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Power Prediction of Wind Turbine Based on The Presumed Shape of Power Curve

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ABSTRACT
An accurate model of power plays a crucial role in turbine energy assessment, wind turbine condition monitoring, estimation of wind energy potential, warranty formulations, power forecasting, wind turbine selection, optimization of the operational cost and expansion of windfarm. To achieve all these, algorithms of linear and cubic law models are used to predict the output power of BWC Excel 10 wind turbine. The comparative results show that the considered models can approximate and satisfactorily predicts the output power of wind turbines when compared with fundamental equation of wind turbine that depends on stringent factors like air density, turbine blade parameters, mechanical and control issues etc to yield similar results.

Keywords : BWC Excel wind turbine, Cubic law mode, Linear model, Power curve, Renewable energy, Wind energy conversion system

I. INTRODUCTION

The increasing need for electrical energy in the modern-day activities, together with the depletion of fossil fuel reserves and increasing concern around the globe over the environmental negativity of rising level of carbon dioxide (CO_2), the need to diversify energy sources to enhance energy security, quality and reliability have led to several changes in energy sector and its policies [1, 2]. Renewable energy (RE) resources especially solar and wind are now in the fore front of replacing the conventional synchronous generation. U.S and South Korea efforts to increase the percentage of electricity generation from solar and wind to 20% of the total energy production by 2030 is an indication that RE generation has come to stay [2, 3]. In the European Union the percentage of RE extended to 32% of electricity generation and 18% of the entire energy consumption in 2018 , these shares are intended to rise to 50% of the electricity and 32.5% of the entire energy by 2030 [4]. Among the RE generation, wind power system has become a global and one of the major contributor to achieving a sustainable energy in the modern power systems and for the realization of this project, correct estimation of the power generated is very vital [5, 6]. In wind energy sector, power curve is useful in expressing the performance of turbine and is also a vital input to planning and achieving a reliable and efficient wind farm design [7]. The electrical output of wind turbine at a particular height of the hub is a function of wind speed, and is usually represented using power curve. The precision of this curve is helpful in turbine energy assessment, wind turbine condition monitoring, estimation of wind energy potential, warranty formulations, power forecasting, and wind turbine selection [2, 8, 9].

Mathematical modelling is an indispensable tool used in sciences and engineering, it prepares a path for an excellent design and cost-effective systems. Proper understanding of all the components part and how they affect or stimulate the operation of the system is a precondition for accurate modelling [10]. This paper presents the deterministic means of predicting wind turbine power output using the algorithms of linear and cubic models. Deterministic forecasting refers to the single-point prediction result, i.e., the expectation of future wind power from the mathematical view [11]. These model uses the cut-in speed, nominal speed, furling speed and the power rating of the turbine for the analysis and does not require much difficult technical details. The traditional way of modelling power output of wind turbine uses the basic equation to determine amount of power present in the wind. However, this is an ideal case and does not always represent the real behaviour of wind turbine. The particular site of turbine, air density, the rotational speed of turbine, wind speed distribution, wind direction, mechanical and control issues, uncertainties in measurements, and turbine blade parameters (e.g angle of attack, pitch angle etc.) are some reasons which may cause empirical power curves differ from theoretical ones [3]. In order to effectively analyse the performance of these models, a commercially available wind turbine, specifically BWC Excel wind turbine actual output power was used to achieve a comparative assessment test.

II. METHODOLOGY

Deterministic prediction using the concept of linear and cubic law is adopted. This forecasting method refers to the single-point prediction result, i.e., the expectation of future wind power from the mathematical view [11]. These model uses the cut-in speed, nominal speed, furling speed and the power rating of the turbine for the analysis. For graphical comparative analysis, power curves are plotted.

Typical Power Curve

A typical hypothetical power curve issued by wind turbine industry and assessed under ideal meteorological and topographical settings of wind turbine is illustrated in Figure 1. There are three major points on the curve which divide the curve into four different regions, each having a different distribution of wind power and wind speed. Point A is the cut-in speed (which is the speed at which turbine first start to rotate to initiate power production), point B is rated speed (speed at which the nominal power of the turbine is reached) and point C is the cut-out speed (at this point wind speed becomes excessively high and the turbine is taken out of operation to avoid defects and damages [12]. The power distribution in these regions are as given in Table 1.

