The 25th Conference of the Mechanical Engineering Network of Thailand
October 19 – 21, 2011, Krabi

Optimal speed for stall-regulated wind turbines in Thailand

Wikanda Sridech[1*] and Tawit Chitsomboon[2]

[1]School of mechanical engineering, Institute of engineering, Suranaree University of Technology
Nakhonratchasima 30000, Thailand
Tel. 0-4422-4410 Fax 0-4422-4411 [2] Email : tabon@sut.ac.th [*] Email winona13_me@hotmail.com

Abstract

The NREL-Phase VI wind turbine which is a stall-regulated, constant speed wind turbine was numerically simulated to determined its optimal annual energy outputs in two local wind statistics in Thailand. The BEM-based computer program "SuWiTStat-2" was used in the simulation. By varying the rotational speeds and tip pitch angles and by integrating with the annual wind statistics the optimal annual energy output could be determined. It was found that in different wind statistics both the rotational speeds and tip pitch angles should be adjusted. It is most likely that these adjusted values would be different from location to location as well as different from the manufacturer settings, in order to get an optimal annual energy output. The finding confirmed that adjustments are important to suit wind conditions in Thailand which are very different from those that were predetermined by the manufacturers.

Keywords: wind turbine, annual energy output, local wind statistics, optimum pitch, optimum rotational speed

1. Introduction

Most small to medium size wind turbines operate under the condition of constant rotational speed, in order to reduce its cost. This type of wind turbine is also called stall-regulated wind turbine. Commercial wind turbines available in the market are designed and optimized at theirs rated wind speeds and theirs wind statistics which are predetermined by the manufacturers. The rated wind speeds are often in the range of 12-14 m/s which is much beyond the wind regime in Thailand. As a result the rotational speeds are correspondingly too high. The cords, tapers, twists are also optimized by BEM-based codes [1],[2],[3] used by the manufacturers. As for the last three parameters, the customer can not change them; but for the tip pitch angles and the rotational speeds a sophisticated customer could modify them to suit his needs or he could ask the manufacturers to modify the speed and tip pitch.

In our previous works, stall-regulated wind turbine (NREL Phase VI) was studied by operating at its designed speed but at various adjusted pitch angles [14],[17],[18]. The optimum pitch angle was evaluated in order to produce the maximum annual energy yield. It was found that the optimum pitch angles were about 1-3 degrees off from the set angles and the energy outputs increased from the set pitch angle by about 2-5%.

We also found that winds of the same average speed but with different Weibul's parameters required different tip pitches to produce optimal energy yields.

Another crucial design parameter is the rotational speed. It is well established in wind turbine theory that for a given wind speed and blade configuration their exist an optimal rotational speed which produces the maximum power output. In stead of rotational speed, the linear speed of the blade tip is often normalized with the wind speed to become the tip speed ratio. In this study, we focus on optimizing the rotational speed of the NREL Phase VI turbine which is a stall-regulated wind turbine [5]. This turbined was rated at wind speed of 9 m/s.

Two sites in Thailand which have reasonably good winds will be selected in this study, namely: Huasai district of Nakornsrithammarat province and Doi Monlarn of Chiangmai Province. Since the average wind speeds of these two locations are quite lower than that used to design the NREL Phase VI turbine, we can expect that the optimal speeds for these two location would be correspondingly lower.

2. Methodology

The tool used to carry out this work is the BEM-based code named "SuWitstat-2." The BEM (Blade Element Momentum) theory is well established and is used widely in the industry to help design wind turbines.

BEM is based on mass, axial momentum and angular momentum conservation equations, together with airfoil data from experiment. Prediction of power by BEM depends on 2-D data from wind tunnel experiment, namely C_l and C_d. Even though the behavior of 2-D flow and 3-D flow at low angle of attack are rather similar but they are quite different at high angle of attacks because of the stall delay phenomena. Therefore the 2-D data should be corrected by corrective models. Conversion from 2-D to 3-D data requires Viterna-Corrigan model [2] and Corrigan-Schillings model [7] in order to enhance the accuracy of the program. Other corrective models are also required such as tip loss and hub loss model as seen in [6].

The modified program is named 'SuwitStat-2', after the first version 'SuWiTStat'. The accuracy of SuWiTStat-2 is the consequence of choosing the suitable corrective models. The Corrigan-Schillings model is applied to modify C_l and Viterna-Corrigan model is applied to modify C_d in order to provide a realistic increase in rotor power due to stall delay phenomena. Then the program is validated with the experimental data of NREL Phase VI (Fig.2) which was the results of a two-bladed rotor with the diameter of 10.1 m and the rated power of 19.8 kW, starting at the cut-in wind speed of 6 m/s.

