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Power Curve of a Wind Generator Suitable for a Low Wind Speed Site to Achieve a High Capacity Factor

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Abstract – It is well known that energy generated by a wind generator (WG) depends on the wind resources at the installation site. In other words, a WG installed in a high wind speed area can produce more energy than that in a low wind speed area. However, a WG installed at a low wind site can produce a similar amount of energy to that produced by a WG installed at a high wind site if the WG is designed with a rated wind speed corresponding to the mean wind speed of the site. In this paper, we investigated the power curve of a WG suitable for Korea's southwestern coast with a low mean wind speed to achieve a high capacity factor (CF). We collected the power curves of the 11 WGs of the 6 WG manufacturers. The probability density function of the wind speed on Korea's southwestern coast was modeled using the Weibull distribution. The annual energy production by the WG was calculated and then the CFs of all of the WGs were estimated and compared. The results indicated that the WG installed on the Korea's southwestern coast could obtain a CF higher than 40 % if it was designed with the lower rated speed corresponding to the mean wind speed at the installation site.

Keywords: Capacity factor, Weibull distribution, Mean wind speed, Power curve, and Wind generator

1. Introduction

Wind energy has become a key solution to environmental problems such as climate change, ozone and resource depletion, and water and air pollution. In addition, wind power generation has already achieved grid parity in some countries due to technological advances and economic viability. On the other hand, the price of oil has increased significantly since the early 2000's and, therefore, the prices of primary sources (coal, natural gas, and oil) of electrical energy have increased as well. Countries with fewer primary energy sources, in particular, are keen on finding solutions in order to achieve energy security.

In Korea, approximately 180 billion USD were spent on importing 265 million tons of oil equivalence (TOE), such as fossil fuel and nuclear fuel, for primary energy from overseas countries in 2011 [1], which corresponds to 96.5 % of Korea's total primary energy. More than 25 % of the primary energy was wasted during the conversion process from primary energy to final energy. The conversion loss was primarily caused by electricity generation since the average conversion rate from primary energy to electrical energy is approximately 40 %. Therefore, approximately 36% of the primary energy is estimated to be used for electricity generation, while electrical energy shares less than 20% of the final energy such as fuel oil, heat, natural gas, and electrical energy. As a result, renewable energy will play a very important role in reducing the import of primary energy in Korea.

On the other hand, Korea has the geographical potential for wind energy of 550 TWh, which includes 145 TWh from onshore and 405 TWh from offshore locations [2]. This statistic indicates that Korea's wind potential is large enough to cover nearly 93 % of the electricity consumption, which is predicted to be 590 TWh in the year 2020 [3].

Global wind power generation has grown substantially during the last decade. The global installed capacity of wind generation was 282 GW in 2012 and is expected to reach 536 GW by 2017 [4]. In Korea, the installed capacity of wind generation was approximately 482 MW in 2012 and a 2.5 GW offshore wind power plant (WPP) project was started on the southwestern coast [5, 6] in 2011. This project consists of three stages. During the first stage, a 100 MW WPP will be constructed by 2014 and during the second stage, a 400 MW WPP will be constructed for diffusion by 2016. During the final stage, a 2,000 MW WPP will be constructed by 2019 for commercial operation.

The levelized cost of energy (LCOE) is a metric used to evaluate the economic value of an energy-generating system. The LCOE is defined as the ratio of the life-cycle cost of generation, which includes all of the costs (initial investment cost, operation and maintenance costs, capital cost, etc.), to the energy generated over its lifetime. Wind

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generation requires a large amount of initial investment cost compared with conventional generating units. Therefore, the LCOE for wind energy is large, and a longer investment payback period for wind generation is inevitable. Although wind energy has achieved grid parity in some countries, the LCOE of wind energy is still high compared with conventional thermal power generation. Therefore, the reduction of the LCOE of wind energy is essential in order to enhance the economic value of wind energy.

There are many ways to reduce the LCOE of wind energy, i.e., to reduce the total cost and/or to increase the generated energy. In addition, it is very difficult to evaluate the LCOE, because all of the costs depend on the installation site. Therefore, we only focused on increasing the energy generated by a wind generator (WG) in this paper.

