Article

Research of Power Control for Grid-connected Wind Turbine with Differential Speed Regulation

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Abstract: The differential gear train and speed regulating motor constitute the variable ratio transmission for grid-connected wind turbine with differential speed regulation. The synchronous generator in the system can accessing the power grid without frequency converter. The transmission can realize the mode of variable speed constant frequency that the wind rotor speed is varying and the generator rotor speed is constant. The power control method is studied under the different wind speed which is lower or higher than rated wind speed with using the relational expression of utilization rate of wind energy Cp, pitch angle β and the tip speed ratio λ. The SIMULINK software is used to build the 1500 kW wind turbine model with differential speed regulation. Some different wind speed is made as input. The feasibility of power control method for grid-connected wind turbine with differential speed regulation is verified by the comparison between the simulation results and the theoretical value of the key parameters.

Keywords: Grid-connected wind turbine; Differential speed regulation; Power control; Simulation

1. Introduction

The basic scheme of the grid-connected wind turbine using special generators, such as permanent magnet generator and doubly-fed generator, adopts high power frequency conversion device to regulate the wind rotor speed sothat the wind turbine work under variable speed and constant frequency. This kind of wind turbine with high power frequency convertor brings about problems such as the high current harmonic current, the high reactive power and the complex structure of special generator (Tang X and Miao F,et al 2014).

In this background, some scholars put forward a differential speed control device for wind turbine. The motor is used to regulate the speed of wind rotor through differential gear train. The synchronous generator works as the end of transmission chain. The stator of generator connects the grid directly sothat the rotor speed is locked fixed by the grid frequency (Tang X and Miao F,et al 2014).

The solution of wind turbine with differential speed regulation was first put forward by Mangialardi L and Mantriota G(1992). The model reference adaptive control method for the wind turbine with differential speed regulation was studied by Freeman J and Balas M J (1998). The corresponding robust control method is proposed and the further perfecting the concept of wind turbine with differential speed regulation by Idan M and Lior D(2002). The research of flexible hybrid scheme of wind turbine was made by Zhang T and Li W,et al (2005). The angular velocity relations of members of the wind turbine with differential speed regulation was analyzed by Anle M and Hongzhao L, et al(2008). The simulation of the wind turbine with differential speed regulation based on bladed were researched by Chenyao(2012).

The kinematic principle analysis of wind turbine with differential speed regulation is studied by related research mostly. The power control method for this kind of wind turbine under different wind speed is not provided. In view of this deficiency, the power control method for the wind turbine with differential speed regulation is studied and the simulation of all system is carried out.

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2. The principle of differential speed regulation

As shown in Fig.1, the wind turbine with differential speed regulation consists of wind rotor, gearbox, differential gear train, speed regulating motor and grid-connected synchronous generator. The differential gear train includes the carrier, ring gear and the sun gear.

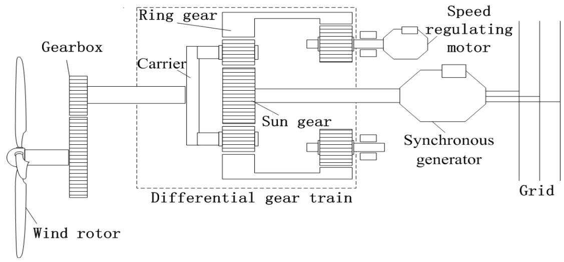

Fig.1 The structure diagram of wind turbine with differential speed regulation

The differential gear train's degrees of freedom is 2. N_R is the speed of the ring gear, N_C is the speed of the carrier, N_S is the speed of the sun gear and they meet the Eq.(1) below.

$$N_S + uN_R - (1+u)N_C = 0 \tag{1}$$

In Eq.(1), u is the structure parameter of differential gear train. It's value is equal to the ratio of the ring gear radius and sun gear radius. The speed of generator which equals to the sun gear speed N_S is fixed by the grid frequency and it meets the Eq.(2).
According to Eq.(1), the N_C can be regulated by the speed regualting motor through contolling the N_R. Regulating the carrier speed is equivalent to regulate the wind rotor speed for the reason that the ratio of gearbox between the carrier and wind rotor is constant.

$$\frac{60f}{p} = N_S \tag{2}$$

In Eq.(2), f is the grid frequency, it equals 50Hz or 60Hz. p is the pole pairs of the synchronous generator.