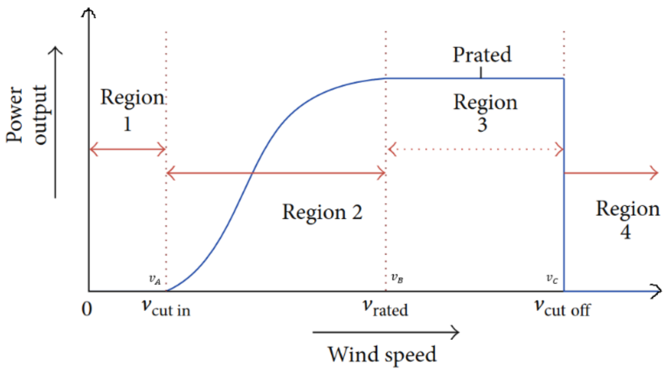


Figure 1 : Typical wind turbine power curve [13]

TABLE I

DISTRIBUTION OF WIND SPEED AND WIND POWER IN THE POWER CURVE

Wind velocity distribution	Electrical power output
$v < v_A$	$P_e = 0$
$v_A \leq\leq v_B$	$P_e = \frac{1}{2}\rho A v_w^3 C_p(\lambda, \beta)\eta_t\eta_g$

$v_B \leq v \leq v_C$	$P_e = Rated\ power$
$v > v_C$	$P_e = 0$

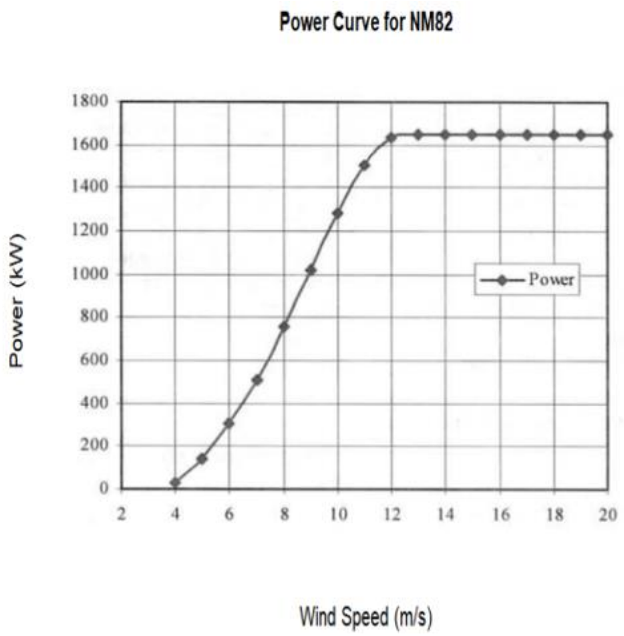
where v is the mean wind speed, v_A is the cut-in speed, v_B is the nominal speed and v_C is the furling speed (or cut-out speed), all speed parameters are measured in m/s. Power curves of wind turbines may come in different shapes depending on the design techniques. Figure 2 illustrates the theoretical power curve of two different wind turbines, depicting different shapes.

Models for characterizing the power output of wind turbine

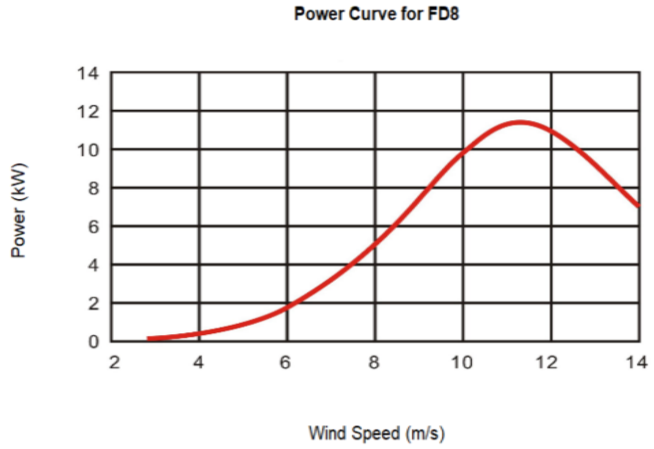
The models for characterizing wind turbine are generally categorized into two [10];

(i) Models based on fundamental equations of power available in the wind.

