Comparative Analysis of Conventional and Multi-Rotor Wind Turbines

N. S. Sandhu, S.Chanana

***Abstract*—** Due to continuous increase of power demand and on the other hand shortage of fossil fuels have diverted the focus of scientists towards alternate energy resources. Out of these, wind energy is emerging as a potential renewable energy resource and at present acquired the substantial share. Conventional wind turbines are used to extract the energy associated with moving wind. However the rotor size of such turbines increases with their rating. Increased rotor size results in to many problems such as its weight, complicated design, increased noise pollution & cost etc. Large rotor size and turbine cost have diverted the attention of scientists from single-rotor to multi-rotor wind turbines. Aim of this paper is to find out the most suitable power curve model for the analysis of multi-rotor wind turbines. New models have been developed for the energy estimation of a three rotor wind turbine. Simulation results as presented in the paper are helpful to decide the best suitable power curve model for single-rotor as well as for multi-rotor wind turbine. Further as observed, three-rotor wind turbine yields more energy in contrast to single rotor configuration. This increase is 6.34% with mean wind speed of 8m/s & 4.76% with mean wind speed of 12m/s. Analysis, as reported, shows that an equivalent three rotor configuration results into higher annual energy yield with low installation cost.

***Keywords*—** Multi-rotor wind turbine, Performance Coefficient, Power curve model, Wind energy.

I. INTRODUCTION

Out of all renewable energy resources, wind energy is emerging as the fastest growing resource. Today it has acquired the substantial share as for as renewable energy sector growth is concerned. The horizontal axis wind turbine approach currently dominates and acceptable to harness wind energy worldwide [1-3]. The power output of wind turbine is expressed as:

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

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)

As evident from equation (1), power developed by wind turbine is dependent upon the rotor swept area (A), coefficient of performance (C_p) & wind speed (v). In order to increase the power production, manufacturer developed the conventional wind turbine with large rotor size. At present wind turbine with very large ratings (>10MW) are under development stage. Recent studies [4] have proposed a single wind turbine with a rating of 20 MW. However major problems associated with large rotor size [5, 6, 7] are:

- Costly due to increased mass. The mass of a set of blades for any wind turbine is: $M = kpD^3$ where M = Mass in kg, D = Rotor diameter in meter, k_p = Constant of proportionality.
- Restriction on rotor size due to tower height & proximity to the ground.
- Complicated design due to bending and tensile stresses of longer blades.
- The weight of gearbox increases with rotor size.
- Increased blade weight to power output ratio results into uneconomical operation with increased noise pollution.

Multirotor configuration is a solution to overcome some of the problems. Major advantages of multirotor wind turbines are [8]:

- The structure becomes economical with large capability than a single rotor wind turbine. The cost of the multi-rotor system is quantified as $\frac{1}{\sqrt{N}}$ times the single rotor structure. 'N'describe the number of rotors for a multirotor wind turbine. It is due to the reduction in mass.

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- The presence of a number of small rotors in space on one tower gives the possibility of better utilization of a wind site.

On other hand, major problems associated with multirotor structure are mutual interaction between rotors, special tower, and gear arrangements. Multirotor wind turbines (i.e. two or more rotor on a single support) are an old concept [9] and in 1978 dick [10] observed the performance of a downstream turbine rotor just behind the upstream turbine rotor. Later on Kotb et al. [11] investigated the performance of staggered horizontal axis rotors and predicted the power loss due to the upstream rotor. 15% power loss was predicted for a 0.26 overlap area ratio. No et al. [12] developed a FORTRAN and Matlab/Simulink software to predict the performance of a dual rotor wind turbine generating system. In order to reduce power block, the size of the upstream rotor was considered small as compared to the downstream rotor. Yap et al. [13] discussed the electricity generation due to dual rotor wind turbine located near the exhausting gasses in a plant and its effects on the performance of cooling tower. Riadh et al. [14] investigated a dual rotor scaled down turbine structure and conclude that a dual-rotor turbine may produce up to 60% more power than a single rotor turbine. Some of the researchers [15-16] made a comparison of single rotor & dual rotor turbines under transient disturbances. It was observed that dynamic response of a dual rotor system is more stable. Jamieson et al. [8] made a detailed comparison of 20 MW conventional wind turbine with a 20 MW multirotor turbine comprising of four rotors with each one of 5 MW. It was observed that four 5 MW rotors will cost ≈ 80% of a 20 MW single rotor structure and there is a further scope to reduce its cost. It was suggested that there is a need to focus more attention on the research related to multi-rotor turbines. Hunag et al. [17] also made a comparison of a single rotor and multirotor wind turbines when used in a wind solar hybrid generation. It was found that at low wind speeds, the multirotor wind turbine-solar hybrid generation performs better in contrast to single rotor wind turbine-solar hybrid generation. Jamieson et al. [18] also investigated the support structure consideration and presented one potential structure layout for a 20 MW multirotor turbine.