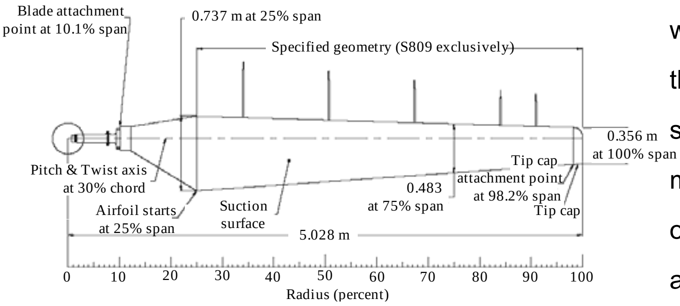

Fig. 2 size and geometry of NREL Phase VI

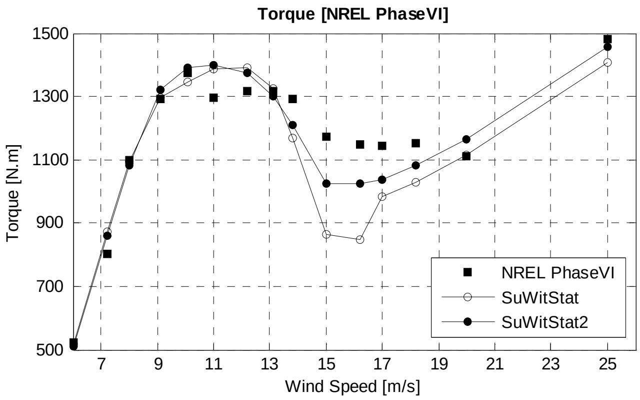

Fig. 3 Comparison of measured and predicted performance for the NREL Phase VI

From Fig.3 it is seen that the predicted power curve from SuWiTStat-2 agrees better with the experimental data of NREL Phase VI than that of SuWiTStat, especially at high wind speed range (19-25 m/s). At moderate wind speed range of 9-11 m/s, however, the predicted data from SuWiTStat-2 slightly over-predict the results of SuWiTStat.

3. Typical wind statistics

The probability distribution curves as seen in Figs. 4-5 show the wind characteristics in Doi Monlarn [15] and Huasia [16]. Obviously, the wind speed in Huasai is higher than Doi Monlarn remarkable from the skewness of Weibull's probability distribution. The scale parameter, c, is used to indicate how windy the site is (on average) and the shape parameter, k, tells where peaked the distribution is. From Fig.4, the value of c and k parameter from Doi Monlarn site are 6.34 and 2.69, respectively with the mean wind speed of 5.64 m/s whereas the value of c and k parameter from Huasai site are 7.98 and 2.02, respectively with the mean wind speed of 7.07 m/s as seen in Fig.5. According to the Weibull's parameters and the mean wind speeds of these 2 sites indicate that the wind site in Huasai is windier than the wind site in Doi Monlarn.