A capacity factor (CF), which is defined as the ratio of the actual generated energy to the potential generated energy, is directly related to the generated energy. In other words, a WG with a higher CF will generate more energy. Therefore, the CF of a WG is also used in order to evaluate the economic value of the wind generation. In addition, a high CF will help achieve high wind energy penetration without the installation of many WGs. The CF of a WG depends on the generated energy of the WG, which is calculated using its power curve and the wind resources at the installation site. Therefore, it is known that a WG installed at a high wind speed site can produce more energy in a cost-efficient manner.

On the other hand, the mean wind speed on Korea's southwest coast is lower than that in Northern Europe and it belongs to Class III or IV, where the mean wind speed is less than 7.5 m/s, as specified in the International Electrotechnical Commission (IEC) [7]. Therefore, if the WGs suitable for the wind conditions in the European countries such as Denmark and Germany are installed on Korea's southwestern coast, then a low CF is inevitable. However, if the WG is designed with the rated wind speed suitable for the mean wind speed at the installation site, then the generated energy will increase.

Several studies on the CF of WGs have been conducted [8-11]. In [8], the potential assessment of the wind resource from the HEMOSU-1 was performed on Korea's southwestern coast in 2011. The HEMOSU-1 is an offshore meteorological tower used to assess the potential of offshore WG. The mean wind speed on the southwestern coast of Korea is approximately 6.08-7.12 m/s, which is significantly lower than that of Northern Europe. The CFs of six WGs from three WG manufacturers with rated wind speeds above 12 m/s were calculated with the wind speed data measured on Korea's southwestern coast. In [9], the installation site's potential was evaluated by monthly and annual CFs using three kinds of mean wind speed data: arithmetic mean, root mean, and cubic mean wind speed. In [10], the factors influencing the CF were analyzed. Among these, such as cut-in, cut-out, and rated wind speed of the WG, the rated wind speed had a strong effect on the CF. In [11], a program was developed to select the proper WG in terms of the CF. However, the characteristics of the power curve in the region below the rated wind speed of the WG, which is the most important factor for producing a large output, were not analyzed in [11].

In this paper, we investigated the power curve of a WG suitable for Korea's southwestern coast with a low mean wind speed to achieve a high CF. To reduce the LCOE of wind energy, this paper only focused on increasing the generated energy, which is related to the CF. The 11 commercial WGs of the six manufacturers with different rated wind speeds, rated powers, and blade lengths, as well as the probability density function of the wind speed on Korea's southwestern coast, were used. In this paper, the probability density function of the wind speed on Korea's southwestern coast was modeled as the Weibull distribution. At first, the wind energy was calculated using the power curves of the WGs and the wind speed distribution. Then, the CFs of the 11 commercial WGs were estimated and compared. Finally, the power curve suitable for Korea's southwestern coast to obtain a high CF was suggested.

2. Procedure for Calculating the CF of a WG

The CF of a WG is the ratio of the actual generated energy to the total potential generated energy. In designing a WPP, the CF of the WG is very crucial to the economic viability, because a higher CF guarantees a higher return on investment (ROI). In order to calculate the CF, the power curve of a WG and the probability density function of the wind resources at the installation site are needed. In this section, a typical procedure for calculating the CF of a WG will be described.

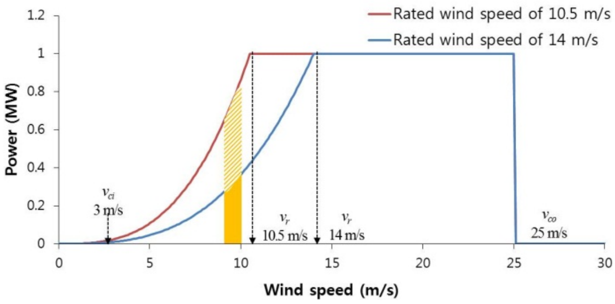
Fig. 1 shows the calculation process of the annual energy production (AEP) of a WG. Fig. 1a shows the typical power curves of the two WGs with the rated power (P_{rated}) of 1 MW. They have different rated wind speeds (v_r) of 10.5 m/s and 14 m/s, while their cut-in wind speed (v_{ci}) and cut-out wind speed (v_{co}) are the same, 3m/s and 25m/s, respectively.

