Rotational Speed Based Power Curve Model of Wind Turbine

Navjot Singh Sandhu, Saurabh Chanana

Abstract— The power curve of a wind turbine is one of its major characteristics and is used to compute its power output. Estimation of power output and energy yield of a wind turbine is required for performance analysis, planned economical operation and energy management. All this require power curve data and such data as supplied by the manufacturer is neither site-specific nor it accounts the wear and tear of the turbine. It can be used only if a wind turbine is operated as per its design specifications. Hence there is a need to develop the power curve model of a wind turbine which should include the effects of environmental changes such as temperature, pressure, and humidity etc. Moreover, it should include the effects of any wear and tear of the turbine on its output. Keeping it in view, in this paper, a new rotational speed based power curve model is proposed. Proposed model needs only site-specific rotational speed data of the turbine corresponding to its cut-in and rated wind speed. This makes the model accountable to climatic changes and mechanical issues of the wind turbine. Comparative analysis as presented in the paper proves the accuracy of proposed power curve model.

Keywords— Energy Error, Performance Coefficient, Power Curve Model, Wind Energy.

I. INTRODUCTION

WIND energy is emerging as a potential candidate for future energy supply in many areas of the world. Horizontal axis wind turbine approach currently dominates and is acceptable to harness wind energy worldwide [1]. Major components of a wind energy conversion system are as:

i) Turbine rotor to extract wind power for its utilization as mechanical power.

ii) Mechanical transmission to produce the required rotational speed. This part may not be present in the direct drive system.

iii) Generator to convert mechanical energy into electrical energy.

Power output of wind turbine and is expressed as:

$$P = \frac{1}{2}\rho C_p A v^3 \tag{1}$$

Where;

P = Power output of wind turbine (watt),
ρ = Air Density (kg/m^3),
C_p = Power Coefficient
A = Rotor Area (m^2),
v = Wind Speed (m/s)

Power curve which is one of the major characteristics of a wind turbine may be used to compute its output even during wind variations. Figure 1 shows the representation of a power curve for a wind turbine. Manufacturer power curve data for any wind turbine (which gives the relationship between power output and wind speeds) may be used to find out its power output. But this data is applicable only if operating conditions are as per turbine specifications. Power curve data as supplied by the manufacturer is neither site-specific nor its accounts the wear and tear of wind turbines. Hence there is a need to develop the power curve model which can account such effects.

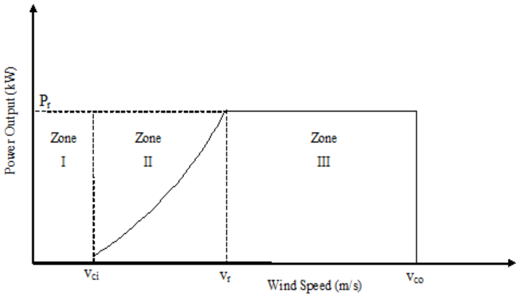

Fig. 1 Power output curve of wind turbine

The output power of a wind turbine under wind variations may be computed using equation (2). In this equation power output 'P(v)', for zone-ii (figure1) varies with wind speed and hence need an appropriate expression for its solution. Such representation with equation (2) is called power curve model of the wind turbine and can be used for its power and energy forecasting.

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$$P = \begin{Bmatrix} 0 & v < v_{ci} \quad or \quad v > v_{co} \\ P(v) & v_{ci} \le v \le v_r \\ P_r & v_r \le v < v_{co} \end{Bmatrix} \tag{2}$$

Where

v_{ci} = Cut-in wind speed

v_{co} = Cut-out wind speed

v_r = Rated wind speed

$P(v)$ = power output of wind turbine corresponding to wind speed in between cut-in to rated value

‘Energy prediction’ [2-3] and ‘loss of power supply’ [4-7] in a wind power plant, during wind variations will need accurate modelling of power output curve. Researchers employed either ‘linear power curve model’ or ‘polynomial power curve model’ for developing the power curve of the wind turbine.

One of the researchers [8] addressed the problem of site matching with turbines and recommended the use of normalized power curve of wind turbines. Where [10] investigated the site matching with the help of a case study of the Gulf of Suez region in Egypt and recommended second order power curve model. Another [11] used the linear power curve model to compute the power output of wind turbines for their planned operation. As observed, the desirable plan would be one that results in higher peak load generation in comparison off-peak generations. Reduction of power output fluctuations [12] due to unpredictable nature of wind is another current research area. Sudden wind power fluctuations of wind turbine feeding power network may affect the grid frequency. This also requires accurate power output estimation of wind turbines which in turn depends upon power curve model of the turbine. Further wind power being part of the hybrid system [14-20] requires wind turbine modelling for computation of its size, performance and power management for achieving economic & reliable operation. Researcher adopted either linear or polynomial power curve model for the computation of power output of wind generating unit. Researcher [21] tried to give a comparative analysis of various methods for mathematical modelling of wind turbines.

