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Research Article

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Study on short-term energy storage characteristics of accumulators of hydrostatic wind turbine system

Fuzhu Li[1], Zhenzhi He[1], Wen Chen[2] and Yuqin Guo[3]

[1]School of Mechanical and Electrical Engineering, Jiangsu Normal University, Xuzhou, China
[2]Division of Engineering Technology of Wayne State University, Detroit, MI, 48202, USA
[3]School of Mechanical Engineering, Jiangsu University, Zhenjiang, China

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ABSTRACT

The impact of micro scale turbulence wind speed on wind power generation is studied in this paper. The relationship between turbulence wind components and some key parameters, such as the accumulator effective volume, unit mass energy storage and state of charge, is analyzed when the micro scale turbulence wind speed is equal to the rated one. And then, a hydrostatic wind turbine system and its corresponding control method are proposed, which can not only realize the short-term energy storage, but also keep the wind turbine working under the rated power condition. Finally, aimed at a 10 kw hydrostatic wind turbine system with an accumulator to implement short-term energy storage, the simulation analysis is carried out when the micro scale turbulence intensity is 12% of the rated wind speed. The results showed that the output energy of the hydrostatic wind turbine system with a short-term storage accumulator is 11.3% larger than that of the corresponding system without accumulator.

Keywords: Hydrostatic System, Wind Power Generation, Accumulator, Short-term Storage.

INTRODUCTION

Despite the low efficiency of the hydraulic system, the hydraulic variable speed constant frequency (VSCF) wind turbine system may avoid to use gearbox and power electronic devices, and also achieve short-term energy storage and release easily through accumulator, which could stabilize power quality of wind turbines [1, 2]. With the continuous improvement of the hydraulic technology and the evaluation research of its overall competitiveness, the hydrostatic wind power technology has attracted wide attention in the current world wind power countries [3]. It is qualified as one of the hot issues of next generation of wind power technology by United State Department of Energy in June 2010 [4]. However, recent researches are mainly focused on the system controlling and efficiency improvement. The researches about influence of random micro scale turbulent wind speed on wind power, together with the characteristics and the effects of short-term energy storage of accumulators of hydrostatic wind turbine system, are rarely studied. Moreover, the utilization of accumulator in hydrostatic wind turbine system not only improve the quality of wind power, but also is an effective means of expanding the scope of wind energy, improving the efficiency of wind energy and making hydrostatic wind turbine up.

In wind turbine systems, the main purpose of short-term energy storage device such as flywheels and super capacitor is to improve the power quality, smooth power fluctuations and improve the low-voltage ride-through capability [5,6]. The energy storage of accumulator of wind turbine system was studied in literature [7], however the characteristic and effect of energy storage of accumulator under random turbulence wind speed are absent. In addition, the accumulator has been studied on the hybrid vehicles as energy storage device, which mainly recovers the braking energy and improve the overall efficiency of the engine [8].

On the basis of the impact of micro scale turbulence wind speed on wind energy output of wind turbine system, the relationship between turbulence wind components and some key characteristic parameters is analyzed in this paper, when the micro scale turbulence wind speed is equal to the rated wind speed. In addition, the effect of hydrostatic wind turbine system with short-term energy storage accumulator is also studied.

EXPERIMENTAL SECTION

1. Impact of micro scale turbulence wind speed on wind power generation

1.1 Model of micro scale turbulence wind speed

Turbulence is a very complex physical phenomenon, and the wind speed of the spectral gap of wind-velocity spectrum is considered to be the micro scale turbulence wind speed, with the variation period from 30 seconds to several minutes [9]. Spectral gap may not exist in many cases, but to the needs of engineering applications and theoretical researches, it is assumed that there is an obvious spectral gap, and that micro scale turbulence wind speed is the average wind speed superimposed with a Gaussian random variable with zero mean, which is expressed as [9].

$$u = \overline{u} + \tilde{u} \qquad (1)$$

where, $\overline{u}$ is the average wind speed, $\tilde{u}$ is the Gaussian random variable with zero mean. The standard deviation could be written as $\sigma = \overline{u}I$, where I is turbulence intensity.