The power (P_{mech}) transformed from the wind to the WG can be represented by:

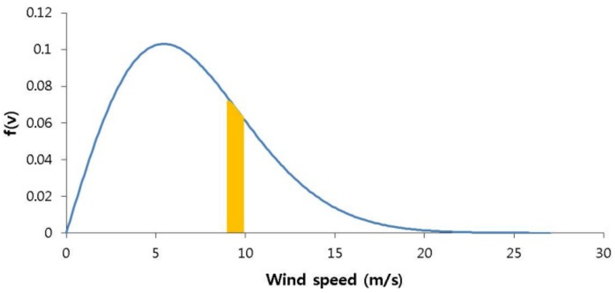
$$P_{mech}(v) = \frac{1}{2}\rho\pi R^2 v^3 c_P \quad (1)$$

where ρ is the air density, R is the blade length, v is the wind speed, and c_P is the power coefficient.

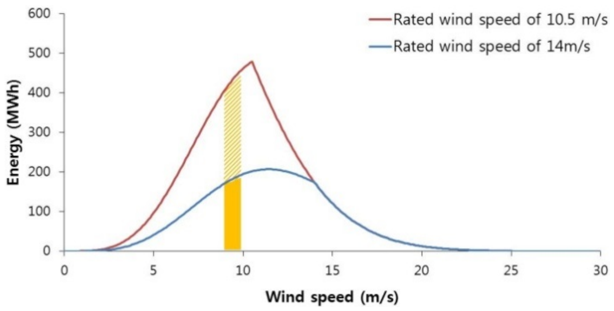
In the region below the v_r, the WG is typically operating in a maximum power point tracking (MPPT) control mode to produce the maximum power. To achieve this, the c_P is typically set to the maximum value and, therefore, the output power is typically proportional to the cubic of v depending on R. Therefore, a WG with a larger blade



(a) Power curves of two WGs



(b) Wind speed distribution of HEMOSU-1 [7]



(c) AEP

Fig. 1. Calculation of the AEP of a WG

generates a higher output than that with a smaller blade in the MPPT region. In Fig. 1a, the blade lengths of the WGs with a v_r of 10.5 m/s and 14 m/s are 43 m and 27.9 m, respectively.

On the other hand, a typical wind speed distribution can be represented as the Weibull distribution,

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{\left(\frac{v}{c}\right)^k} \tag{2}$$

where k and c are the shape parameter and scale parameter, respectively. The wind speed distribution depends on the measured height and the site, which affect the Weibull distribution parameters. k can be obtained using the standard deviation and the mean wind speed, while c can be obtained using the mean wind speed and the gamma function of k [9].

Fig. 1(b) shows the wind speed distribution on Korea's southwestern coast, which was based on the measured wind speed data of HEMOSU-1 at 96.31 m in 2011. k and c of the wind speed distribution are 1.87 and 7.82, respectively. The mean wind speed is 6.94 m/s [7].

The AEP of a WG can be represented by multiplying the power curve of a WG by the wind speed distribution, section by section, and can be expressed as:

$$\text{AEP} = 8,760\sum_{i=1}^{N_v} f_i P(v_i) \tag{3}$$

where N_v is the number of wind speed values, f_i is the discrete probability distribution of the wind speed in bin i, v_i is random variable representing the wind speed in bin i, and P is the power of the WG.

The first step of calculating the AEP of a WG is as follows. If the frequency at a wind speed (yellow region in Fig. 1b) is multiplied by 8,760, then the cumulative time data for the wind speed for one year is obtained. Then, if the power curve at the corresponding wind speed is multiplied by the cumulative time data, the generated wind energy for one year is obtained as shown in Fig. 1c. Summing the wind energy production along with the wind speed provides the AEP of a WG.

Finally, the CF is calculated by:

$$CF = \frac{\text{AEP}}{8,760 \times \text{P}_{\text{rated}}} \times 100(\%)$$

The AEPs and CFs of WGs with v_r values of 10.5 m/s and 14 m/s are 3.29 GWh and 37.6 % and 1.87 GWh and 21.3 %, respectively.