Keeping in view the advantages of a multi-rotor wind turbine, in this paper a modified power curve model is employed to find out the power and energy output of a multi rotor wind turbine. Comparative analysis as presented using simulation results proves the following.

1) Superiority of linear power curve model.
2) Economics operation of equivalent multi rotor wind turbine.

II. POWER CURVE MODEL

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. Power output curve appears to be nonlinear between cut-in and rated wind speeds.

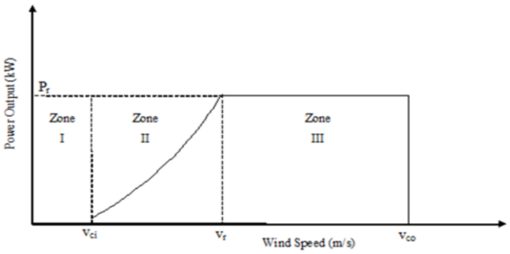


Fig. 1 Power output curve of wind turbine

Zone-ii, nonlinear part of wind turbine curve requires power curve modelling to estimate power output in case wind speed lies in this zone. Power output forecasting for a given wind spectrum using power output curve from cut-in to cut-out wind speeds may be useful for the following research areas.

Performance Analysis, Reliability Assessment and Loss of Power Supply [19-25]: Power output of a wind turbine being one of the major performance depicting parameters requires maximum attention. Its estimation [20-21] under varying wind conditions gives wind energy prediction during a specified interval (month/year). ‘Reliability assessment’ and ‘loss of power supply’ as discussed [22-25] need proper focus due to intermittent and uncertain mature of wind. The standard method to evaluate such factors requires the difference between ‘load duration curve’ and ‘generated power curve’. Researchers employed either linear power curve model or polynomial power curve model for developing the generated power curve of the wind turbine.

Optimal Site Matching, Planned Operation, Power Output Fluctuations & Economic Analysis [26-31]: Pairing between the wind turbine and installation sites is also very important for utilizing best possible wind energy. Jangamshetti et.al [26] addressed the problem of site matching and recommended the use of normalized power curve of wind turbines. For a given wind regime, a wind turbine with specified values of V_{ci}(cut-in wind speed), V_r(rated wind speed) & V_{co}(cut-out wind speed) is to be selected as to maximize the power output [27]. Shimy [28] investigated the site matching with the help of a case study of the Gulf of Suez region in Egypt and recommended the accurate modelling of wind turbine output-power-curve. Second order power curve model has been employed for the site matching.

Ray [29] used the linear model to compute the power output of wind turbines, required for 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 [30] due to unpredictable nature of wind is one of the current research areas. Sudden wind power fluctuations of a wind turbine feeding power network may affect the grid frequency. Properly designed filters may be incorporated to avoid such occurrence. All these necessities accurate power output estimation of wind turbines which in turn depends upon power curve model of the turbine.

Economic dispatch model [31] includes two wind power generators along with two conventional generators feeding a load. Because of the uncertainty of the wind, factors for overestimation and underestimation are to be included. Hence accuracy of a power-output-curve model of the wind turbine may affect the values. As observed, linear power curve model is used to estimate the wind power output.

Sizing, Performance Analysis & Power Management of Hybrid Generating System with Wind Power as a Generating Resource [32-39]: Major drawback associated with the wind and solar power is their unpredictable nature. Moreover, such resources also depend upon weather and climate changes. However, due to a high degree of complementarity between these resources, both can be operated in parallel to feed the load in isolation or to the power network. Such operation of generating units is called Hybrid generating system [32-39]. Wind power being one part of the system, it 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.

Thapar et al. [40] tried to give a comparative analysis of various methods for the modelling of power output curve for its nonlinear region between cut-in to rated wind speeds. Analysis, as presented, is based upon the two categories as:

- Models based on the shape of the power curve. Such models need a few information related to wind turbine such as cut-in speed, rated speed and rated power etc.
- Models based on the actual power curve supplied by the manufacture. Such models [41-43] require complete power output data points corresponding to wind velocities in between cut-in and rated speed. Nacelle Power Curve as recommended by Paiva et al. [44] is one of them.

As per literature review, most of the researchers employed the models based upon the shape of the power curve. It is due to the advantage that such models require a little bit of information contrary to a model based upon actual power data supplied by the manufacturers. Power curve models generally employed by the researchers are as discussed below.