As per literature review, most of the researchers employed the models which require a little bit of information contrary to models based upon actual measured power data. However, these models are found to be incapable to account the environmental effects as well as mechanical issues. Keeping it in view, in this paper, a new ***rotational speed based power curve model*** is proposed. Model as developed need only site-specific measured rotational speed data of the turbine corresponding to its cut-in and rated wind speed. In ideal case, these values must be same as defined by the manufacturer. However, any change in air density, temperature, pressure and mechanical issues (due to any wear and tear) of the turbine will affect the rotational speeds. Hence such changes (as mentioned above) will be accounted automatically during proposed power curve modelling. Simulated results as obtained using proposed model are compared with the results using existing power curve models on a wind turbine (Vestas 90 3000kW). Comparative analysis as presented in section-5 proves the accuracy and effectiveness of proposed approach to forecast the power and energy of a wind turbine.

II. CONVENTIONAL POWER CURVE MODELS

Major power curve models as discussed in the literature are as:

A. *Linear power curve model [LPCM]*

As per this model [21], power output of wind turbine is assumed to be linear with the wind speed variation (from cut-in speed to rated speed) and it is given as:

$$P(v) = \frac{v - v_{ci}}{v_r - v_{ci}} P_r \tag{3}$$

B. *Cubic law power curve model [CLPCM]*

As discussed by [16], the power output of wind turbine (from cut-in to rated wind speed) may be computed using a model based upon cubic law and is defined by equation (4).

$$P(v) = av^3 - bP_r \tag{4}$$

Where,

$$a = \frac{P_r}{v_r^3 - v_{ci}^3},$$

$$b = \frac{v_{ci}^3}{v_r^3 - v_{ci}^3}$$

C. *Weibull power curve model [WPCM]*

Model as proposed by [14] depends upon the shape factor (k) of Weibull wind distribution and power output for the zone-ii may be obtained using equation (5).

$$P(v) = a + bv^k \tag{5}$$

Where,

$$a = \frac{P_r v_{ci}^k}{v_{ci}^k - v_r^k},$$

$$b = \frac{P_r}{v_r^k - v_{ci}^k}$$

k = Shape factor (corresponding to Weibull distribution with mean wind speed as rated wind speed)

D. *Polynomial power curve model [PPCM]*

In this model a second order polynomial curve [22] is fitted for the nonlinear portion of power output curve and it is expressed as:

$$P(v) = (k_1 + k_2 v + k_3 v^2) P_r \tag{6}$$

Where k_1, k_2 and k_3 are:

$$k_1 = \frac{1}{(v_{ci} - v_r)^2}\left[v_{ci}(v_{ci} + v_r) - 4v_{ci}v_r(\frac{v_{ci} + v_r}{2v_r})^3 \right]$$

$$k_2 = \frac{1}{(v_{ci} - v_r)^2}\left[4(v_{ci} + v_r)(\frac{v_{ci} + v_r}{2v_r})^3 - 3v_{ci} - v_r \right]$$

$$k_3 = \frac{1}{(v_{ci} - v_r)^2}\left[2 - 4(\frac{v_{ci} + v_r}{2v_r})^3 \right]$$

E. General power curve model [GPCM]

General power curve model derived here is same as named 'exponential power curve' [22] can be adopted only if manufacturer power curve data is available. It is derived using the power output expression for $P(v)$ [23] as:

$$P(v) = \left[\frac{v^{\alpha} - v_{ci}^{\alpha}}{v_r^{\alpha} - v_{ci}^{\alpha}} \right] P_r \qquad (7)$$

This can be modified as:

$$P = \frac{1}{2}\rho A k_p (v^{\alpha} - v_{ci}^{\alpha}) \qquad (8)$$

Where, $k_p = \left[\frac{2P_r}{\rho A(v_r^{\alpha} - v_{ci}^{\alpha})} \right]$

α is a constant whose value depend upon the design of turbine.

F. Equivalent Cp power curve model [ECPCM]

This model is based upon the basic power equation [8, 22] of the wind turbine. It is obtained by making some minor modifications ($v_{ci} = 0$ and α= 3) in equation (8).

$$P = \frac{1}{2}\rho A C_{p.eq} v^3 \qquad (9)$$

Where '$C_{p.eq}$' is a constant equivalent to the power coefficient.