(ii) Models based on the concept of power curve of wind turbine



(a)



(b)

Figure 3 : Theoretical power curve for two different wind turbine a) Turbine model NM82, b) Turbine model FD8

Models based on fundamental equations of power available in the wind

Simplified functional block diagram of a typical power units of wind power system (WPS) depicted in figure 3. The instantaneous power $P_w(watt)$ in the wind with mean velocity v flowing into the rotor blades is given by [14];

$$P_w = d(Kinetic\ Energy) = \frac{1}{2}\rho A v^3 \quad (1)$$

The extracted mechanical power (P_m) by the wind turbine that flows into the transmission system is given by [15];

$$P_m = C_p P_w \quad (2)$$

Where C_p, is the power coefficient. The mechanical transmission system (gear train) is a conditioning unit that helps to step up the slow rotational speed of the turbine rotor to a higher speed that is desired to drive the electrical generator and its power output (P_t) in Watt is given by;

$$P_t = P_m \eta_t \quad (3)$$

The electrical output power (P_e) from the wind generator and power converter is therefore defined as;

$$P_e = P_t \eta_g \quad (4)$$

Where η_g , is the efficiency of the generator. By combining equations (1) to (4), the electrical power output from the Wind energy conversion systems (WECS) is given as;

$$P_e = \frac{1}{2}\rho A v_w^3 C_p(\lambda, \beta)\eta_o \qquad (5)$$

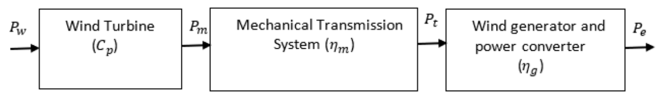


Figure 3: Simplified block diagram of WECS

It was discussed in [16] that wind power output can be determined using equation (5) above. [17] uses an optimization technique to calculate the electrical power generated from WECS by assuming that; (i) electrical and mechanical efficiency of 100% and (ii) the turbine blades were pitched at $\beta = 0$ which according to Bertz, corresponds to maximum aerodynamic efficiency of 0.593. The resulting equation based on the optimization is given by equation (6).

$$P_e = \frac{1}{2}\rho A v_w^3 \qquad (6)$$

It is good to note here that 100% efficiency of electrical and mechanical systems is unrealistic as there would be wear and tear in the moving parts of the gear system and the generator and also the copper and iron losses in the generator cannot be zero. Usually, modelling using the basic equation of power present in the wind is found to be difficult to use and does not suitably represent the behaviour of real wind turbine, it depends on several parameters as discussed earlier. For example, air density is a function of environmental factors like atmospheric moisture content, pressure and temperature which may vary from one wind farm location to another. So, it is often essential to use wind data obtained from a particular site location to get a more precise power curve[8].

Models based on the concept of power curve of wind turbine

Wind turbine power curve (WTPC) is used to establish input-output relationship between the generated electrical power and the wind speed. A reliable power curve model is not easy to obtain because of indeterminate relationship between wind velocity and its power output [7, 18]. Deterministic modelling with power curves is much more convenient as it does not require much more detailed information like modelling using the basic equation of power present in the wind. Modelling with power curve can be categorized into two namely;

(i) Model based on the presumed shape of the power curve

(ii) Model based on the actual power curve given by the manufacturer.

A. Model based on presumed shape of power curve

The modelling in this category is assumed to follow the typical power curve shown in figure 1. The power output of wind turbine can be written in piece-wise linear characteristic form as follows [5];

$$P_e = \begin{cases} 0 & v_m < v_A \text{ and } v_m > v_C \\ q(v) & v_A \le v_m \le v_B \\ P_r & v_B \le v_m \le v_C \end{cases} \qquad (7)$$

Quite number of methodologies have been proposed in literatures, ranging from quadratic model, cubic law model, linear model, Weibull parameter-based exponential power curve models to define $q(v)$, which represent the power output characteristic of wind turbine during the transient region (i.e between the cut in speed and the nominal speed) [5, 19]. P_r defines the rated power of the wind turbine. This paper, however uses both linear and cubic law models to predict power output of BWC Excel 10 Wind turbine and then compare with the power output specified by the manufacturer.