3. The power control method

The utilization of wind energy C_p is adjusted for the power regualting of the variable speed and constant frequency wind turbine. The wind rotor should obtain power as much as possible while the wind speed is less than the rated value. The wind rotor should obtain power as much as the rated capacity of wind turbine. The wind power and the wind rotor power meet the Eq.(3).

$$P_{rotor} = P_{wind} C_p = \frac{1}{2}\rho A V^3 C_p \tag{3}$$

In Eq.(3), P_{rotor} is the power obtained by wind rotor. P_{wind} is the wind rotor. ρ is the air density. A is the swept area of wind rotor.

The relationship among the C_p, pitch angle β and the tip speed ratio λ meet the Eq.(4) (Slootweg J G and Polinder H,et al 2003).

$$\begin{cases} C_p(\beta,\lambda) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\beta^{C_5} - C_6\right)e^{-\frac{C_7}{\lambda i}} \\ \lambda_i = \cfrac{1}{\cfrac{1}{\lambda + C_8\beta} - \cfrac{C_9}{\beta^3+1}} \end{cases} \tag{4}$$

In Eq.(4), C_1=0.73; C_2=151; C_3=0.58; C_4=0.002; C_5=2.14; C_6=13.2; C_7=18.4; C_8=-0.02; C_9=-0.003.

3.1 The power control method below the rated wind speed

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The power obtained by wind rotor is less than the rated capacity of generator while the wind speed V is below the rated vlaue. The wind rotor should deliver wind power into the generator as much as possible to increase the electric energy production. The relation curve of C_p and λ is shown in Fig.2 when the β should be kept for 0°.

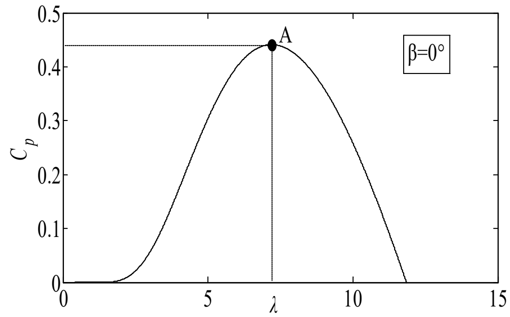

Fig.2 The relation curve of C_p-λ when β=0°

The λ should reach the abscissa of the peak point A in Fig.2 for keeping the maximum of C_p.

The relationship between λ and N_{rotor} meets the Eq.(5).

$$\lambda = \frac{\pi N_{rotor} R}{30V} \tag{5}$$

In Eq.(5), N_{rotor} is the wind rotor speed, r/min. R is the radius of wind rotor, m; V is the wind speed, m/s.

For an example of these parameters' value, R=30m, u=2, the gearbox ratio is 80, the transmission ratio between the speed regualting motor and the ring gear is 1, the rated speed and the rated power of the synchronous generator are 1800r/min and 1500kW respectively.

While the wind turbine runs in the peak point A and the wind rotor power equals the rated power of generator, the rated wind speed is 12.7m/s according to the Eq.(3).

The coordinate value of the point A is (λ=7.3, C_p=0.43) according to the Fig.2.

As shown in Tab.1, some main parameters are calculated under the wind speed 9m/s, 10m/s and 11m/s which is below the rated wind speed 12.7m/s according to Eq.(1~5).