As Cp varies with wind velocity (usually from 0.1 to 0.5), therefore a single equivalent value is not justified. However, for proceeding with this model it can be taken as:

i) $$C_{p.eq} = \frac{Cp(v_i) + Cp(v_r)}{2}$$

$Cp(v_i)$ =Power coefficient corresponding to wind speed v_i

$Cp(v_r)$ = Power coefficient corresponding to wind speed v_r

ii) $$C_{p.eq} = \frac{Cp(\max) + Cp(\min)}{2}$$

iii) $$C_{p.eq} = \frac{\sum_{i=0}^{n} Cp_i}{n}$$

Models i, ii & iii (as above under section 2.6) are named as '**equivalent Cp power curve model-1[ECPCM1]**', '**equivalent Cp power curve model-2[ECPCM2]**' '**equivalent Cp power curve model-3 [ECPCM3]**'respectively. In case its value is taken as $C_{p\max}$, it turns out to be '**approximate cubic power curve model [ACPCM]**' [22].

G. Quadratic power curve model [QPCM]

Equation (7) with α=2 results into the quadratic model [9, 24] and is defined as:

$$P(v) = \left[\frac{v^2 - v_{ci}^2}{v_r^2 - v_{ci}^2} \right] P_r \qquad (10)$$

Many researchers used it to compute the capacity factor of the wind turbine.

H. Speed cube power curve model [SCPCM]

Power output $P(v)$ depends upon wind speed and hence can be defined in its simplified form as discussed below.

$$P(v) = \frac{1}{2}\rho C_p A v^3$$

$$P(v) = \frac{1}{2}\rho C_p A v_r^3 \left(\frac{v^3}{v_r^3} \right)$$

If, $C_p \approx C_p(v_r)$

$$P(v) = \left(\frac{v^3}{v_r^3} \right) P_r \qquad (11)$$

III. PROPOSED POWER CURVE MODEL

Power output of wind turbine may be defined as:

$$P(v) = \frac{1}{2}\rho C_p(v) A v^3 \qquad (12)$$

Whereas $C_p(v)$ is performance coefficient of wind turbine corresponding to wind speed (v). It also varies with wind speed (from cut -in wind speed to rated) in a specific manner. Generally maximum value of C_p (usually 0.5) appears in a wind speed range of 5 m/sec to 9 m/sec [25]. Value of C_p can be obtained from C_p - λ curve [26-28] and is defined as:

$$C_p(\lambda, \beta) = 0.5176(\frac{116}{\lambda 1} - 0.4\beta - 5).e(-\frac{21}{\lambda 1}) + 0.0068\lambda \quad (13)$$

Where, $\frac{1}{\lambda 1} = \frac{1}{\lambda + 0.008\beta} - \frac{0.035}{\beta^3 + 1}$

With pitch angle (β) as zero, it comes out to be as:

$$C_p(v) = 0.5176\left(\frac{\{116*(1-(0.035*\lambda(v)))\}}{\lambda(v)} - 5\right)*e^{\left(\frac{\{21*((0.035*\lambda(v))-1)\}}{\lambda(v)}\right)} + 0.0068*\lambda(v) \quad (14)$$

Variation of $\lambda(v)$ with wind variations may be described as:

$$\lambda(v) = TipSpeedRatio = \frac{\omega(v)R}{v} \quad (15)$$

Where; $\omega(v) = A\left(1 - e^{-Bv}\right)$

Constants 'A' and 'B' are dependent upon the rotational speed of turbine corresponding to cut-in and rated wind speed i.e. w_{ci} & w_r. Whereas on-site measurement of these speeds will depend upon the followings factors:

- Air density of site: Value of air density varies with temperature, pressure, and humidity of the site. On the other hand, any change in air density will affect the power output of wind turbine accordingly. For given wind speed power output increases with an increase of air density [29] and vice versa. This happens due to the increase or decrease of the rotational speed of the turbine with the same value of wind speed. On the other hand, any change of temperature or pressure of the site may also affect the rotational speed of the turbine.
- Mechanical issues of turbine: Any wear and tear of turbine rotor during its transportation, installation or after its maintenance may affect the rotor speeds corresponding to cut-in and rated wind speed.

Model as proposed need only site-specific rotational speed data of the turbine corresponding to cut-in and rated wind speed. Therefore any change in air density and mechanical issues (due to some wear and tear of the rotor) will be accounted by rotational speed based power curve model of wind turbine.

For simulation purpose (Section5), rotational speeds have been taken as those specified by the manufacturer. Constants A and B are evaluated using curve fitting through 'Sigma Plot Software' and for Vestas-90, 3MW wind turbine under specified rated conditions these values are 1.6312 & 0.23 respectively. Using these values the power output $P(v)$ as obtained from equations (12) – (15) should be close to manufacturer power curve data.