A. Linear Power Curve Model, LPCM [40]

$$P(v) = \frac{v - v_{ci}}{v_r - v_{ci}} P_r \qquad (2)$$

Where

$P(v)$ = Power output of wind turbine corresponding to any wind speed between cut-in to rated values

P_r = Rated power output of wind turbine

B. Cubic Law Power Curve Model, CLPCM [35]

$$P(v) = av^3 - bP_r \qquad (3)$$

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 [33]

$$P(v) = a + bv^k \qquad (4)$$

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 [45]

$$P(v) = (k_1 + k_2 v + k_3 v^2) P_r \qquad (5)$$

Where k_1, k_2 and k_3 are:

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

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

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

E. Quadratic Power Curve Model, QPCM [46]

$$P(v) = \left[\frac{v^2 - v_{ci}^2}{v_r^2 - v_{ci}^2} \right] P_r \qquad (6)$$

F. Speed Cube Power Curve Model, SCPCM [47]

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

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

If, $C_p(v) = C_p(r)$;

$$P(v) = \left(\frac{v^3}{v_r^3} \right) P_r \qquad (7)$$

In the present paper power curve models as discussed above have been adopted to analyze the output of NORDEX- N117-3000 kW wind turbine and a multi-rotor turbine comprising of three LEITWIND- LTW77-1000 kW identical wind turbines [Appendix A].

III. POWER AND ENERGY OUTPUT OF SINGLE ROTOR WIND TURBINE

The power output of a wind turbine as shown in figure 2 may be obtained using equation (8). Wind speed is considered at the hub height of wind turbine.

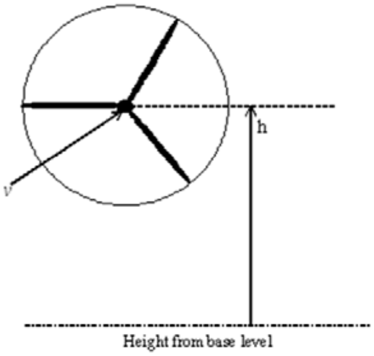


Fig. 2 Single-rotor wind turbine representation

$$P = \begin{cases} 0 \quad v < v_{ci} \quad or \quad v > v_{co} \\ P(v) \qquad v_{ci} \le v \le v_r \\ P_r \qquad v_r \le v < v_{co} \end{cases} \qquad (8)$$

Where

v_{ci} = Cut-in wind speed, v_{co} = Cut-out wind speed, v_r = Rated wind speed

Two parameters Weibull Function [48] is found to be best to fit the wind speed distribution over a period of time. However selection of shape parameter (k) and scale parameter (c) as used are 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 the value of 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:

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \qquad (9)$$

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

$$E = \sum_{v_{ci}}^{v_r} P(v) * f_{II}(v) * 8760 + \sum_{v_r}^{v_{co}} P_r * f_{III}(v) * 8760 \qquad (10)$$

‘ $f_{II}(v)$ & $f_{III}(v)$ ’are speed frequencies of zone-ii & zone-iii respectively.

IV. POWER AND ENERGY OUTPUT OF MULTI-ROTOR WIND TURBINE

Multirotor wind turbine has two or more rotors and these may be arranged either in a plane or along the same axis. Such turbines are named as coplanar or coaxial multi-rotor wind turbines respectively. Figure 3 shows an equivalent three rotor wind turbine. Three hubs in case of the multirotor turbine are at different heights in comparison to the hub height of single rotor turbine.

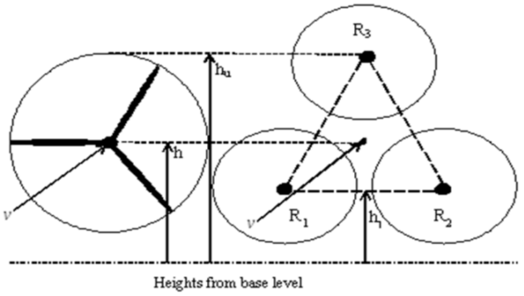


Fig. 3 Multi-rotor equivalent representation of wind turbine

Figure 4 shows the power output curve for the three identical rotors R_1 (Rotor-1), R_2 (Rotor-2) and R_3 (Rotor-3) of a multirotor turbine. For the purpose of the equivalence between the single rotor and multirotor structure, variation of wind speed is considered at a height ‘h’ as in the case of single rotor turbine. Due to the displacements of hub heights of multi-rotor configuration, wind speeds appearing at the respective hub heights of rotors are totally different as compared their values at the hub height of single rotor configuration.