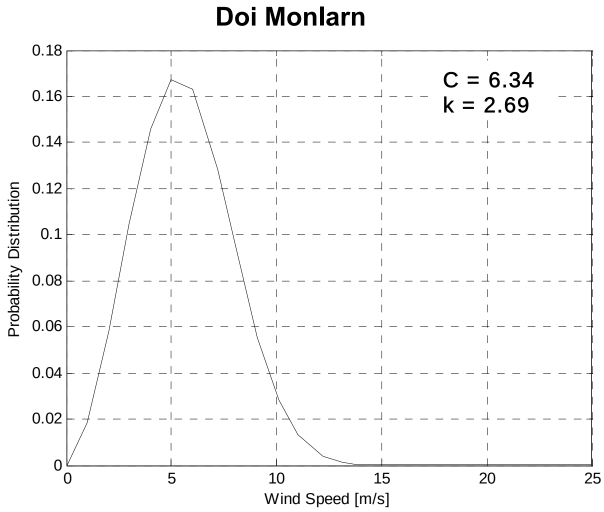

Fig.4 wind speed distribution at Doi Monlarn site

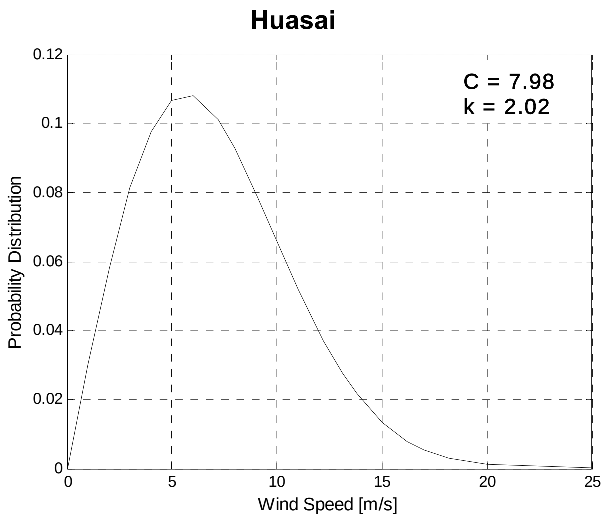

Fig.5 wind speed distribution at Huasai site

The annual yield can be obtained by integrating the combined effects of the predicted power and the probability curves as in the eq.(1),

$$P_{annual} = 8760 \int_u PDF \cdot P_t \, dV \quad (1)$$

where P_{annual} is the annual yield, PDF and P_t are the Weibull's probability density function and wind turbine power at instantaneous wind speed, respectively.

4. Results and discussion

The predicted data by solely optimized pitch angle are shown in Table 1. The results show that the pitch variation of the wind turbine operating under 2 local wind characteristics collected from 2 provinces have influences on the annual yields. The predicted results could illustrate that the annual yields tend to increase when pitch angles were varied from the design tip pitch angle (3 degree). The maximum annual works for Doi Monlarn and Huasai site were achieved at the tip pitch angle of 1 and 4 degree, respectively.

Table 1 The annual work by optimizing tip pitch angle in 3 provinces

Tip Pitch	Annual work [MW.h/year]	
	Doi Monlarn	Huasai
-4	2.86	2.38
-3	3.21	2.93
-2	3.49	3.45
-1	3.67	3.88
0	3.76	4.26
1	**3.78**	4.57
2	3.70	4.77
3	3.55	4.90
4	3.35	**4.96**
5	3.08	4.94

Due to the diversity of wind characteristic in various observed sites, the rotational speed of stall-regulated wind turbine which was designed based on a specific wind data should be optimized for a proper operation in a local wind characteristic. In this study, *tip pitch and rotational speed* were simultaneously varied in order to search for the maximum annual work. The effect of tip pitch and rotational speed on the annual work in Doi Monlarn and Ubonratchathani are shown in Figs.6-7 and Tables 2-3. In Figs.6-7, the local peaks of the annual work were obtained as the consequence of the rotational speed variation. The maximum annual work, 54.92 MW.h/year for Doi Monlarn site, occurred at the tip pitch and the rotational speed take values of -1 degree and 12.5 rad/s, respectively. Likewise, the maximum annual work for Huasai site is equal to 132.28 MW.h/year occurred at the tip pitch and the rotational speed take values of -1 degree and 18.5 rad/s, respectively.

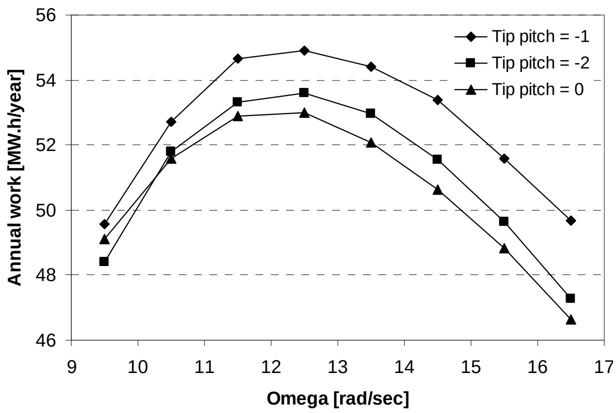

Fig.6 Effect of the rotational speed on the annual yield in Doi Monlarn.

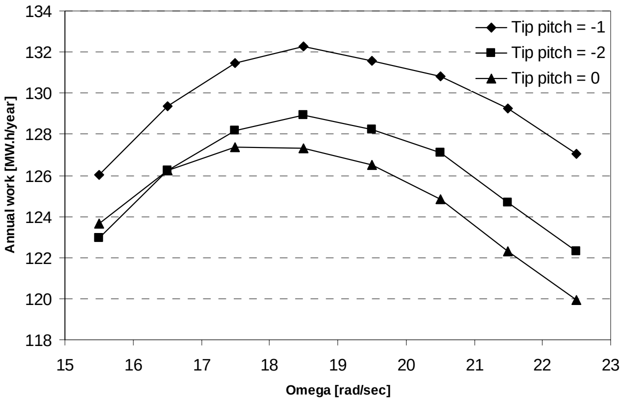

Fig.7 Effect of the rotational speed on the annual yield in Huasai.

