper, the controller of the servo machine consists of a parallel structure of two PI controllers, which can have different gains. One PI controller controls the speed of the main shaft to track the power curve of the turbine. Meanwhile the other controls the speed of the synchronous generator to be synchronous speed.

Fig.3 shows the parallel structure of the controller of the servo machine. The parameters of the power curve controller (lower part) and the synchronous speed controller (upper part) have different gain $k(\omega_t)$, which depends on the turbine speed. At low wind speed, the synchronization of the synchronous generator is much critical than the optimal tip speed ratio tracking, the weighting of the synchronization controller should be larger than the other. The parameters of the controller can also be a variable of the turbine speed. When the turbine speed reaches its maximum value, the gain of the power curve controller can be enlarged to prevent the turbine from accelerating when a wind gust arrives. The performance of the parallel controller will be shown in the next section.

V. SIMULATION RESULTS

The simulation of the power split wind turbine with the proposed configuration and control strategy is implemented in Matlab/Simulink. The simulation structure is shown in Fig.4. The wind turbine is modeled with rated power 855 kW and rated wind speed 16 m/s. The power curve of the turbine is implemented as the curve shown in fig.2. The models of the planetary gearbox and the synchronous generator with 2 pole pairs are utilized from the SimDrive and SimPower toolboxes respectively. According to the optimization of the wind turbine in the previous section (a = 0.946), the configurations of the turbine and rated values of the servo machine are designed and shown in table 1 (with base speed 1500 rpm and base power 855 kW).

In the simulation, the servo machine is chosen as an induction machine whose torque is limited by the given rated torque in table 1 and the field weakening is implemented. The steady state behavior of the wind turbine is first simulated with constant wind speed from 4 m/s to 18 m/s. The speed and power of the sun gear, ring gear and the carrier are shown in fig. 5. It is shown that the speed variation of the sun gear is almost proportional to the speed variation of the carrier with factor i_0. When the wind speed is small, the servo machine is working in motor mode. When the wind speed increases, the servo machine is switched to the generator mode. From the power curves in fig. 5, it is shown that the peak power delivered to the sun gear is 0.054 *pu* in both motor and generator modes, which proves the analysis in the previous sections. It can also be mentioned, with such configurations of the wind turbine, the servo machine has very small rated speed but large speed variation range. So the induction machine is more suitable than the synchronous machine due to its excellent field weakening characteristics.

Fig. 6 shows the power characteristic of the wind turbine depending on the turbine speed. The power curve of the carrier fits the power curve of the turbine shown in fig. 2 yet the maximum power of the sun gear is limited to 0.054 *pu*.

The transient behavior of the mentioned wind turbine with optimal power splitting is investigated by the simulation with time variant wind speed. The wind speed is shown in fig. 7, which is almost from 4 m/s to 18 m/s.

TABLE I

SPECIFICATIONS OF THE WIND TURBINE.

Specification	Value
Ratio of the planetary gearbox i0	-3
Max. speed of the main shaft	0.793 pu
Synchronous speed	1 pu
Max. power of the sun gear	0.054 pu
Rated speed of the servo machine	0.171 pu
Rated Torque of the servo machine	0.315 pu

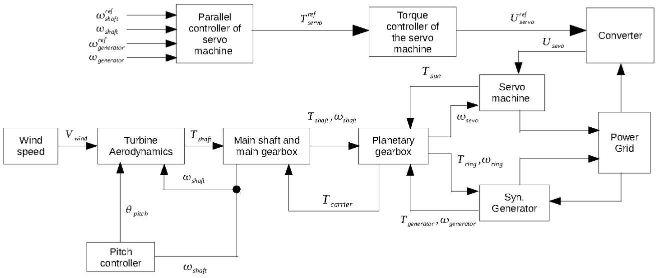

Fig. 4: Simulation structure of the wind turbine with planetary gearbox.

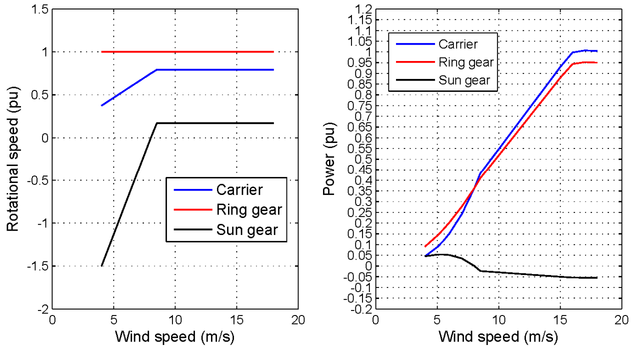

Fig. 5: Simulation results with different wind speed in steady state.

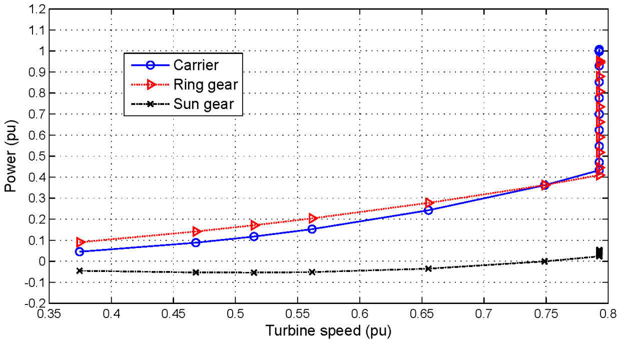

Fig. 6: Simulation results of the power curve.