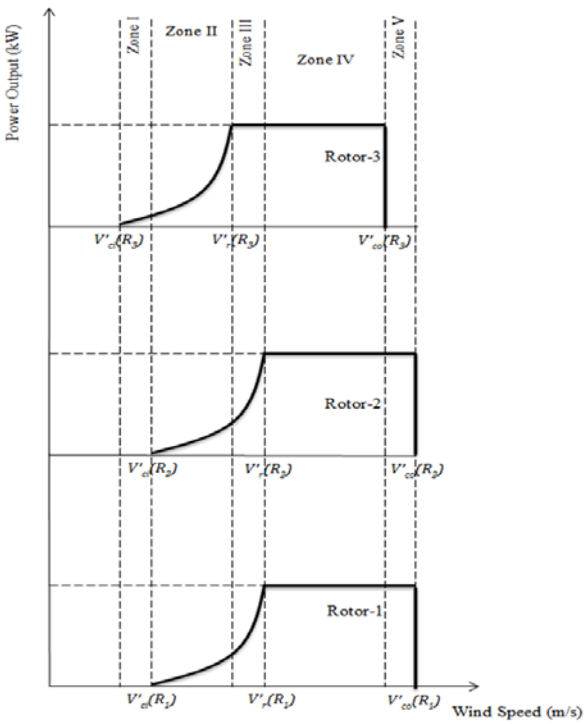


Fig. 4 Power output curves of multi-rotor wind turbine

As shown in figure 4, It results in to the followings:

- $v'_{ci}(R_1)$, $v'_{ci}(R_2)$ & $v'_{ci}(R_3)$ are the effective values of cut-in speeds of rotor R_1, R_2 & R_3.
- $v'_r(R_1)$, $v'_r(R_2)$ & $v'_r(R_3)$ are the effective values of rated speeds of rotor R_1, R_2 & R_3.
- $v'_{co}(R_1)$, $v'_{co}(R_2)$ & $v'_{co}(R_3)$ are the effective values of cut-out speeds of rotor R_1, R_2 & R_3.

Where;

$$\begin{array}{lll} v'_{ci}(R_1)>v_{ci}(R_1) & v'_r(R_1)>v_r(R_1) & v'_{co}(R_1)>v_{co}(R_1) \\ v'_{ci}(R_2)>v_{ci}(R_2) & v'_r(R_2)>v_r(R_2) & v'_{co}(R_2)>v_{co}(R_2) \\ v'_{ci}(R_3)<v_{ci}(R_3) & v'_r(R_3)<v_r(R_3) & v'_{co}(R_3)<v_{co}(R_3) \end{array}$$

$\left.\begin{matrix} v_{ci}(R_1) \\ v_{ci}(R_2) \\ v_{ci}(R_3) \end{matrix}\right]$ are respective cut-in wind speeds of three rotors.

$\left.\begin{matrix} v_r(R_1) \\ v_r(R_2) \\ v_r(R_3) \end{matrix}\right]$ are respective rated wind speeds of three rotors.

$\left.\begin{matrix} v_{co}(R_1) \\ v_{co}(R_2) \\ v_{co}(R_3) \end{matrix}\right]$ are respective cut-out wind speeds of three rotors.

Effective cut in, rated and cut-out wind speed for the three rotors can be obtained using the power rule [49] and power output of three-rotor turbine can be defined as:

$$P=\begin{bmatrix} P=0 & if & v<v'_{ci}(R_3) & or & v>\left\langle v'_{co}(R_1)=v'_{co}(R_2)\right\rangle \\ P_{m1}(v) & if & v>v'_{ci}(R_3) & \& & v\le\left\langle v'_{ci}(R_1)=v'_{ci}(R_2)\right\rangle \\ P_{m2}(v) & if & v>\left\langle v'_{ci}(R_1)=v'_{ci}(R_2)\right\rangle & \& & v\le v'_r(R_3) \\ P_{m3}(v) & if & v>v'_r(R_3) & \& & v\le\left\langle v'_r(R_1)=v'_r(R_2)\right\rangle \\ P_{m4}(v) & if & v>\left\langle v'_r(R_1)=v'_r(R_2)\right\rangle & \& & v\le v'_{co}(R_3) \\ P_{m5}(v) & if & v>v'_{co}(R_3) & \& & v\le\left\langle v'_{co}(R_1)=v'_{co}(R_2)\right\rangle \end{bmatrix}$$

……. (11)

Where;

$P_{m1}(v)$ = "As per power curve model of rotor-1"; when v varies from $v'_{ci}(R_3)\ to \left\langle v'_{ci}(R_1)=v'_{ci}(R_2)\right\rangle$

$P_{m2}(v)$ = "As per power curve model of all rotors"; when v varies from $\left\langle v'_{ci}(R_1)=v'_{ci}(R_2)\right\rangle to\ \ v'_r(R_3)$