Tab.1 The ideal value of main parameters under different wind speed which is below the rated wind speed

main parameters	V(m/s)		
	9	10	11
C_p	0.43	0.43	0.43
λ	7.3	7.3	7.3
β(°)	0	0	0
N_{rotor}(r/min)	20.9	23.2	25.6
N_R (r/min)	1608	1884	2172
N_S (r/min)	1800	1800	1800
P_{wind} (kW)	1236.1	1695.6	2256.8
P_{rotor} (kW)	531.5	729.1	970.4

3.2 The power control method above the rated wind speed

The instantaneous power of wind turbine exceeds the rated capacity of generator while the wind speed V is above the rated vlaue. The power obtained by the wind rotor should be reduced to the rated power of generator by decreasing C_p.

Fig.3 describes the different curve C_p-λ while the pitch angle equals to β_1, β_2, β_3. β_1=0° and β_1<β_2<β_3. The coordinates of the point A , B, C, D are (λ_A, C_{p1}), (λ_B, C_{p2}), (λ_C, C_{p2}), (λ_D, C_{p2}) respectively.

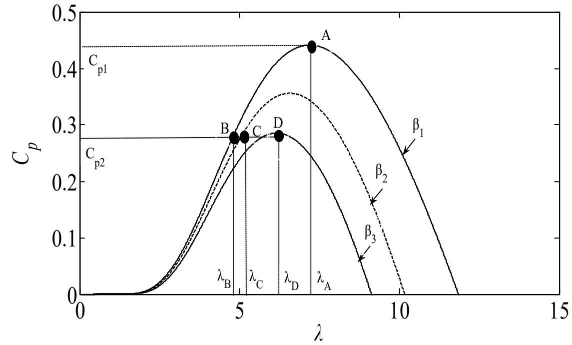

Fig.3 The relation curve of Cp-λ when β=β_1、β_2、β_3

While the wind speed is below the rated value , the wind turbine runs at point A(λ_A, C_{p1}) and β_1=0°. While the wind speed increases suddenly and exceed the rated value, the C_{p1} should be reduced to C_{p2} in order to decrease power to rated value and three methods is proposed to achieve this aim.

Method(1): Keep the β_1=0° and use the speed regualting motor to control the wind rotor speed. The wind tubine's working point runs along the curve C_p-λ(β_1) from point A(λ_A, C_{p1}) to point B (λ_B, C_{p2}).

Method(2): Increase β_1 to β_3 and use the speed regualting motor to control the wind rotor speed. The wind turbine's working point runs from point A(λ_A, C_{p1}) to point D(λ_D, C_{p2}) on the curve C_p-λ(β_3).

Method(3): Increase β_1 to a certain value β_2 belong to (β_1, β_3) and use the speed regualting motor to control the wind rotor speed. The wind turbine's working point runs from point A(λ_A, C_{p1}) to point C(λ_C, C_{p2}) on the curve C_p-λ(β_2).

The method(1) only takes action of regulating the wind rotor speed to reduce the C_p. The speed regualting motor must has the ability of changing the speed of the large rotary inertia wind rotor in a relatively short time. It demands higher performance for the speed regulating system.

The method(3) takes actions of regulating the wind rotor speed and changing the pitch angle to reduce the C_p.The method(2) is the limiting case of the method(3).

As shown in Tab.2, some key parameters are calculated under the wind speed 14m/s, 15m/s and 16m/s which is above the rated wind speed 12.7m/s according to Eq.(1~5).

In Tab.2, the λ, β, N_{rotor}, N_R are expressed in the form of interval. The left boundary value of each interval represents the parameter calculated by the method(1). The right boundary value of each interval represents the parameter calculated by the method(2). The other values in each interval represents the parameter calculated by the method(3).

