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Wind Turbine Aerodynamic Characteristics in Wind Heating System

Lihua Cao*, Bo Li*, Tieliu Jiang*[1], Zhongbin Zhang*, and Lidong Zhang*

Abstract – *In this paper, the theory of aerodynamics and NACA series airfoil is used to analysis Darrieus type vertical axis wind turbine of wind heating system after setting up the relevant structure parameters. Through reasonable correction, the curve of wind energy utilization coefficient of wind turbine is obtained. According to the operating characteristics of wind turbine, the reliability of the wind energy heating system installed in certain area is analyzed. At the same time, the system configuration suggestions are put forward. Based on the curve of wind energy utilization coefficient, Description of variable speed operation of wind turbine will effectively improve the efficiency of wind energy utilization.*

Keywords – aerodynamic characteristics, NACA series airfoils, vertical axis wind turbine, wind energy heating system, wind energy utilization coefficient

1. INTRODUCTION

At present, the utilization of wind energy resources in renewable energy is mainly concentrated in the field of wind power generation. Electric energy has the characteristics of convenient transmission and wide application. Because of the volatility of wind energy, the increase of wind power generator installed capacity has caused a series of problems related with wind power accommodation [1]-[2]. Generally speaking, wind energy density is usually higher in high latitude cold regions. For example, Northern Europe countries such as Norway, Sweden and Iceland, as well as China's north areas, have the corresponding heating demand in winter [3]-[4]. Therefore, consider the use of wind energy heating system independent operation or coupling operation with other systems has great significance [5]. Meanwhile, It can reduce the environmental pollution caused by conventional heating methods and promoted the diversified development of wind energy utilization. Wind energy heating system mainly including heating by stirring, heating by friction and heating by eddy current etc. [6]. The domestic and foreign scholars have studied the operation characteristics of the wind energy heating system by experiments and numerical simulation [7]-[11]. However, above researches mainly focus on the optimization of the heat generator and the system efficiency experiment. Measures to maximize the utilization of wind energy under certain wind conditions in a certain area are not be point out. In the paper, through the dynamic characteristics calculation [12], [13] of a Darrieus type vertical axis wind turbine, the reliability of the heating system was evaluated. Meanwhile, the operation strategy improved wind energy utilization coefficient is pointed out, it provides a theoretical basis for the optimal matching of wind energy heating system.

2. CALCULATION MODEL AND DATA

2.1 Heating System Efficiency

Wind energy heating system mainly consists of wind turbine and heat generator. In the transformation process, the wind turbine will convert the energy captured from the natural wind into the mechanical energy of the output shaft. Afterwards heat generator converts mechanical energy into heat energy. Heat dissipation loss will be inevitable in the operation process of heating system. Therefore, the system efficiency is the product of the efficiency of the wind turbine and the efficiency of the heat generator, which considers the heat dissipation loss.

$$\eta_s = (\eta_{wt} \cdot \eta_h)(1-\varepsilon) \tag{1}$$

$$\varepsilon = f(t, \lambda, \phi) \tag{2}$$

Where, η_s is efficiency of heating system, η_{wt} is efficiency of vertical axis wind turbine, η_h is efficiency of heater, ε is rate of heat dissipation, t is operating temperature of heater, λ is thermal conductivity of thermal insulation material, ϕ is active area of thermal insulation material.

The heat generator converts the mechanical energy into heat energy, efficiency will reach 90% and above. Therefore, in order to improve the energy efficiency of heating systems, mainly depends on the wind energy capture. Wind energy utilization coefficient was defined to evaluate the standard of wind energy capture, described as follows：

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$$C_P = \frac{2P}{\rho S V^3} \tag{3}$$

Where, C_P is wind energy utilization coefficient, P is wind energy capture, ρ is air density, S isswept area of wind turbine rotor, V is wind speed.