These results clearly indicate that a WG with a smaller rated wind speed produces more AEP than that with a larger rated wind speed and, consequently, the former has a higher CF than the latter.

As the CF is proportional to the actual energy, a high CF guarantees a high ROI. That is why the CF of a WG is crucial to its economic viability for designing a WPP.

3. Power Curve of a WG Suitable for an Offshore WPP for a High CF

As mentioned in the Introduction, Korea started a 2.5-GW offshore WPP project on the southwestern coast in 2011. The construction will be completed by 2019 and more than 9 billion USD are to be invested in the project. In general, the total installation cost of an offshore WPP is estimated to be approximately twice that of an onshore WPP. Therefore, the generated energy of an offshore WPP should be more than that of an onshore WPP to guarantee the economic viability.

In order to generate more energy, high wind resources are necessary. However, the mean wind speed on Korea's southwestern coast is approximately 6.08-7.12 m/s [7], which belongs to the IEC wind class III or IV and is significantly lower than the mean wind speed of Northern Europe. Thus, installation of WGs that are suitable for Northern Europe on Korea's southwestern coast will produce less generated energy and, in turn, a lower CF. As a result, more investment is inevitable in order to achieve a high wind energy penetration level and, therefore, the LCOE of wind energy will remain high.

We collected the power curves of 11 commercial WGs from six WG manufacturers that had different rated wind speeds, rated capacities, and blade lengths to determine a WG suitable for Korea's southwest coast. They were used to determine Korea's southwestern coast wind conditions to estimate the AEP and CF. In addition, we compared the power curves of the WGs with the same rated wind speed and different blade lengths in terms of the CF. Finally, the power curve of a WG suitable for Korea's southwestern coast was suggested to guarantee the high CF.

3.1 Power curves of the commercial WGs

Table 1 shows the characteristics of the 11 commercial WGs, which had different rated wind speeds, rated powers, and blade lengths. The 11 WGs were UP77 and UP82 from United Power; MM100, 5M, and 6M from REpower; S95 and S97 from Suzlon; V112-3MW and V164-8MW from Vestas; SWT-3.6-107 from Siemens; and E-126 from Enercon [13-21]. Fig. 2 shows the power curves of the 11 WGs. However, the Korean manufacture s' WGs were not included in this paper, because they are still under development.

Table 1. Characteristics of the commercial WGs

Company	Model	P_{rated} (MW)	v_{ci} (m/s)	v_r (m/s)	v_{co} (m/s)	R (m)
United power	UP77	1.5	3	10.5	25	38.7
Repower	MM100	1.8	3	10.5	22	50
United power	UP82	1.5	3	11	25	41.4
Suzlon	S95	2.1	3.5	11	20	47.5
Suzlon	S97	2.1	3.5	11	25	48.5
Vestas	V112-3MW	3	3	12	25	56
Repower	5M	5	3.5	13.5	30	63
Vestas	V164-8MW	8	4	13.5	25	82
Siemens	SWT-3.6-107	3.6	3−5	14	25	53.5
Repower	6M	6.15	3.5	15	30	63
Enercon	E-126	7.58	3	17	32	63.5

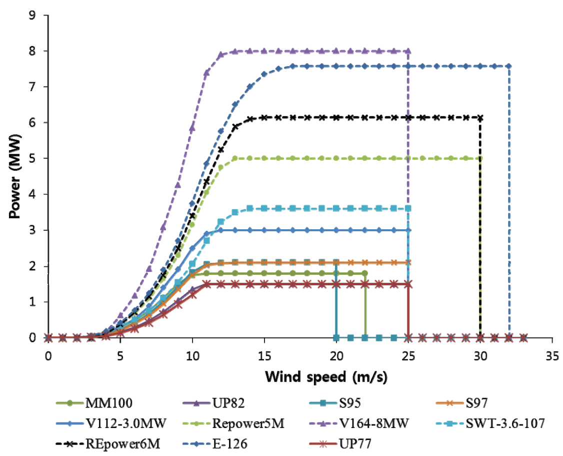


Fig. 2. Power curves of the 11 commercial WGs [13-21]

3.2 CFs of the commercial WGs

In order to determine a WG suitable for a low wind speed area such as Korea's southwestern coast, the AEPs and CFs of the commercial WGs shown in Table 1 were evaluated with the wind distribution on Korea's south-western coast and are shown in Table 2.