In order to study the impact of micro scale turbulence wind speed on output power and energy storage of wind turbine, the actual or simulated wind speed can be used. The actual wind speed can reflect actual situation more accurately, however it is difficult to measure, and is without universality. Therefore, based on the random white noise and the Kalman Filter theory, a two-dimensional micro scale turbulence wind speed generated by MATLAB is selected as the research object, the spectrum of which is

$$S_k(f) = \frac{4\sigma_k^2 L_k / \overline{u}_{hub}}{(1+\frac{6fL_k}{\overline{u}_{hub}})^{\frac{5}{3}}} \qquad (2)$$

where, f is the frequency, L_k is the scale of Euler's integral, σ_k is wind speed, $\overline{u}_{hub}$ is standard deviation, and S_k is vertical power spectral density.

1.2 Impact of micro scale turbulence wind speed on wind power generation

Assume that the power of micro scale turbulent wind speed P is

$$P = \frac{1}{2}\rho A u^3 \qquad (3)$$

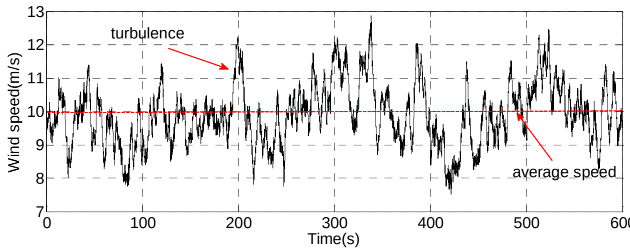
where, ρ is the air density, and A is the rotor swept area.

The expected value of power of micro scale turbulent wind speed $E(P)$ is

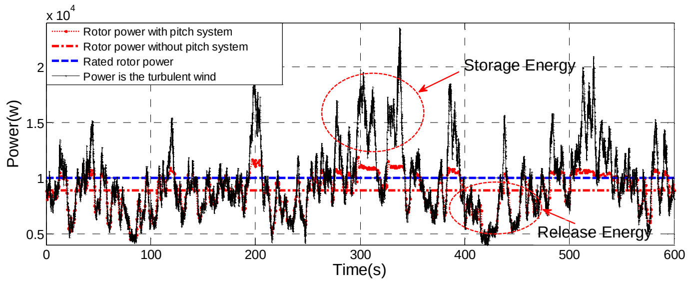
$$E(P) = \frac{1}{2}\rho A[\overline{u}^3 + 3\overline{u}E(\tilde{u}^2) + 3\overline{u}^2 E(\tilde{u}) + E(\tilde{u}^3)] \qquad (4)$$

where, $E(\tilde{u})$ is the expected value of random variables with Gaussian distribution. For Gaussian distribution with zero mean, $E(\tilde{u})$ and $E(\tilde{u}^3)$ are both zero, and $E(\tilde{u}^2) = \sigma^2 = (\overline{u}I)^2$. Then, micro scale turbulent wind speed is 1.12 times the power of the average wind speed when the turbulence intensity I equals to 20%.

In Figure 1, Figure (a) is the distribution of micro scale turbulent wind speed as the average wind speed is 10 m/s and the turbulence intensity is 12%. Figure (b) is the output power of wind turbine with the rated power of 10 kw, the wind speed of which is shown in Figure (a).