2.2 Aerodynamic Characteristics of Wind Turbine

Vertical axis wind turbines are different from horizontal axis wind turbines applied in wind power generation for large scale. Resistance type wind turbine blades are usually used for traditional vertical axis wind turbine, which mainly used for lifting water and irrigation. The wind energy utilization efficiency is lower than which installed lift type blade [14]. The wind energy direct heating system described in this paper is a small capacity energy supply system. Therefore, the wind turbine configured in this system need high energy utilization efficiency. The Darrieus type vertical axis wind turbine was selected in the system described in this article, which has a higher tip speed ratio and wind energy utilization coefficient [15].

Darrieus type wind turbine has a fixed blade and the periodic change of angle of attack，rotating around the vertical axis. Meanwhile，due to the difference of blade shape and blade installation position, the outer surface formed by the rotating sweep of the blade can constitute many shapes such as cylindrical, spherical and parabolic shapes.

In order to simplify the derivation, make the following assumptions:

(1) The rotor is in the state of motion under the wind.

(2) Wind speed and direction is constant through the rotor.

(3) The angle of attack between the relative wind speed and the airfoil will never exceed the limit value

According to the above hypothesis, the wind turbine blade meets the following velocity relationship at all positions:

$$\vec{V} = \vec{U} + \vec{W} \tag{4}$$

where, is wind velocity, is linear velocity of blade, is relative velocity between airflow and blade.

As shown in Figure 1, cylindrical Darrieus rotor center as O and the height is 2H. Define the Oxyz coordinate system in Figure 1. Vertical axis Oz parallel to the rotation axis of rotor. The direction Ox is the same as that the wind speed passing through the rotor. At the same time, the blade element chord midpoint is defined as M, chord length is defined as l, blade element length is defined as dz.

The component of $\vec{W}$ perpendicular to the blade element is expressed as follows:

$$W_n = V \sin\theta \tag{5}$$

The other component of $\vec{W}$ can be expressed as:

$$W_t = U + V\cos\theta = r\omega + V\cos\theta \tag{6}$$

Therefore, the force acting on the blade element is determined by formula (5) and formula (6):

$$W_u^2 = W_n^2 + W_t^2 = V^2 \sin^2\theta + \left(r\omega + V\cos\theta\right)^2 \tag{7}$$

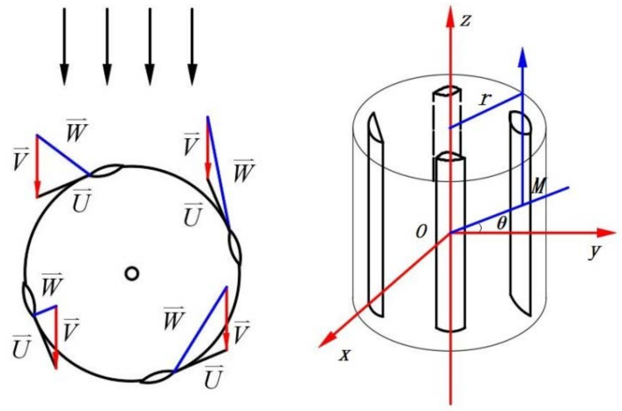

Fig. 1. Force analysis of Darrieus wind turbine.

Based on the above velocity decomposition relation, the blade angle of attack is expressed as follows：

$$\tan\alpha = \frac{V\sin\theta}{r\omega + V\cos\theta} \tag{8}$$

The aerodynamic pressure acting on the blade can be expressed as:

$$Q = \frac{1}{2}\rho W_u^2 \tag{9}$$

The blade element Lilienthal aerodynamic coefficients expressed as:

$$\begin{cases} C_t = C_l \sin\alpha - C_d \cos\alpha \\ C_n = C_l \cos\alpha + C_d \sin\alpha \end{cases} \tag{10}$$

where, is lift coefficient, is resistance coefficient.

The component at normal of blade element and Chord direction:

$$\begin{cases} dN = C_n Q l dz \\ dT = C_t Q l dz \end{cases} \tag{11}$$

Further, the above component is decomposed into the direction of the wind. The resultant force of the rotor in this direction can be expressed as follow:

$$\begin{aligned} dF &= dN\sin\theta - dT\cos\theta \\ &= Ql\left(C_n \sin\theta - C_t \cos\theta\right)dz \end{aligned} \tag{12}$$

If the blade chord is constant, the force acting on the rotor can be expressed as follows:

$$F=\frac{bl}{2\pi}\int_{-H}^{+H}\int_{0}^{2\pi}Q\left(C_n\sin\theta-C_t\cos\theta\right)d\theta dz \qquad (13)$$

where, b is the number of blades.