IV. ENERGY OUTPUT ESTIMATION

Two parameters Weibull Function [30] is found to be best to fit the wind speed distribution over a period of time. Selection of shape parameter (k) and scale parameter (c) is significant to define the mean speed of the wind at a specific site. The scale factor is usually taken 1.1 times the average or mean wind speed. k > 3 is an indication of regular and steady wind. For k=1, the relative frequency distribution appears to be flat i.e. highly variable wind regime. For k=2, distribution is called Rayleigh distribution. Weibull distribution is given as:

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \quad (16)$$

Weibull distribution function as expressed above and power curve model as proposed may be used to estimate the annual energy yield (E) of the wind turbine as:

$$E = \sum_{v_{ci}}^{v_r} P(v) * f(v_{ii}) * 8760 + \sum_{v_r}^{v_{co}} P_r * f(v_{iii}) * 8760 \quad (17)$$

$f(v_{ii})$ & $f(v_{iii})$ are the speed frequencies of zone-ii & zone-iii respectively

'$P(v)$' is estimated by using different power curve models. The first part of the equation (17) can be defined as $E(v)$ i.e. the annual energy yield due to the operating zone-ii (figure 1) of wind turbine only. This yield as defined below depends upon the type of model selected for wind turbine curve.

$$E(v) = \sum_{v_{ci}}^{v_r} P(v) * f(v_{ii}) * 8760 \quad (18)$$

V. RESULTS AND DISCUSSIONS

Wind turbine VESTAS-V90-3MW [Appendix A] is selected to compare the simulated results under specified conditions using 'existing power curve models' and 'proposed Power Curve Model'.

Table. 1 Manufacturer Power Curve Data

Wind speed (m/sec)	Power Output (kW)		Wind speed (m/sec)	Power Output (kW)	
	Air Density = 1.225 kg/m^3	Air Density = 1.27 kg/m^3		Air Density = 1.225 kg/m^3	Air Density = 1.27 kg/m^3
4	77	81	10	1710	1775
5	190	198	11	2145	2226
6	353	368	12	2544	2628
7	581	604	13	2837	2889
8	886	921	14	2965	2981
9	1273	1322	15 to 25	3000	3000

Manufacturer power curve data which is to be followed under such designed operating conditions (as shown in Table 1 is used as reference data for comparative analysis.

A. Power output simulations

Power curve models as described by equations (3) to (15) in section 2 & 3 are used to compute the per unit power output of wind turbine for operating zone-ii (figure 1) at different hub heights. Effect of hub heights is represented in terms of air density. Figure 2(a) & 2(b) shows the comparison of the power output of wind turbine for zone-ii in terms of per unit power when wind speed varies from v_{ci} to v_r and air density as 1.225 kg/m^3 . Similarly, Figure 3(a) & 3(b) shows the comparison of power output simulation results with air density as 1.27 kg/m^3.

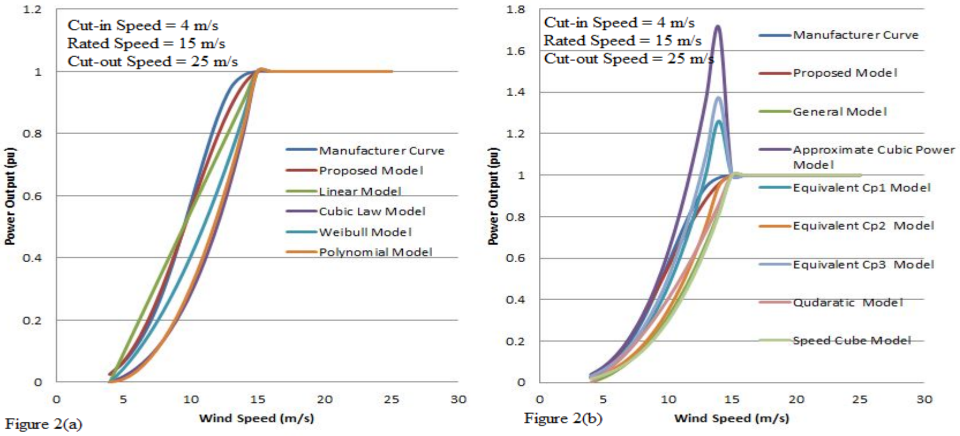


Figure 2(a) Figure 2(b)

Fig. 2 Power output curve of wind turbine’Vestas90’ for ‘zone-ii’, air density 1.225 kg/m3, (a) using power curve models as shown in Part I, (b) using power curve models as shown in Part II.

For the purpose of clarity, comparison is made in two parts as:

- In Part-I figure includes the comparison of manufacture data with Proposed Power Curve Model, Linear Power Curve Model, Cubic Law Power Curve Model, Weibull Power Curve Model & Polynomial Power Curve Model.
- In Part-II figure includes the comparison of manufacture data with Proposed Power Curve Model, General Power Curve Model, Equivalent Cp Power Curve Model i.e. ECPCM1, ECPCM2, ECPCM3 & ACPCM, Quadratic Power Curve Model & Speed Cube Power Curve Model.