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Tab.2 The ideal value of main parameters under different wind speed which is higher than the rated wind speed

main parameters	V(m/s)		
	14	15	16
C_P	0.32	0.26	0.22
λ	[5.1, 6.4]	[4.6, 6.0]	[4.3, 5.8]
β(°)	[0, 4.1]	[0, 6.8]	[0, 8.9]
N_{rotor}(r/min)	[22.7, 28.6]	[22.0, 28.7]	[21.9, 29.5]
N_R (r/min)	[1824, 2532]	[1736,2544]	[1728, 2640
N_S (r/min)	1800	1800	1800
P_{wind} (kW)	4687.5	5769.2	6818.2
P_{rotor} (kW)	1500	1500	1500

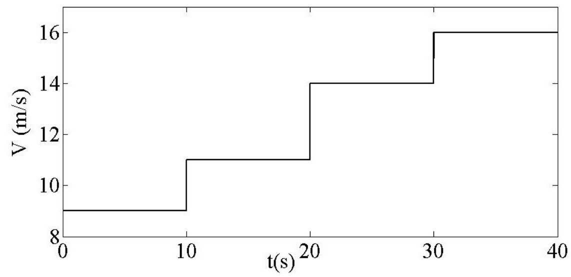

Fig.4 The step wind speed

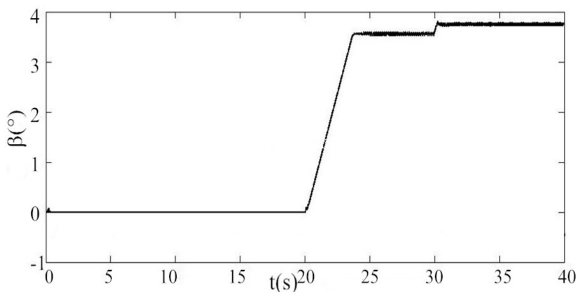

Fig.5. The pitch angle β

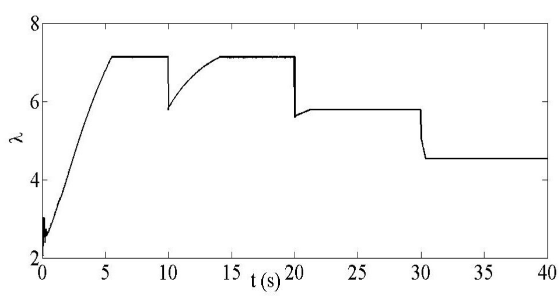

Fig.6 The tip speed ratio λ

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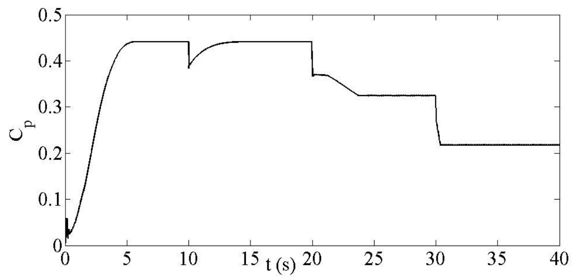

Fig.7 The utilization ratio of wind energy Cp

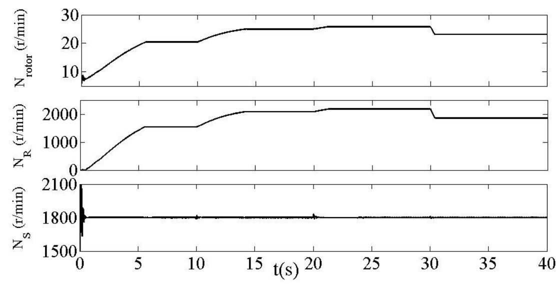

Fig.8 Speed of wind rotor, speed regulating motor and synchronous generator

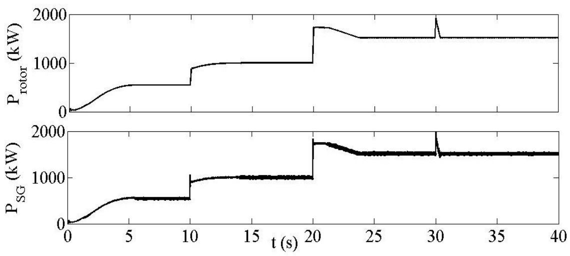

Fig.9 Power of wind rotor and synchronous generator

4. Discussion

The model of wind turbine with differential speed regulation is built in SIMULINK. The differential gear train model, the speed regualting motor model and the synchronous generator model are the built-in module of SIMULINK. The model of wind rotor with variable pitch is designed for the simulation (Xiaoguang L 2012) (Yigang S 2013).