The rotor rotating shaft torque is provided by the force acting on the blade element can be expressed as follows:

$$dM=dTr=C_lQlrdz \qquad (14)$$

The torque of the whole rotor can be obtained by the integral of formula (14):

$$M=\frac{bl}{2\pi}\int_{-H}^{+H}\int_{0}^{2\pi}C_lQrdzd\theta \qquad (15)$$

Therefore, the power can be expressed as follows:

$$P=M\omega=\frac{bl}{2\pi}\int_{-H}^{+H}\int_{0}^{2\pi}C_lQr\omega dzd\theta \qquad (16)$$

In order to determine the performance of a Darrieus type vertical axis wind turbine under certain wind speeds, suppose that Bates theory is suitable for vertical axis wind turbine, for further analysis.

Applying the Bates theory, the force acting on the horizontal axis wind turbine under certain wind speed can be expressed as follows:

$$\begin{cases}F=\rho SV\left(V_1-V_2\right)\\ V_2=kV_1\end{cases} \qquad (17)$$

where, ρ is air density, *S* is rotor swept area, *V* is wind velocity at rotor plane, V_1 is wind velocity before rotor plane, V_2 is wind velocity after rotor plane, *k* is scale factor.

The wind speed through rotor can be expressed as follows:

$$V=\frac{1}{2}\left(V_1+V_2\right)=V_1\frac{\left(1+k\right)}{2} \qquad (18)$$

Through formula (17) and formula (18) can obtained:

$$\begin{aligned}F&=\frac{1}{2}\rho S\left(V_1^2-V_2^2\right)\\&=\frac{1}{2}\rho SV_1^2\left(1-\mathrm{k}^2\right)=2\rho SV^2\left(\frac{1-k}{1+k}\right)\end{aligned} \qquad (19)$$

Through Formula (13) and formula (19) can obtained:

$$\begin{aligned}&2\rho SV^2\left(\frac{1-k}{1+k}\right)\\&=\frac{bl}{2\pi}\int_{-H}^{+H}\int_{0}^{2\pi}Q\left(C_n\sin\theta-C_t\cos\theta\right)d\theta dz\end{aligned} \qquad (20)$$

Through Formula (9) and formula (20) can obtained:

$$\begin{aligned}&K=\frac{1-k}{1+k}=\\&\frac{bl}{8\pi S}\int_{-H}^{+H}\int_{0}^{2\pi}\frac{W_u^2}{V^2}\left(C_n\sin\theta-C_t\cos\theta\right)d\theta dz\end{aligned} \qquad (21)$$

The following relations can be obtained from the velocity triangle and the geometric relation:

$$\begin{cases}\dfrac{W_n^2}{V^2}=\left(\dfrac{r}{R}\dfrac{\omega R}{V}+\cos\theta\right)^2+\sin^2\theta\cos^2\delta\\ k=\dfrac{1-G}{1+G}\\ \lambda_0=\dfrac{\omega R}{V_1}=\dfrac{\omega R}{V}\left(\dfrac{1+k}{2}\right)=\dfrac{\omega R}{V\left(1+G\right)}\end{cases} \qquad (22)$$

where, λ_0 is tip speed ratio, G is intermediate variable. Wind energy utilization coefficient can be expressed as follows:

$$\begin{cases}C_p=\dfrac{2P}{\rho SV_1^3}\\ =\dfrac{bl}{2\pi S}\displaystyle\int_{-H}^{+H}\int_{0}^{2\pi}C_l\frac{W_u^2}{V_1^3}\frac{\omega r}{\cos\delta}d\theta dz\\ \dfrac{W_u^2}{V_1^3}\omega r=\dfrac{W_u^2}{8V^2}\dfrac{\omega R}{V}\dfrac{r}{R}\left(1+k\right)^3\end{cases} \qquad (23)$$

The parameters of wind turbine structure and the parameters related to blade airfoil are substituted into the above equations. The relationship between the coefficient of wind energy utilization and the tip speed ratio can be obtained.