(a) Distribution of micro-scale wind speed as the average wind speed is 10 m/s and the turbulence intensity is 12%



(b) Output power of wind turbine as the average wind speed is 10 m/s and the turbulence intensity is 12%

Fig.1 Impact of micro-scale turbulence wind speed on output power of 10 kw wind turbine

When the wind speed exceeds the rated speed, the excess wind power is generally removed through variable-pitch structure in VSCF wind turbine system to ensure running the wind turbine under rated conditions. It is shown in Figure (a) that there will be some micro scale turbulence wind speed exceeds the average rated one. Figure (b) shows that the theoretical output power of wind turbine should be 10 kw when the rated wind speed is 10 m/s. However, the average output power of traditional VSCF wind turbine is only 8.9 kw with the action of micro scale turbulence wind speed of 10 m/s, that is 11% less than the theoretical value. It can be seen that the micro scale turbulent wind has a great influence on the output power of wind machine. If storing the extra turbulence wind power when turbulent wind speed is more than average value using the accumulator in hydrostatic wind turbine systems, while releasing wind power when it is less, the utilization scope of wind energy can be effectively expanded and the output power of wind turbine can be improved.

The section headings are in boldface capital and lowercase letters. Second level headings are typed as part of the succeeding paragraph (like the subsection heading of this paragraph). All manuscripts must be in English, also the table and figure texts, otherwise we cannot publish your paper. Please keep a second copy of your manuscript in your office. When receiving the paper, we assume that the corresponding authors grant us the copyright to use the paper for the book or journal in question. When receiving the paper, we assume that the corresponding authors grant us the copyright to use the paper for the book or journal in question. When receiving the paper, we assume that the corresponding authors grant us the copyright to use.

2. Short-term energy storage scheme of hydrostatic turbine system

2.1 Approaches to acquire the excess energy

The characteristic curve of the torque- rotate speed of VSCF wind turbine with different wind speeds is shown in Figure 2.

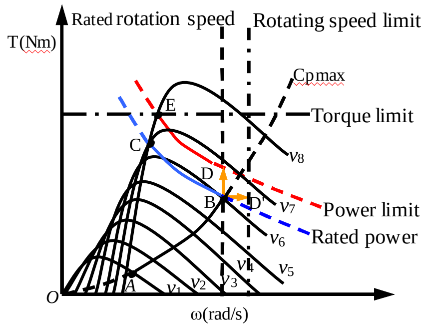


Fig.2 Characteristics curve of the torque- rotate speed of wind turbine

Generally, VSCF wind turbine system extract wind energy in the way of maximum power tracking in the AB segment, and will run with constant torque after reaching the rated power of B-point. However, the micro scale turbulence in rated wind speed will affect the output power of wind turbine. The hydrostatic wind turbine system does not use power- limited hydraulic power electronic converter equipment, thus the wind turbine may run in power limit mode which is exceed the B-point when ensuring the generator in rated power operation.

There are two different ways to increase the output energy of wind turbine, one is to keep torque constant and increase rotation speed which is along BD', the other is to keep rotation speed constant and increase torque which is along BD.
2.1.1 Rotation speed increasing while torque is constant

The rotation speed of wind turbine is limited by the blade tip speed ratio which is the main factor of wind turbine noise and generally less than 65 m/s, therefore, the method to obtain turbine wind energy through increasing rotation speed while torque is constant is not considered in this paper.

2.1.2 Torque increasing while rotation speed is constant
The rated power of rotor is as following,

$$P_r = T_r\omega_r = \frac{1}{2}\rho AC_p(\lambda,\beta)u^3 \qquad (5)$$

where, T_r is the rated torque, ω_r is the rated speed, λ and β are the pitch angle and the blade tip speed ratio respectively, with $\lambda = \omega R / u$, and $C_p(\lambda,\beta)$ is the power factor of the wind turbine.

Then the total power output when increasing torque while rotation speed is constant can be written as

$$P_t = T_r\omega_r + \Delta T\omega_r \qquad (6)$$

where, P_t is the total power output of the wind turbine, and ΔT is the torque increment.