The step wind including 9m/s, 11m/s, 14m/s, 16m/s is used as the input of the model. Each section of the step wind lasts 10 seconds. The simulation results are shown in Fig.4~ Fig.9.

In Fig.4, V=9m/s and V=11m/s are all below the rated wind speed. The V=14m/s and V=16m/s are all above the rated wind speed. As shown in Fig.5~9, 0~5s is the starting stage of wind turbine model after the wind begins inputting. The variation of parameters are detailed studied in the period of 5~40s.

V=9m/s is the input of simulation in 5~10s and it is below the rated wind speed. The pitch angle keeps 0°. The tip speed ratio is 7.2. The utilization of wind energy is 0.45. The power obtained by wind rotor is 500kW. The wind turbine model runs in the vicinity of the point A as shown in Fig.2.

The V=9m/s changes to V=11m/s at the time of t=10s and it is still below the rated wind speed. The instantaneous speed of wind rotor doesn't changes immediately for the reason that the wind rotor owns high rotary inertia. So, the immediately decreasing of tip speed ratio results in the decreasing of utilization of wind energy. The wind turbine comes back to the working point A at the time of t=15s with the help of speed regulating motor. The power obtained by wind rotor is 1000kW.

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The V=11m/s changes to V=14m/s at the time of t=20s and it is above the rated wind speed,

The instantaneous power obtained by the wind rotor bumps up and it exceed the rated power of the synchronous generator. The power control method above the rated wind speed is adoped for reduce the utilization of wind energy. The pitch angle starts regulating. The β=0°changes to β=3.5°in 3s. The speed regulating motor starts working for controlling the tip speed ratio. These measures make the wind turbine work at point C in Fig.3. The power obtained by wind rotor reduces to 1500kW.

The V=14m/s changes to V=16m/s at the time of t=30s and the instantaneous power obtained by the wind rotor bumps up. The pitch angle is regualted from β=3.5°to β=3.7°. The speed regulating motor adjusts the tip speed ratio by controlling the wind rotor speed. The power obtained by wind rotor reduces to 1500kW, too.

5. Conclusions

The control strategy of the grid-connected wind turbine with differential speed reuglation is studied. Below the rated wind speed, the utilization of wind energy is made to be the maximum by means of changing the tip speed ratio through regulating the wind rotor speed. Above the rated wind speed, the utilization of wind energy is made to be decreasing for reducing the power of generator to the rated value. The measures includes regulating pitch angle and controlling the wind rotor speed.

The power control method is studied on the condition that the wind speed is below or above the rated value. The relational expression of utilization rate of wind energy Cp, pitch angle β and the tip speed ratio λ is analyzed. The operating parameters of wind rotor, speed regulating motor and synchronous generator are calculated under different wind speed which is lower or higher than rated wind speed with using the relational expression of utilization rate of wind energy Cp, pitch angle β and the tip speed ratio λ.

The SIMULINK software is used to build the 1500kW wind turbine model with differential speed regulation. Some different wind speed is made as input. The feasibility of power control method for grid-connected wind turbine wth differential speed regulation is verified by the comparison between the simulation results and the theoretical value of the key parameters.

The value of calculated parameters and the results of the simulation have a good agreement. The feasibility of the power control method for the wind turbine with differential speed regulation is verified.

Author Contributions: Conceptualization, Su Rui. and Wang Fujun; Methodology, Wang Fujun and Zhang Huan; Software, Li Gangjun; Validation, Su Rui; Formal Analysis, Su Rui; Investigation, Su Rui; Resources, Su Rui; Data Curation, Su Rui.; Writing-Original Draft Preparation, Su Rui; Writing-Review & Editing, Su Rui; Visualization, Su Rui; Supervision, Su Rui; Project Administration, Su Rui.

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