2.3 Operation Parameters and Data

The wind turbine structural parameters and the lift coefficient and drag coefficient of airfoil as shown in Table 1.

Table 1. Parameters of wind turbine.

H/m	R/m	C_l	C_d
3.0	1.5	0.8513	0.0095

In order to analyze the heating reliability of the wind heating system, Monthly mean wind speed data and temperature data for certain area are required, as shown in Figure 2. In addition, in order to evaluate the difference of system heating capacity caused by the difference of wind energy utilization coefficient provided wind data at the different height of a day, as shown in Figure 3.

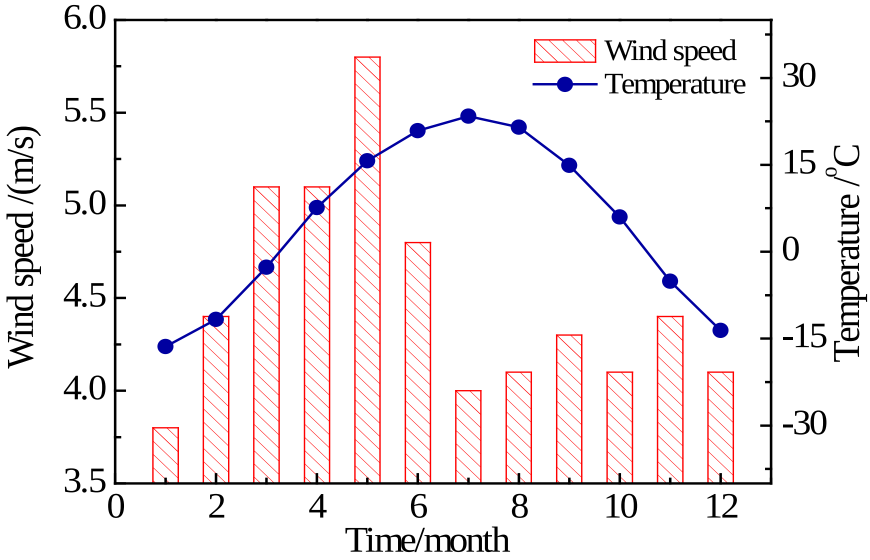

Fig. 2. Wind speed and temperature of each month.