$P_{m3}(v)$ = Rated power of rotor-3 + "As per power curve model of rotor-1&2"; when v varies from $v'_r(R_3)\ to \left\langle v'_r(R_1)=v'_r(R_2)\right\rangle$

$P_{m4}(v)$ = "Sum of rated power of all rotors"; when v varies from $\left\langle v'_r(R_1)=v'_r(R_2)\right\rangle to\ \ v'_{co}(R_3)$

$P_{m5}(v)$ = "Sum of rated power of rotors-1 &2"; when v varies from $v'_{co}(R_3)\ to \left\langle v'_{co}(R_1)=v'_{co}(R_2)\right\rangle$

Weibull distribution function as obtained using equation (9) and power curve model as defined above may be used to estimate the annual energy yield

(E_{MR}) of the multirotor wind turbine as:

$$E_{MR} = \left\{ \begin{array}{c} \sum_{v'_{ci}(R_3)}^{v'_{ci}(R_1)=v'_{ci}(R_2)} P_{m1}(v) * f_{mI}(v) * 8760 \\ + \\ \sum_{v'_{ci}(R_1)=v'_{ci}(R_2)}^{v'_{r}(R_3)} P_{m2}(v) * f_{mII}(v) * 8760 \\ + \\ \sum_{v'_{r}(R_3)}^{v'_{r}(R_1)=v'_{r}(R_2)} P_{m3}(v) * f_{mIII}(v) * 8760 \\ + \\ \sum_{v'_{r}(R_1)=v'_{r}(R_2)}^{v'_{co}(R_3)} P_{m4}(v) * f_{mIV}(v) * 8760 \\ + \\ \sum_{v'_{co}(R_3)}^{v'_{co}(R_1)=v'_{co}(R_2)} P_{m5}(v) * f_{mV}(v) * 8760 \end{array} \right\}$$

……. (12)

$f_{mI}(v)$, $f_{mII}(v)$, $f_{mIII}(v)$, $f_{mIV}(v)$ and $f_{mV}(v)$ are the respective speed frequencies as per Weibull distribution.

V. SIMULATION RESULTS

Wind turbine NORDEX- N117-3000 kW and LEITWIND-LTW77-1000 kW [Appendix A] are selected to compare the simulated results in case of single-rotor and multi-rotor wind turbines respectively. Manufacturer power curve data as shown in appendix-A is used as reference data for comparative analysis.

A. Single-Rotor Wind Turbine Simulations

Figure 5 shows the comparison of power output of single-rotor wind turbine when wind speed varies from v_{ci} to v_r and air density as 1.225 kg/m$^{3.}$ Correlation factor between simulation and manufacturer data is shown in Figure 6. The correlation coefficient (R), measures the strength and a correlation greater than 0.98 is generally described as very strong.