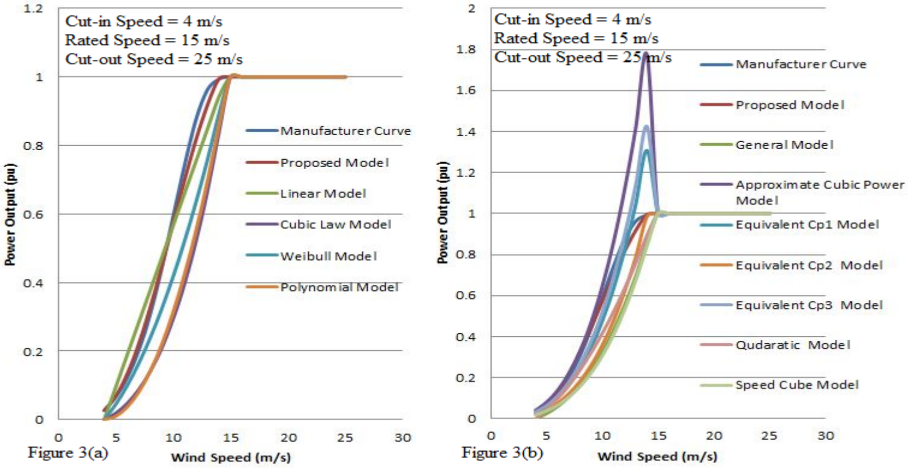


Figure 3(a) Figure 3(b)

Fig. 3 Power output curve of wind turbine’Vestas90’ for ‘zone-ii’, air density 1.27 kg/m3, (a) using power curve models as shown in Part I, (b) using power curve models as shown in Part II.

As observed from Figure 2 & Figure 3, power curve as obtained using ‘Proposed Model’ appears to be closest to manufacturer power curve.

Table. 2 Relative Power error of different power curve models, air density 1.225 kg/m^3

Absolute Power Error, p(err)												
Wind speed (m/s)	4	5	6	7	8	9	10	11	12	13	14	15
Proposed	0.003906	0.04107	0.09269	0.09711	0.0657	0.01367	0.031053	0.057063	0.070755	0.063452	0.029546	0.0001
LPCM	1	0.43602	0.54592	0.40857	0.23129	0.07118	0.042982	0.10993	0.142335	0.134729	0.080138	0
CLPCM	1	0.709321	0.609694	0.564566	0.541822	0.52675	0.504035	0.464755	0.407311	0.318739	0.181018	0
WPCM	1	0.319115	0.186224	0.184401	0.222147	0.267028	0.294912	0.297343	0.27783	0.225783	0.128605	0
PPCM	1	0.848341	0.698129	0.599174	0.539451	0.503653	0.471053	0.428392	0.372524	0.289552	0.1624	0
GPCM	1	0.620853	0.509354	0.471074	0.459871	0.457695	0.446842	0.417622	0.369929	0.291244	0.165132	0
ACPCM	0.558594	0.230648	0.145408	0.104855	0.080935	0.071176	0.09386	0.160559	0.270519	0.448604	0.731053	1.1042
ECPCM1	0.148438	0.091627	0.155612	0.185434	0.202845	0.209993	0.193509	0.144196	0.063208	0.068211	0.276535	0.5517
ECPCM2	0.132813	0.315956	0.363946	0.38688	0.399932	0.405374	0.392807	0.355664	0.294693	0.195854	0.039057	0.1681
ECPCM3	0.253906	0.011058	0.079932	0.112603	0.131392	0.139288	0.121228	0.067552	0.020755	0.163811	0.390772	0.6906
QPCM	1	0.319115	0.186224	0.184401	0.222147	0.267028	0.294912	0.297343	0.27783	0.225783	0.128605	0
SCPCM	0.257813	0.415482	0.455782	0.475207	0.486285	0.490926	0.480175	0.448392	0.396226	0.311548	0.177375	0

Table. 3 Relative Power error of different power curve models, air density 1.27 kg/m^3

Absolute Power error, p(err)												
Wind speed(m/s)	4	5	6	7	8	9	10	11	12	13	14	15
Proposed	0.020862	0.035164	0.086626	0.093902	0.062737	0.012028	0.032136	0.057997	0.067412	0.046592	0.000737	0.036838
LPCM	1	0.427866	0.537344	0.404459	0.227872	0.069441	0.044052	0.110811	0.13925	0.119152	0.051434	0.036735
CLPCM	1	0.710971	0.611859	0.565838	0.543094	0.527516	0.504589	0.465285	0.405179	0.306475	0.155462	0.036735
WPCM	1	0.322981	0.190738	0.186784	0.224306	0.268215	0.2957	0.298038	0.275233	0.211845	0.101413	0.036735
PPCM	1	0.849202	0.699804	0.600345	0.54073	0.504457	0.471644	0.428958	0.370267	0.276762	0.136263	0.036735
GPCM	1	0.623006	0.512075	0.47262	0.461371	0.458573	0.44746	0.418199	0.367663	0.278484	0.13908	0.036735
ACPCM	0.532063	0.223661	0.139055	0.101627	0.077934	0.069441	0.092637	0.15941	0.275089	0.474682	0.78507	1.181497
ECPCM1	0.128889	0.096784	0.160296	0.187814	0.205058	0.211272	0.19441	0.145043	0.059838	0.087441	0.316369	0.608701
ECPCM2	0.147574	0.319839	0.367473	0.388672	0.401598	0.406336	0.393486	0.356302	0.292156	0.181378	0.009071	0.21101
ECPCM3	0.232562	0.016673	0.085035	0.115196	0.133803	0.140682	0.12221	0.068476	0.024426	0.184763	0.434171	0.752704
QPCM	1	0.322981	0.190738	0.186784	0.224306	0.268215	0.2957	0.298038	0.275233	0.211845	0.101413	0.036735
SCPCM	0.270446	0.4188	0.458801	0.47674	0.487711	0.491751	0.480756	0.448938	0.394055	0.299154	0.151706	0.036735