Table 2 The annual work in MW.h/year by optimizing rotational speed at Doi Monlan

omega [rad/sec]	Tip pitch [degree]				
	β = -3	β = -2	β = -1	β = 0	β = 1
4.5	4.77	6.34	7.34	8.65	9.83
5.5	11.27	13.63	15.95	17.90	19.34
6.5	21.95	24.47	26.76	28.68	29.41
7.5	32.14	34.94	36.71	37.63	37.76
8.5	40.30	42.87	44.35	44.58	43.64
9.5	45.95	48.40	49.57	49.09	47.01
10.5	49.27	51.81	52.71	**51.59**	48.71
11.5	**50.36**	53.32	54.67	52.91	**49.14**
12.5	50.07	**53.61**	**54.92**	**52.98**	48.19
13.5	48.88	52.97	54.42	52.08	46.79
14.5	46.90	51.55	53.40	50.62	44.76
15.5	44.52	49.63	51.57	48.81	41.91
16.5	41.84	47.25	49.66	46.64	39.13
17.5	38.75	45.15	47.52	43.97	38.20

Table 3 The annual work in MW.h/year by optimizing rotational speed at Huasai

omega [rad/sec]	Tip pitch [degree]				
	β = -3	β = -2	β = -1	β = 0	β = 1
11.5	84.12	90.80	95.70	96.83	95.73
12.5	94.97	101.92	105.90	106.50	103.66
13.5	104.00	111.05	114.42	113.98	109.75
14.5	110.85	117.89	121.23	119.68	113.98
15.5	115.62	122.95	126.04	123.65	116.22
16.5	118.47	126.23	129.36	126.23	117.42
17.5	119.55	128.21	131.47	**127.36**	**119.23**
18.5	**120.05**	**128.95**	**132.28**	127.34	115.92
19.5	118.89	128.22	131.56	126.51	114.40
20.5	116.51	127.12	130.80	124.86	111.43
21.5	113.96	124.70	129.24	122.29	108.19
22.5	110.86	122.28	127.03	119.93	103.86
23.5	107.47	119.41	124.82	117.01	99.56
24.5	103.78	115.86	122.60	113.13	95.35

Table 4 The annual work produced by the original WT, the optimum tip pitch WT and the optimum tip pitch + optimum rotational speed

	Annual work [MW.h/year]		
	original	opt. tip pitch	opt. (pitch+omega)
Doi Monlarn	35.49	37.76	54.92
Huasai	49.01	49.58	132.28

Interestingly, the increasing value in the maximum annual works by optimizing both tip pitch and rotational speed are beyond expectation as shown in Table 4. The percent increasing is approximately 45% for Doi Monlarn site and 167% for Huasai site. It is worthy of considering the smaller generator which slower rotates than the bigger one, in order to gain more power especially in the low wind sites.

5. Conclusions

This paper presents the results from the code, based on BEM and Weibull's PDF at 2 sites. The code was used to design for optimum tip pitch and optimum rotational speed for a stall-regulated wind turbine operating on year-round basis on 2 different wind statistics. It was found that rotational speed should be varied from the design point (7.5 rad/s) in order to enhance the maximum annual work in other cases and tip pitch should be re-adjusted to find the new optimum point as well. Different tip pitch and rotational speed provided the maximum annual work approximately 100% higher than of the original design. This proves that design of a stall-regulated wind turbine in accordance with the known local wind statistics is important for the economy of a commercial endeavor.

References

[1] Spera, A.D., "Wind Turbine Technology : Fundamental Concept of Wind Turbine Engineering", ASME Press, 1994

[2] Eggleston, D.M. and Stoddard F. S., "Wind Turbine Engineering Design", Van Nostrand Company, 1987

[3] Burton, T. et al., "Wind Energy Handbook", John Wiley & Son, 2001

[4] Manwell, J. F., McGowan J.G. and Rogers A.L., "Wind Energy Explained", John Wiley & Son, 2002

[5] Jonkman, J. M., "Modeling of the UAE Wind Turbine for Refinement of FAST_AD", *NREL/TP-500-34755*, National Renewable Energy Laboratory, Colorado, 2003

[6] Viterna, L .A., and Corrigan, R. D., "Fixed Pitch Rotor Performance of Large Horizontal Axis Wind Turbines," DOE/NASA Workshop on Large Horizontal Axis Wind Turbines, Cleveland, Ohio, July 1981.