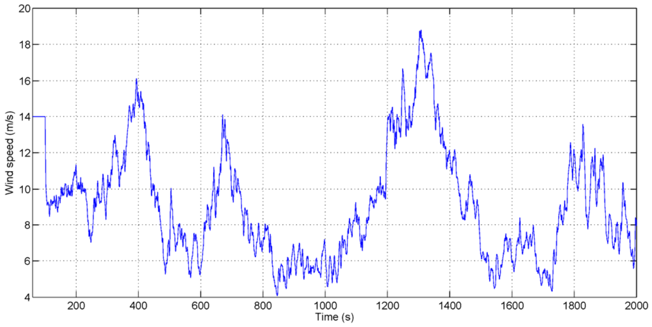

Fig. 7: Wind speed for the simulation.

The study of the optimal tip speed ratio and the synchronous speed tracking are collected in fig. 8. The reference speed of the main shaft according to the power curve in fig. 2 is shown by the red line in fig. 8 on the upper side. The dark and light blue curves show the speed of the main shaft with the constant controller shown in [3] and with the

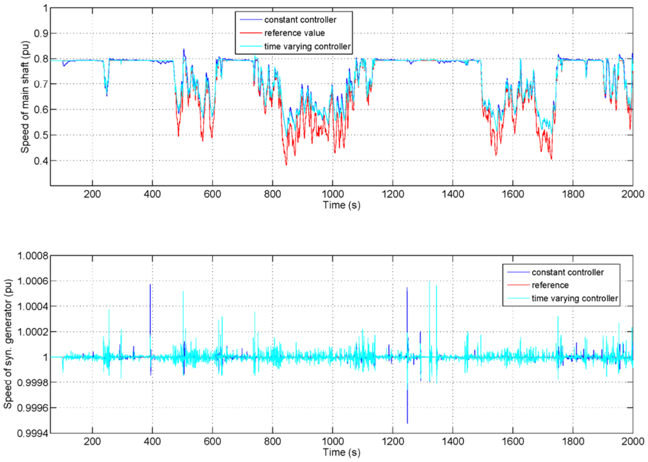

Fig. 8: Speed of the main shaft and the synchronous generator.

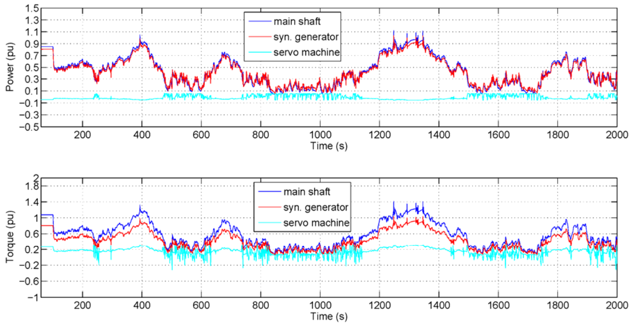

Fig. 9: Power and torque of the wind turbine.

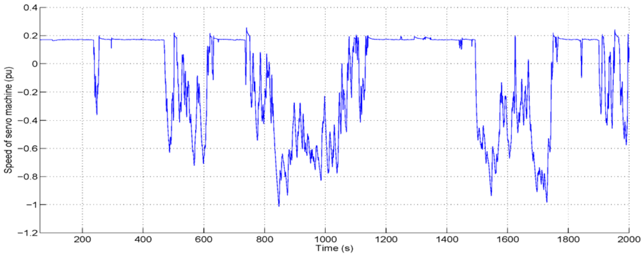

Fig. 10: Speed of the servo machine.

time varying parallel controller described in this paper. It can be noticed that both controllers can track the reference value. At the high wind speed range, the speed of the main shaft has fewer oscillations when controlled by the time varying parallel controller, which is a benefit for the mechanical system. The dark and light blue curves in the figure on the lower side in fig. 8 show the speed of the synchronous generator. It is shown that the speed of the synchronous generator has quite small oscillation for both controllers under strong wind variation. It can be concluded that the wind turbine with optimum power split can track the power curve and the synchronous generator can be directly connected to the power grid.

Fig. 9 shows the simulation results of the power and torque of the main shaft, synchronous generator and the servo machine. The power and torque of the servo machine are limited to the designed rated values. However, the functionality of the wind turbine can still be achieved even when the wind gust comes. Fig. 10 shows the speed variation of the servo machine when the wind changes from 4 m/s to 18 m/s. The speed of the servo machine almost stays at its rated speed when the maximum speed of the main shaft is reached. On the other hand, the speed variation with time variant wind is smaller than it in steady state (in fig. 5) due to the damping of the mechanical inertia. However, the speed variation of the servo machine is very large compared to its rated speed. So the induction machine fits for the servo machine better compared to the PMSM.

VI. CONCLUSIONS

This paper presents the structure of a novel concept wind turbine with a planetary gearbox. The optimum configuration of the wind turbine is studied for the optimum power split, which is also the minimum power rating of the converter required by the servo machine. The torque and speed ranges of the servo machine corresponding to the optimum configuration are given for the design of the servo machine. A time variant parallel controller is discussed in this paper to track the optimum speed ratio and the synchronous speed. The validation of the optimum power split and the speed tracking is demonstrated by the simulation, where the optimum configuration can achieve the mentioned functionality and the time varying parallel controller shows better performances at high wind speed. The speed range of the servo machine is shown, which indicates that, the induction machine has advantages for the servo machine compared to the PMSM.

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