Table 2 & Table 3 include the ‘Relative Power Error’ data for different power curve models. As observed, the magnitude of this error comes out be low for proposed model irrespective air density. This is true almost for all of the wind speeds. Range of power error [table 2 & 3] in case of proposed model is from ‘0.01% to 9.7 %’ and ‘0.07% to 9.3%’ corresponding to air densities 1.225 kg/m3 & 1.27 kg/m3.

Relative Power Error, $$p(err) = \frac{|p(v) - p(m)_v|}{p(m)_v} \qquad (19)$$

$p(v)$ = per unit (pu) simulated power output of wind turbine corresponding to wind speed v.

$p(m)_v$ =per unit (pu) manufacturer power output of wind turbine corresponding to wind speed v.

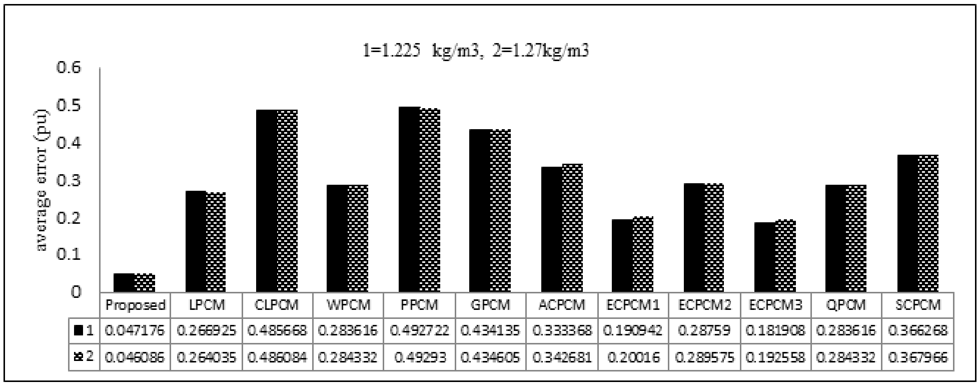
Average Power Error, $$p_{av}(err) = \frac{\sum_{i=1}^{n} p_i(err)}{n} \qquad (20)$$

n = No of intervals for wind speeds in between v_{ci} to v_{r}.

Root Mean Square Power Error

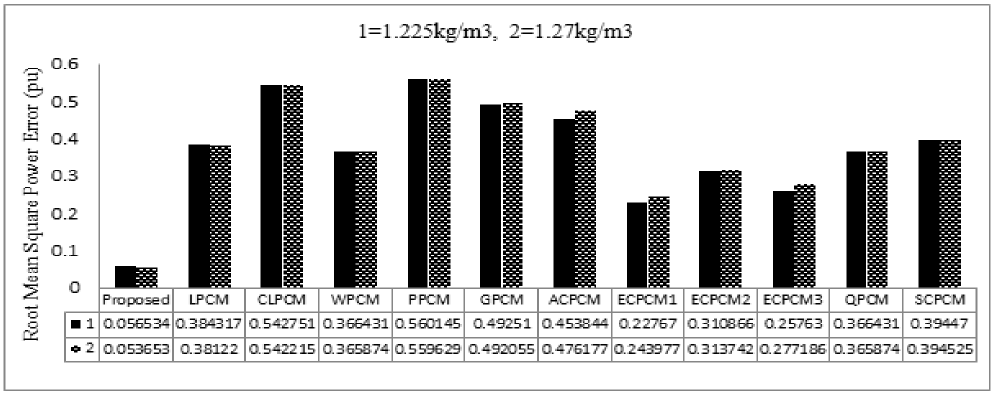
$$p_{rms}(err) = \left[\frac{\sum_{i=1}^{n} (p(v)_i - (p(m)_v)_i)^2}{n} \right]^{1/2} \qquad (21)$$

‘Average Power Error’ and ‘Root Mean Square Power Error’ as obtained in the case of different power curve models is shown in Figure 4 & 5 respectively. As observed, $p_{av}(err)$ & $p_{rms}(err)$ appears to be very low for proposed power curve model in contrast to all existing models. ‘Average errors’ as obtained [figure 4] using proposed model with air density as 1.225 kg/m3 and 1.27 kg/m3 are 4.7% and 4.6% respectively. A ‘Root Mean Square Power Error’ value comes out to be as 5.6% and 5.3% respectively. Except proposed model there is no another power curve model which results in the minimum values of such power errors simultaneously. Moreover average and root mean square power error as observed in the case of proposed model is negligible in contrast to other models. This model appears to be the most accurate power curve model and can be adopted to predict the power output without losing accuracy.