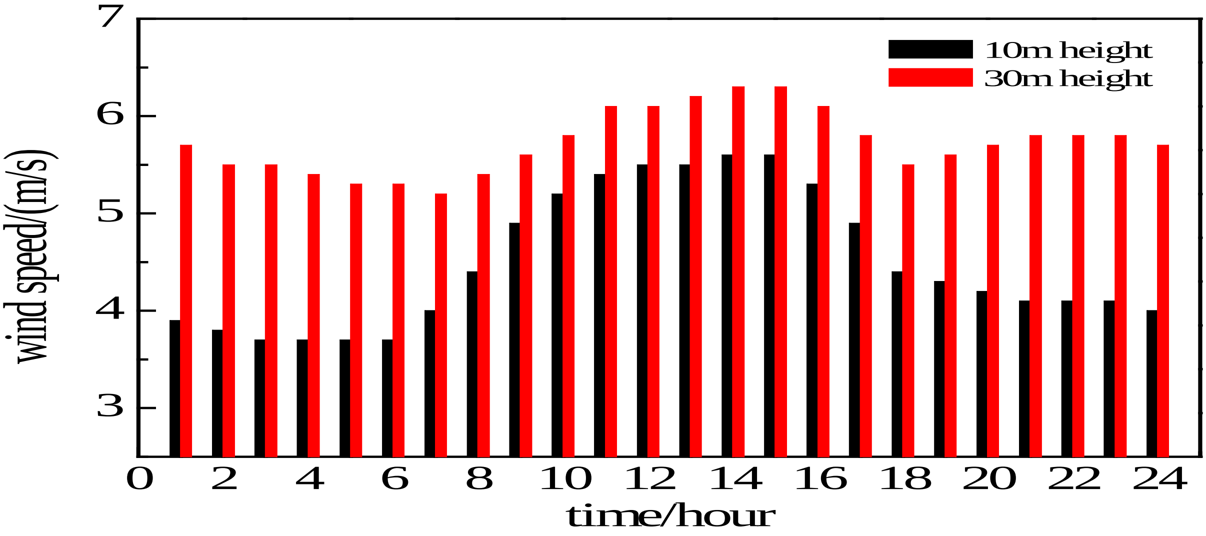

Fig. 3. Wind speed of each hour at different height.

3. RESULTS AND ANALYSIS

3.1 The Heating Reliability of the Heating System

According to the selected area meteorological data, as shown in Figure 2. It can be seen that the area of the coldest month of November to March of the following year, winter minimum temperature reached 20 degrees below zero. Therefore, it can be determined that winter heating is needed in this area, and it is reasonable to use the meteorological data for theoretical calculation. The wind speed data shows that the wind speed was low in the winter, but heat load was high. In the absence of reasonable allocation of heating system capacity, it will lead to cannot meet the heat load requirements in winter. The relationship between the heating system power and the heat load is obtained by calculation, as shown in Figure 4. It can be seen that under the condition of local wind speed and temperature heating power cannot meet the heating demand from November to February of the following year. At the same time, there will be a large number of surplus power in the summer. In this case, the heating system can be combined with other heating systems to meet the demand of heat load. In addition, increasing the heating capacity of the system and considering the reasonable consumptive power surplus in summer also can solve this problem.

The heating power system is also related to the installation location. In the same area, the difference in the arrangement of the heating system at different heights is shown in Figure 5.

The main reason of the differences which airflow near the ground affected by surface obstacles. The effect is smaller at higher heights. Therefore, when the wind heating system is arranged, we should try to consider area where affected by external factors smaller. Take the operation data of 30m height and 10m height as an example, within 24 hours, the 30m height will capture at least 25% more energy than the height of the 10m. In addition, the higher position wind speed is relatively low, which is conducive to the smooth operation of the wind turbine.

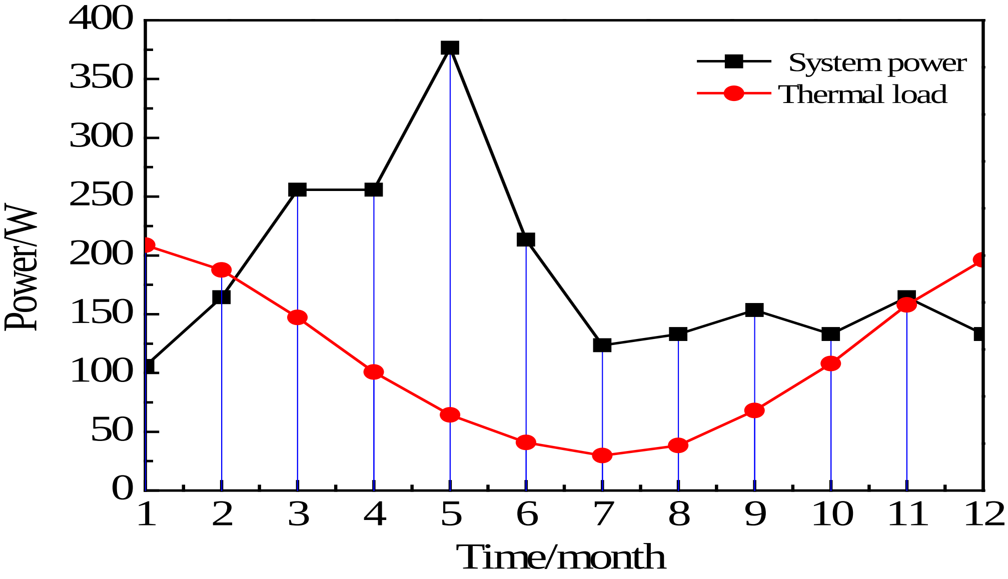

Fig. 4. Comparison of heating system power and thermal load.