Model based on parametric cubic law model

Cubic polynomial model was reported in [20] to estimate electrical power generated from WECS measured in KW/m^2 and is expressed as follows;

$$P_{wd} = \begin{cases} 0 & v < v_A \\ \frac{P_{er}}{v_B^3 - v_A^3} v^3 - \frac{v_A^3}{v_B^3 - v_A^3} P_{er} & v_A < v_m < v_B \\ P_{er} & v_B < v_m < v_C \\ 0 & v_m > v_C \end{cases} \quad (8)$$

Electrical power output from the WECS is therefore given as;

$$P_e = P_{wd} \eta_o A \quad (9)$$

Model based on parametric segmented linear model

This is the most easily employed parametric model which uses piecewise linear approximation to predict the power generated by WECS [10, 19]. The power output P_e, of wind turbine was proposed according to the equation of a line given as;

$$P_e(v) = \beta v + k \quad (10)$$

where β is the sectional gradient, and k is a constant in the section. When there is only one section between the cut in speed and the nominal speed, then the equation of a line passing through two points can be used to obtain β and, in that case, $k = 0$. Thus,

$$q(v) = P_{er} \frac{v - v_A}{v_B - v_A} \quad (11)$$

Equation (11) is derived on the assumption that only one segment exists between the cut in speed and the nominal speed, in this case, the power output of the wind turbine grows in a linear manner with wind speed and then it stays constant from rated to cut-out speed. The expression that characterizes the linear model is given as;

$$P_e = \begin{cases} 0 & v < v_A \\ P_{er} \frac{v - v_A}{v_B - v_A} & v_A \le v_m \le v_B \\ P_{er} & v_B \le v_m \le v_C \\ 0 & v_m > v_C \end{cases} \quad (12)$$

III. RESULT AND DISCUSSIONS

MATLAB codes was developed for both linear model and cubic law model to predict the output power of a commercially available wind turbine (i.e BWC Excel 10 Wind turbine). Table 2 illustrates the comparison of the electrical output power obtained from manufacturer's data sheet [21] with the parametric models under discussion. Figure 4 clearly shows the piecewise linear characterization of the linear model. The turbine starts generating electricity at a cut-in speed of 2.5m/s and follows through this linear transient with positive slope until the nominal speed is reached (14m/s). At 20m/s, the turbine was taken out of operation to prevent damage. Figure 5 is a comparative assessment between the predicted linear model and BWC Excel 10 WT. The curves show that the predicted model is not completely correct in the range of cut in speed to nominal speed as power curve of wind turbine is rarely linear in that region but they are more satisfactory compared with modelling using basic equation of power available in the wind. Figure 6 shows proposed cubic law model while the Figure 7 illustrates the comparative assessment with the actual power output data from the manufacturer. The two responses follow a similar non-linear pattern but with significant errors during the transient state. Between the rated speed to the furling speed of 21m/s, the power generated are closely matched.

More generally, linear model, cubic model and model based on actual data from the manufacturer uses the characteristic equations obtained using the machine reading provided by manufacturer at fixed interval of points but again the behaviour of the machine at different site conditions are not considered. In this category, only cut-in, furling and nominal speeds and the nominal power are employed in generating the model, which are not adequate enough to precisely represent the actual behaviour of wind turbine.

TABLE 2

COMPARATIVE RESULTS OF THE ELECTRICAL POWER GENERATED BASED ON LINEAR MODEL, CUBIC MODEL AND DATA OBTAINED FROM MANUFACTURER'S SPECIFICATION FOR BWC EXCEL 10 WIND TURBINE

Wind speed (m/s)	Electrical power generated (KW)		
	Cubic law model	Linear model power	Actual power output
2.0	0	0	0
2.5	0	0	0.039
3.0	0.052	0.543	0.102
3.5	0.125	1.090	0.229
4.0	0.222	1.6304	0.399
4.5	0.346	2.1739	0.596
5.0	0.501	2.7174	0.848
5.5	0.691	3.2609	1.151
6.0	0.918	3.8043	1.510
6.5	1.187	4.3478	1.938
7.0	1.5	4.8913	2.403
7.5	1.861	5.4348	2.949
8.0	2.274	5.9783	3.602
8.5	2.742	6.5217	4.306
9.0	3.268	7.0652	5.071
9.5	3.856	7.6087	5.96
10.0	4.510	8.1522	6.856
10.5	5.232	8.6957	7.849
11.0	6.026	9.2391	8.863
11.5	6.896	9.7826	9.928
12.0	7.845	10.3261	10.885
12.5	8.877	10.8696	11.619
13.0	10.000	11.413	12.019
13.5	11.200	11.9565	12.276
14.0	12.500	12.500	12.395
14.5	12.500	12.500	12.449
15.0	12.500	12.500	12.495
15.5	12.500	12.500	12.508
16.0	12.500	12.500	12.546
16.5	12.500	12.500	12.555
17.0	12.500	12.500	12.503
17.5	12.500	12.500	12.528
18.0	12.500	12.500	12.442
18.5	12.500	12.500	12.396
19.0	12.500	12.500	12.208
19.5	12.500	12.500	11.878
20.0	12.500	12.500	11.989
20.5	12.500	12.500	11.495
21.0	12.500	0.000	-
21.5	0.000	0.000	-
22.0	0.000	0.000	-
22.5	0.000	0.000	-
23.0	0.000	0.000	-
23.5	0.000	0.000	
24.0	0.000	0.000	
24.5	0.000	0.000	