	Proposed	LPCM	CLPCM	WPCM	PPCM	GPCM	ACPCM	ECPCM1	ECPCM2	ECPCM3	QPCM	SCPCM
■ 1	0.047176	0.266925	0.485668	0.283616	0.492722	0.434135	0.333368	0.190942	0.28759	0.181908	0.283616	0.366268
▨ 2	0.046086	0.264035	0.486084	0.284332	0.49293	0.434605	0.342681	0.20016	0.289575	0.192558	0.284332	0.367966

Fig. 4 Average power error of different power curve models



	Proposed	LPCM	CLPCM	WPCM	PPCM	GPCM	ACPCM	ECPCM1	ECPCM2	ECPCM3	QPCM	SCPCM
■ 1	0.056534	0.384317	0.542751	0.366431	0.560145	0.49251	0.453844	0.22767	0.310866	0.25763	0.366431	0.39447
▨ 2	0.053653	0.38122	0.542215	0.365874	0.559629	0.492055	0.476177	0.243977	0.313742	0.277186	0.365874	0.394525

Fig. 5 Root mean square power error of different power curve models

VI. ENERGY OUTPUT SIMULATIONS

VESTAS-90 3MW turbine installed at many places [e.g. Barrow offshore wind farm United Kingdom & Belwind wind farm Near Belgian Port Belgium] is used for energy output estimation. Weibull distribution of the wind (Figure 6) is considered with a mean wind speed of 12 m/sec. This value of mean wind speed [offshore] can be experienced at many places such as Randolph New Hampshire and Duolun Xillingol Inner Mangolia [31, 32] Many offshore wind projects have been commissioned in Taiwan Strait Sea, China [33], where mean wind speed is greater than 12m/s.

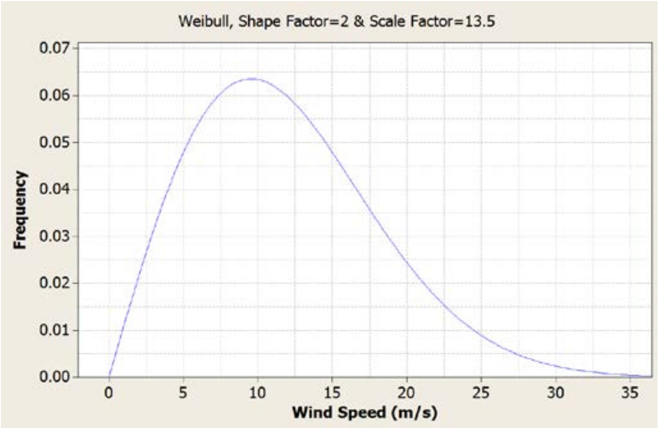


Fig. 6 Weibull distribution with mean wind speed 12 m/sec

Energy output simulations have been obtained using the equations (17) & (18). Energy error as shown in Figures 7(a-b) includes the followings.