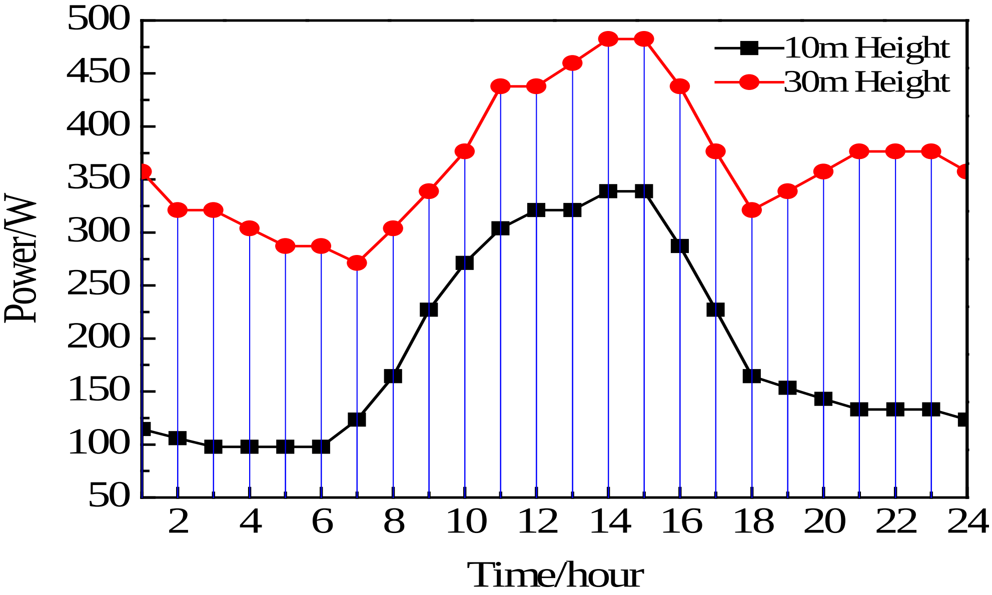

Fig. 5. Wind turbine power at different heights.

3.2 Wind Energy Utilization Coefficient of the Heating System

According to the structure parameters of wind turbine and airfoil parameters of blade, the relation curve between the tip speed ratio and the wind energy utilization coefficient is obtained as shown in Figure 6. It can be seen from the figure that when the wind speed is 3m/s, the utilization coefficient of wind energy decreases at 4 of the tip speed ratio. Under the other conditions of wind speed, when the tip speed ratio is less than 4, the utilization coefficient of wind energy is on the rise. Because of the NACA lift airfoil is chosen for the vertical axis wind turbine blade in this paper, it has higher utilization coefficient of wind energy under higher tip speed ratio. Therefore, the wind turbine should be operated at a high tip speed ratio. In general, wind turbines are mainly constant speed operation. In this case, the wind turbine is not always near the optimum power point. Therefore, considering the variable speed operation of the wind turbine, the optimal power point is tracked to maximize the energy capture. When the wind speed is constant, the power difference between the constant speed operation and the variable speed operation of the wind turbine is shown in Figure 7. It can be seen that the method of variable speed operation will effectively improve the wind energy capture efficiency of wind turbines. At the same time, the efficiency is more significant in the high wind speed region. Therefore, when matching the wind turbine with the heat generator, it is necessary to ensure that the wind turbine works in the best working range.

The control strategy of the wind turbine can be designed according to the curve shown in Figure 6. When wind speed changes, the maximum value of wind energy utilization coefficient can be calculated at this time according to the current wind speed. Then find out the corresponding speed ratio at this time, the corresponding rotation speed of wind turbine can be learned. Through control speed of rotor and achieve variable speed operation, the efficiency of heating system was improved significantly.