2.2 Relationship between micro scale turbulence and system pressure
After ignoring the friction, damping and leakage losses of the rotor and pump, the following relationship can be obtained according to energy balance,

$$P_t = P_p + \Delta P = P_r + \Delta T\omega_r \qquad (7)$$

where, P_p and ΔP are the rated power of pump and the power increment of wind turbine respectively, with P_p=P_r. The hydraulic system pressure will be rose when the torque increasing while the rotor speed of wind turbine is constant.

$$\Delta P = \Delta pD_p\omega_r = (p_2 - p_r)D_p\omega_r = \Delta T\omega_r \qquad (8)$$

where, p_r and p_2 are the rated pressure and the system pressure after torque increasing respectively, and D_p is the rated capacity of pump.

By substituting the equations (5) and (6) into equation (8), it becomes:

$$\Delta pD_p\omega_r = \frac{1}{2}\rho AC_p(\beta,\lambda)(u^3 - \bar{u}^3) \qquad (9)$$

By substituting the equation (1) into equation (9), the relationship between system pressure variation and turbulence can be expressed as

$$\Delta p = \frac{1}{2D_p\omega_r}\rho AC_p\tilde{u}(\tilde{u}^2 + 3\bar{u}\tilde{u} + 3\bar{u}^2) \qquad (10)$$

3. Relationship between characteristic parameters of accumulator and turbulence
3.1 Effective volume
Bohr gas law gives the following equation

$$p_rV_1^n = p_2V_2^n = p_aV_a^n = const \qquad (11)$$

where, V_1、V_2 and V_a, are the volume correspond respectively to the lowest pressure p_r, the highest pressure p_2 and the random pressure p_a of the accumulator, n is the polytropic exponent of gas.

Effective volume ΔV is the amount of volume changed corresponding to the change of gas pressure within the accumulator, i.e.,

$$\Delta V = V_1 - V_2 \qquad (12)$$

V_1 and V_2 can be obtained from equation (11). By letting $r=p_r/(p_r+\Delta p)$ and combining equations (10) and (12), relationship between the effective volume ΔV of accumulator of the hydrostatic wind turbine system and the micro scale turbulence wind speed can be expressed as

$$\Delta V = V_1(r - r^{\frac{1}{n}}) \qquad (13)$$

Figure 3 shows the relationship between the effective volume ΔV of accumulator and turbulence component $\tilde{u}$.

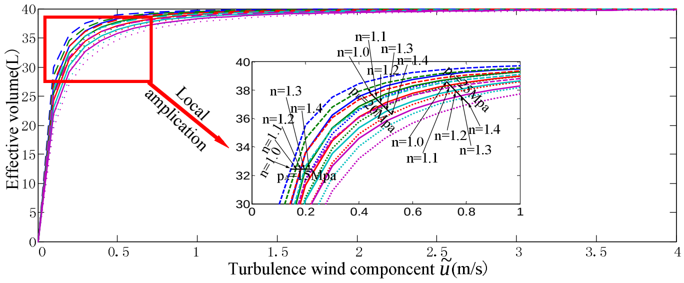


Fig.3 Relationship between the accumulator effective volume and turbulence wind components

It can be seen that the effective volume of accumulator changes rapidly when the turbulence component $\tilde{u} < 0.2$ m/s with the same initial volume, which is mainly due to that the gas with free state in the accumulator is compressed quickly. Conversely, the volume changes smoothly when turbulent component $\tilde{u} > 1.5$ m/s. And it also can be seen that the effective volume decreases as the system rated pressure p_r and polytropic exponent n increases.

3.2 Unit mass energy storage

Assuming E is the total energy stored in the accumulator, the unit mass energy storage of accumulator will be $E_m=E/(\rho_a V_1)$. After combining equations (10) and (11), it gives

$$E_m = \frac{E}{\rho_a V_1} = \frac{\dfrac{(p_1+\Delta p)}{1-n}(r^{1/n} - r)}{(\rho_{or}+\rho_0)(1-r^{1/n}) + \rho_{gr} r^{1/n}} \qquad (14)$$

where, ρ_a、 ρ_{or}、 ρ_o and ρ_{gr} are the densities of accumulator and its air bags, hydraulic fluid and gas respectively.