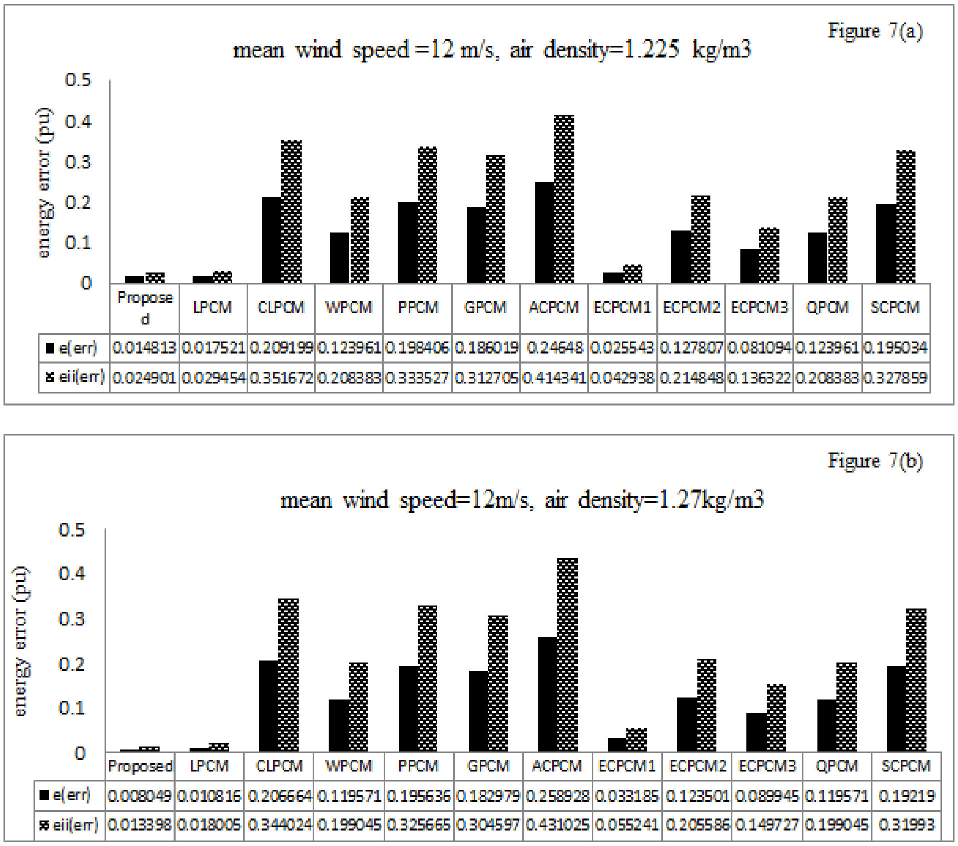
Per unit energy error for annual energy prediction;

$$e(err) = \frac{|E - E_m|}{E_m} \tag{22}$$

Per unit energy error for annual energy prediction due to operating zone-ii (Figure 1);

$$e_{II}(err) = \frac{|E(v) - E_m(v)|}{E_m(v)} \tag{23}$$

E_m = Annual energy production using manufacturer data, $E_m(v)$ = per unit annual energy production using manufacturer data for operating zone-ii only.



	Proposed	LPCM	CLPCM	WPCM	PPCM	GPCM	ACPCM	ECPCM1	ECPCM2	ECPCM3	QPCM	SCPCM
■ e(err)	0.014813	0.017521	0.209199	0.123961	0.198406	0.186019	0.24648	0.025543	0.127807	0.081094	0.123961	0.195034
▨ eii(err)	0.024901	0.029454	0.351672	0.208383	0.333527	0.312705	0.414341	0.042938	0.214848	0.136322	0.208383	0.327859

	Proposed	LPCM	CLPCM	WPCM	PPCM	GPCM	ACPCM	ECPCM1	ECPCM2	ECPCM3	QPCM	SCPCM
■ e(err)	0.008049	0.010816	0.206664	0.119571	0.195636	0.182979	0.258928	0.033185	0.123501	0.089945	0.119571	0.19219
▨ eii(err)	0.013398	0.018005	0.344024	0.199045	0.325665	0.304597	0.431025	0.055241	0.205586	0.149727	0.199045	0.31993

Fig. 7 Energy error comparison, (a) with mean wind speed as 12 m/s and air density as 1.225 kg/m^3, (b) with mean wind speed as 12 m/s and air density as 1.27 kg/m^3

Simulation results as shown (figure 7) results into following observations:

- ‘$e(err)$’ & ‘$e_{II}(err)$’ comes out to be minimum in case of proposed model and it is irrespective of the air density.

- ‘$e(err)$’ in each case appears to be low as compared to its value for $e_{II}(err)$. It is due to the addition of wind speeds corresponding to operating zone-iii (figure 1).
- Energy error ‘$e(err)$’ for proposed model is found to be 1.4% and 0.8% with air densities as 1.225 kg/m^3 and 1.27 kg/m^3. It is followed by LPCM with respective values as 1.7% and 1.08%.

From above it can be concluded that proposed model can be used for energy forecasting of wind turbines with substantial accuracy. As described earlier proposed model is capable of accounting the site-specific conditions as well as any mechanical issues of the turbine rotor. Which is not so in the case of other models including LPCM.

VII. CONCLUSION

In this paper, a new site-specific power curve model of the wind turbine has been developed to forecast its power and energy yield. Power output simulation results as obtained using proposed model (Rotational Speed Based Power Curve Model) are found to be in good agreement with manufacturer power curve. Model as proposed is capable of accounting the effects of any change in climatic conditions such as pressure, temperature, humidity etc. Moreover, it is the first model to include the effect of mechanical issues of the turbine such as any wear and tear of the rotor. Minimum values of average power error and root mean square error proves its superiority over the other existing power curve models. Comparative analysis in terms of energy error (as shown in figure 7) also proves its effectiveness for energy forecast.

APPENDIX-A

Model	Capacity (MW)	Blade Length (m)	Hub Height (m)	Total Height (m)	Swept Area (m^2)	RPM Range	Maximum Blade Tip Speed (mph)	Rated Wind Speed(m/s)
Vestas V90	3.0	45	80	125	6362	9-19	200	15

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