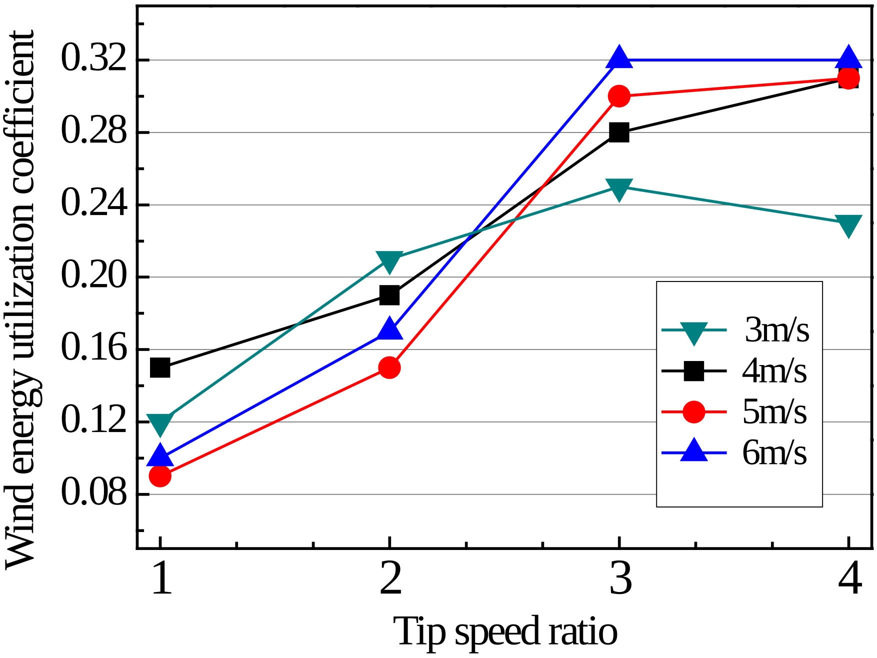

Fig. 6. Curve of wind energy utilization coefficient.

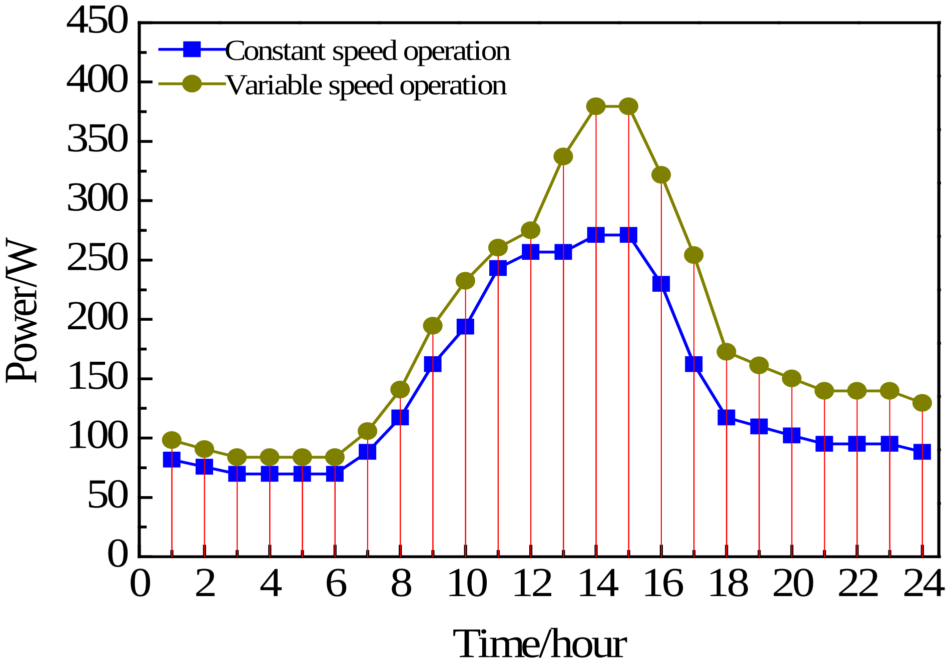

Fig. 7. Curve of operating power.