The relationship between the accumulator unit mass energy storage and the turbulence components $\tilde{u}$ is shown in Figure 4.

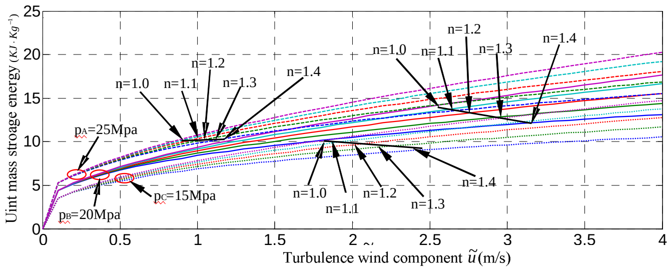


Fig.4 Relationship between the accumulator unit mass energy storage and turbulence wind components

It can be seen that the accumulator unit mass energy storage is essentially independent of multilateral index when the turbulent component $\tilde{u}$ <0.1, and only relates to the system rated pressure. The greater the pressure the greater the unit mass energy storage. It increases as the turbulent component increases when $\tilde{u}$ > 0.1.

3.3 Charge and discharge of accumulator

Accumulator state of charge (SOC) represents the ratio of fluid volume in accumulator and the initial volume of accumulator. According to equations (10) and (11), it can be expressed as

$$SOC = 1 - r^{1/n} \qquad (15)$$

The relationship between the accumulator state of charge and turbulence components $\tilde{u}$ is shown in Figure 5.

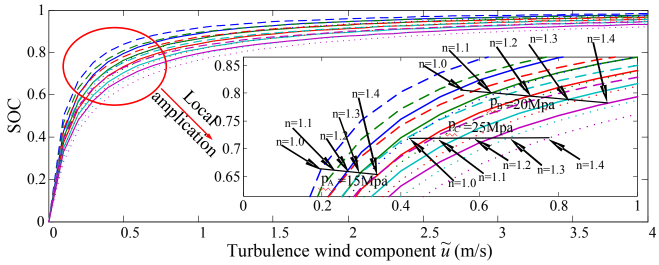


Fig.5 Relationship between the accumulator state of charge and turbulence wind components

It can be seen that the accumulator state of charge will make up to 40% even when there is small turbulent component, and then increased slowly. Its state of charge decreases as the initial pressure of accumulator or system rated pressure increase.

4. Case study

4.1 Short-term energy storage hydrostatic wind turbine system

The speed regulating system adopted in current hydrostatic wind turbine system is mainly the quantitative pump-variable motor systems or variable pump- quantitative motor systems, the disadvantages of which are reflected in large overflow losses, low system response, limited speed range [11,12]. Therefore, according to the method to obtain more energy by torque increasing while rotation speed is constant, and the requirements to run the generator under rated conditions, the structure of hydrostatic wind turbine system with short-term energy storage is shown in Figure 6.

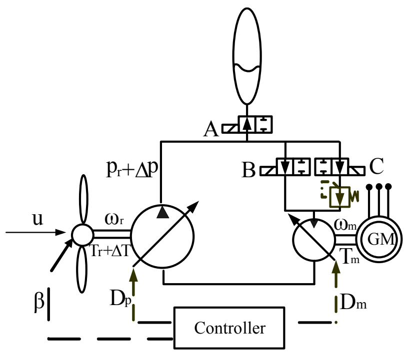


Fig. 6 Short-term storage energy structure of a hydrostatic wind power generation system

When the wind speed is higher than the rated micro scale turbulence wind speed, the valve C is turned on while valve B disconnected, meanwhile, the wind turbine will keep the speed constant and increase torque to obtain more wind energy until the accumulator is full of energy, in which the function of reducing valve is to ensure the power of hydraulic motors constant. On the contrary, when the wind speed is lower than the rated wind speed, the accumulator will release energy. When the inlet pressure of reducing valve reaches to the rated pressure, valve B will be disconnected while valve C turned on, then the system running normally.