[7] Tangler, J.L. and Selig , M.S., "An Evaluation of an Empirical Model for Stall Delay due to Rotation for HAWTS", NREL/CP-440-23258, National Renewable Energy Laboratory, Colorado, July 1997.

[8] Tangler, J.L. and Kocurek , J.D., "Wind Turbine Post-Stall Airfoil Performance Characteristics Guidelines for Blade-Element Momentum Methods", NREL/CP-500-36900, National Renewable Energy Laboratory, Colorado, October 2004.

[9] Moriarty P.J. and Hansen A.C., "AeroDyn Theory Manual", NREL/TP-500-36881, January 2005

[10] Lanzafame, R., and Messina, M., "Fluid dynamics wind turbine design: Critical analysis, optimization and application of BEM theory". Renew Energy (2007), doi:10.1016/j.renene.2006.12.010

[11] Simms, D. A., Hand, M. M., Fingersh, L.J., Jager, D.W., "Unsteady aerodynamics experiment Phases II–IV test configurations and available data campaigns", National Renewable Energy Laboratory, Colorado, July 1999.

[12] Simms, D.A., Hand, M. M., et. al., "Unsteady aerodynamics experiment Phases VI: Wind tunnel test configurations and available data campaigns", NREL/TP-500-29955, National Renewable Energy Laboratory, Colorado, December 2001.

[13] Freris, L.L., 1990, “Wind Energy Conversion Systems”

[14] Sridech, W. and Chitsomboon, T., “Optimal stall-regulated wind turbines in unique local wind statistic” Proceedings of the 7th Conference on Energy Network of Thailand, 3-5 May 2011, Phuket, Thailand.

[15] กว้าน สีตะธานี, การวิเคราะห์พลังงานลมในประเทศไทย, วิทยานิพนธ์ ปริญญาวิทยาศาสตรมหาบัณฑิต, สาขาเทคโนโลยีพลังงาน, คณะพลังงานและวัสดุ, มหาวิทยาลัยเทคโนโลยีพระจอมเกล้าธนบุรี.

[16] ชนะ จันทร์ฉ่ำ, นฤทธิ์ กล่อมพงษ์, วรพงศ์ พวงแก้ว และ จอมภพ แววศักดิ์, การวิเคราะห์ศักยภาพลมบริเวณอำเภอหัวไทรในจังหวัดนครราชศรีธรรมราช, วารสารมหาวิทยาลัยทักษิณ ปีที่ 12 ฉบับที่ 2, กรกฎาคม-ธันวาคม 2552.

[17] วิกันดา ศรีเดช และ ทวิช จิตรสมบูรณ์, การออกแบบกังหันลมให้สอดคล้องกับสถิติลมจำเพาะพื้นที่, การประชุมวิชาการเครือข่ายวิศวกรรมเครื่องกลแห่งประเทศไทยครั้งที่ 22, มหาวิทยาลัยธรรมศาสตร์ ศูนย์รังสิต

[18] วิกันดา ศรีเดช และ ทวิช จิตรสมบูรณ์, มุมเผินที่ดีที่สุดของใบกังหันลมสำหรับสถิติลมจำเพาะพื้นที่, การประชุมเชิงวิชาการเครือข่ายพลังงานแห่งประเทศไทยครั้งที่ 4, มหาวิทยาลัยศิลปากร จังหวัดนครปฐม

Biography

1. Wikanda Sridech

Ph.D. Candidate (Mechanical Engineering) at Suranaree University of Technology since 2008. Fields of research are wind turbine aerodynamics and computer aided design.

2. Assoc. Prof. Dr. Tawit Chitsomboon

Ph.D. : 1986, in Mechanical Engineering. Worked as a research engineer with NASA Langley Research Center, USA, (7 years); GE Aircraft Engines (1 year); NASA Lewis Research Center (5 years); and has been teaching at Suranaree University of Technology, Thailand, since 1995. Fields of research are: wind turbine aerodynamics; solar chimney power plant; grain drying; solar still; natural ventilation; CFD; optimization; heat removal from power plant; appropriate technology for rural applications; mechanical anthropology; and others. Published about 60 research papers in journals and conference proceedings.