As mentioned in Section 2, at lower wind speeds, the CF of a WG with a smaller rated wind speed is higher than that of a WG with a larger rated wind speed. To verify this, Fig. 3 shows the mean CF of the WGs with the same rated wind speed. The mean CF of UP77 and MM100 with the smallest rated wind speed (10.5 m/s) was 39.8 % and the mean CF of E-126 with the largest rated wind speed (17 m/s) was 25.2 %. The mean CF of the WGs with the smallest rated wind speed was 158 % greater than that of the WGs with the largest rated wind speed. These results indicate that a WG with a smaller rated wind speed can achieve a larger CF at a low wind speed site.

Table 2. AEP and CFs of the commercial WGs

Company	Model	v_r (m/s)	P_{rated} (MW)	AEP (GWh)	CF (%)
United power	UP77	10.5	1.5	4.7	35.8
Repower	MM100	10.5	1.8	6.9	43.9
United power	UP82	11	1.5	5.0	38.3
Suzlon	S95	11	2.1	7.0	37.8
Suzlon	S97	11	2.1	6.8	36.7
Vestas	V112−3MW	12	3	9.7	36.9
Repower	5M	13.5	5	13.4	30.6
Vestas	V164−8MW	13.5	8	23.3	38.1
Siemens	SWT−3.6−107	14	3.6	9.3	29.4
Repower	6M	15	6.15	14.9	27.6
Enercon	E−126	17	7.58	16.7	25.2

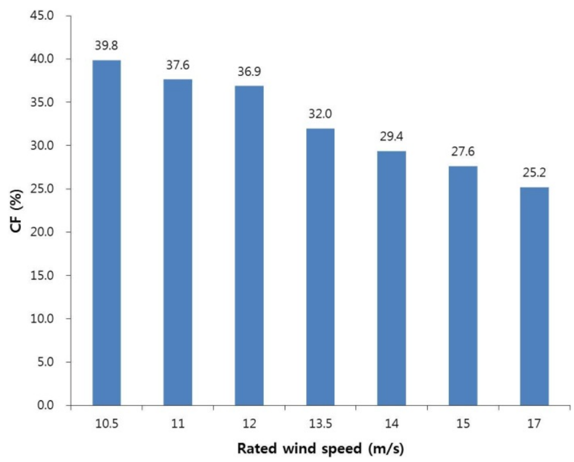
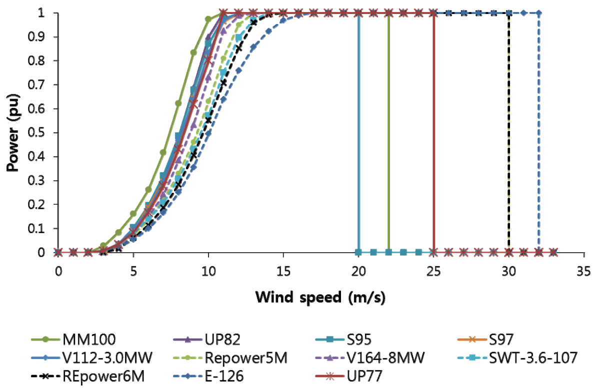
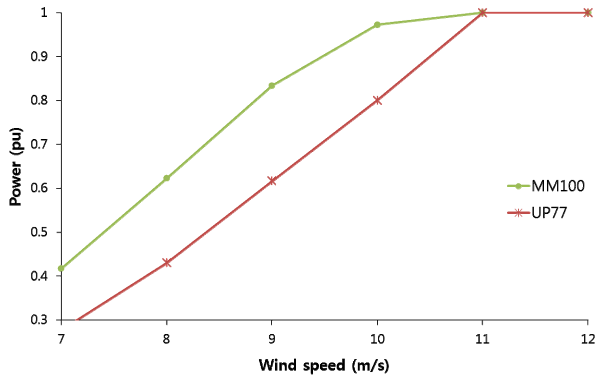