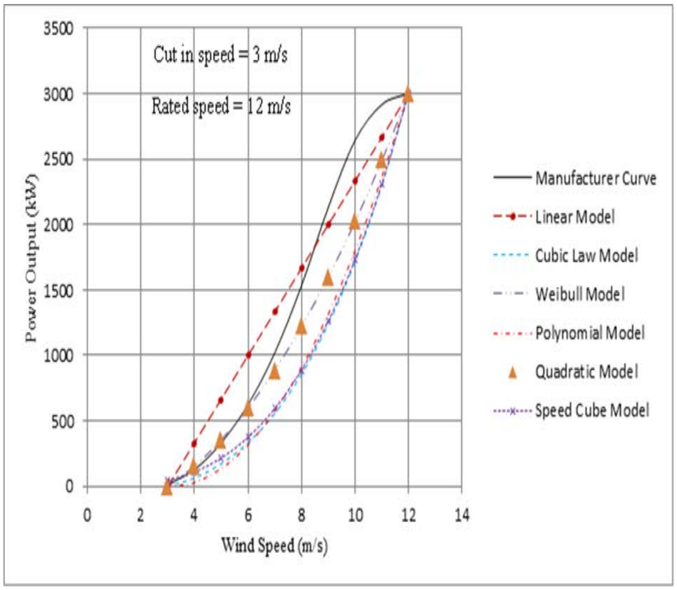


Fig. 5 Power output comparison of single-rotor wind turbine

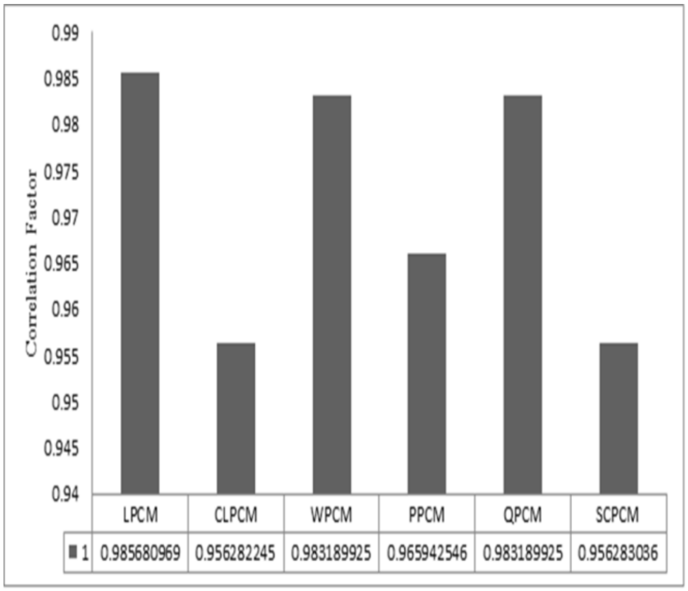


Fig. 6 Correlation coefficient of different power curves used for single-rotor wind turbine

In order to compute the energy yield of NORDEX-N117turbine, Weibull distributions of the wind as shown in Figure 7 are taken corresponding to mean wind speed of 8m/sec and 12 m/sec. One of the mean speeds is selected near to the rated wind speed of the turbine. Such wind speeds can be experienced at many places such as Randolph New Hampshire [51] & Duolun Xillingol Inner Mangolia [52].

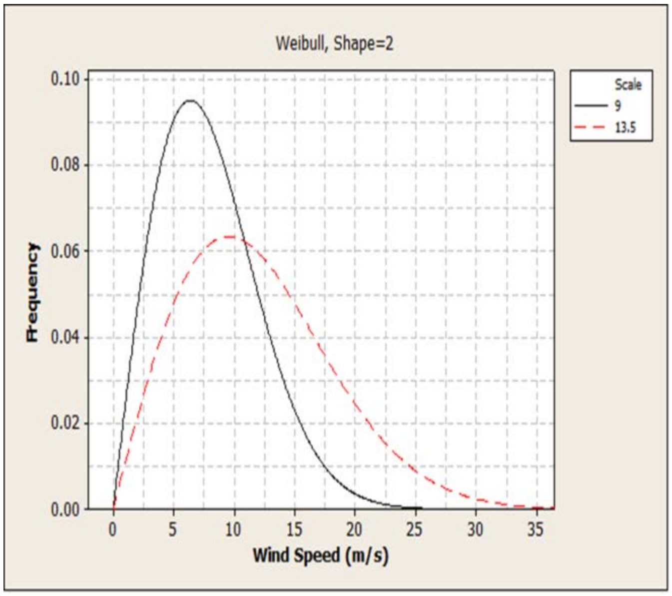


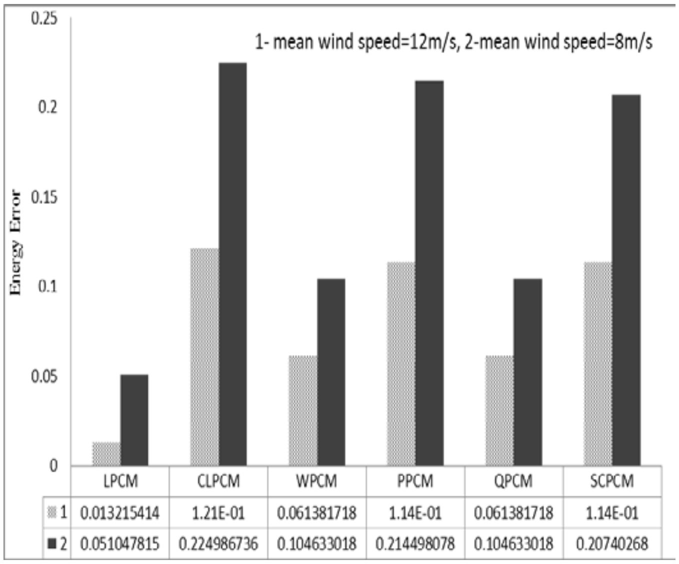
Fig. 7 Weibull distribution with mean wind speed of 8m/sec &12 m/sec

Annual energy errors as obtained are shown in Figure 8. As observed performance of linear power curve model is found to be excellent with minimum errors (1.3 % & 5.1 % for mean wind speeds of 12m/sec and 8m/sec respectively) and hence may be adopted without any hesitation for energy forecast of the single rotor wind turbine. WPCM & QPCM follows it with respective annual energy errors as 6.1% & 10.4%.