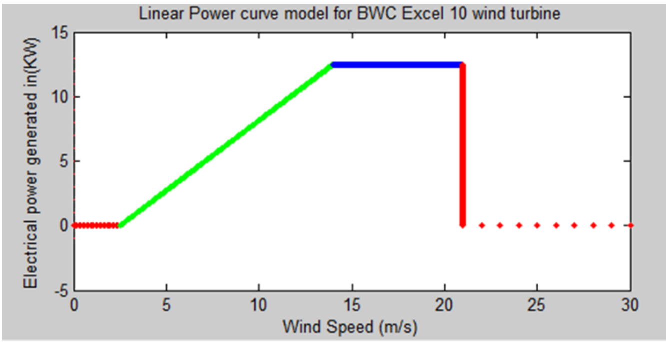


Figure 4: Parametric linear model for BWC Excel Wind turbine

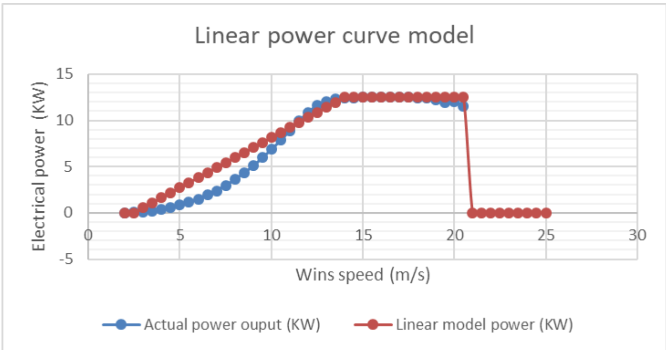


Figure 5: Comparison of actual and proposed linear power curve

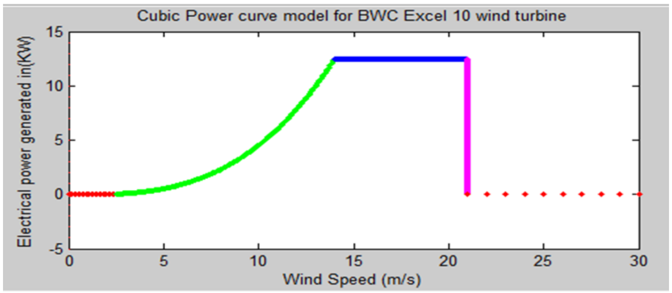


Figure 6: Output simulation results of the proposed cubic model

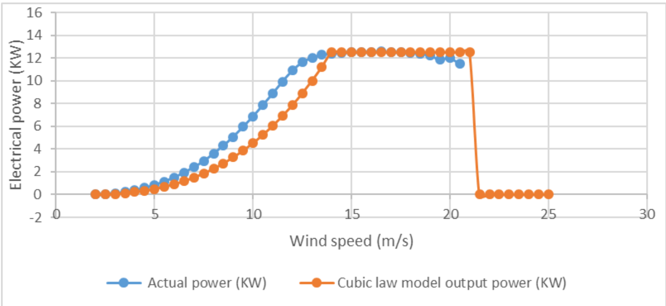


Figure 7: Comparison of actual and proposed cubic power curve

IV. CONCLUSION

In this article, comparative assessment of linear segmented parametric model, cubic law model and actual data supplied by the manufacturer of BWC Excel 10 wind turbine have been carried out. The need for power curve in planning and achieving a reliable and efficient wind farm design has also been discussed. The predicted models use only the cut-in speed, nominal speed, furling speed and the power rating of the turbine to predict the electrical power output of wind turbines and does not require additional technical details. The results obtained shows that cubic law model gives a more satisfactory outputs during transient while both models generally shows excellent performance between the rated speed and furling speed.

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