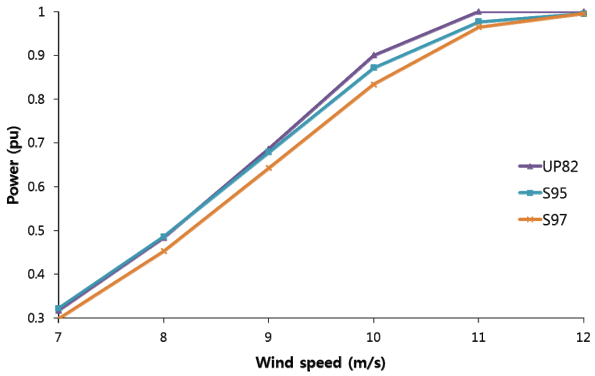
Fig. 3. Average CFs of the commercial WGs with the rated wind speed



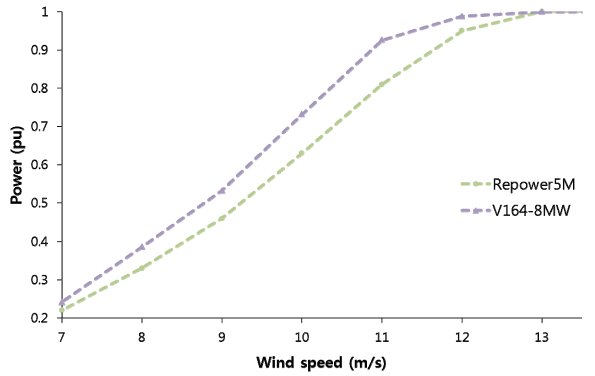
(a) Normalized power curves



(b) For the rated wind speed of 10.5 m/s



(c) For the rated wind speed of 11 m/s



(d) For the rated wind speed of 13.5 m/s

Fig. 4. Normalized power curves of the commercial WGs

The mean CF of UP77 and MM100 with the lowest v_r (10.5 m/s) was 39.8 % and the mean CF of 6M with the highest v_r (17 m/s) was 25.2 %.

On the other hand, as noted in Section 2, the output power was assumed to be proportional to the cube of the wind speed in the region below the v_r. However, it should be noted that the WGs with the same v_r had different CFs. To analyze this, the power curves of the commercial WGs were normalized and are shown in Fig. 4(a). Figs. 4(b)-(d) show the expanded power curves below the v_r for v_r values of 10.5 m/s, 11 m/s, and 13.5 m/s, respectively.

For a v_r of 10.5 m/s, the CFs of MM100 and UP77 were 43.9 % and 35.8 %, respectively, as shown in Fig. 4(b). It should be noted that the area of MM100 between the power curve and the wind speed axis below the v_r was larger than that of UP77. Similarly, as shown in Fig. 4(c) for the v_r of 11 m/s, the CFs of UP82, S95, and S97 were 38.3 %, 37.8 %, and 36.7 %, respectively. In addition, for a v_r of 13.5 m/s, the CFs of V164-8MW and 5M were 38.1 % and 30.6 %, respectively.

These results clearly indicate that the CF of a WG depends on the area under the power curve below the v_r. In other words, the larger the area is, the higher the CF is. Among the CFs in this study, the CF of MM100 was the largest, because the area below the v_r was the largest. On the other hand, the cut-out speed did not have a large effect on the CF.

4. Conclusions

In this paper, we investigated the power curve of a WG suitable for an offshore WPP on Korea's southwestern coast with a low mean wind speed to achieve a high CF. The power curves of the 11 commercial WGs with different rated wind speeds, rated powers, and blade lengths were applied in order to determine the wind distribution on Korea's southwestern coast.

The results clearly indicated that using a WG with a smaller rated wind speed ensures a higher CF. In addition, a larger area under the power curve below the rated wind speed guarantees a higher CF. Therefore, in a low wind speed area, such as that on Korea's southwestern coast, a WG with a lower rated wind speed of 10.5 m/s or less is suitable for a high CF.

A WG with a lower rated wind speed requires longer blades and, therefore, the production cost will be increased. However, the production cost depends on the manufacturers and is out of the scope of this paper. This paper only addressed the requirements for a higher CF. The LCOE, as well as the CF, should be considered when evaluating the economic viability of WGs. Countries, including China, will support the subsidy depending on the wind class.

Acknowledgements

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