Per unit energy error for annual energy, prediction is defined as:

$$e(err) = \frac{|E - E_m|}{E_m} \qquad \text{---- (13)}$$

E_m = Annual energy production using manufacturer data



	LPCM	CLPCM	WPCM	PPCM	QPCM	SCPCM
▨ 1	0.013215414	1.21E-01	0.061381718	1.14E-01	0.061381718	1.14E-01
■ 2	0.051047815	0.224986736	0.104633018	0.214498078	0.104633018	0.20740268

Fig. 8 Annual energy error of different power curve models when used for single-rotor wind turbine

B. *Multi-Rotor Wind Turbine Simulations*

Figure 9 shows the comparison of power output of multi- rotor wind turbine when wind speed varies from $v_{ci}^{'}(R_3)$ to $\left\langle v_r^{'}(R_1) = v_r^{'}(R_2) \right\rangle$ and air density as 1.225 kg/m^3. Correlation factor(R) as obtained are shown in figure 10. Better correlation factor for LPCM, WPCM and QPCM makes them better models in comparison to others. Annual energy errors as obtained in the case of equivalent multi-rotor wind structure are shown in figure 11. LPCM results into minimum annual energy errors (1.2 % & 3.8 % for mean wind speeds of 12m/sec and 8m/sec respectively) as compared to other power curve models. WPCM & QPCM follows it with respective annual energy errors as 4.3% & 8.3%. Once again LPCM performs best.

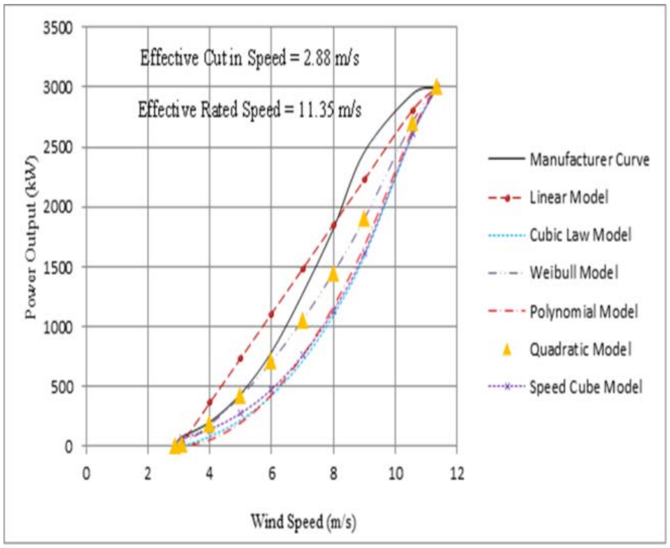
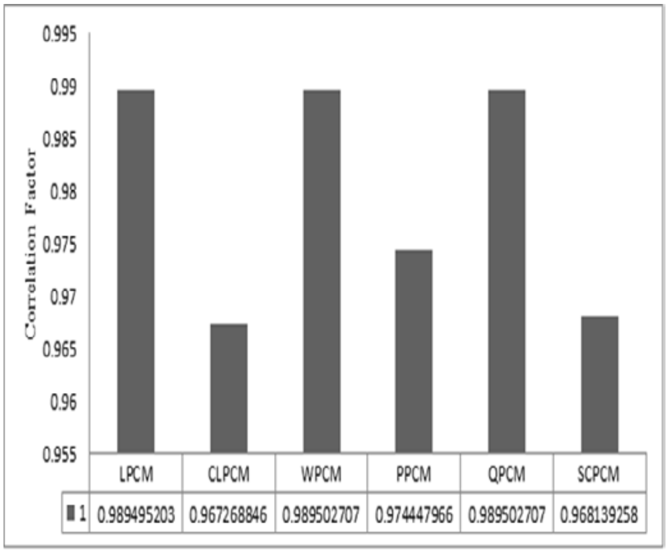


Fig. 9 Power output comparison of multi-rotor wind turbine



	LPCM	CLPCM	WPCM	PPCM	QPCM	SCPCM
■ 1	0.989495203	0.967268846	0.989502707	0.974447966	0.989502707	0.968139258

Fig. 10 Correlation coefficient of different power curves used for multi-rotor wind turbine