4.2 Control strategy

When the average wind speed equals to the rated one, the dynamics equation of hydraulic pumps and wind machine can be expressed as following

$$T_t\omega_r - D_p p_2 = J_t\dot{\omega}_r + B\omega_r \qquad (16)$$

where, T_t=T_r+ΔT=P_t/ω_r, J_t is the sum of rotational inertia of wind turbine and pump, and B is the damping coefficient of the torque. By substituting the equation (5) into equation (16), the equation becomes:

$$p_2 = \frac{1}{D_p}[\frac{\omega_r^{\ 2}R}{2\lambda^3}\rho AC_P(\lambda,\beta) - J\dot{\omega}_r - B\omega_r] \qquad (17)$$

In order to ensure the rotate speed ω_r constant, it is only needed to control the hydraulic system pressure p_2 to track the changes of turbulent wind speed.

4.3 Simulation results

A wind turbine system with the power of 10 kw is adopted in this case study, the main technical parameters of which are:R=4m、ω_r=200rpm、P_r=10kw、 $\bar{u}$ =10m/s，D_p=628cc/rev, length of pipe l=2m, diameter of pipe d=25mm, the volume of accumulator V_1=40L, nominal pressurep_1=20MPa，J_t=8kg.m^2，B= 0.019N·m/(rad·s^{-1}), ρ=1.25kg/m^3.

Figure 7shows the distribution of micro scale wind speed within 600s as the turbulence intensity is 12% and the average wind speed is 10 m/s.

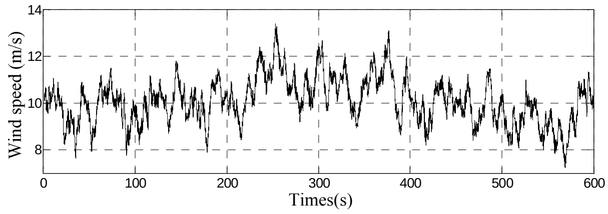


Fig.7 Distribution of wind speed as the turbulence intensity is 12% and the average wind speed is 10m/s

The Comparison of output power of wind turbines with and without accumulator is shown in Figure 8

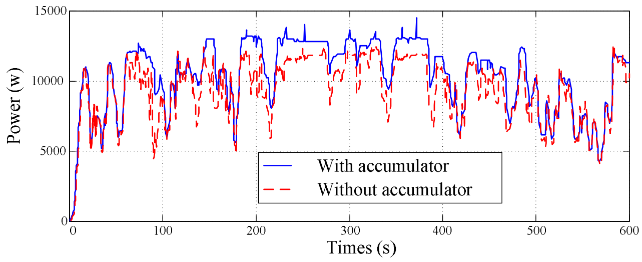


Fig. 8 Comparison of output power of wind turbines with/without accumulator

Thanks to the short-term energy storage of accumulator, the output energy of hydrostatic wind turbine system is approximately 4.06×106J with accumulators, while about 3.6×106J without accumulators. So the energy stored by accumulator is about 4.6×105 J. The output energy of the hydrostatic wind turbine system with accumulator is 11.3% larger than that of the corresponding system without accumulator.

CONCLUSION

1) Micro scale turbulent wind speed is 1.12 times the power of the average wind speed when the turbulence intensity I equals to 20%, that is to say that the micro scale turbulent wind has a great influence on the wind turbine system.

2) The relationship between turbulence wind components and some key performance parameters of accumulator in hydrostatic wind turbine system, such as the effective volume, specific energy and state of charge, is given when the micro scale turbulence wind speed is equal to the rated wind speed.

3) A hydrostatic wind turbine system with the short-term energy storage accumulator and its corresponding control method are proposed. The results showed that the output energy of the hydrostatic wind turbine system with a short-term storage accumulator is 11.3% larger than that of the corresponding system without accumulator, when the initial volume of accumulator V_1 equals to 40L and the turbulence intensity I equals to 12%.

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