4. CONCLUSIONS

A. Under the condition that the wind turbine structure parameters and airfoil parameters are known, the corresponding relationship between the coefficient of wind energy utilization and the tip speed ratio can be obtained by the aerodynamics theory. Through reasonable correction, aerodynamic characteristics of wind turbines can be expressed.

B. Through the relevant meteorological data and operation characteristics of wind turbine, the reliability of the wind heating system to meet the needs of thermal users can be evaluated. At the same time, a reasonable configuration scheme can be given.

C. Compared with constant speed operation of wind turbine, variable speed operation can significantly improve the efficiency of wind energy utilization. The energy conversion efficiency of the heating system can be improved by controlling the speed of wind turbine.

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REFERENCES

[1] Kubik M.L., Coker P.J. and Barlow J.F., 2015. Increasing thermal plant flexibility in a high renewables power system. *Applied Energy*.154: 102-111

[2] Schlachtberger D.P., Becker S., Schramm S., and Greiner M., 2016. Backup flexibility classes in emerging large-scale renewable electricity systems. *Energy Conversion and Management* 125: 336-346.

[3] Zvingilaite E. and O. Balyk. 2014. Heat savings in buildings in a 100% renewable heat and power system in Denmark with different shares of district heating. *Energy and Buildings* 82: 173-186.

[4] Salpakari J., Mikkola, J. and Lund P.D., 2016. Improved flexibility with large-scale variable renewable power in cities through optimal demand side management and power-to-heat conversion. *Energy Conversion and Management*. 126: 649-661.

[5] Wang X., Li Y.G., Wang K., Zhang L.H., Weng J.H. and Wu M.L., 2015. Economy analysis of wind heating. *Renewable Energy Resources*. 33(1): 75-81.

[6] Liu Y. and Y.H. Hu. 2014. Parameter design of stirring wind thermal device. *Renewable Energy Resources* 35(10): 1977-1980.

[7] Zhao J.Z., Zong Y.F., Wang G.Y., Huang S.J. and Li G.J., 2014. Study of heating efficiency of layered-hydraulic stirring heating system. *Renewable Energy Resources* 35(6): 1034-1039.

[8] Guo X.S., Zhao Z.X. and Tang G.H., 2004. Experimental study on wind energy converting to heat by increasing fluid pressure and flow throttling. *Acta Energiae Solaris Sinica* 25(2): 157-161.

[9] Li Y.G., Zhang, Z.F., Wang, J.H., Zhang, L.H., Wu, M.L., Zhang, Y., Liang, M.H. and W Chen.2014.Experimental study of heating by stirring with wind power. *Journal of Shanghai University of Electric Power* 30(2): 111-114.

[10] Wang F.B., Zheng M.S., Teng H.P., Tian Y.Y., Zhu J.W., Zhou Y., Ma Y.P., Yu L.J. and Hu M.L., 2013. Matching of vertical resistance difference type wind turbine with magent eddy current induced heating. *Journal of Northwest University* 43(4): 545-548.

[11] Chen C.C., Chen J.Q. and Liu X.H., 2011. Application of eddy current in wind energy heating. *Power System and Clean Energy* 27(2): 71-73.

[12] Scungio M., Arpino F., Focanti V., Profili M. and Rotondi M., 2016. Wind tunnel testing of scaled models of a newly developed Darrieus-style vertical axis wind turbine with auxiliary straight blades. *Energy Conversion and Management* 130: 60-70.

[13] Zamani M., Nazari S., Moshizi S.A. and Maghrebi, M.J., 2016. Three dimensional simulation of J-shaped Darrieus vertical axis wind turbine. *Energy* 116: 1243-1255.

[14] Bedon G., Betta S.D. and Benini E., 2016. Performance-optimized airfoil for Darrieus wind turbines. *Renewable Energy*. 94: 328-340.

[15] Batista N.C., Melicio R., Mendes V.M.F., Calderon M. and Ramiro A., 2015. On a self-start Darrieus wind turbine: blade design and field tests. *Renewable and Sustainable Energy Reviews* 52: 508-522.

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