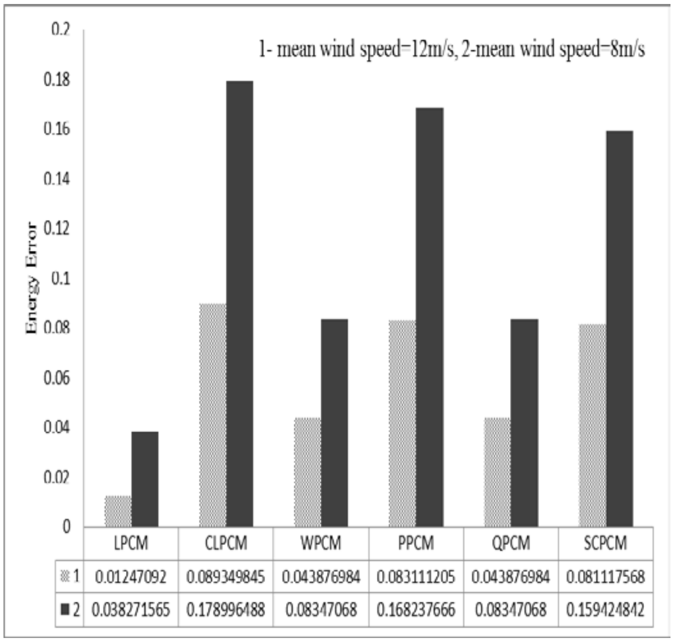


Fig. 11 Annual energy error of different power curve models when used for multi-rotor wind turbine

VI. Discussion on Results

Critical analysis of simulation results as obtained may be summarized as:

- The correlation coefficient (R), measures the strength of a linear relationship between two variables. A correlation greater than 0.8 is generally described as marginally strong and a correlation less than ‘0.5’ may be described as weak. Therefore, models with highest values of correlation coefficient may be screened as better models. On this basis LPCM, WPCM and QPCM appear to be better as compared to others in both types of turbines i.e. single-rotor and multi-rotor configuration.

- Linear power curve model (LPCM) gives excellent energy prediction with minimum annual energy errors for both types of wind turbines i.e. single-rotor as well as for multi-rotor wind turbines. Hence it can be selected as the best fit model for the performance analysis of any wind turbine.

Cost Analysis: Many researchers [53-59] tried to analyze the cost of conventional wind turbine. Keeping in view the formulation developed, Table 1 shows the cost comparison of two types of wind turbines.

Table. 1 Cost analysis if multi-rotor wind turbine

Project cost of 3000kW wind turbine = 3417843£
Cost of wind turbine = 69% of wind project cost
= 2358311 £
Foundation cost = 16% of total Project Cost
Tower cost = 16.38 % of total Project Cost
Gear box cost = 8.2624 % of total Project Cost

Sr No	**Wind turbine component**	**Component costs (£) of Single-rotor wind turbine**	**Component costs (£) of Multi-rotors wind turbine**
1	Rotor Blades	483882	448521
2	Rotor Hub	78806	108970
3	Rotor Bearing	56113	38016
4	Pitch System	126040	122289
5	Gearbox	282395	282395
6	Tower	559842	391889
7	Foundation	546854	315726
8	Other components	224374	224374
9	Support Structure (Spars + Cables)	---------	36138
Total Cost		2358306	1968318

VII. Conclusion

Large rotor size and turbine cost have diverted the attention of scientists from single-rotor to multi-rotor wind turbines. Power and energy output estimation of such turbines using conventional power curves with some modifications, will be helpful to performance of such turbines.

As per discussions in section 5 and 6, Linear Power Curve Model [LPCM] appears to be excellent among all models and hence may be adopted for power and energy forecast for any wind turbine. Annual energy yield as obtained is shown in table 2.

Multirotor wind turbine yields more energy in contrast to single rotor construction. This increase is 6.34% with mean wind speed of 8m/s & 4.76% with mean wind speed of 12m/s. Table 1 shows the cost comparison of multi rotor wind turbine with that of single rotor configuration. Cost of a multirotor wind turbine (3*1000 kW) appears to be 83.47% of single rotor wind turbine (3000 kW). Analysis, as reported, shows that an equivalent three rotor configuration results into higher annual energy yield with low installation cost.

Table. 2 Annual energy yield of wind turbine

Mean Wind Speed (m/s)	Annual Energy Yield (kWh)	
	Single Rotor	Multi Rotor
8	13516967	14374110
12	18284456	19155680

APPENDIX-A

Specifications & power output data of single-rotor turbine:

NORDEX- N117-3000 kW, Cut in speed = 3 m/s, Rated speed = 12 m/s, Cut-out speed = 25 m/s

Wind speed (m/sec)	Power Output (kW)	Wind speed (m/sec)	Power Output (kW)
3	16	8	1534
4	129	9	2131
5	333	10	2643
6	624	11	2916
7	1020	12-25	3000

Specifications & power output data of multi-rotor turbine:

LEITWIND- LTW77-1000 kW, Cut in speed = 3 m/s, Rated speed = 11 m/s, Cut-out speed = 25 m/s

Wind speed (m/sec)	Power Output (kW)	Wind speed (m/sec)	Power Output (kW)
3	24	8	617
4	69	9	839
5	150	10	952
6	269	11	1000
7	433	12-25	1000

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